

## **Basin-Scale 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 ( $1/32^\circ$  Atlantic subtropical gyre,  $9^\circ$ - $51^\circ$ N, which includes the Intra-Americas Sea) and a global model with progressively increasing resolution,  $1/16^\circ$  in 2001 and ultimately  $1/32^\circ$  resolution. These systems will include data assimilation of satellite altimetry, sea surface temperature and in-situ data.

### **OBJECTIVES**

The development and validation of global and basin-scale ocean prediction systems. This includes skillful nowcasts and forecasts of ocean thermal structure and currents. High horizontal resolution is required 1) to depict eddies and meandering inertial jets/oceanic fronts which can span large ocean basins, 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 Global, subtropical Atlantic and North Pacific basins which supports planned 6.4 transitions.

The nowcast/forecast system will include assimilation of observations of the global ocean surface with unprecedented accuracy and resolution, especially from satellite altimeters and AVHRR sensors. Up to five existing and approved altimeter missions will be orbiting simultaneously for the next several years. The Naval Oceanographic Office's Altimetry Data Fusion Center (ADFC) is distributing processed data from these sensors to operational users in near real time.

### **APPROACH**

The modeling effort is aimed at eddy-resolving models for the global, Atlantic and Pacific Oceans and associated model development in collaboration with other projects. A variety of model/data comparisons are performed to evaluate assimilative and nonassimilative model experiments. Hydrodynamic and thermodynamic versions of NLOM are used with grid resolutions of  $1/2^\circ$  to  $1/32^\circ$  for each variable and 5 to 7 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 (SST) is under development. The

## Report Documentation Page

*Form Approved*  
*OMB No. 0704-0188*

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1. REPORT DATE <b>30 SEP 1999</b>	2. REPORT TYPE	3. DATES COVERED <b>00-00-1999 to 00-00-1999</b>			
4. TITLE AND SUBTITLE <b>Basin-Scale Ocean Prediction System</b>		5a. CONTRACT NUMBER			
		5b. GRANT NUMBER			
		5c. PROGRAM ELEMENT NUMBER			
6. AUTHOR(S)		5d. PROJECT NUMBER			
		5e. TASK NUMBER			
		5f. WORK UNIT NUMBER			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Naval Research Laboratory, Ocean Dynamics and Prediction Branch, Stennis Space Center, MS, 39529</b>		8. PERFORMING ORGANIZATION REPORT NUMBER			
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)			
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)			
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Same as Report (SAR)</b>	18. NUMBER OF PAGES <b>10</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

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 primitive equation ocean model in existence in terms of computer time per model year. Altimetric sea surface height (SSH) will be assimilated using a combination of optimum interpolation (OI), subsurface statistical inference, and nudging. Substantial effort will be devoted to optimizing the performance of this combination using both real and simulated data. More advanced methods of assimilation such as adjoint and Kalman filtering techniques are not yet affordable in eddy-resolving global and basin-scale ocean models.

## **WORK COMPLETED**

During FY99, the project had 25 publications (submitted to in print, excluding abstracts), 12 refereed.

1. 1/16° vs 1/4° nowcast/forecast demo: The 1/16° thermodynamic NLOM Pacific Ocean model north of 20°S and 1/4° global thermodynamic NLOM were used to assimilate satellite altimeter data from TOPEX/POSEIDON (T/P) and ERS-2 using a 3-day data window and daily OI analyses of the deviations from the model state. Both started from a spun-up atmospherically-forced initial state in 1998 and are currently running in near real-time using the same covariance functions for the daily OI analyses. The covariance functions were calculated from T/P, ERS-2 and Geosat-ERM data. Model-data comparisons against unassimilated data include independent MODAS SST analyses (especially for the Kuroshio pathway), unassimilated BTs (both dynamic height and synthetic T/S profiles), tide gauge sea level time series, and drifter data. Mean SSH from the model was compared with mean surface dynamic height from the MODAS hydrographic climatology (4 cm rms agreement). Synoptic model SSH fields were also compared with MODAS OI analyses of SSH. Month-long forecasts were initialized from some of the data-assimilative model states. So far results have been included in 3 publications (Hurlburt et al., 1999; LeTraon et al., 1999; Smedstad et al., 1999). The Co-PI of this project is a member of both the International and US Scientific Steering Teams of the multi-national Global Ocean Data Assimilation Experiment (GODAE).

2. While the nowcast/forecast demo used real altimeter data, altimeter data were also simulated by the 1/16° Pacific model to provide data with realistic mesoscale variability where the “truth” is precisely known for all model variables everywhere. The simulated data were used in test and evaluation of data assimilation techniques/parameters and in observing system simulation studies for satellite altimeter data, especially studies for evaluation of data assimilation skill at depicting mesoscale variability as a function of satellite orbit and number of satellites. Results are included in Hurlburt et al. (1999), Jacobs et al. (1999), Smedstad et al. (1999) and Stammer et al. (1999).

