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14. ABSTRACT
Over the past decade, the Naval Research Laboratory (NRL) has been actively working on the problem of eddy-resolving global ocean modeling and prediction. The world's first global ocean nowcast/forecast system has been developed at NRL and is running in real-time at the Naval Oceanographic Office (NAVO). The system consist of the 1/16 degree 7-layer, thermodynamic, finite depth version of the Navy Layered Ocean Model (NLOM) for the global ocean (72 degrees to 65 degrees north) and includes a mixed layer and sea surface temperature (SST). It spun-up to real-time using high frequency wind and thermal forcing from the Fleet Numerical Meteorology and Oceanography Center's Navy Operational Global Atmospheric Prediction system. It includes assimilation of SST and near real-time TOPEX/POSEIDON and ERS-2 altimeter data made available from NAVO's Altimeter Data Fusion Center NAVO is scheduled to begin operational testing of the system on 15 December 2000 and pending a successful outcome it will become an operational product. system gives a real-time view of the ocean down to 50-200 km scale of ocean eddies and the meandering of ocean currents and fronts. Figure 1 is an example of sea surface height (SSH) and SST for the Gulf Stream in the Atlantic.

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Nowcasting & Forecasting the Global Ocean

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Over the past decade, the Naval Research Laboratory (NRL) has been actively working on the problem of eddy-resolving global ocean modeling and prediction. The world's first global ocean nowcast/forecast system has been developed at NRL and is running in real time at the Naval Oceanographic Office (NAVO).

The system consists of the 1/16° seven layer, thermodynamic, finite depth version of the Navy Layered Ocean Model (NLOM) for the global ocean (72°S to 65°N) and includes a mixed layer and sea surface temperature (SST). It was spun-up to real time using high frequency wind and thermal forcing from the Fleet Numerical Meteorology and Oceanography Center's Navy Operational Global

represents a zone of fresher water with low scattering and low chlorophyll growth. Ternary diagrams may provide a new way to classify the complex, coastal Case II waters into biogeochemical provinces.

Summary

With the availability of new ocean color sensors, the application of remote sensing for understanding coastal processes is beginning. The rich spectral signature of coastal waters allows an opportunity to separate the in-water components into tracers of processes. Improved atmospheric and in-water algorithms in bio-optical sensing have been extended into coastal waters. Unlike open ocean waters, coastal waters have a complex variety of combinations of particles, (organic and inorganic), and absorption components (chlorophyll and colored dissolved organic matter).

Because coastal waters are more complex than open ocean waters, improved methods of classification are needed to account for a variety of processes. By basing a classification on remote sensing bio-optical products, we enhance our ability to understand the spatial variability of the processes.

