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A RAPIDLY RELOCATABLE OCEAN PREDICTION SYSTEM

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Accurate ocean forecast requires and combines knowledge in physics, mathematics, computer sciences, drawing greatest advantage of the new technologies for access, analysis and distribution of the data. We will describe NCOM_OS, a portable, relocatable, and user-friendly prediction system based on the Naval Coastal Ocean Model (NCOM). The system has been developed and routinely applied in support of naval operation. With this product, analysis and prediction can be provided for any part of the word, usually within six hours of the request. For a rapid configuration, a set of data and products are available on a global scale (bathymetry, forecasted winds, analysis of the remote sensing data). These products are generally on a low resolution and the system has the capability of replacing them with local and high-resolution databases. The simulations are usually on multiple 1-way nesting domains. The open boundary conditions for the outer nest are extracted from a operational, real-time global version of NCOM with approximately $1/8^o$ resolution at mid-latitudes. We will present the results from some real-time exercises in coastal areas. One of the current applications is in support of the Autonomous Underwater Vehicle (AUV) testing exercise off Panama City, Fla. A preliminary configuration started running in a pseudo-operational mode (real-time forecast with forecasted winds) on August 15 2004. We will present this configuration and discuss how it was able to model in real-time the effects of Hurricanes Ivan and Katrina on the Gulf of Mexico and its coastal areas.

1. Introduction

The capability of describing and predicting the structure and the dynamic state of the ocean has important applications not only in the scientific oceanographic disciplines, but also for every social-economical activity aimed to the exploitation, protection and control of the resources of the marine ecosystem. Ocean studies and marine operations involve the realistic estimates of physical fields (velocities, pressure, temperature, and salinity) from both ocean observing and modeling simulations. This involves a description of the current state (nowcast) from dynamical interpolations of available data and nowcast and forecast from data-driven models, requiring and combining knowledge in physics, mathematics, computer sciences, and drawing greatest advantage of the new technologies for access, analysis and distribution of the data.

Wind and thermohaline driven currents characterize the large-scale long-term circulation in the deep ocean: these currents are forcing the shelf regions that are acting as a dissipative boundary layer for the ocean basin. Moreover, the coastal and deep-ocean dynamics are quite different. For example, typical time scales over the shelf are generally much shorter than in deep water; indeed, the detailed connections between the basin slowly-varying and the coastal high-frequency dynamics are so far no completely understood. Therefore, modeling coastal and littoral areas cannot be achieved without taking into account the influences of the basin-scale processes and the mutual interactions between the shallow and deep waters. A coastal environmental prediction system at short and medium time scales would require the understanding and modeling of the large spatial and long time scales, as well as the local and short scales. A possible methodological approach, such as the one addressed in this study, is to build a hierarchy of nested models from global to regional to high-resolution coastal domains.

This paper is organized as follows. Sect 2 introduces the mathematical formulation of the ocean dynamics models, Sect 3 presents the real-time operational configuration and Sect. 4 discusses the criteria for the evaluation. Finally, Sect 5 summarizes this study.

2. The mathematical model

The starting point of a dynamic ocean model is constituted by the Navier-Stokes (NS) equations. The principal hypothesis and approximations that apply to ocean circulation models are:

- Water is incompressible (except for sound propagation problems).
- The water columns are assumed to be parallel since the ocean depth (order of 5000m) is small as compared as to the Earth's radius (order of 6000 km).
- Boussinesq approximation: it is possible to neglect the effects of density variations on the mass but not on the weight.
- Hydrostatic equilibrium: The pressure difference between two points on the same water column is equal to the weight as if the fluid were at rest.

