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Towards a High-Resolution Global Coupled Navy Prediction System

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1. Introduction

A computational project is underway to bring about the realization of a high-resolution global coupled atmosphere/ocean/ice prediction system for Navy meteorological and oceanographic forecasting. A fully coupled near-global ocean/atmosphere prediction system has been constructed using resolutions of 0.75° in the atmosphere and 0.5° in the ocean (eddy-permitting) at the Naval Research Laboratory at Monterey (NRL-MRY). The system consists of the Navy Operational Global Atmospheric System (NOGAPS) that incorporates the NRL Atmospheric Variational Data Assimilation Scheme (NAVDAS), the Los Alamos National Laboratory Parallel Ocean Program (POP), and the Navy Coupled Ocean Data Assimilation (NCODA), an optimal interpolation scheme (see Figure 1). The next steps in the development of this system are the inclusion of ice, improving the data assimilation scheme, and moving to higher resolution; fulfillment of these goals is being advanced by university and national laboratory partners. An eddy-permitting fully global coupled ocean/ice simulation is underway using POP and the Los Alamos sea ice model known as CICE. Ensemble runs are being conducted using eddy-permitting global POP and the Simple Ocean Data Assimilation Scheme (SODA). SODA (Carton et al., 2000), also an optimal interpolation scheme, uses advanced error statistics that are flow dependent, anisotropic, and latitude-depth dependent. Finally, a short (two-year) high-resolution (0.1°, 40-level) global POP simulation forced with daily NOGAPS fluxes is complete following a 2-decade spin-up of this model using National Center for Environmental Prediction (NCEP) atmospheric fluxes.

POP, the ocean model common to all these efforts, is a multi-level, primitive equation general circulation model with a free surface boundary condition. POP has been used widely on massively parallel architectures since 1992 when (Smith et al., 1992) reconfigured the Bryan-Cox-Semtner ("GFDL") ocean model to run on a Connection Machine 5 (CM5). Since then it has been ported to other platforms (SGI Origin 2000, SGI Origin 3000, Cray T3E, and IBM SP, Cray X1, Earth Simulator, among others) and LANL scientists continue to improve its efficiency. Improvements to physics packages by the modeling community at large are progressively incorporated into POP.

2. Fully Coupled NOGAPS/POP with NCODA

The global coupled NOGAPS/POP system (Figure 1) is being used to investigate seasonal forecasts of both the atmosphere and ocean. Seasonal forecasts may provide useful predictions of phenomenon such as the Madden-Julian Oscillation, onset of the Indian Ocean Monsoon, and perhaps even El Niño. Forecasts from the coupled model can also be used to investigate variability in ocean heat storage and the flux, cloud, and boundary layer parameterizations in the atmospheric model. With the fully integrated ocean data assimilation system (NCODA) estimates of both the initial and final states of the ocean are available for proper model initialization and for extensive quantitative forecast error statistics.

In the tightly coupled system NOGAPS forecasts of momentum, heat, and moisture fluxes are passed to the ocean model every three hours. POP forecasts of the sea-surface temperature (SST) are returned to the atmospheric model as lower boundary conditions. Ocean and atmosphere are free to run on their own numerical grids but share the same set of processors. The system allows for the exchange of fluxes and SSTs at any time interval down to about one hour. In an operational setting the coupled forecast system would be periodically updated with three-dimensional temperature and salinity fields from NCODA.

For a recent set of coupled experiments, NOGAPS was configured as T159L30 (0.75° horizontal spacing with 30 vertical levels) and POP on a 0.5° Mercator grid (40 km spacing at 45°N) with 36 levels. The 90-day forecast sea-surface temperature bias (forecast SST minus analyzed SST from a forecast starting 1 June 2002) shows regional warm and cold forecast temperature biases in the northern hemisphere (Figure 2) whose spatial patterns correspond closely to cloud distributions in the atmospheric model. The influence of atmospheric cloud patterns on energy exchanges in the coupled system and the parameterization of clouds in the atmospheric model is an area of continuing research that has important implications to long-term climate modeling.

