GLOBAL OCEAN PREDICTION SYSTEM

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LONG-TERM GOALS: An eddy-resolving nowcast/forecast system for the global ocean with embedded basin-scale systems (1/16° Pacific north of 20°S and 1/32° Atlantic subtropical gyre, 9°-51°N, which includes the Intra-Americas Sea) and a global model with progressively increasing resolution, 1/4°, 1/8° and ultimately 1/32° resolution. These systems will include data assimilation of satellite altimetry, sea surface temperature and in-situ data.

OBJECTIVES: The development and validation of basin and global scale ocean prediction systems. This includes skillful nowcasts and forecasts of ocean thermal structure and currents. High horizontal resolution is required 1) to depict current meanders, fronts and eddies, 2) to provide boundary conditions for coastal models with even higher resolution and 3) for upper ocean - topographic coupling via mesoscale flow instabilities. The latter is required for accurate positioning of current systems including the Gulf Stream and Kuroshio. The modeling effort focuses on the development and validation of the NRL Layered Ocean Model (NLOM) for the North Atlantic and North Pacific basins, the Atlantic as part of the ONR-sponsored Data Assimilation and Model Evaluation Experiments-North Atlantic Basin (DAMEE-NAB) effort, while the Pacific modeling work supports a planned 6.4 transition.

APPROACH: The modeling effort is aimed at eddy-resolving models for the Atlantic and Pacific Oceans and associated model development in collaboration with other projects. Hydrodynamic and thermodynamic versions of NLOM are used with grid resolutions of 1/2° to 1/32° for each variable and 5 to 6 Lagrangian layers in the vertical. The model has a free surface and allows diapycnal mixing, isopycnal outcropping and inflow/outflow through ports in the model boundaries. A version which includes a mixed layer and sea surface temperature is under development. The model runs efficiently and interchangeably on all DoD HPC platforms designed to handle applications this large, including massively parallel distributed memory computers and multi-processor shared memory computers. In general, NLOM is the most efficient ocean model in existence in terms of computer time per model year. Model-data comparisons are an important part of this effort and several are prescribed for the DAMEE-NAB project.

WORK COMPLETED: The project had 16 publications (submitted to in print, excluding abstracts) and 17 presentations (scientific meetings/workshops (14), to dignitaries (3)), 12 invited or requested.

Atlantic Ocean Modeling: This effort had 5 publications (submitted to in print, excluding abstracts). A series of 1/16° and 1/32° 5-layer subtropical Atlantic simulations were run to investigate the effects of grid resolution, bottom topography, eddy viscosity, diffusion formulation, and the global thermohaline component, including the design of the northern and southern boundary conditions used to provide this component. The model domain covers 9°-47°N or 9°-51°N and includes the Intra-

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Americas Sea. Eleven 1/32° simulations were run an average of 10 years each, extended from a spun-up 1/16° simulation or an earlier 1/32° simulation. Model-data comparisons were performed with satellite altimetry and IR, current transport measurements, hydrographic climatologies, deep eddy kinetic energy (EKE) from current meters and current system schematics based on observations. In addition, linear 1.5-layer reduced gravity simulations (30°S-65°N) at 1/2°, 1/4°, 1/8° and 1/16° resolution were forced by 6 more wind sets, mostly new reanalysis products from the National Centers for Environmental Prediction (NCEP) and the European Centre for Medium-range Weather Forecasts (ECMWF).

Pacific Ocean Modeling: This effort had 4 publications plus 2 more on Sea of Japan modeling (submitted to in print, excluding abstracts). Toward the understanding of ocean nowcast sensitivity to atmospheric forcing, three additional 1/8° Pacific simulations were performed using new reanalysis products from NCEP (surface stresses) and ECMWF (1000 mb and 10 m). During FY97, four additional 1/16° Pacific simulations north of 20°S were performed to further investigate the dynamics of the bifurcation of the Kuroshio Extension at the Shatsky Rise in response to reviewer comments. Development and tuning of a 1/16° thermodynamic, finite depth Pacific model began and continues with two simulations completed so far. This model is planned for transition to NRL's Data Assimilation and Rapid Transition (DART) group for use in a Pacific basin nowcast/forecast system.

