AN UNSTRUCTURED-GRID, FINITE-VOLUME COASTAL OCEAN MODEL (FVCOM) SYSTEM

BY CHANGSHENG CHEN, ROBERT C. BEARDSLEY,
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The coastal ocean extends from the land-sea interface where freshwater enters the ocean through rivers and estuaries to beyond the continental shelf. Due in part to its shallow and complex bathymetry and coastline, the coastal ocean is quite dynamic and can feature large waves and currents driven by atmospheric storms and ocean tides, and large changes in water temperature and salinity due to seasonal changes in the surface weather and river runoff. The coastal ocean is also extremely productive, supporting a rich and diverse ecosystem and many major fisheries. With increasing human use and exploitation of the coastal ocean, scientific interest in understanding and predicting coastal ocean processes has increased dramatically. The first ocean circulation model designed specifically for coastal application—the Princeton Ocean Model (POM) developed by Blumberg and Mellor (1987)—led immediately to new understanding of a number of important physical phenomena driven by tidal and wind forcing and provided the first core model for coupled physical-biological modeling. Although POM and the development of other coastal ocean circulation models have advanced coastal ocean science significantly in the last 25 years, these existing models have limitations that prevent their universal application in the coastal ocean.

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A state-of-the-art coastal ocean circulation model system requires: (1) grid flexibility to resolve complex coastline and bathymetry; (2) accurate numerical methods that conserve mass, momentum, heat, and salt; (3) proper parameterization of vertical and horizontal mixing; (4) modular design to facilitate selection of the essential model components needed in scientific or management applications; and (5) the ability to use a wide variety of input data, especially as more real-time atmospheric and coastal ocean measurements become available for assimilation. This model system should be robust, have a flexible user interface, and be an "open" community model, supported by an expanding base of users that continue to improve it.

A major step towards such a system has been taken recently by a team of University of Massachusetts-Dartmouth and Woods Hole Oceanographic Institution researchers (Chen et al., 2003; Chen et al., 2004) who have developed a new prognostic, unstructured-grid, Finite-Volume, free-surface, three-dimensional primitive equation Coastal Ocean circulation Model (FVCOM) for physical and coupled physical/biological studies in coastal regions characterized by complex coastlines and bathymetry and diverse forcing. Used widely in computational fluid mechanics and engineering, the finite-volume method used in this model combines the advantage of finite-element methods for geometric flexibility and finite-difference methods for simple discrete computation (Figure 1). Verified through comparisons with analytical solutions and numerical simulations made with POM and other popular finite-difference models in idealized test cases (Chen et al., submitted), FVCOM has been successfully applied in a number of estuarine, continental shelf, and regional/open ocean studies involving realistic model domains (for more information see http://codfish.smast.umassd.edu). For hindcast and forecast applications, an integrated coastal ocean model sys-

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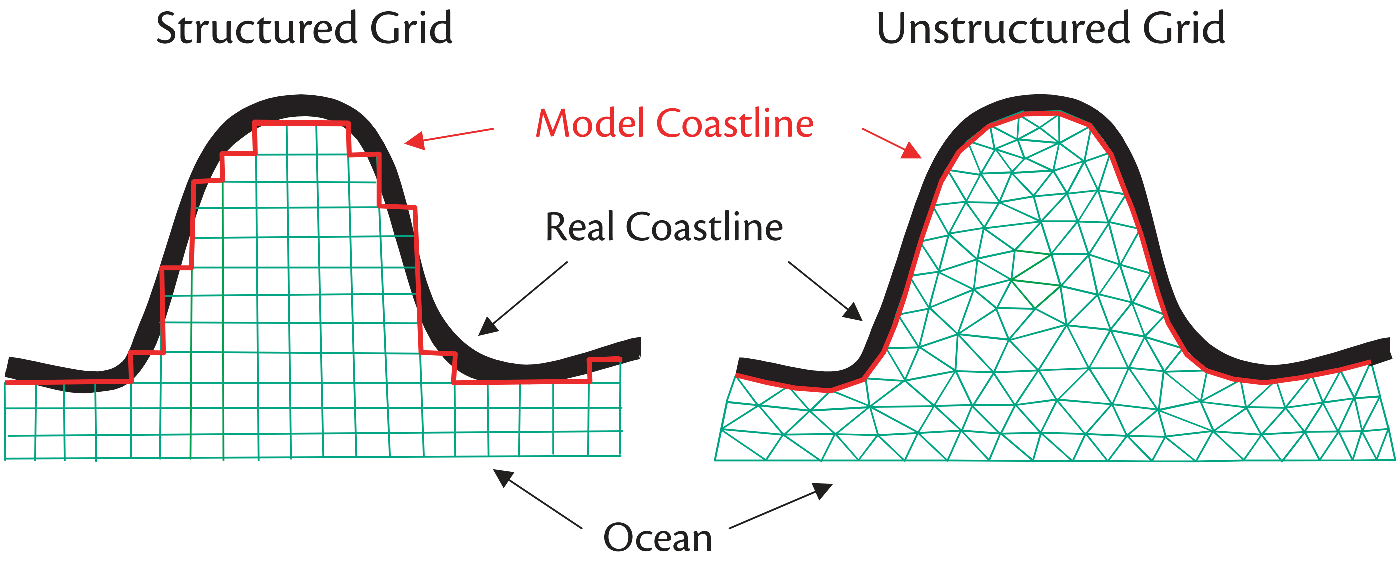

Figure 1. An example of fitting a structured grid (left) and an unstructured grid (right) to a simple coastal embayment. The true coastline is shown in black, the model coastline in red. Note how the unstructured triangular grid can be adjusted so that the model coastline follows the true coastline, while the structured grid coastline is jagged—which can result in unrealistic flow disturbance close to the coast.

tem has been built by coupling FVCOM with the fifth-generation National Center for Atmospheric Research/Pennsylvania State University (NCAR/Penn State) mesoscale meteorological model (MM5) for realistic surface forcing and the addition of advanced data assimilation.