3. NLOM mixed layer/SST development and evaluation: Development of an embedded mixed layer for NLOM is essentially complete. Numerous improvements were made in the process of extensive testing and evaluation using a 1/2° resolution global ocean domain. The embedded mixed layer has been tested using both climatological forcing with 12 hourly variability superimposed on the wind field and by running the model 1979-1998 using 6-12 hrly wind and heat flux forcing from the European Centre for Medium-Range Weather Forecasts (ECMWF). Results were substantially improved using wind stress and latent and sensible heat flux formulations developed in this project by Kara et al. (1999a). Initial testing has begun using 1/8° and 1/16° resolution globally. A mixed layer climatology was developed and tested (Kara et al., 1999b,c) to aid in the evaluation. Climatological

NLOM SST evaluation was accomplished using the monthly COADs SST climatology and monthly climatologies at 11 hydrographic stations repeated for 42 years and at 40 buoy locations around the world (including 20 in the equatorial Pacific). Daily time series at the 40 buoy locations have been the primary means of non-climatological SST evaluation so far.

4. Development and testing of global NLOM at  $1/8^\circ$ ,  $1/16^\circ$  and  $1/32^\circ$  resolution: The first  $1/32^\circ$  simulation was run for 8 years in hydrodynamic mode starting from a spun-up  $1/16^\circ$  simulation. Up to 1152 Cray T3E processors were used under early access time provided by Cray/SGI (Wallcraft, 1999) and the run was completed under DoD Challenge at the NAVO MSRC. A snapshot from this simulation appeared on the cover of the Marine Technology Society Journal. A  $1/16^\circ$  thermodynamic global NLOM simulation with an embedded mixed layer and “high frequency” climatological forcing is now running under DoD Challenge. The simulation was initialized from a spun-up  $1/8^\circ$  simulation and so far has run 22 years at  $1/16^\circ$ . The  $1/16^\circ$  model is planned for transition to operational testing in 2001 with data assimilation added.

5. In FY98, the project submitted two papers for the special journal issue devoted to the multi-institutional ONR project Data Assimilation and Model Evaluation Experiment - North Atlantic Basin (DAMEE-NAB), Hurlburt and Hogan (1999) and Townsend et al. (1999). The first is now in press and the second has been accepted.

6. Shriver and Hurlburt (1999) submitted a journal article on the global non-steric contribution to SSH variability. The paper uses  $1/16^\circ$  global NLOM results and thus could examine both wind-driven and eddy-driven contributions.

## RESULTS

1. The nowcast/forecast demo results constitute a feasibility demonstration of ocean model eddy-resolving nowcast/forecast skill using satellite altimeter data. The  $1/16^\circ$  model forecasts showed skill for at least a month in comparison with the assimilative model states and independent MODAS SST analyses (e.g. see Fig. 1). The  $1/16^\circ$  results are a dramatic improvement over the  $1/4^\circ$  results. Overall, the results demonstrate (1) that satellite altimetry is an effective observing system for mesoscale oceanic features, (2) that an ocean model with high enough resolution can be a skillful dynamic interpolator for satellite altimeter data in depicting mesoscale oceanic variability, and (3) that the high resolution ocean model can provide skillful forecasts of mesoscale variability for at least a month, when model assimilation of the altimeter data is used to define the initial state.

2. The  $1/16^\circ$  eddy-resolving simulated data results show that substantial skill at depicting the mesoscale is obtained using even one altimeter, with the Geosat 17-day repeat and ERS 35-day repeat orbits preferable to the T/P 10-day repeat orbit. However, errors can be reduced significantly by using up to 3 satellites. Covariance functions calculated directly from Geosat, ERS and T/P data give the best results for data assimilation of any tried so far.

3. The embedded mixed layer in NLOM gives accurate SST with atmospheric forcing even with no SST relaxation/assimilation. In this case  $1/2^\circ$  global NLOM gave global rms error  $< .5^\circ\text{C}$  for the annual mean and  $< .7^\circ\text{C}$  over the seasonal cycle with climatological atmospheric forcing. The 40 buoys yielded 340 years of complete daily time series of SST over the time frame 1980-1998. When  $1/2^\circ$

global NLOM was run 1979-1998 with 6-12 hrly ECMWF forcing, model SST comparisons to the 340 year-long SST time series gave median values of .82°C for rms error, .92 for the correlation coefficient, –.09°C for the bias and .84 for the skill score. Again there was no assimilation of SST.