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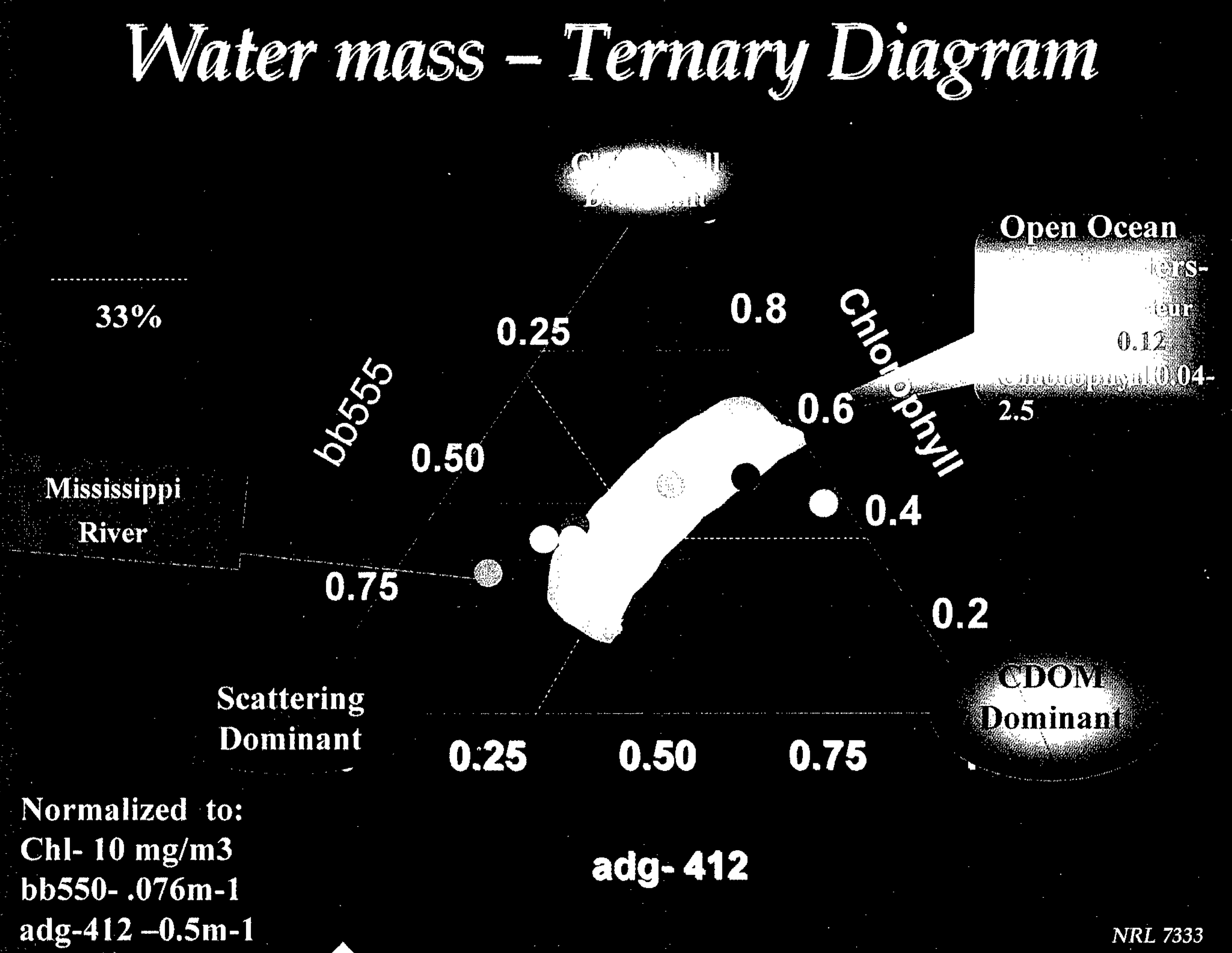

Figure 4. *Coastal waters are complex mixtures of backscattering (550 nm), chlorophyll concentration and absorption from colored dissolved organic matter. These three Seawifs products are classified using a ternary diagram, which bases a water mass on the percentage of each component. The colors represent mean water mass from the scatter plot (Figure 3) and illustrate the transition of coastal to open ocean waters based on these components.*