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STRUCTURE AND FUNCTION OF FVCOM

In common with other coastal ocean models, FVCOM uses the modified Mellor and Yamada level 2.5 (MY-2.5) and Smagorinsky turbulent closure schemes as the default for vertical and horizontal mixing and a terrain-following vertical coordinate to follow bottom topography. Unlike finite-difference and finite-element models, FVCOM solves the flux form of the governing equations in unstructured triangular volumes with second-order accurate discrete flux schemes. This numerical approach provides an accurate representation of mass, momentum, heat, and salt conservation. Accurate representation is an essential feature of finite-volume methods, making them widely used in other branches of computational fluid dynamics where nonlinear advection with sharp property gradients makes conservation of scalars (like mass and heat) difficult. This conservative nature of FVCOM plus its great grid flexibility and code simplicity make FVCOM ideally suited for interdisciplinary application in the coastal ocean.

The present version of FVCOM includes a number of options and components (Figure 2), including: (1) choice of Cartesian or spherical coordinate system, (2) a mass-conservative wet/dry point treatment to simulate the flooding/drying process, (3) the General Ocean Turbulent Model (GOTM) modules (Burchard et al., 1999; Burchard, 2002) for optional vertical turbulent mixing schemes, (4) a water-quality module to simulate dissolved oxygen and other environmental indicators, (5) four-dimensional nudging and Reduced/Ensemble Kalman Filters (implemented in collaboration with P. Rizzoli; Zang and Rizzoli, 2003) for data assimilation, (6) a fully nonlinear ice model (implemented by F. Dupont) for Arctic Ocean studies, (7) a three-dimensional sediment transport module (based on the U.S. Geological Survey community sediment transport model) for estuarine and near-shore applications, and (8) a generalized biological module (GBM) for food-web dynamics study. GBM includes seven groups: nutrients, autotrophy, heterotrophy, detritus, dissolved organic matter, bacteria, and other. With various pre-built functions and parameters for these groups, GBM allows users to either select a pre-built biological model (e.g., NPZ, which has nutrient, phytoplankton, and zooplankton components) or to build their own biological model using the pre-defined pool of biological variables and parameterization functions. As shown in Figure 2, some components (e.g., an unstructured-grid surface wave model) still need to be added to form a complete integrated coastal ocean model system, which we hope to do in the near future. FVCOM is written in Fortran 90 with MPI (Message Passing Interface) parallelization, and runs efficiently on single

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and multi-processor computers.

The FVCOM grid is created using a grid-generation program and two input files—the coastline file and bathymetry data. While there are a number of such programs available, we use the grid-generation module developed for the finite-element Surface-water Modeling System (SMS). This software allows the user to specify the horizontal resolution in different parts of the domain as desired, and to easily change the resolution of an existing grid either locally or globally. Our verification studies using idealized problems and model studies using realistic domains and forcing show that the different physical processes controlling currents and stratification in the coastal ocean have inherent temporal and spatial scales that must be carefully considered when determining model grid resolution for accurate simulations. Thus, FVCOM shows great utility in examining questions of numerical convergence and determining the minimum spatial resolution needed in different parts of a model domain to obtain accurate simulation of physical processes in a region with complex coastlines and bathymetry. Because the run times of FVCOM and popular