The model comprises 5 prognostic equations (the 2 horizontal velocity components u and v; the sea surface elevation, h, and the constituent temperature, T, and salinity, S). The complete set of equations can be found in Barron *et. al.* (2005). From a mathematical point of view, the equations (often referred as to primitive equations) are a combination of parabolic (heat equation), hyperbolic (wave equation), and, sometimes with further physical hypothesis and/or specific numerical methods, elliptic (potential) equations. Phenomena of turbulence and features at a scale smaller than the grid resolution are generally parameterized by closure tensorial schemes of the 2nd order. This implies two additional prognostic variables (Blumberg and Mellor, 1983).

More complex is the specification of the fields at the boundaries that generally include open portions. It is well known that problems with open boundary conditions (OBC) are ill posed: uniqueness and existence of the solutions is known only for a limited class of operators. Numerical formulations usually require that the phenomena propagating inside the domain are known and specified as external forces, and utilize algorithms to allow the features propagating outside the domain to leave *unchanged.* The external forces are represented by the energy from the winds and the transfer of heat and evaporation at the surface, generally obtained from meteorological models. Tidal flow is usually specified at the boundaries and estimated from the global tidal model developed at Oregon State University (Erofeeva *et.al*., 2003).

3. Real-time forecasting applications

The main purpose of this paper is to describe a real time ocean prediction system developed at the Naval Research Laboratory (NRL) in support of naval operations. The system is portable on several computer platforms and operating systems, and rapidly relocatable. Analysis and prediction are available for any part of the world usually within a few hours from the request, making it a particularly useful system in emergency situations. For a rapid configuration, the system relies on a set of data and products available on a global scale (bathymetry, winds, analysis of the remote sensing data). These products are generally on a low resolution and there is the capability of replacing them with local and high-resolution databases. The prediction system is routinely applied in naval operations, and it has been successfully applied in several emergency situations such as the attempted rescue of the Russian submarine Kursk in the Barents Sea (August 2000), the recover of the Japanese fishing vessel Ehime sunk near Pearl Harbor (August 2001), and the cleaning and recovering operations of the oil tanker, Prestige, sunk off the Spain coast (November 2000).

The main engine is based on the Naval Coastal Ocean Model (NCOM) (Martin, 2000). The NCOM has been developed for use in a coupled ocean-atmosphere model for simulating mesoscale and coastal dynamics. The NCOM is similar in its physics and numerics to the Princeton Ocean Model (POM) (Blumberg and Mellor, 1987), but has some differences and additional physical and numerical options that make the model physically accurate, computationally efficient, and easily portable. A set of programs and scripts prepares the input (i.e., initial and open boundary conditions, atmospheric forcing) and the output files for further applications/ models/graphics. Switches and flags control the numerical and physical parameters. The major challenge is to offer a default set of parameters that can provide accurate solutions for any given configuration, yet allowing the flexibility of tuning and calibrating for a given domain configuration. Since is it unrealistic to assume data are available at the spatial and temporal resolutions necessary for specification of the boundary conditions, the system has the capability of multiple 1-way nesting from basin-scale to regional to high-resolution coastal domains,. The OBC for the outer nest are extracted from NCOM configured on a global scale (global models do not have open boundary conditions!) at about a 1/8° resolution in latitude and longitude (Barron *et. al.*, 2005). The global model (henceforth referred as to NCOM_GLB) is running operationally on a daily base at the Naval Oceanographic Office (www7320.nrlssc.navy.mil/global_ncom/index.html). However, the procedure is not restricted to NCOM to NCOM nesting, but it is possible to couple the outer nest with several other dynamical model formulations.

The daily predictive cycle is as follows:

- NCOM is started from yesterday's nowcast (-24 hr) and forced by the available operational winds.
- During the nowcast, T and S are nudged to the nowcast field of the parent simulations. No data are assimilated or nudged into the prediction system after the nowcast (0 hr). Work is in progress to develop a more comprehensive data assimilation scheme of all available real-time observations and measurements.
- A short-term (2-day) forecast is provided. The 48-hour interval has been chosen because this is the typical period in which meteorological mesoscale forecasts are available and reliable.
- OBC, initial and nudging fields are extracted from the simulation of the parent domain for the total length of the simulation.

