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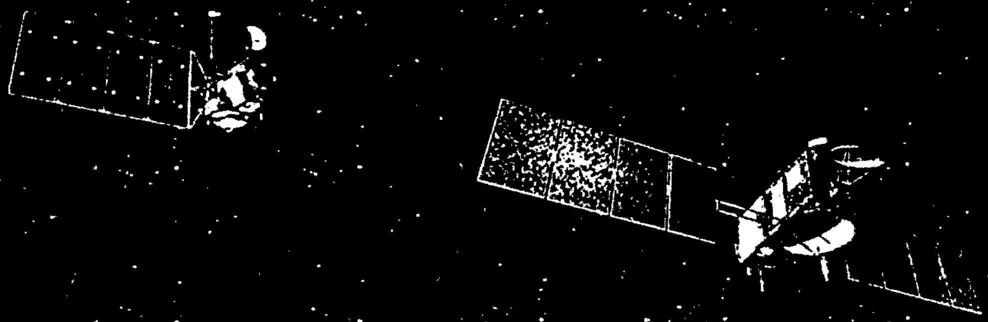

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The Modeling Component of Ocean Forecasting

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Abstract – The ocean numerical model is one of the three essential components of an ocean forecasting system. Observational data, via data assimilation, set the stage for the model forecast. The quality of the forecast will primarily depend on the ability of the ocean numerical model to faithfully represent the ocean physics and dynamics. Even the use of an infinite amount of data to constrain the initial conditions will not necessarily improve the forecast against persistence of a poorly performing ocean numerical model. In this paper, we briefly review the present state of the art of numerical models within the context of operational global ocean prediction systems, discuss their limitations, and present some of the challenges associated with global ocean modeling. We also briefly address how ocean model development can benefit from such operational systems.

1 – Introduction

The purpose of this paper is to briefly review the present state of the art of numerical models within the context of operational global ocean prediction systems, and to address how ocean model development can benefit from such operational systems. The emphasis is on what is needed for the ocean model to get the dynamics right, since the model will act as a dynamical interpolator in conjunction with the data assimilation to provide a nowcast followed by an ocean forecast.

2 – Brief overview of ocean models

This section is heavily borrowed from the overview article of Griffies et al. (2000a). Despite the emphasis of Griffies et al. (2000a) on ocean climate models, most of the points discussed in that article are relevant to global ocean forecasting models, although there are some differences and additional points to consider.

Historically, ocean models have been used primarily to numerically simulate the space-time scales that characterize the ocean system. Realizing simulations of physical integrity requires both an ability to accurately represent the various phenomena that are resolved, and an ability to parameterize those scales of variability that are not resolved (Chassignet and Verron, 1998). For example, the representation of transport falls into the class of problems addressed by numerical advection schemes, whereas parameterizing sub-grid scale transport is linked to turbulence closure considerations. Although there are often areas of overlap between representation and parameterization, the distinction is useful to make and it generally lies at the heart of various model development

Before the Navier-Stokes differential equations can be solved numerically, they must be converted into an algebraic system, a conversion process that entails numerous approximations. Numerical modelers strive to achieve numerical accuracy. Otherwise, the discretization or "truncation" error introduced when approximating differentials by finite differences or Galerkin methods becomes detrimental to the numerical realization. Sources for truncation errors are plentiful, and many of these depend strongly on model resolution. Examples include horizontal coordinates (spherical and/or generalized orthogonal), vertical and horizontal grids, time stepping schemes, representation of the surface and bottom boundary layers, bottom topography representation, equation of state, tracer and momentum transport, subgridscale processes, viscosity, and diffusivity. Numerical models have improved over the years not only because of better physical understanding, but also because modern computers permit a more faithful representation of the differential equations by their algebraic analogs.

A key characteristic of rotating and stratified fluids, such as the ocean, is the dominance of lateral over vertical transport. Hence, it is traditional in ocean modeling to orient the two horizontal coordinates orthogonal to the local vertical direction as determined by gravity. The more difficult choice is how to specify the vertical coordinate. Indeed, as noted by various ocean modeling studies such as DYNAMO (Meincke et al., 2001) and DAMEE-NAB (Chassignet and Malanotte-Rizzoli, 2000), the choice of a vertical coordinate system is the single most important aspect of an ocean model's design. The practical issues of representation and parameterization are often directly linked to the vertical coordinate choice. Currently, there are three main vertical coordinates in use, none of which provides universal utility. Hence, many developers have been motivated to pursue research into hybrid approaches.