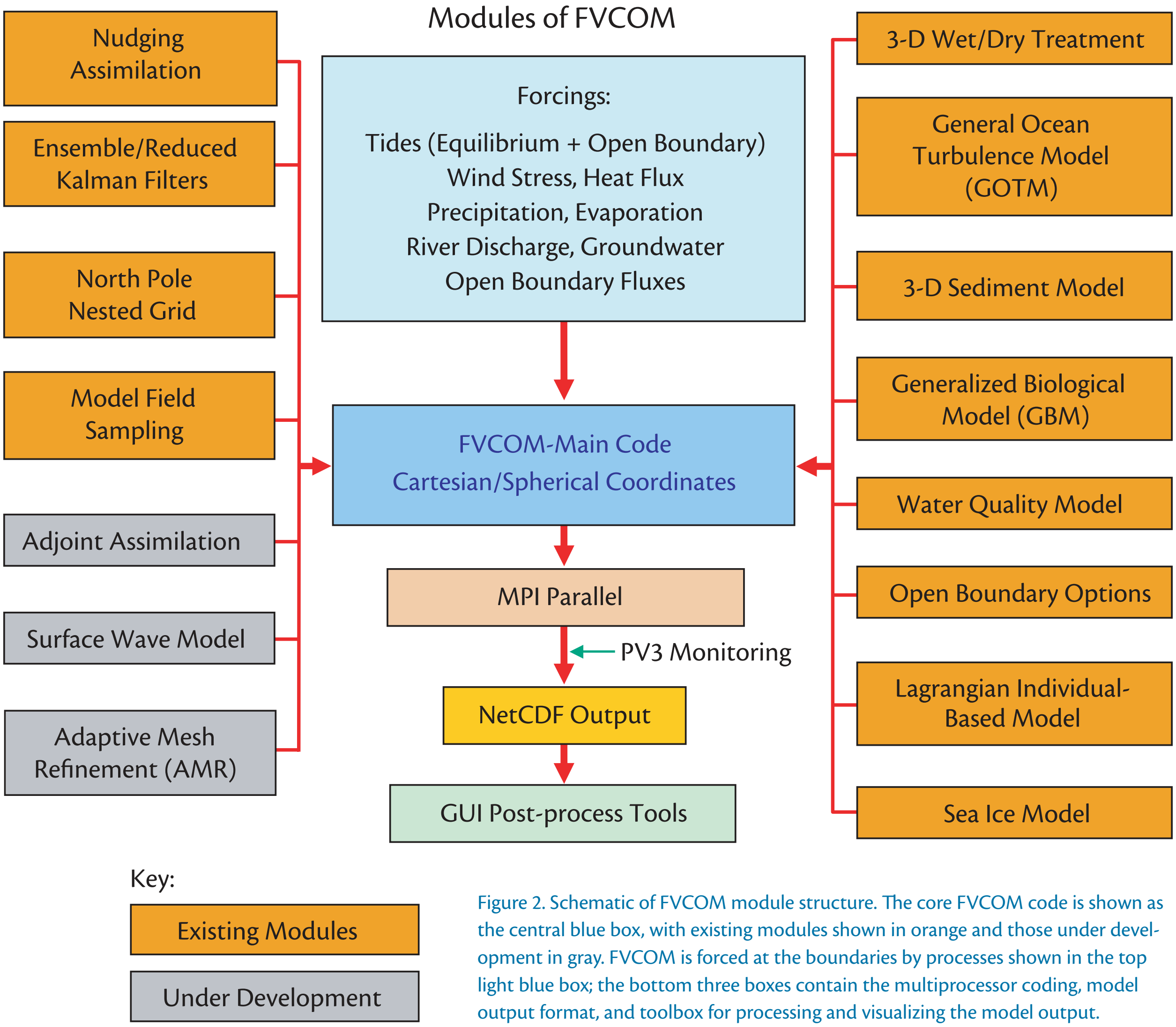


Figure 2. Schematic of FVCOM module structure. The core FVCOM code is shown as the central blue box, with existing modules shown in orange and those under development in gray. FVCOM is forced at the boundaries by processes shown in the top light blue box; the bottom three boxes contain the multiprocessor coding, model output format, and toolbox for processing and visualizing the model output.

finite-difference models scale by the total number of grid points in the model domain, the ability of an unstructured grid to reduce the number of grid points while keeping sufficient resolution in the critical regions of the domain reduces the run time relative to the structured grid models. For coastal regions with complex coastlines and/or bathymetry, this relative speed-up can be quite significant, making the FVCOM studies, described next, feasible with modest computers.

FVCOM APPLICATIONS

The Satilla River, Georgia

FVCOM was originally developed to investigate flow and stratification in the Satilla River Estuary, Georgia, after attempts to use an existing curvilinear-coordinate finite-difference model failed to capture the spatial structure. The Satilla Estuary features tidal creeks and extensive inter-tidal salt marsh zones. The resulting FVCOM grid (Figure 3) has horizontal resolution that varies with bathymetry and coastal geometry, with about 40 m in the narrow tidal creeks. With eleven σ levels, the vertical resolution in the main channel is ≤1 m. This model has been run