3. Global Coupled POP and CICE

The global coupled ocean/ice model is composed of POP (0.4° and 40-levels) and CICE, a dynamic-thermodynamic sea ice model. The horizontal resolution of the coupled model is about 13 km in the Arctic. CICE incorporates the energy conserving thermodynamics model of (Bitz and Lipscomb, 1999) with four layers of ice and one layer of snow in each of five ice thickness categories, the energy-based ridging scheme of (Thorndike et al., 1975), an ice strength parameterization given by (Rothrock, 1975), elastic-viscous-plastic ice dynamics of (Hunke and Dukowicz, 1997) and horizontal advection via a new incremental remapping scheme (Lipscomb and Hunke, 2004). More complete details can be found in (Hunke and Lipscomb, 2002). CICE was designed to be compatible with POP; here they run on the same displaced North Pole grid. At first, the components were communicating through a flux coupler; however this proved to be inefficient and the code was rewritten with CICE as a subroutine of POP.

The model was initialized with a uniform ice thickness of 2 m. It was largely forced with reanalyzed National Center for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) daily fluxes (Doney et al., 2002) for 1979–2003 and, in a second experiment, NOGAPS fields for 1999–2000. We will continue the NOGAPS run through 2003 to explore the effects of different wind forcing for a five-year period. As well, we have run CICE stand-alone (climatological ocean mixed layer only) with the same sets of forcing to understand differences in the ice solution when a real ocean rather than a climatological ocean is active below the ice.

The effects of synoptic storm activity on the sea ice during winter in the Arctic are examined using output from the NCEP coupled simulation. The deformation of ice is due to the opening, closing, ridging, and sliding primarily in response to the wind field (Moritz and Stern, 2001). Here we qualitatively relate changes in the wind stress field to convergences and divergences in the ice field. A daily sequence of ice divergence, wind stress and divergence, and daily changes in ice thickness for the period 12–15 January 1999 are seen in Figure 3. Focusing on the central Arctic away from land, regions of convergence (green-blue) and divergence (yellow-red) can be seen in the ice divergence Figures for 13 and 14 January 1999. A divergent ice feature is seen near the North Pole on 13 January; winds over this region were divergent on 12 January. The winds in this region became progressively more convergent on 13 and 14 January producing a convergent ice field on 14 January. The ice thickness decreased on January 14 relative to its value on January 13 in the divergent region. By January 15, the ice thickness has increased relative to the previous day in the associated convergence region. Quantitative analyses of these types of events and their relationship to the wind forcing are underway.

4. Global POP and SODA

Using SODA, the model forecast from 0.4° global POP has been combined with an estimate of corrections based on a set of observations consisting of temperature and salinity from hydrography, satellite-derived SST, and sea level height from altimetry. The scheme consists of a multivariate two-stage sequential updating algorithm whereby the model bias is first corrected followed by the model state producing the analysis. SODA minimizes the mean square error for both the forecast bias and the analysis equations that depend on the forecast, observation, and bias error covariances. Background errors of temperature and salinity vary spatially, with expanded zonal scales in the tropics and with structures that evolve with the flow field. These specifications of the error statistics are more complex than the homogeneous, stationary empirical estimates in NCODA.

To date, efforts in this project have focused on reducing the influence of the bias on the analysis. There are several causes for this basis: insufficient resolution, inadequate modeling of unresolved physics, biases in the surface forcing fields, initial fields, and the model numerics (Carton et al., 2000). One effect of such biases is to produce an ocean state that is too cold or too hot. Comparisons of the POP-SODA fields and independent data in the equatorial Pacific (not shown) and the North Atlantic demonstrate the integrity of the scheme. In Figure 4, the root-mean-square (RMS) sea level variability in the Gulf Stream from SODA-POP (10 years) is compared with that from altimetry (20 months). Altimetry data has been withheld from SODA in this case. Both the distribution and magnitude of the SODA-POP variability is in reasonable agreement with the data. Without SODA, a model of this resolution misrepresents both aspects of the variability (McClean et al., 1997).