4. Both the 1/16° and 1/32° global NLOM simulations showed robust Gulf Stream separation at Cape Hatteras and a realistic Gulf Stream pathway between Cape Hatteras and the Grand Banks (not simulated at 1/8° resolution). They also showed overall realistic gyre structure, current pathways and strengths, and global thermohaline circulation. The high resolution enabled them to simulate ocean fronts that span major ocean basins such as the North Pacific (not simulated at 1/8°), upper ocean – topographic coupling via flow instabilities which can strongly influence upper ocean current pathways (not simulated in most regions at 1/8°) and much greater mesoscale variability than at 1/8°.

5. The Hurlburt and Hogan (1999) paper discusses the impact of 1/8° to 1/64° Atlantic model resolution on model-data comparisons in the Gulf Stream region. In revision, comparisons to eddy statistics, distribution and behavior from Auer (1987) and other sources were added. The good agreement at 1/16° and higher indicates that the 5-layer simulations realistically simulate mesoscale variability, eddy dynamics and the associated mixed baroclinic-barotropic instabilities.

6. Using 1/16° global NLOM, Shriver and Hurlburt (1999) showed that the non-steric contribution to SSH variability is > 50% over much of the world ocean, a contribution that increases with latitude. The wind-driven contribution is largely deterministic and can be simulated using a barotropic model, but there is a substantial eddy-driven contribution, particularly in regions of high mesoscale variability, which is non deterministic.

## **IMPACT/APPLICATION**

1. & 2. The 1/16° Pacific NLOM feasibility demonstration of ocean model eddy-resolving nowcast/forecast skill is a critical milestone in the development of a truly eddy-resolving global ocean prediction system for the U.S. Navy. Earlier there was doubt that satellite altimeter data was a sufficient observing system for mapping the evolution of oceanic mesoscale features such as eddies and the meandering of oceanic currents and fronts. This work demonstrates that satellite altimetry is sufficient for that purpose. Furthermore, it shows that an ocean model with sufficiently high horizontal resolution can have dynamic interpolation skill in data assimilation and at least one month forecast skill for mesoscale variability using satellite altimetry as the observing system. The results are also relevant to GODAE, the multinational project designed to help justify a permanent global ocean observing system by demonstrating useful real-time operational ocean products.

3. Model-data comparisons indicate that NLOM SSTs have the accuracy needed for assimilation of SST data and for SST forecasting. The high accuracy of NLOM SSTs was unexpected because of the vertical resolution of NLOM. Because NLOM has also demonstrated eddy-resolving nowcast/forecast skill and the ability to simulate realistic pathways for current systems like the Gulf Stream and the Kuroshio, this is relevant to long-range weather forecasts of a week or longer. Ocean model forecast skill is also relevant on such time scales.

4. & 5. Resolution of 1/32° is the highest to date for a global ocean model and it is the ultimate target resolution for the planned global nowcast/forecast system. The research results have shown

substantial improvement with resolution increases up to  $1/32^\circ$  and more modest improvements with further increases (Hurlburt and Hogan, 1999). Ocean model simulation skill for oceanic features is a prerequisite for ocean model skill in dynamic interpolation in data assimilation and in forecasting of these features. Increasing the model resolution from  $1/8^\circ$  to  $1/16^\circ$  affects not only the mesoscale but also the large scale, e.g. the ability to simulate inertial currents and fronts that span major ocean basins (Hurlburt et al., 1996) and the large-scale shape of ocean gyres (Hurlburt and Hogan, 1999). In addition, we have found widespread impact of upper ocean – topographic coupling via mesoscale flow instabilities in steering upper ocean currents. Very fine resolution of mesoscale variability is required to obtain sufficient coupling, at least  $1/16^\circ$  in most regions. Mean SSH is added to the altimetric deviations. High resolution is needed to obtain accurate mean SSH for features like inertial jets.

6. An ocean model is needed to distinguish between the steric and non-steric contributions to SSH. A data-assimilative eddy-resolving model is needed to find the non-deterministic eddy driven contribution. The ability to distinguish between these contributions is needed in data assimilation and in the calculation of synthetic temperature and salinity profiles from SSH (e.g. in the MODAS system which is operational at NAVO), particularly since the non-steric contribution to SSH is  $> 50\%$  over much of the world ocean.

## **TRANSITIONS**

None in FY99. The  $1/16^\circ$  NLOM-based global ocean nowcast/forecast system is planned for transition in FY01.