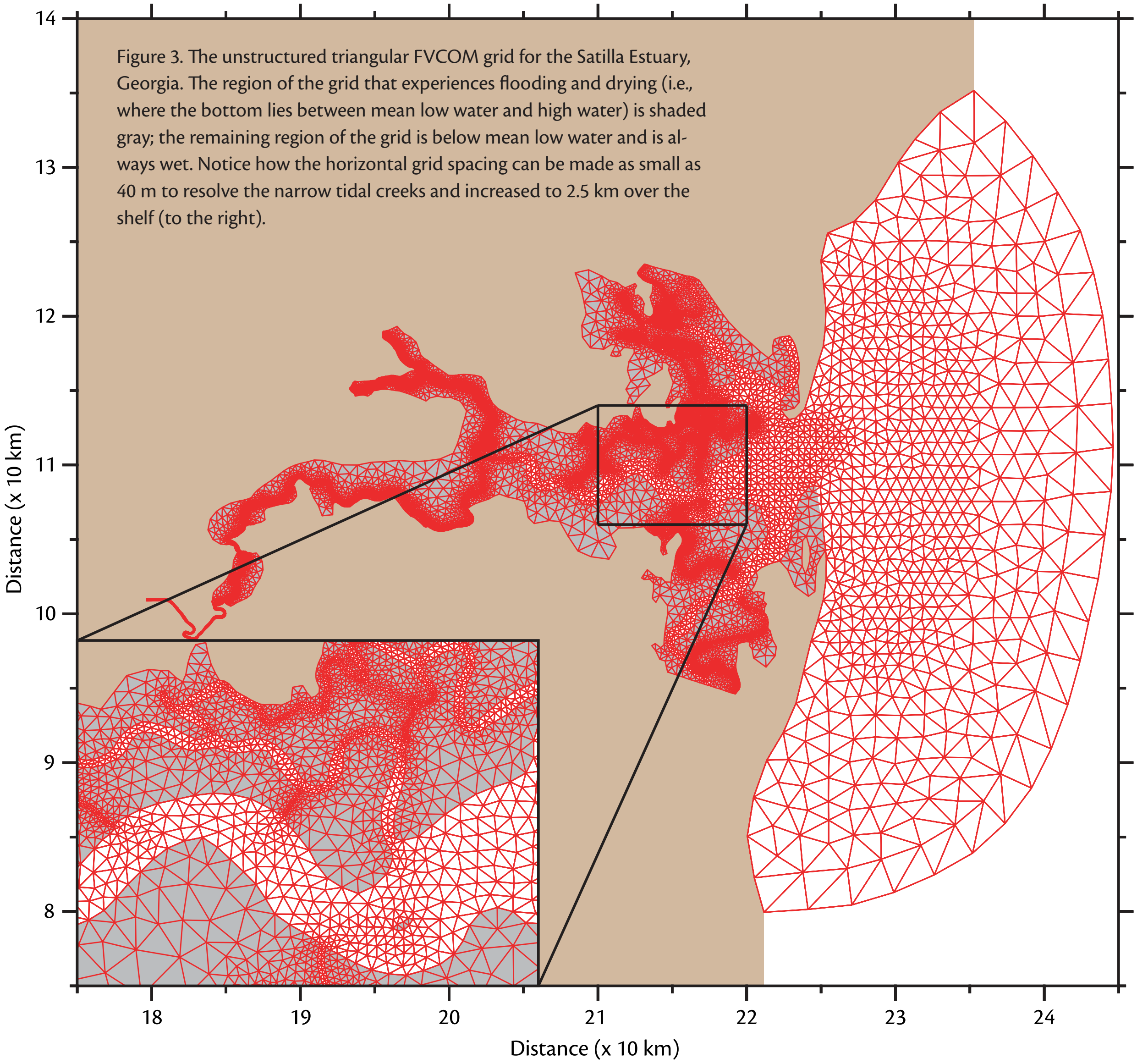


Figure 3. The unstructured triangular FVCOM grid for the Satilla Estuary, Georgia. The region of the grid that experiences flooding and drying (i.e., where the bottom lies between mean low water and high water) is shaded gray; the remaining region of the grid is below mean low water and is always wet. Notice how the horizontal grid spacing can be made as small as 40 m to resolve the narrow tidal creeks and increased to 2.5 km over the shelf (to the right).

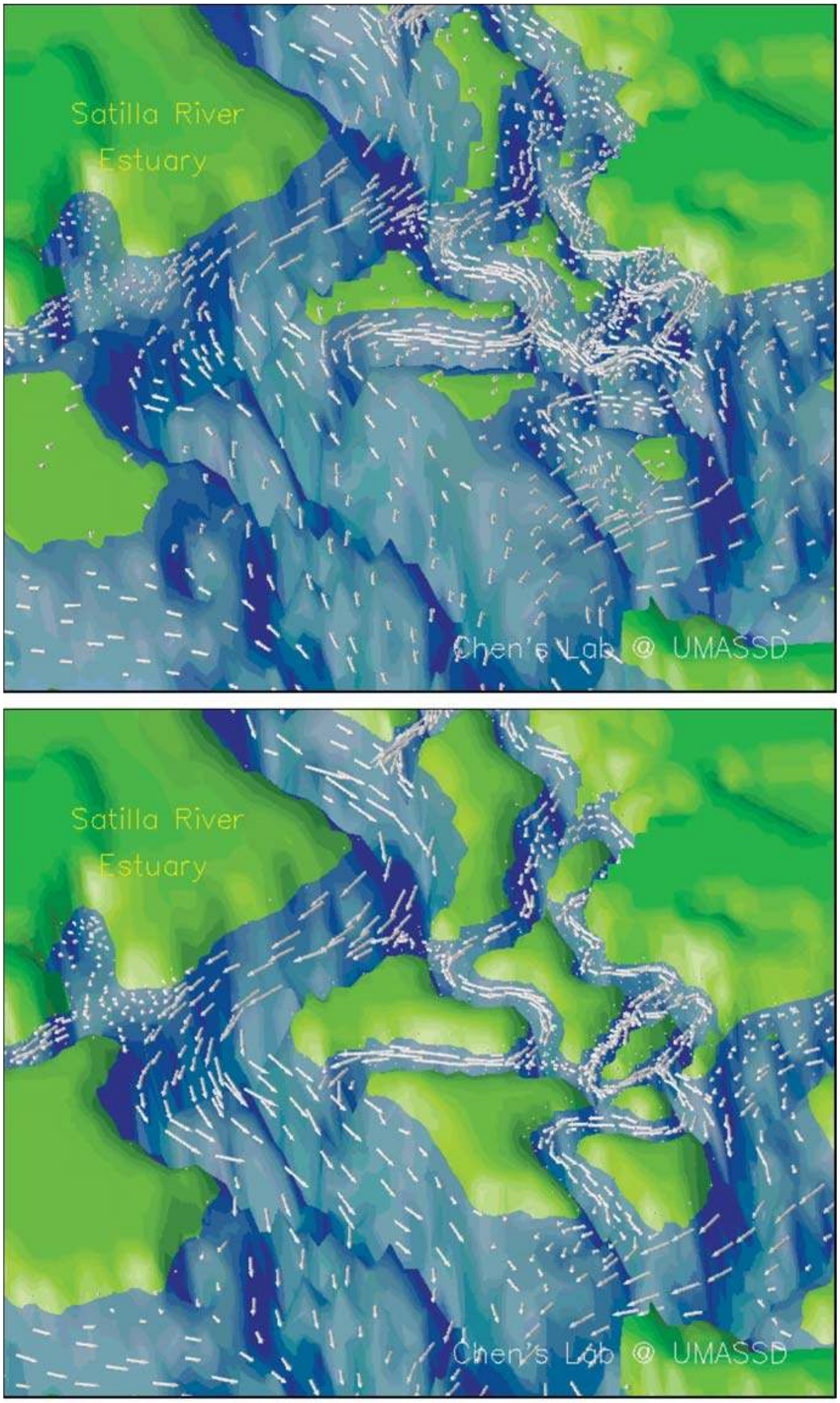
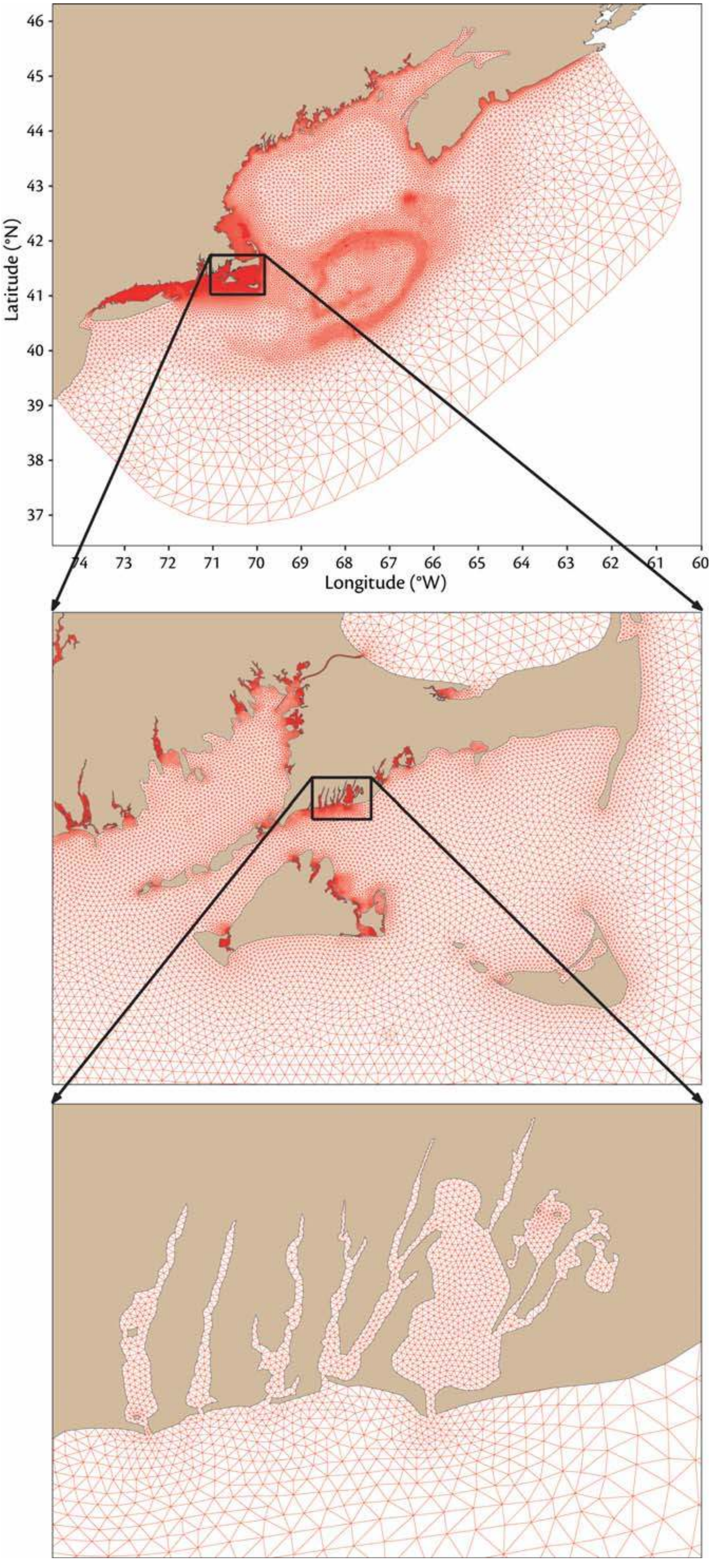


