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A Global Ocean Nowcast/Forecast System

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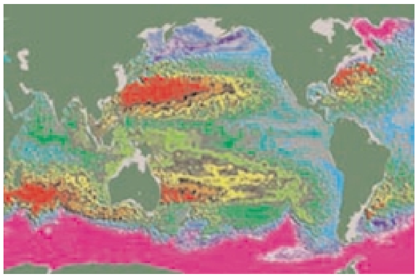

Project:
Global and Basin-Scale Ocean Modeling and Prediction

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Assigned Site/System:
NAVO MSRC SGI/Cray T3E

CTA:
Climate/Weather/Ocean Modeling and Simulation

URL:
http://www7320.nrlssc.navy.mil/global_nlom/index.html

This project is aimed at developing an ocean prediction system that will revolutionize the ability to nowcast and forecast the global ocean circulation down to the scale of oceanic fronts and eddies. A real-time demonstration for the Pacific Ocean is currently running in real time at NAVO MSRC with 1/16° resolution, a demonstration that will be expanded to the global ocean in the near future. Department of Defense (DoD) High Performance Computing (HPC) resources and DoD HPC Challenge projects at NAVO MSRC and U.S. Army Engineer Research and Development Center (ERDC) MSRCs have been critical to this effort.

INTRODUCTION

DoD HPC and a DoD HPC Challenge grant on the NAVO MSRC SGI/Cray T3E are critical components of a coordinated 6.1-6.4 Naval Research Laboratory (NRL) effort on the "Grand Challenge" problem of eddy-resolving global ocean modeling and prediction. The goal is a fully eddy-resolving, data assimilative global ocean prediction system with at least 1/16° (~7.5 km) resolution in the near term, with an upgrade to 1/32° when the available computer power is sufficient. A 1/16° system is currently running in demonstration mode for the Pacific north of 20°S, and expansion to the global ocean is planned in the near future using DoD HPC Challenge resources at the NAVO MSRC and the NRL Layered Ocean Model (NLOM).

The 1/16° Pacific NLOM system already gives a real-time view of the ocean down to the 50-200 km scale of ocean eddies and the meandering of ocean currents and fronts, a view with unprecedented resolution and clarity. This can be seen at the URL. The system has demonstrated forecast skill for a month or more for many ocean features, including the fronts and eddies. The assimilation of satellite altimeter data into this system makes effective use of the near-real-time altimeter data from TOPEX/POSEIDON and ERS-2 that is available from Naval Oceanographic Office's (NAVOCEANO's) Altimetry Data Fusion Center (ADFC). The effectiveness of the model assimilation of altimeter data is greatly enhanced by the 1/16° resolution of the Pacific system, as demonstrated by comparison to corresponding results at coarser resolution. Other data, such as sea surface temperature and sparse vertical profiles of temperature and salinity, will be assimilated as well.

BACKGROUND

Ocean forecasting is in principle similar to atmospheric forecasting, but with two major complications: (a) ocean eddies, at about 100 km across, are typically 20 to 30 times smaller than comparable atmospheric highs and lows which means that roughly four orders of magnitude more computer time and three orders of magnitude more computer memory are required; and (b) there are relatively few observations below the ocean surface, so data assimilation is effectively confined to using satellite observations of the surface. The duration of forecast skill for the ocean is not restricted to the 10- to 14-day limit for atmospheric highs and lows. We have demonstrated at least 30-day predictive skill for ocean eddies and the meandering of ocean currents and fronts, given sufficient ocean model resolution and satellite altimeter data from TOPEX/POSEIDON and ERS-2.

A major component of NRL's ocean modeling program has been a detailed study of the resolution required for ocean prediction. We have strong evidence that NLOM and other ocean models (including all the popular global and basin-scale ocean models) need to use grid cells for each prognostic variable that are at most about 8 km across at mid-latitudes. Our research has shown that doubling the resolution to 4 km per cell gives substantial improvement but doubling again to 2 km gives only modest additional improvement. Due to ocean modeler preference and choice of finite difference grid design, there is significant variation in how such resolution is expressed in degrees, the most common way to describe ocean model resolution. For the NLOM grid it translates to 1/16°, 1/32°, and 1/64° resolution, respectively. This is for the global and basin-scale. Coastal models would use the global forecast for boundary conditions and would require much smaller cells, but would cover only a limited region.