Global Ocean Modeling: This effort had 2 publications (submitted to in print, excluding abstracts). A global version of NLOM was spun-up from rest, driven by monthly climatological winds at progressively higher resolutions of 1/2°, 1/4° and 1/8°. Under a DoD HPC Challenge project, it was continued at 1/16°. Additionally, two 1/16° simulations were run 1979-1996 forced by ECMWF-reanalysis winds. A new thermodynamic finite depth version of the global model was developed and spun-up at 1/2° and 1/4° resolution using climatological forcing, then continued from 1990 to near real time forced by Fleet Numerical Meteorology and Oceanography Center (FNMOC) wind stresses. This model is planned for transition to the DART group and FNMOC.

Model Development: This effort had 3 publications (accepted to in print, excluding abstracts). The scalable, portable version of NLOM was set up and optimized for five more supercomputers: Cray T3E, Cray T90, HP SPP2000, IBM SP and SGI Origin 2000. NLOM development included the capability to discard tiles at compile time on the Cray T3E and other "large node count" optimizations. The embedded mixed layer is still experimental, but in the released model code.

RESULTS: Atlantic Ocean Modeling: O(1) changes from linear solutions are required to simulate realistic Gulf Stream separation from the coast at Cape Hatteras and a realistic Gulf Stream pathway between Cape Hatteras and the Grand Banks. Realistic Gulf Stream separation was sometimes achieved at 1/16° resolution and required the presence of the Deep Western Boundary Current (DWBC), which is part of the global thermohaline circulation. At 1/32°, realistic Gulf Stream separation and pathway are very robust results in the simulations with realistic topography and the upper ocean contribution from the global thermohaline circulation, but with or without the DWBC. In many of the simulations the simulated Gulf Stream pathway is very accurate from the coast to 64°W and qualitatively similar the rest of the way to the Grand Banks in comparison to mean pathways determined from satellite IR and altimetry (see figure). We find that upper ocean - topographic coupling via mesoscale flow instabilities is crucial for accurately simulating the Gulf Stream and 1/32° resolution is required to get sufficient coupling. In comparison to the 1/16° simulations, the 1/32° simulations also showed 1) much greater eastward penetration of the nonlinear recirculation gyre with positioning and eastward extent in accord with the Navy's GDEM oceanic climatology, 2) much greater eastward penetration of the high sea surface height (SSH) variability and generally good agreement with SSH variability from TOPEX/POSEIDON altimetry, including the eastern end of the nonlinear recirculation gyre, but with variability still much too low south and east of the Grand Banks, 3) much greater eastward penetration of the high abyssal EKE with surprisingly good quantitative agreement with current meter measurements, and 4) that the nonlinear recirculation gyre in the 1/32° model contributes greatly to the observed C-shape of the Atlantic subtropical gyre, thus demonstrating the effect of 1/32° resolution on the large scale gyre circulation. In addition, the grid resolution (in the nonlinear simulations much more than the linear ones) affected transports through some of the passages in the Caribbean, Bahamas, Gulf of Mexico region, especially through Windward Passage and the Yucatan Channel, including the change from 1/16° to 1/32° resolution.

Pacific Ocean Modeling: Operational wind products tend to be plagued by spurious temporal variability which has been introduced by modifications to the operational atmospheric prediction system. The reanalysis products from NCEP and ECMWF eliminate this source of error due to a static model formulation. Analysis of the reanalysis products has shown them to be more consistent through time, especially in the tropical latitudes. NLOM simulations forced with these winds have shown that the ECMWF 1000 mb and 10 m winds produce better overall model-data correlations for sea level than those forced with the operational ECMWF winds or the NCEP reanalysis winds. The NCEP reanalysis winds tend to be too weak, especially in equatorial latitudes. The experiments to study the bifurcation of the Kuroshio Extension at the Shatsky Rise helped refine our understanding of topographic steering of upper ocean currents in this region through upper ocean - topographic coupling via mesoscale flow instabilities. The 1/16° thermodynamic finite depth model produces a more accurate basin-wide SSH field than its hydrodynamic counterpart, especially in the subtropical gyre south of the Kuroshio and in the east-west SSH gradient along the equator. Quantitatively, it agrees to within a few centimeters with surface dynamic height climatologies (see the figure in the Basin-Scale Ocean Prediction System report).