Figure 4. Distributions of water level and near-surface currents during the flood (upper) and ebb (lower) tidal stages in the lower Satilla River estuary. The viewer is looking from near the mouth of the river into the estuary. Note how the flow is tightly constrained in the narrow tidal creeks during ebb as the tidal flats emerge and dry. The white current vectors are sub-sampled to make the image viewable.

in hindcast mode starting on August 15, 2003 using real-time tidal forcing at the open boundary, MM5-output surface wind stress and heat flux, and freshwater discharge at the river head. Comparisons with *in situ* hydrographic, surface drifter, and aircraft water-level measurements indicate that FVCOM accurately captures the tidal-, wind-, and buoyancy-driven flow (including tidally induced flooding and drying) in this estuarine-tidal creek-intertidal salt marsh complex (Figure 4) and correctly predicts the seasonal variation in salinity. This model system is currently being transitioned to Georgia Sea Grant management and the Georgia Department of Natural Resources for routine prediction of flow, stratification, and water quality in the Satilla River Estuary.

The Gulf of Maine/Georges Bank/ New England Shelf

As part of the U.S. GLobal Ocean ECosystems (GLOBEC) Georges Bank program, FVCOM is being used to hindcast currents and hydrography in the Gulf of Maine/Georges Bank/New England Shelf region for the 1995–1999 field observation period (Figure 5). To date, model simulations have been completed for two years (1995 and 1999) using realistic ocean tidal and GoM-MM5 mesoscale surface forcing (Chen et al., 2005), four-dimensional data assimilation of five-day averaged satellite sea surface temperature (SST) and available moored current data, and open boundary conditions. The model tides compare very well with available surface elevation and current data, with overall uncertainties for the dominant semidiurnal M_2 component of less than 3 cm in amplitude, 5° in phase,