At 4 km, the optimal resolution is finer than might be expected based on the size of eddies. In relation to ocean eddy size, it is similar to the resolution currently used by the leading weather forecasting models in relation to the size of atmospheric highs and lows. More specifically, our research has shown that fine resolution of the ocean eddy scale is required to obtain coupling between upper ocean currents and seafloor topography via turbulent flow instabilities. This coupling can strongly affect the pathways of upper ocean currents and fronts, including the Gulf Stream in the Atlantic and the Kuroshio in the Pacific. The high resolution is also required to obtain sharp fronts that span major ocean basins and a nonlinear effect on the large scale C-shape of ocean gyres, such as the Sargasso Sea in the Atlantic.

TECHNICAL APPROACH

As far back as 1989, the President's Office of Science and Technology recognized global ocean modeling and prediction as a "Grand Challenge" problem, defined as requiring a computer system capable of sustaining at least one trillion floating point adds or multiplies per second. By taking a multi-faceted approach to cost minimization, we are solving the problem on systems capable of only a small percent of this performance. One facet is experiment sequences that use the largest cell size possible and an ocean basin rather than the entire globe whenever possible. This only gets us so far, since in the end there is no substitute for small cells and a global domain.

Another facet is the use of the NLOM which has been specifically designed for eddy-resolving global ocean prediction. It is tens of times faster than other ocean models in computer time per model year for a given horizontal resolution and model domain. NLOM's performance is in turn due to a range of design decisions, the most important of which is the use of isopycnal (density tracking) layers in the vertical rather than the more usual fixed depth cells. Density is the natural vertical coordinate system for the stratified ocean, and it allows seven NLOM layers to replace the 100 or more fixed levels that would be needed at 1/16° resolution. Another important advantage of this approach is that there is less need to increase the number of density tracking layers as the horizontal cell size is reduced. With NLOM, halving the cell size requires about 8 times as much computer power (4 times from the number of cells plus 2 times from the required smaller time step), but with fixed-level ocean models, the number of cells in the vertical should also be doubled, requiring about 16 times as much computer power.