Global Ocean Modeling: The 1/16° simulations have the finest resolution globally so far. Outside NRL, approximately 1/5° is the finest resolution used for global ocean modeling. The resolution increase allows sharper definition of oceanic fronts and better simulation of meandering currents and the mesoscale eddy field. The identical twin 1979-1996 interannual simulations help distinguish between deterministic and non-deterministic model responses to the atmospheric forcing and are valuable in model-data comparisons and dynamical studies of oceanic anomalies. Both the reduced gravity and finite depth versions of the 1/4° thermodynamic model, forced by FNMOC wind stresses to near real time, realistically depict the evolution of the 1997 El Niño, including the large Kelvin wave pulse at the start in April. At this resolution the most notable improvement of the finite depth version over the reduced gravity version is a realistic Agulhas retroflection south of Africa, which was lacking in the reduced gravity version.

Model Development: The 5 new supercomputers that NLOM was ported to during FY97 (Cray T3E, Cray T90, HP/Convex SPP2000, IBM SP and SGI Origin 2000) accounted for 77% of the project's total DoD HPC usage for FY97. Overall, the project used 21 DoD HPC computer systems of 11 different designs (i.e. brand/model such as Cray T3E) at 8 different sites.

IMPACT/APPLICATIONS: Atlantic Ocean Modeling: Realistic simulation of Gulf Stream separation from the coast at Cape Hatteras and its pathway from Cape Hatteras to the Grand Banks is a "Holy Grail" problem in ocean modeling, where many have tried and failed. The NRL 1/32° subtropical Atlantic model is the first to achieve this in a robust fashion. In the past this has been achieved only 1) as a transient or 2) with realistic separation at Cape Hatteras but a grossly unrealistic pathway in the interior of the basin or by using 3) unusual atmospheric forcing, 4) a limited area model, 5) a partially diagnostic model, or 6) unobserved inflows from the north above the abyssal layer.

Atlantic, Pacific, Global Ocean Modeling: Resolution of 1/16° (1/32°) for each variable, used in this project, is the highest to date for a global (basin-scale) ocean model. We are discovering an increasingly widespread importance of mesoscale flow instabilities in allowing bottom topography to steer major and minor upper ocean currents, as ocean model horizontal grid resolution is increased. The upper ocean currents do not need to impinge on the bottom topography for upper ocean - topographic coupling via mesoscale flow instabilities to occur, and they don't impinge over much of the world ocean. However, this type of coupling does require that mesoscale variability be very well resolved to obtain sufficient coupling. Thus, this major topographic effect is missed at coarser resolution and can even lead to false conclusions about the role of topography and unexplained errors in simulations of the mean pathways of ocean currents, including the Gulf Stream and Kuroshio. Results so far suggest that this type of coupling is widespread outside the tropics and that 1/32° resolution is required to obtain worldwide coverage with this type of coupling in the places where it occurs, although it has been obtained at lower resolutions in some regions.

Nesting of finer resolution limited-area models in coarser resolution larger-scale models is often suggested as a way to obtain sufficient resolution in regions of interest. However, results from very high resolution global and basin-scale ocean models in this project show that the additional nonlinearity found in these models can alter large scale features of the circulation, including 1) the basic shape of a gyre (demonstrated in a 1/32° Atlantic model), 2) the eastward extension/sharpness of currents/fronts that span an ocean basin (demonstrated in a 1/16° Pacific model), 3) mass transports through passages (demonstrated for passages in the Caribbean/Bahamas/ Gulf of Mexico region and the Philippines/Indonesian archipelago), and 4) the pathways of ocean currents on large and small scales through upper ocean - topographic coupling via mesoscale flow instabilities (demonstrated in many regions including the Gulf Stream, Kuroshio, and Sea of Japan). Thus, there are serious pitfalls in the nesting approach and great caution is required in determining the situations and subdomains where it is appropriate.