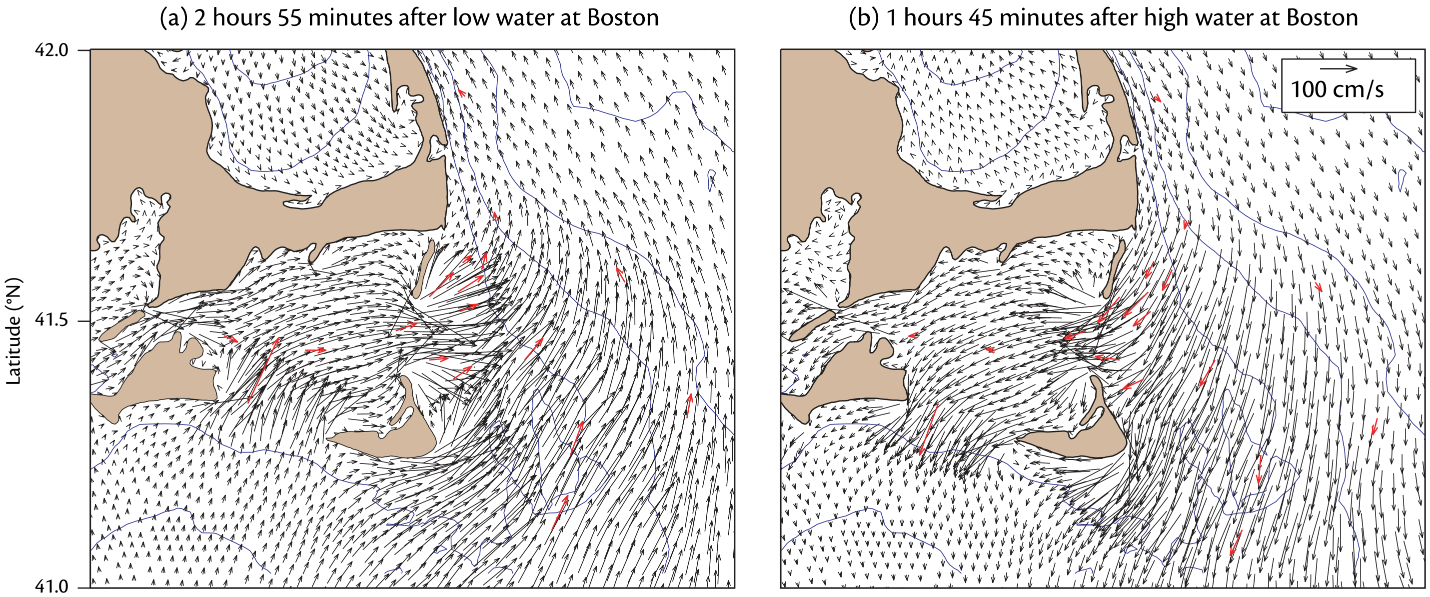


and 3 cm/s in the tidal current major axis. The model subtidal currents and stratification also compare well with existing *in situ* measurements, capturing the seasonal cycle in vertical stratification and increased around-bank circulation from June to September. These two one-year hindcasts clearly illustrate significant short-term (daily to weekly) and long-term (seasonal and interannual) variability in the subtidal currents and stratification on Georges Bank. Particle tracking experiments using the model flow field also illustrate the sensitivity of the exact location and timing of release on the retention of particles on the bank. These initial hindcasts indicate the importance of using the GoM-MM5 mesoscale surface forcing fields with four-dimensional SST data assimilation to accurately capture subtidal current and water-property variability. Figure 6 shows model computed M_2 currents over a tidal cycle in and near Nantucket Sound compared with Haight's (1942) measurements. The model flow structure helps explain the high spatial variability seen in the sparse field measurements, and shows clearly the process of flow separation at abrupt changes in coastline orientation (e.g., headlands and points) described by Signell (1989). As a result, the time-mean flow field exhibits strong gyres east of Nantucket and Cape Cod (Figure 7).

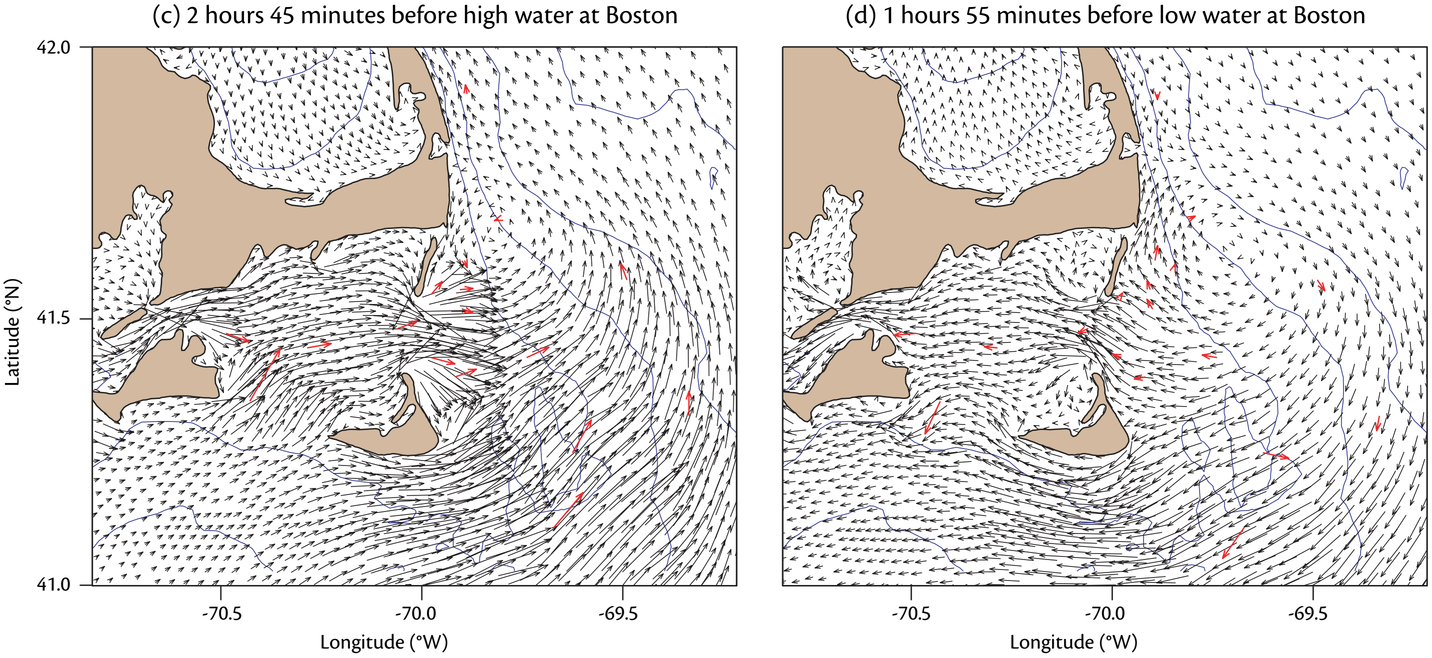
Figure 5. The FVCOM grid for the Gulf of Maine/Georges Bank/New England Shelf region, with horizontal resolution ranging from 0.5–1.0 km on Georges Bank, 0.3–0.5 km near the coast and in Nantucket Sound, and 20–70 m in rivers, inlets, and adjoining coastal area to as much as 10 km towards the open boundary off the shelf.