There are three regimes of the ocean that need to be considered when choosing an appropriate vertical coordinate. First, there is the surface mixed layer. This is a region that is generally turbulent and dominated by transfers of momentum, heat, freshwater, and tracers. It is typically very well mixed in the vertical through three-dimensional convective/turbulent processes. These processes involve non-hydrostatic physics, which require very high horizontal and vertical resolution to explicitly represent (i.e., a vertical to horizontal grid aspect ratio near unity). A parameterization of these processes is therefore necessary in primitive equation ocean models. In contrast, tracer transport processes in the ocean interior predominantly occur along constant density directions (more precisely, along neutral directions). Therefore, water mass properties in the interior tend to be preserved over large space and time scales (e.g., basin and decade scales). Finally, there are several regions where density driven currents (overflows) and turbulent bottom boundary layer processes act as a strong determinant of water mass characteristics. Many such processes are crucial for the formation of deep water properties in the World Ocean.

The simplest choice of vertical coordinate is z, which represents the vertical distance from a resting ocean surface. Another choice for vertical coordinate is the potential density (rho) referenced to a given pressure. In a stably stratified adiabatic ocean, potential density is materially conserved and defines a monotonic layering of the ocean fluid. A third choice is the terrain following sigma-coordinate.

The depth or z-coordinate provides the simplest and most established framework for ocean climate modeling. It is especially well suited for situations with strong vertical/diapycnal mixing and/or low stratification, but has difficulty in accurately representing the ocean interior and bottom. The density coordinate, on the other hand, is well suited to modeling the observed tendency for tracer transport to be along density (neutral) directions, but is inappropriate in unstratified regions. The sigma-coordinate provides a suitable framework in situations where capturing the dynamical and/or boundary layer effect associated with topography is important. Sigma-coordinates are particularly well-suited for modeling flows over the continental shelf, but remain unproven in a global modeling context. They have been used extensively for coastal engineering applications and prediction [see Greatbatch and Mellor (1999) for a review], as well as for regional and basin-wide studies.

Ideally, an ocean model should retain its water mass characteristics for centuries of integration (a characteristic of density coordinates), have high vertical resolution in the surface mixed layer for proper representation of thermodynamical and biochemical processes (a characteristic of z-coordinates), maintain sufficient vertical resolution in unstratified or weakly-stratified regions of the ocean, and have high vertical resolution in coastal regions (a characteristic of sigma-coordinates). This has led to the recent development of several hybrid coordinate numerical models that combine the advantages of different types of coordinates in optimally simulating coastal and open-ocean circulation features [i.e., sigma-z (OPA: Madec et al., 1996; NCOM: Rhodes et al, 2002), rho-z-sigma (HYCOM : Bleck, 2002)].

Within the GODAE context, the global ocean models that are presently used or tested for ocean forecasting systems can be divided into two categories: fixed coordinates (MOM, OPA, MIT, NCOM, POP, OCCAM, ...) or Lagrangian coordinates (NLOM, MICOM, HYCOM, POSEIDON, ...). The reader is referred to Griffies et al. (2000a) for a definition of the acronyms and for the relevant references.

3 – Ocean model requirements for GODAE

The specific objectives of GODAE are to:

a) Apply state-of-the art ocean models and assimilation methods to produce short-range open-ocean forecasts, boundary conditions to extend predictability of coastal and regional subsystems, and initial conditions for climate forecast models.

b) Provide global ocean analyses for developing improved understanding of the oceans, improved assessments of the predictability of ocean variability, and as a basis for improving the design and effectiveness of a global ocean observing system.

The requirements for the ocean model differ among these objectives. High resolution operational oceanography requires accurate depiction of mesoscale features such as eddies and meandering fronts and of upper ocean structure. Coastal applications require accurate sea level including wind, tidal and surface pressure. Seasonal-to-interannual forecasts require a good representation of the upper ocean mass field and the coupling to an atmosphere. This diversity of applications implies that no single model configuration will be sufficiently flexible to satisfy all the objectives.

For high resolution operational oceanography, the models will be global and eddy-resolving, with high vertical resolution and advanced upper ocean physics, and use high-performance numerical code and algorithms. In order to have a good representation of the mesoscale variability, the horizontal grid spacing must be fine enough to provide a good representation of baroclinic instability processes. Recent numerical simulations suggest that a minimum grid spacing on the order of 1/10 degree (Smith et al., 2000; Hurlburt and Hogan, 2000; Chassignet and Garraffo, 2001; Hurlburt et al., 2002, this volume) is needed for a good representation of western boundary currents (including their separation from the coast) and of the eddy kinetic energy. The computational requirements for basin-scale ocean modeling at this resolution are extreme and demand the latest in high performance computing. For that reason, there are only a few eddy-resolving global ocean models that are being integrated at the present time: the first generation NAVY ocean model/ocean prediction system (NLOM, see Rhodes et al., 2002; Hurlburt et al., 2002, this volume for details), the global POP which is in its tenth year (McClean and Maltrud, personal communication), and the global OCCAM which is in its second year (Webb and Coward, personal communication).