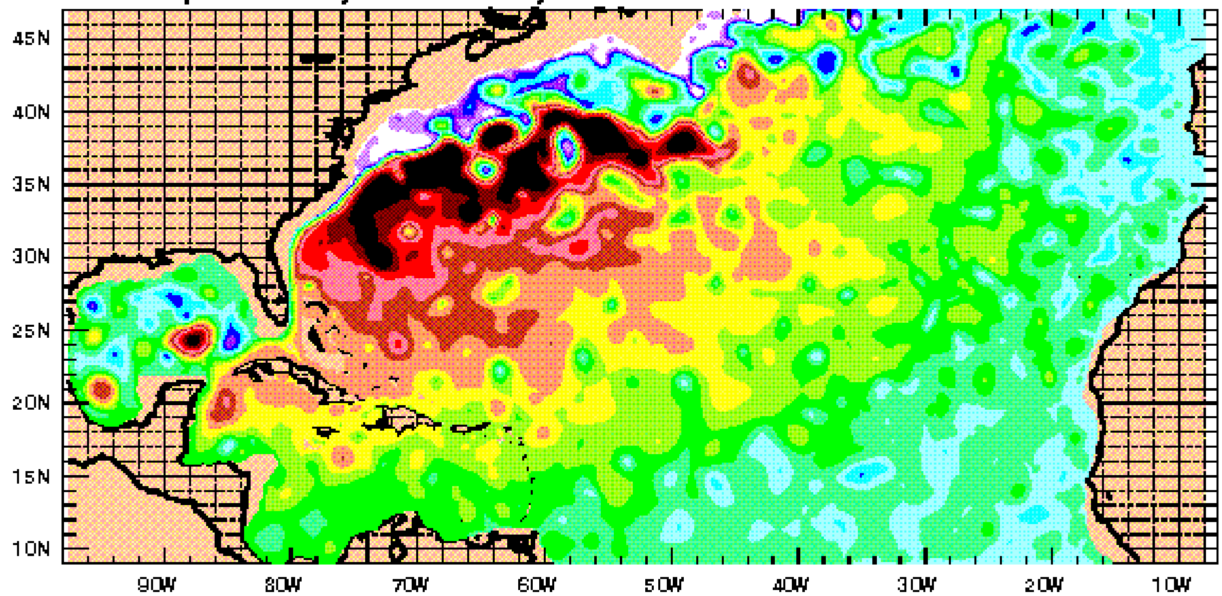
<u>Model Development:</u> NLOM can run efficiently and interchangeably on a wider variety of computer platforms than any other ocean model, including scalable systems (e.g. CM5, Cray T3D and T3E, IBM SP, SGI Origin 2000 and HP/Convex SPP2000), Cray PVP systems (e.g. Y-MP, M98, C90, J90, and T90) and workstations. During FY97, for the first time Cray PVP supercomputers became uncompetitive with the scalable systems for global and basin scale NLOM applications. The value of having a very portable computer code in the diverse DoD HPC environment was also demonstrated especially well. This greatly enhances research productivity and should facilitate operational application and code migration to new computer systems. The importance of high resolution in ocean models makes cost-effective ocean model design essential for global and basin-scale ocean models. No other existing ocean model can get by with lower resolution than NLOM.

TRANSITIONS: A 1/4° 5.5-layer reduced gravity thermodynamic global ocean model was transitioned to FNMOC in FY96 via the data assimilation group. Due to the limitations of the reduced gravity formulation, and the continued advances of the finite depth model, it was decided that a 1/4° 6.0-layer finite depth thermodynamic global model should be used instead. This model has been transitioned to the DART group.