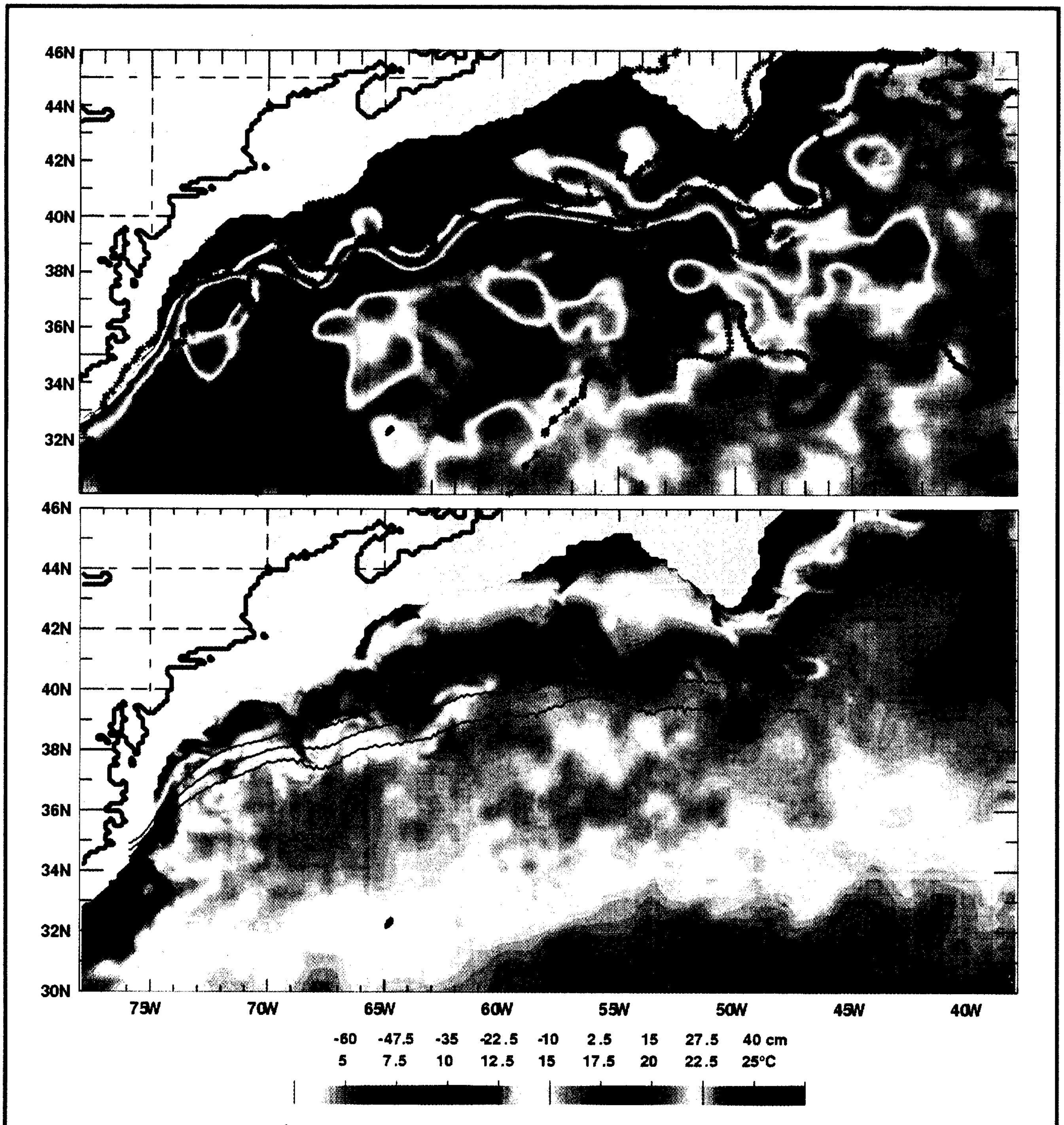

Figure 1. *Snapshots of sea surface height (top) and sea surface temperature (bottom) zoomed in on the Gulf Stream region for 6 December 2000 from the real time 1/16° global nowcast/forecast system with assimilation of SST and satellite altimeter data from Topex/Poseidon and ERS-2. Superimposed on the sea surface height (SSH) is the frontal analysis based on infrared satellite imagery from the Warfighting Support Center at NAVO. Superimposed on the SST is the Gulf Stream IR northwall 1982-96 mean ± standard deviation determined by P. Cornillion (University of Rhode Island) and Z. Sirkes (University of Southern Mississippi).*

Atmospheric Prediction System. It includes assimilation of SST and near-real time Topex/Poseidon and ERS-2 altimeter data made available from NAVO's altimeter data fusion center. NAVO began operational testing of the system last December, and pending a successful outcome, it will become an operational product. The system 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. Figure 1 is an example of sea surface height (SSH) and