4 – Issues

In this section, we address some of the issues that have been put forward as the mesh is refined in ocean models and that we think are most relevant to the GODAE goal of high resolution operational oceanography. There are of course others, but space prevents us here from carrying out a full review.

- *Model-related data assimilation issues*

In data assimilation, there is a much larger burden on ocean models than on atmospheric models because (1) synoptic oceanic data is overwhelmingly at the surface, (2) ocean models must use simulation skills in converting atmospheric forcing into an oceanic response, and (3) ocean model forecast skill is needed in the dynamical interpolation of satellite altimeter data (since the average age of the most recent altimeter data on the repeat tracks is 1/2 the repeat cycle plus the delay in receiving the real-time data, typically 1-3 days at present). Specifically, the model must be able to accurately represent ocean features and fields that are inadequately observed or constrained by ocean data. This is an issue for reanalyses, for real-time mesoscale resolving nowcasts and short-range forecasts (up to ~1 month), and for seasonal-to-interannual forecasts, including the geographical distribution of anomalies. Examples where ocean simulation skill is especially important are mean currents and their transports (including flow through straits), surface mixed layer depth, Ekman surface currents, coastal ocean circulation, the Arctic circulation, and the deep circulation (including the components driven by eddies, the thermohaline circulation, and the wind).

In order to assimilate the SSH anomalies determined from satellite altimeter data into the numerical model, it is necessary to know the oceanic mean SSH over the time period of the altimeter observations. Unfortunately, the geoid is not known accurately on scales important for the mesoscale. Several satellite missions are underway or planned to help determine a more accurate geoid, but not on a fine enough scale to entirely meet the needs of mesoscale prediction. Thus, even after these missions, it is of the utmost importance to have a model mean that is resonably accurate, since most oceanic fronts and mean ocean current pathways cannot be sharply defined from hydrographic climatologies alone.

A number of additional issues, theoretical or technical, are raised when the numerical ocean model is used in conjunction with data assimilation techniques. In all data assimilation methods, nonlinearities are a major source of sub-optimality. Variational methods often require development of the adjoint model which is a heavy task. Depending on the vertical coordinates, difficulties arise in dealing with non-Gaussian statistics in isopycnic coordinate models with vanishing layers, or with convective instability processes throughout the vertical columns in z-coordinate models. Finally, the definitions of prior guess errors, model errors, and, to a lesser degree, observation errors are difficult endeavours.

- *Forcing*

The ocean model will respond to the prescribed atmospheric forcing fields. The present models' inability to reproduce the present day ocean circulation when run in free mode is a consequence of inaccuracies in both the forcing and in the numerical models themselves, as well as of the intrinsic nonlinearity of the Navier-Stokes equations. Accurate atmospheric forcing, when computed using bulk formulas that combine the model SST and the atmospheric data, have been shown to be essential for a successful forecast of the sea surface temperature, sea surface salinity, and mixed layer depths. It is important to mention here that the prescription of the surface forcing fields, as currently done in many ocean forecasting systems, does not allow for atmospheric feedbacks. This may have a limited impact on a 15-day forecast, but coupling to an atmospheric model is essential in seasonal-to-interannual forecasting of events such as ENSO (see Rienecker et al., 2002, this volume).

- *Topography*

With high resolution comes the need for high quality topography. Several products have become available recently to replace the widely used ETOPO5 data set, for example, ETOPO2 (2' resolution) (2001, available on CD-ROM at http://www.ngdc.noaa.gov/mgg/fliers/01mgg04.html) which incorporates version 8.2 of the Smith and Sandwell topography (Sandwell and Smith, 2001) and other topographic data sets. A GEBCO 1' topography is under development (Michael Carron, NATO SACLANT Center, La Spezia, Italy, personal communication).

- *Meridional overturning circulation*

A good representation of the overturning circulation is essential for a proper representation of the oceanic surface fields. This is especially true in the North Atlantic where the contribution of the thermohaline meridional overturning circulation accounts for a significant portion of the Gulf Stream transport. Many factors, such as mixed layer physics, ice formation, overflow representation, and interior diapycnal mixing, affect the strength and pathways of the meridional overturning circulation.

- *Ice models*

A global ocean model needs to be coupled to an ice model in order to have the proper forcing at high latitudes and hence the correct dense water mass formation and circulation. A good representation of the ice cycle is challenging, especially when the atmospheric fields are prescribed. Another related issue is the mixed layer parameterization below the ice.