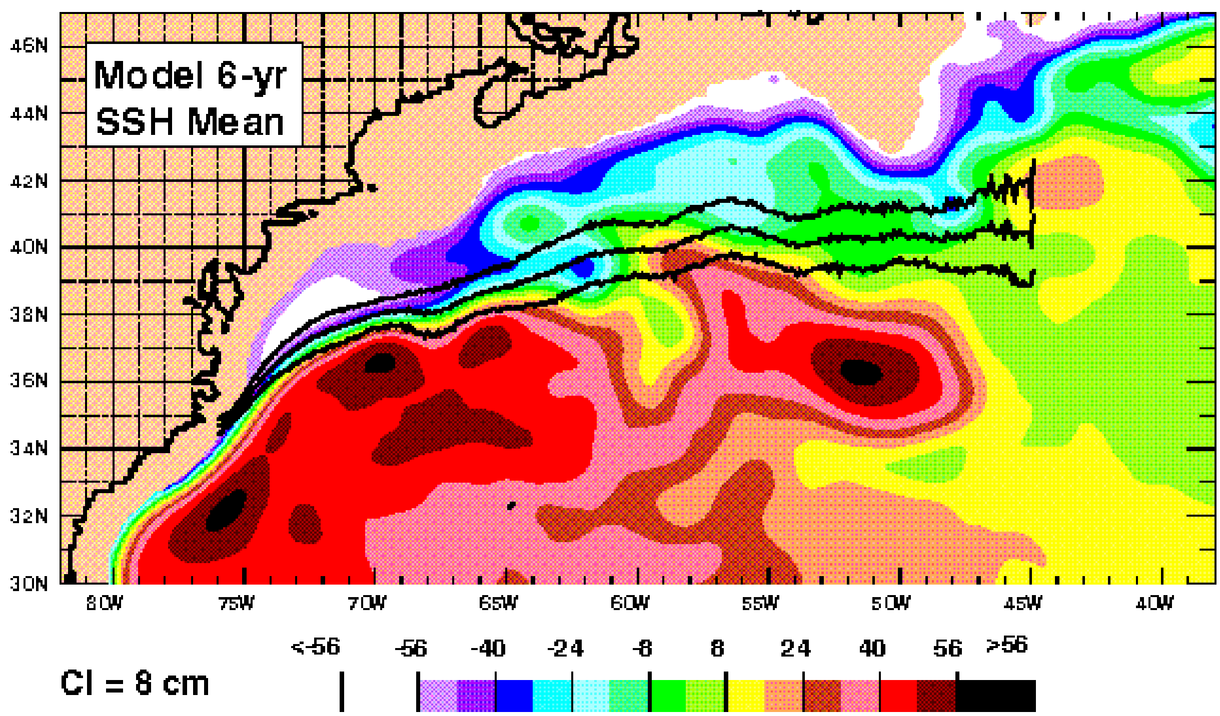
RELATED PROJECTS: The Atlantic effort participates in ONR's DAMEE-NAB project funded FY95-FY98, which includes participants from several universities. The Pacific Ocean modeling feeds into the DART effort in developing an eddy-resolving nowcast/forecast system for the Pacific. Other related research projects include 6.1 Dynamics of Low Latitude Western Boundary Currents, 6.1 Forced Upper Ocean Dynamics (mixed layer development), 6.1 Thermodynamic and Topographic Forcing in Global Ocean Models, 6.2 Basin Scale Prediction System, 6.2 Monitoring the North Pacific (National Ocean Partnership Program (NOPP)) (acoustic tomography focus), 6.3 Scalable Ocean Models with Domain Decomposition (Common HPC Software Support Initiative (CHSSI)), 6.4 DART and 6.4 Large Scale Ocean Models.

NRL 1/32° Atlantic Subtropical Gyre Model
Initialized from spun-up 1/16° simulation

SSH snapshot at day 350 after 11 years at 1/32° A = 5 m^2/s



Gulf Stream IR northwall 1982-1996 mean +/- std dev from Cornillion and Sirkes



Forced by Hellerman-Rosenstein monthly wind stress climatology and ports at the northern and southern boundaries (thermohaline component)