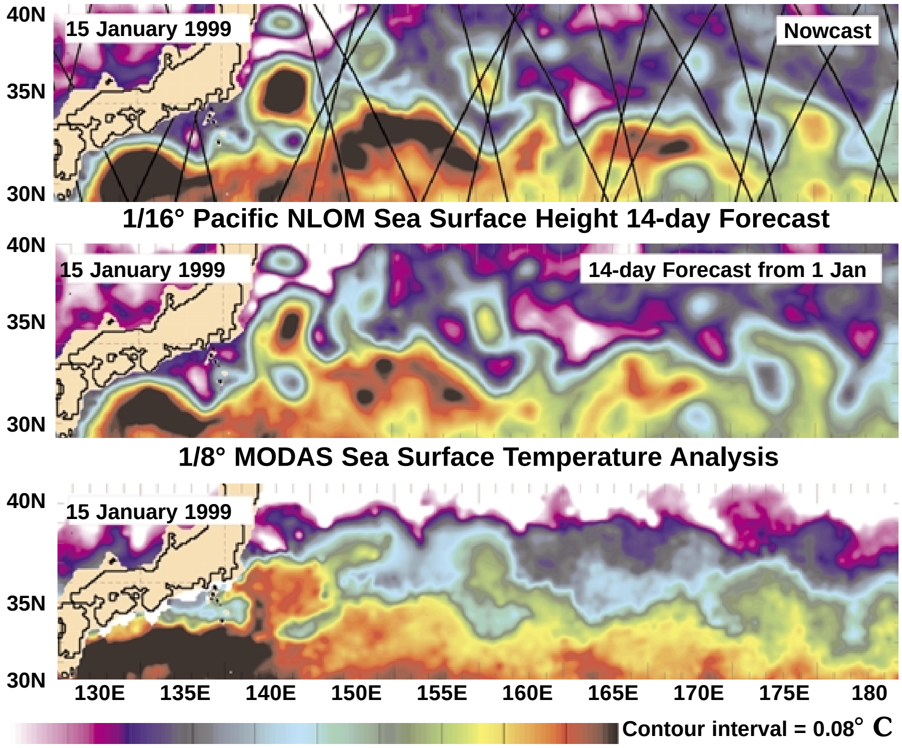

Figure 1. Zoom on the Kuroshio current region south and east of Japan. (Top) Sea surface height (SSH) for 15 January 1999, from the NRL 1/16° Pacific model with assimilation of satellite altimeter data from TOPEX/POSEIDON and ERS-2. The altimeter tracks with data available for this update cycle are overlain. (Middle) Corresponding SSH snapshot from a 14-day forecast initialized from 1 January 1999. (Bottom) MODAS 1/8° SST analysis from satellite IR imagery. The SST color bar is designed to highlight the Kuroshio pathway.

A third facet is a widely portable NLOM computer code, developed under the Common High Performance Computing Software Support Initiative (CHSSI) program, that targets large scalable computers with high-speed network connections. NLOM exhibits very good scalability (wall time speedup as more processors are used) on such systems. For example, we have routinely run NLOM on up to 1,152 Cray T3E processors at up to a sustained speed of about 100 billion useful floating-point operations per second.

A final facet of our efficiency drive is the use of an inexpensive data assimilation scheme backed by a statistical technique for relating surface data to subsurface fields. The statistics are from an atmospherically forced 20-year inter-annual simulation of the same ocean model, an application that requires a model with high simulation skill.

So far it has been possible to run NLOM in demonstration mode with 1/32° resolution globally (72°S-65°N) and 1/64° resolution over the basin-scale subtropical Atlantic (9°N-51°N), including the Caribbean and Gulf of Mexico. While, at present, these require greater computer resources than practical for an operational product, they do give information on the value added of increasing resolution and insight into model performance at 1/16° resolution.

RESULTS

In August 1999, we started running 1/16° Pacific NLOM in near-real time (i.e., updated every few days). In hindcast studies that followed standard nowcast and forecast procedures, but used data from a previous time period, we compared 1/16° Pacific NLOM with 1/4° global NLOM. Both studies assimilated satellite altimeter data from TOPEX/POSEIDON and ERS-2, and then month-long forecasts started from the data assimilative nowcast states were performed. An example is shown in Figure 1 with comparison to an independent 1/8° SST analysis from the Modular Ocean Data Assimilation System (MODAS) that is operational at NAVOCEANO. The SST analysis shows the correspondence between the Kuroshio pathway and some of the eddies seen in the sea surface height field from the Pacific Ocean model, a field observed by satellite altimetry as shown by overlain ground tracks in Figure 1 (top panel).

The 1/16° Pacific model has given the very first basin-wide skillful forecast demonstration of oceanic fronts and eddies for any ocean basin. The Pacific results also demonstrate that altimeter data alone are sufficient to produce an accurate nowcast when a high resolution ocean model is in the loop to fill in the space-time gaps in the altimeter data. The 1/4° global model was much less successful in this feasibility demonstration, as was expected from the earlier discussion of resolution requirements. In addition, the nowcast/forecast results at 1/16° resolution were substantially better than expected for a system that uses satellite altimeter data as the only observing system, due mainly to doubts about the space-time resolution adequacy of the altimeter data. SST assimilation will be added in the near future.

The global results for SST have also exceeded expectations, particularly for a model with only seven layers in the vertical. The embedded mixed layer in NLOM gives accurate SST based on accurate atmospheric forcing even with no assimilation of SST data (or altimeter data). With climatological atmospheric forcing, global NLOM gives SSTs accurate to within .5°C for the annual mean and .7°C for the seasonal cycle. Global NLOM at 1/2° and 1/8° resolution was run 1979-98 with 6-12 hourly atmospheric forcing from ECMWF and no assimilation of SST data, and then compared to 337 year-long daily time series of observed SST around the world over the 1980-98 time frame. The median rms error was .8 to .9°C and the median correlation coefficient was about .9, again with no assimilation of SST data. The modal bin for rms error was .6 to .8°C, and the modal bin for correlation was .95 to 1.0.