The Arctic Ocean

The spherical-coordinate version of FVCOM was first developed to study tidal phenomena in the Arctic Ocean. The model grid closely fits the complex coastal geometry around the Arctic, with horizontal resolution varying from 1–3 km in the Arctic Archipelego, along the coast, and near the shelf break and deep ridges to 10–15 km in the interior basins. When run with tidal forcing at the open Pacific and Atlantic Ocean boundaries and grav-


(a) 2 hours 55 minutes after low water at Boston

(b) 1 hours 45 minutes after high water at Boston


(c) 2 hours 45 minutes before high water at Boston

(d) 1 hours 55 minutes before low water at Boston

Figure 6. Time sequence of vertically averaged tidal current vectors in Nantucket Sound and adjacent regions during a tidal cycle relative to the water elevation at Boston. Red vectors represent the observed currents shown in Haight (1942). HT (High Tide) and LT (Low Tide) indicate high and low water elevation in Boston. Notice the strong flow separation that occurs at the northern tip of Nantucket during flow to the east (panels a and d). This nonlinear process causes an asymmetry in the tidal flow and results in a mean tidally driven residual circulation.

itational forcing within the domain, FVCOM successfully simulates the complex spatial patterns of tidal elevations and currents and provides a detailed view of the tidal energy flux that links the various bays and inter-island areas with the deeper basins. The model-computed M_2 co-tidal chart is shown in Figure 8.

We hope these initial results will encourage others to use FVCOM as an alternative high-resolution model tool for future Arctic Ocean studies.

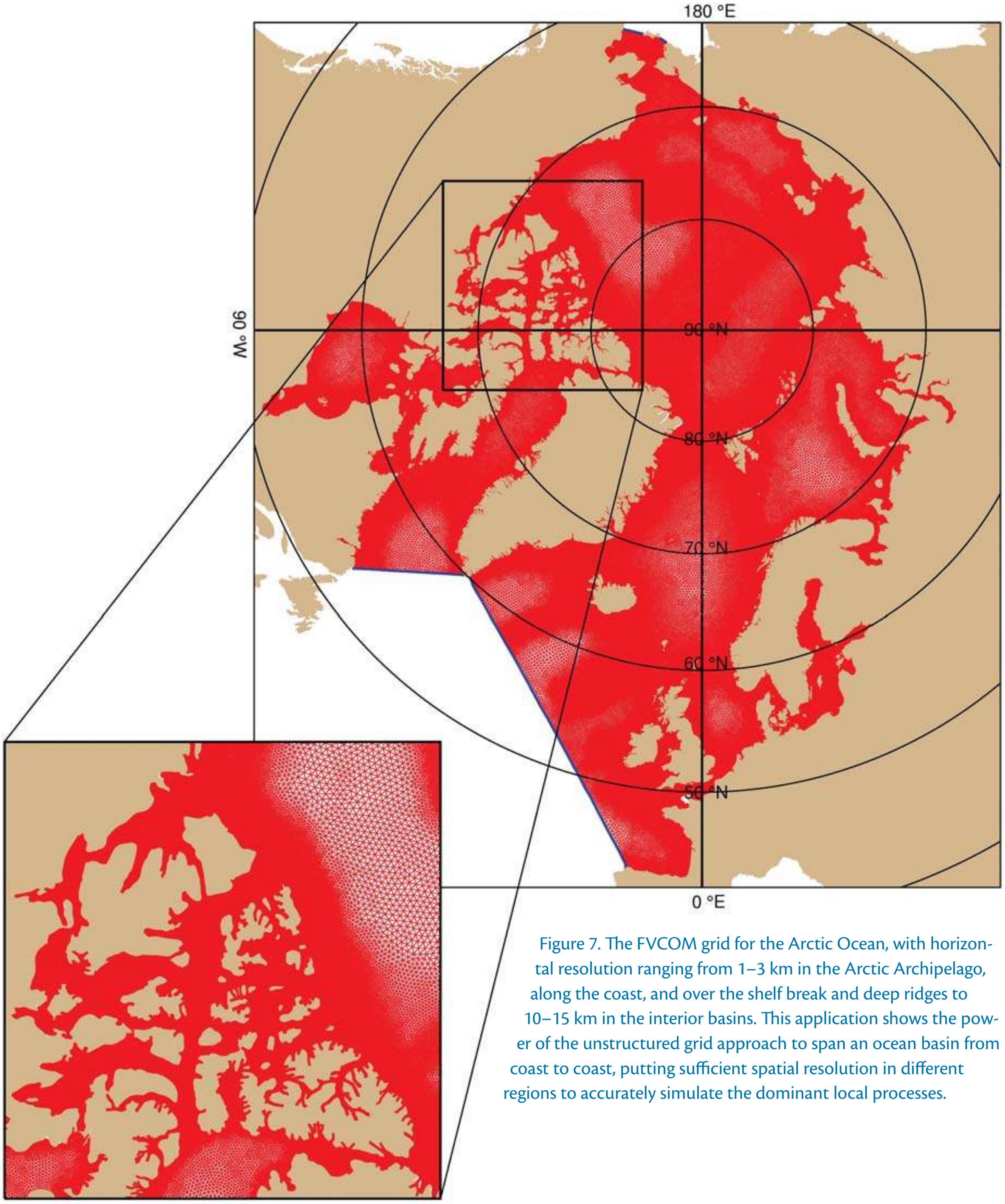


Figure 7. The FVCOM grid for the Arctic Ocean, with horizontal resolution ranging from 1–3 km in the Arctic Archipelago, along the coast, and over the shelf break and deep ridges to 10–15 km in the interior basins. This application shows the power of the unstructured grid approach to span an ocean basin from coast to coast, putting sufficient spatial resolution in different regions to accurately simulate the dominant local processes.