5. High-Resolution Global POP

More than two decades of a global 0.1°, 40-level POP simulation forced with NCEP/NCAR fluxes for 1979–2001 was completed at the Maui High Performance Computing Center (MPHCC). A discussion of the model set-up and analyses of the first 15 years of the run can be found in (Maltrud and McClean, (2004). A second simulation, forced with daily NOGAPS momentum and heat fluxes from 1999 through the present is underway. The horizontal spacing of this model is about 11 km at the equator decreasing to about 3 km in the Arctic Ocean. The (Large et al., 1994) mixed layer formulation, K-Profile Parameterization (KPP), is active. The 0.1° global POP solution forced with NOGAPS fluxes will be compared here to the earlier NCEP simulation and the data from the year 2000. The focus is to evaluate upper ocean model bias introduced by the different atmospheric forcing products.

RMS sea surface height anomaly (SSHA) fields were calculated for the two global runs and Ocean Topography Experiment (TOPEX)/POSEIDON (T/P) and ERS altimetry for 2000 (Figure 5). In the tropical Pacific, differences between the two runs show that the NOGAPS simulation better represents the bands of off-equatorial variability seen in the altimetry field. To see other differences more easily, the RMS SSHA fields have been zonally averaged in 10° bands in the western boundary current regions of the Indian (60°–70°E), Pacific (150°–160°E), and Atlantic (40°–30°W) Oceans, and in the eastern boundary of the Pacific Ocean (140°–130°W). Both simulations are generally in good agreement with the data both in terms of location and magnitude of the variability. The NOGAPS run is more energetic than the NCEP simulation in the tropical (20°S–20°N) Indian and Pacific Oceans—even over-estimating the data in places. Outside of the tropics the two simulations are in close agreement except in the Malvinas-Brazil Current Confluence region (45°S) where the NOGAPS run is in better agreement with the data than the NCEP run. Discrepancies with the data are seen around 40°S where the models underestimate the data and north of 40°N where the North Atlantic Current is too energetic. The variability associated with the Antarctic Circumpolar Current in the Southern Ocean of both models agrees well with observations as it also does in the much more quiescent eastern Pacific.

6. Conclusions

A fully coupled global atmosphere-ocean prediction system for short-term forecasting has been developed at NRL Monterey at modestly high horizontal resolution (0.5° ocean and 0.75° atmosphere). University and national laboratory partners are performing coupled ice/ocean simulations, improving the data assimilation scheme, and running high-resolution ocean simulations with the goal of advancing this prediction system. Sea ice in the 0.4° global coupled ocean/ice system in the Arctic is seen to respond to synoptic wind events on time scales of a day, producing thickening and thinning of the ice. The data assimilation scheme, SODA, when used together with eddy-permitting POP produces variability in the Gulf Stream that is comparable with that from altimetry both in terms of magnitude and distribution. The high resolution global POP forced with NOGAPS surface fluxes produces slightly more realistic variability in the tropical Indian and Pacific Oceans relative to the NCEP-forced simulation. Outside of the tropics, the variability produced by the two simulations is in close agreement; generally both simulations agree with data. The inclusion of ice in the coupled system will produce a more realistic thermohaline circulation in the ocean as well as providing a more realistic time-dependent bottom boundary layer to NOGAPS. The improved data assimilation scheme will produce more realistic analyses, while the use of high-resolution will improve the model forecast by reducing biases resulting from lack of sufficient resolution.

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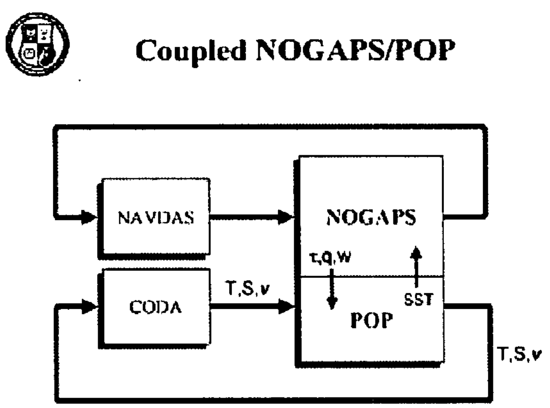