Figure 2 shows similar results from 1/16° Pacific NLOM, but with a comparison between results using Fleet Numerical Meteorology and Oceanography Center (FNMOC) Navy Operational Global Atmospheric Prediction System (NOGAPS) and European Centre for Medium-Range Weather Forecast (ECMWF) winds over the time frame 1990-1998. In both cases ECMWF thermal fields were used because such fields are not available from FNMOC prior to late 1997. However, the winds play a significant role in thermal forcing, and the FNMOC winds were used for that purpose in the FNMOC forced run. As before, there was no assimilation of SST data. In both cases the median rms SST error was .84°C, but outside the equatorial region the SST results using FNMOC were noticeably better, .76°C vs. .84°C, using ECMWF, with median correlation of .96 and .95, respectively. Note the three years of daily SST in Figure 2 show substantial differences in the shape of the annual cycle as well as shorter time-scale variability that is captured by the NLOM SSTs, an indication of skill for both the ocean model and the atmospheric forcing.

These results indicate that NLOM SST is sufficiently accurate to be used as a platform for assimilation of SST data (which has gaps due to cloudiness) and for SST forecasting.

Acknowledgments

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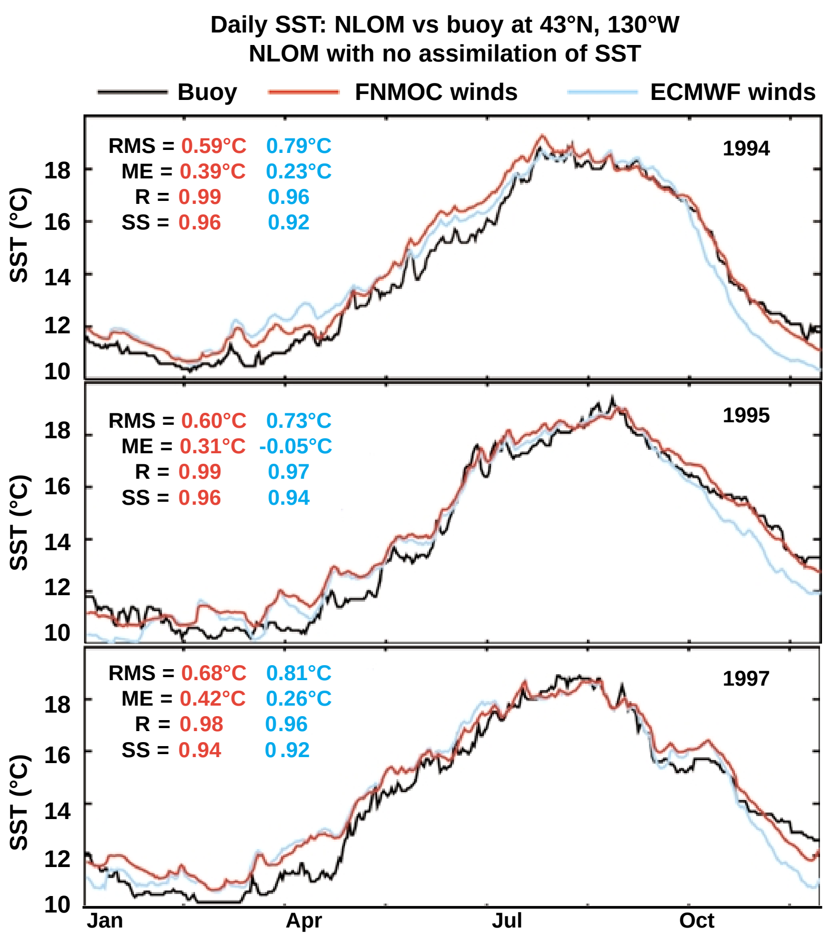

Figure 2. Daily observed SST from a NOAA buoy at 43°N, 130°W (black) and modeled SST from 1/16° Pacific NLOM forced with 6-12 hourly winds from FNMOC NOGAPS (red) and the ECWMF (blue) for 1994 (top), 1995 (middle), and 1997 (bottom). Thermal forcing (except the wind component) is from ECMWF in both cases. NLOM included no assimilation of SST data. Statistics include root mean square error (RMS), mean error (ME), correlation (R), and skill score (SS).