Once each domain has been individually configured, a single script (usually a cron job) launches the nested simulations. The domains are executed in sequence from the outer to the inner nest, but each domain may be executed on a parallel processing environment. Fig. 1 illustrates the nesting procedure in the Gulf of Mexico.

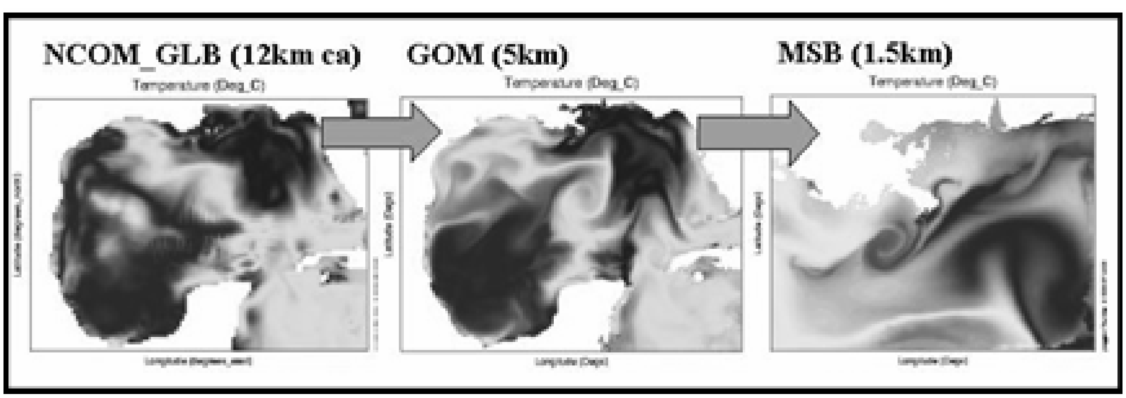

Fig.1 The multiple nesting procedure from global NCOM to the high-resolution coastal model of the Mississippi Bight. Each snapshot represents surface temperature field. Please note the different representation of the coastline in each domain.

4. Model evaluation

There is a fundamental difference between assessing an ocean model configuration in a research and in an operational mode. A research predictive system is designed, calibrated, and evaluated to encompass the dominant dynamics of a given region. The goal is to provide the most accurate representation of the dynamical features of a specific area. A predictive system that supports operational applications must be rapidly relocatable anywhere in the ocean (oil-spill and naval exercises are the most relevant applications), and easily reconfigured. The principal goal is to provide good representations everywhere with the available data (i.e., in spite of the lack of observations). In this respect, different metrics and criteria should define the development and evaluation of the two modeling approaches.

The accuracy of a model solution depends upon the accuracy of the ingested data. Therefore, modelers are on a continuous quest for improved data set and high-frequency measurements. One the major problems in evaluating a real-time forecasting system are the lack of data for validating the results. Most of the applications already lack in situ data to be ingested into the predictive system, so that the model-data comparison is virtually impossible. A posteriori analysis and hindcast simulations are necessary for an overall evaluation of the model performances, but they cannot provide the information necessary during real-time operations. In this regard, the goal is to evaluate the solution, make the necessary changes in the model calibration, and improve the accuracy of the following cycle. Therefore, a timely, useful validation requires real-time, easily accessible data, such as those available from the web.

For example, during the Prestige simulations, a source of real-time data was a series of buoys and tide-gauge stations along the Spanish costs available at: www.puertos.es/index.jsp and drifters launched along the Cantabrian coast at the beginning of the oil spill (Peggion, 2005). Tide gauges and buoys data from the NOAA observational network http://www.co-ops.nos.noaa.gov/ and http://www.ndbc.noaa.gov/ are used for evaluating the model assessment as illustrated in Fig.1 during the passage of Hurricane Ivan on September 2004 (Fig. 2). The model successfully predicts the storm surge and the upwelling along the on the Mississippi coast (Fig. 2a and 2c) and reproduces the higher tidal frequency observed west of the Mississippi river (Fig 2b).