Figure 1. Global Coupled NOGAPS/POP System

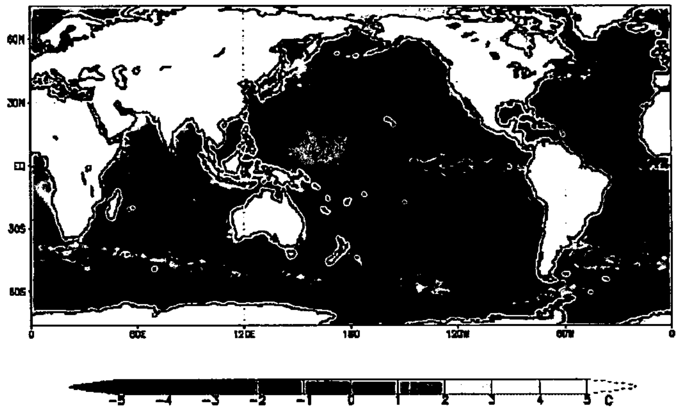

Figure 2. 90-day Forecast Temperature Bias

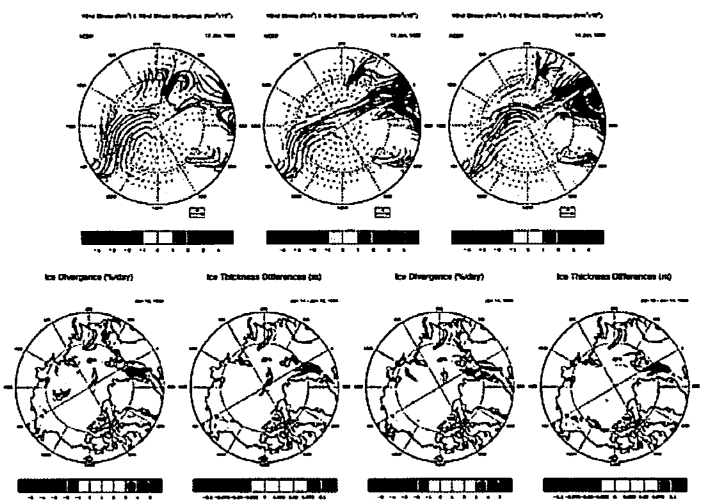

Figure 3. Wind Stresses (N/m^2) and divergences (N/m^{3}x10^{-6}) for 12–14 January 1999, ice divergence (%/day) for 13 and 14 January, and ice thickness differences (m) between 14–13 and 15–14 January

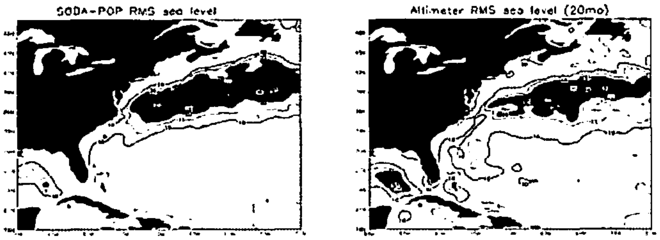

Figure 4. RMS sea level height (cm) from SODA-POP (left) and altimetry (right)

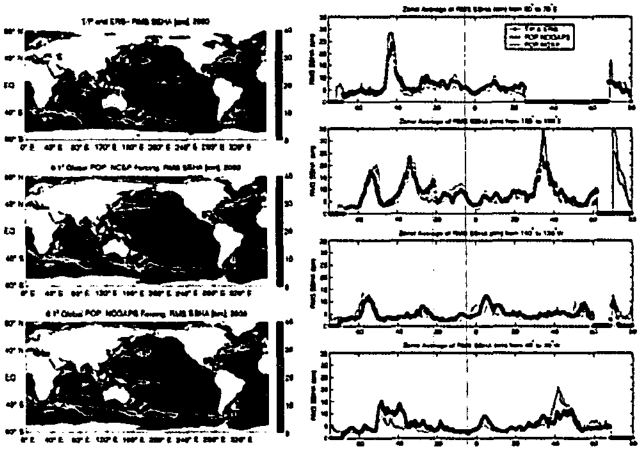

Figure 5. RMS SSHA (cm) from altimetry, 0.1° global NCEP and NOGAPS POP simulations (left panel). Zonally-averaged RMS SSHA (cm) for 60°–70°E (Indian Ocean), 150°–160°E (western Pacific), 140°–130°W (eastern Pacific), and 40°–30°W (Atlantic) in the right panel.