## **RELATED PROJECTS**

6.1 Dynamics of Low Latitude Western Boundary Currents

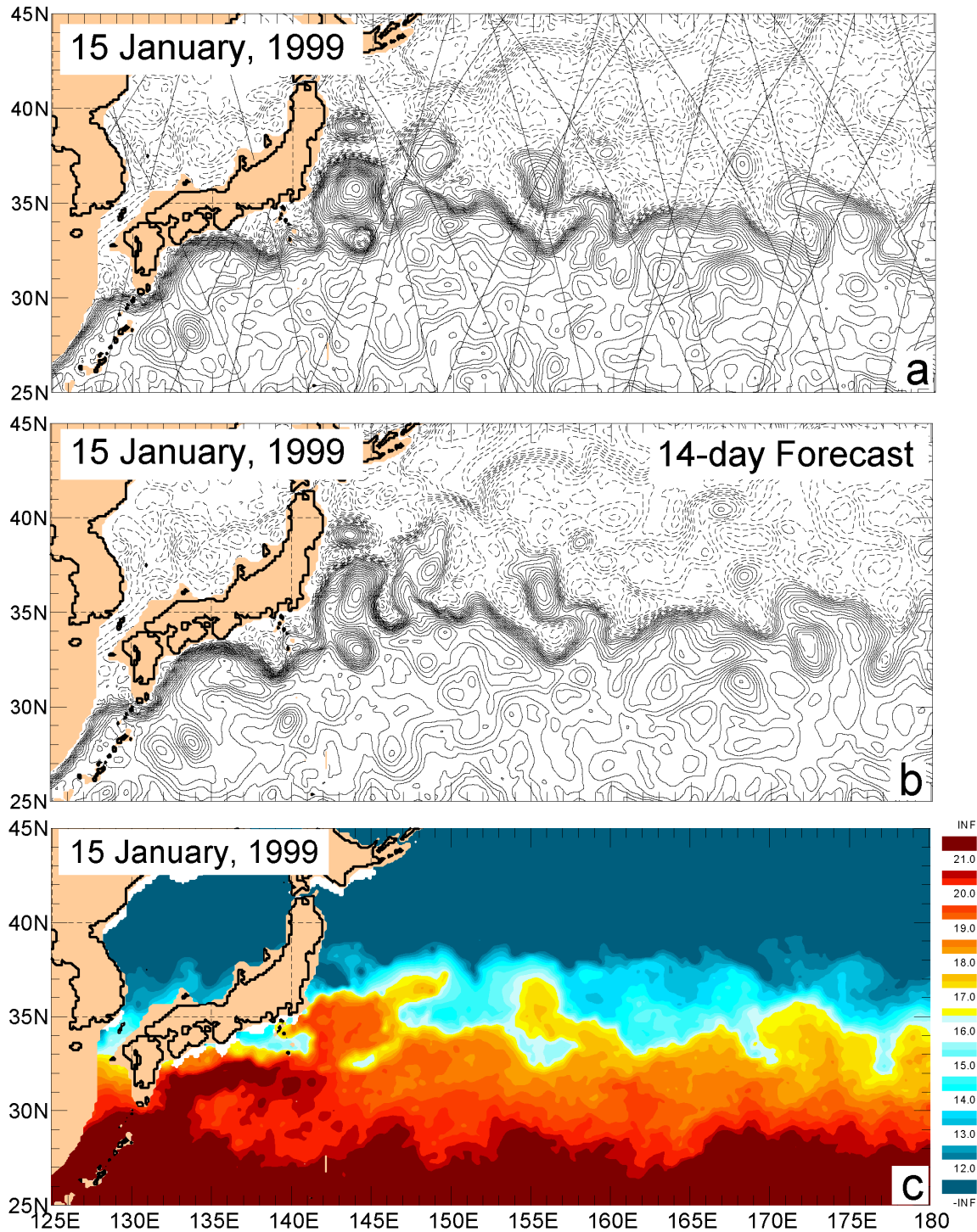
6.1 Forced Upper Ocean Dynamics (mixed layer development)

6.1 Thermodynamic and Topographic Forcing in Global Ocean Models

6.3 Scalable Ocean Models with Domain Decomposition (Common HPC Software Support Initiative (CHSSI))

6.4 Ocean Data Assimilation and 6.4 Large Scale Ocean Models.

The project Co-PI is a member of both the International and U.S. GODAE Scientific Steering Teams.



**1:** (a) Kuroshio region sea surface height (SSH) snapshot for January 15, 1999 from the NRL 1/16° Pacific model with assimilation of T/P and ERS-2 data. (b) Corresponding SSH snapshot from a 14-day forecast initialized on January 1, 1999. (c) 1/8° MODAS sea surface temperature (SST) analysis from satellite IR imagery. The contour intervals are 5 cm for SSH and .5°C for SST.

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