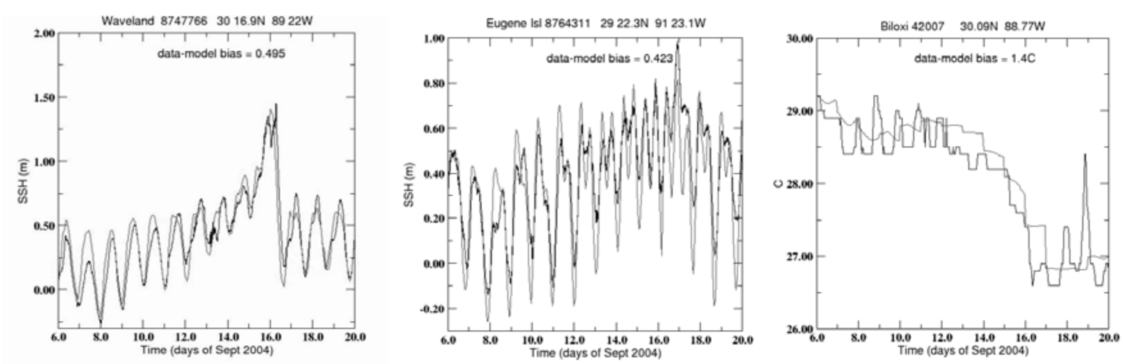

Fig.2. Model-data comparison during the passage of Ivan. Model forecast is from the inner most domain of Fig.1. Data are from tide gauge at (a) Waveland, MS., (b) Eugene, LA., and (c) NOAA buoy off Biloxi MS.

Unfortunately, due to the violence of the storm, data for Hurricane Katrina are too incomplete for a model-data comparison in the vicinity of the landfall. However, preliminary analysis indicates that the model forecast is in agreement with the reported estimates. The model predicts a storm surge in the Mississippi coast at about 3m which is much smaller than the reported estimates (about 8m) but which does not include the wave factor (reported at about 5m height). With respect to New Orleans, the model is able to reproduce the evolution of storm surge in Lake Pontchartrain. As Katrina moved over land on Monday, August 29, 2005; the water it brought surged into Lake Pontchartrain. The lake, which normally is 30cm above sea level, peaked above 2.5m. As the water receded from the Mississippi coast, it inhibited the outflow at the narrow passage connecting the lake with the coastal areas; the straining levees could not hold back the persistent additional volume of water and they broke with the well-known devastating effects. It has been reported that Thursday afternoon the water had dropped only to approximately 75cm above sea level (http://edition.cnn.com/2005/WEATHER/09/01/orleans.levees/index.html) without releasing the pressure on the New Orleans levee system.

5. Conclusion

This study presents NCOM_OS, an ocean prediction system designed in support of real-time naval operations. The physical dynamical model is based on a primitive equation formulation and the data assimilation scheme is based on a nudging algorithm. Work is in progress for developing more complete assimilation schemes.

Sustained accurate ocean estimates of the current state of the ocean and forecast of the flow evolution are now feasible because of the advent of ocean prediction systems. The accuracy of a forecast depends on the knowledge of the current state and accuracy of the derived nowcast. This implies a network of observations and measurements from remote sensing to buoys and moorings, to ships, and most recently to autonomous undersea vehicles, and a timely retrieve of the data. Data usually converge at some laboratory or operational center and are processed and blended with the prior model runs to provide a 3-dimensional representation of the ocean conditions to be used for model initialization and boundary conditions. Meteorological Centers provide the predicted atmospheric forcing. Therefore, the dynamical components are the last rings of a long chain of products. Behind each product, behind each step of the process there is a team of people and computational and technological resources (Rhodes et al., 2002).

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