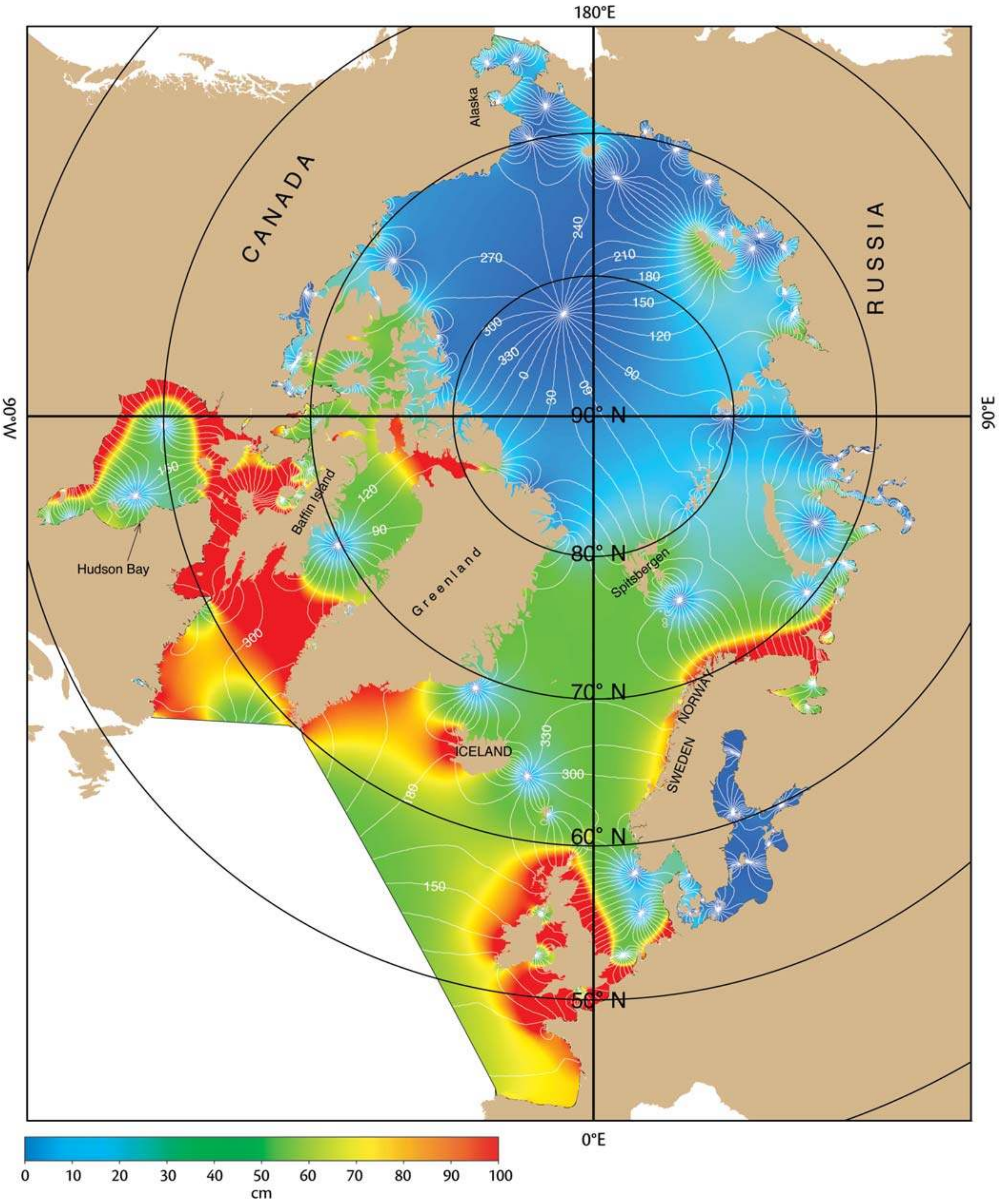


Figure 8. The model-computed M_2 cotidal chart for the Arctic Ocean and adjacent regions. The amplitude of the surface elevation is shown in color, ranging from 0 cm (blue) to 100 cm (red). The solid white lines indicate the phase of high water relative to Greenwich, with a contour interval of 15 degrees. Note the small tide rotating counterclockwise around an amphidromic point in the central Arctic basin, and the very strong tides in the North Sea and parts of the Archipelago.

SUMMARY

The unstructured-grid, finite-volume methods used in FVCOM make it an exciting new research tool for physical and interdisciplinary ocean modeling studies involving domains with complex coastlines and/or bathymetry. Because of current limitations in computational capability, coastal modeling efforts are usually focused on a specific coastal region surrounded by an open boundary. This approach makes it easy to examine the response of the coastal ocean to local forcing, but causes both limitations in the ocean processes that can be included and numerical difficulties in dealing with open boundary conditions. As computer power increases, it will become more feasible and desirable to extend the global ocean model to cover the coastal regions in greater detail. The geometric flexibility inherent in an unstructured-grid model can provide a better alternative to bridge the global and coastal ocean models. We encourage readers to visit the FVCOM web site (http://codfish.smast.umassd.edu/FVCOM.html), ask questions, and consider using FVCOM in future work. The first new-user workshop was held in June 2004, a second will be held in June 2006, and a third is scheduled for June 2008.

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