- *Overflows*

Sill overflows typically involve passages through the ridge and are under the control of hydraulic effects, each of which is highly dependent on topographic details. The downslope flow of dense water, typically in thin turbulent layers near the bottom, may strongly entrain ambient waters and is modulated by mesoscale eddies generated near the sill. The simulation of downslope flows of dense water differs strongly among ocean models based on different vertical coordinate schemes. A major problem of z-models arises from the stepwise discretization of topography, which tends to produce gravitationally unstable water parcels that rapidly mix with the ambient fluid as they flow down the slope. The result is a strong numerically-induced mixing of the outflow water downstream of the sill. This numerically-induced mixing will in principle decrease as the horizontal and vertical grid spacing is refined. It is, however, still an issue at the above mentioned resolution of 1/10 degree.

- *Diapycnal mixing*

This is the observational field that is the least well known and the most difficult field to model correctly, especially in fixed coordinate models (Griffies et al., 2000b; Lee et al., 2002) due to the typically small levels of mixing in the ocean interior away from boundaries (Ledwell et al., 1993). Excessive numerically-induced diapycnal mixing will lead to incorrect water mass pathways and a poor representation of the thermohaline circulation.

- *Internal gravity waves/tides*

Improperly resolved internal gravity waves generate numerically induced diapycnal mixing in fixed-coordinate models. Several numerical techniques can be used to slow down the gravity waves, but ultimately it would be desirable to have a diapycnal mixing parameterization based on the model representation of internal gravity waves. Internal tides become important as the ocean models start to properly resolve the continental shelves and mid-ocean ridges and when the atmospheric forcing includes strong excitation mechanisms, such as tropical cyclones (which are included in present atmospheric forecast models).

- *Barotropic motions*

The use of high frequency (e.g., 6-hourly) forcing generates strong non- steric barotropic motions that are not temporally resolved by satellite altimeters (Stammer et al., 2000). In addition, Shriver and Hurlburt (2000) report that between 5 and 10 cm rms SSH non-steric variability are generated in major current systems throughout the world ocean.

- *Viscosity closure*

Despite the smaller mesh size, the viscosity parameterization remains of importance for the modeled large scale ocean circulation (Chassignet and Garraffo, 2001). When the grid spacing reaches a certain threshold, the energy cascade from small to large scales should be properly represented by the model physics. Dissipation should then be prescribed for numerical reasons only in order to remove the inevitable accumulation of enstrophy on the grid scale. This is the reason why higher order operators such as the biharmonic form of friction have traditionally been favored in eddy-resolving or eddy-permitting numerical simulations. Higher order operators remove numerical noise on the grid scale and leave the larger scales mostly untouched, by allowing dynamics at the resolved scales of motion to dominate the subgrid-scale parameterization (Griffies and Hallberg, 2000). In addition to numerical closure, the viscosity operator can also be a parameterization of smaller scales. One of the most difficult tasks in defining the parameterization is the specification of the Reynolds stresses in terms of only the resolved scales' velocities. The common practice has been to assume that the turbulent motion acts on the large scale flow in a manner similar to molecular viscosity. However, the resulting Laplacian form of dissipation removes both kinetic energy and enstrophy over a broad range of spatial scales, and its use in numerical models in general implies less energetic flow fields than in cases with more highly scale-selective dissipation operators. Some Laplacian dissipation is still needed to define viscous boundary layers and to remove eddies on space scales too large to be removed by biharmonic dissipation and too small to be numerically accurate at the model grid resolution.

- *Coastal transition zones*

A strong demand for ocean forecasts will come from the offshore industry which has extended its activities from the shallow shelf seas to exploration and production on the continental slope where oceanographic conditions play a much more critical role in safe and environmentally acceptable operations. Exploration and production is now taking place in water depths in excess of 2000 meters in a number of oil and gas basins around the world. The proper modeling of the transition area between the deep ocean and shallow continental shelves imposes strong requirements on the ocean model. It should be capable of modeling the typical shallow waters on the shelf with its characteristic well-mixed water masses and strong tidal and wind-driven currents. Furthermore, it also must properly represent and distinguish between water masses of vastly different characteristics in the deep ocean and near the surface during very long time integrations. The interaction with the continental shelf/slope is also an intriguing problem due to the impact on internal tides and the wave modes developing and propagating along the continental shelf/slope. This includes remotely generated wave modes, such as equatorially-generated Kelvin waves which play a large role in El Nino events and which can strongly impact distant coastal regions.

4 – .Model error: What can we learn from an ocean forecasting system?

One of the greatest uncertainties in setting up a data assimilative system is the error one needs to attribute to the numerical model. To a certain extent, the rate at which a model moves away from the assimilative state will provide some indications of the model's performance. A careful comparison with observations (see LeProvost et al., 2002, this volume) in assessing the model's performance with and without data assimilation will help in identifying the model biases and the areas that need major improvements, either in representation or in parameterization. The routine analysis of model forecasts will provide a wealth of information that the modeler can use to improve the model's physics, especially if additional forecasts/hindcasts can be performed after the fact to assess the effectiveness of the changes.

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