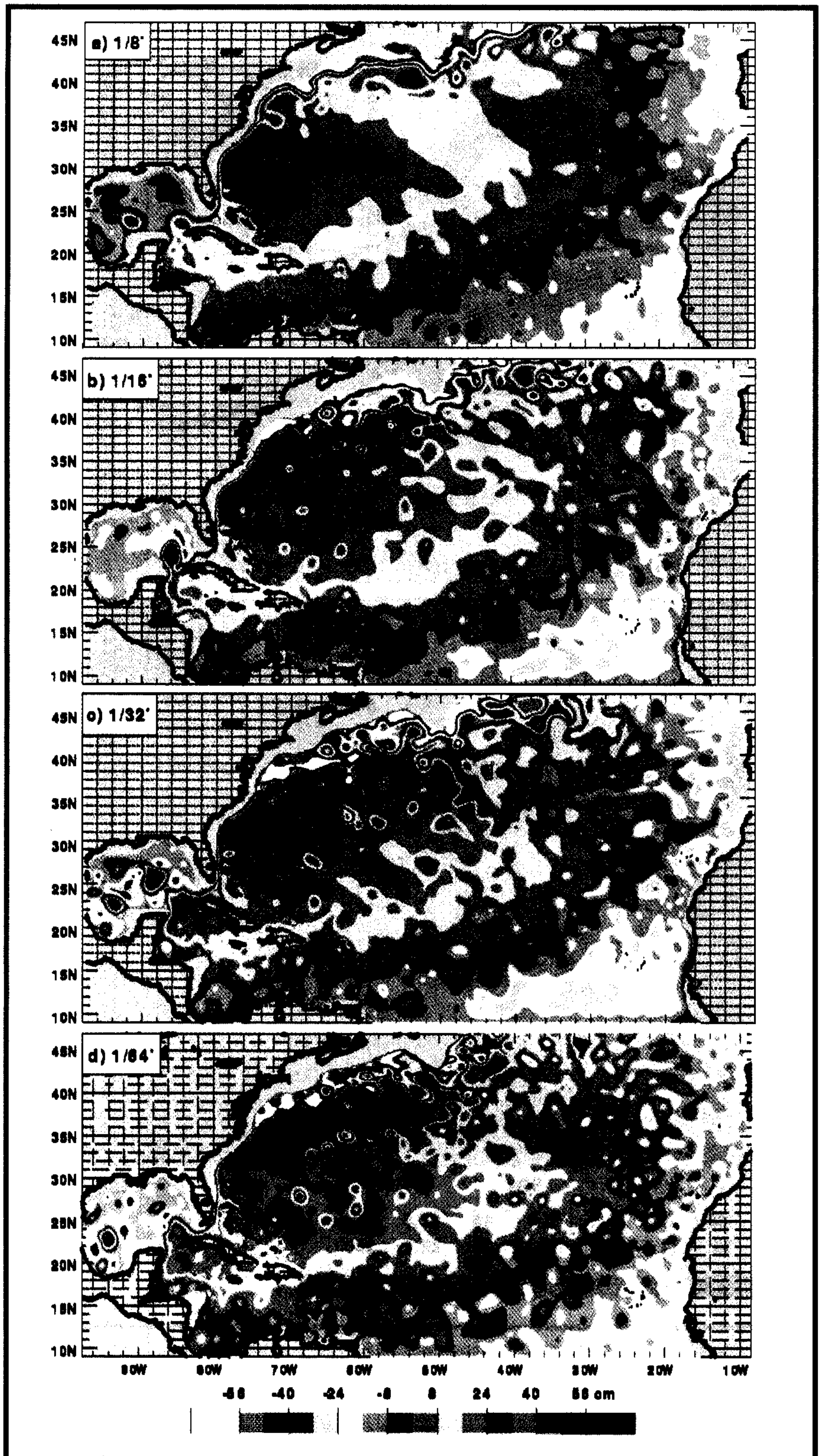

Figure 2. *Snapshots of sea surface height (SSH) for the North Atlantic Ocean from four simulations using the Navy Layered Ocean Model at a) 1/8°, b) 1/16°, c) 1/32°, and d) 1/64° resolution. The model is forced by the monthly wind stress climatology from Hellerman and Rosenstein (1983) and a port driven thermohaline circulation. There is no SSH assimilation in these model results. Adapted from Hurlburt and Hogan (2000).*

SST for the Gulf Stream in the Atlantic.

Atmospheric Versus Oceanic Prediction

The first operational weather prediction occurred in May 1955 as a joint air force, navy and weather bureau project. In principle, numerical ocean modeling is similar to atmospheric modeling but global operational oceanography has lagged far behind because of two major complications. (1) Oceanic space and time scales are much different than those of the atmosphere. Ocean eddies are typically about 100 km in diameter which makes them 20 to 30 times smaller than comparable atmospheric highs and lows. This means that approximately four orders of magnitude more computer time and three orders of magnitude more computer memory are required. (2) Unlike the meteorological radiosonde network that provides initial conditions from the surface to near the top of the atmosphere, there are very few observations below the ocean surface at the synoptic time scale. Thus, any effective oceanic data assimilative technique will be limited to surface satellite observations. One advantage ocean modeling enjoys is that sea surface height forecast skill is longer than the 10 to 14 day limit for atmospheric pressure systems as will be shown later.

Model Resolution Requirements

A major component of NRL's ocean modeling program has been a detailed study of the resolution required for ocean prediction. There is strong evidence that the Navy Layered Ocean Model and other popular ocean models need to use grid cells for each prognostic variable that are at most about 8 km across at mid-latitudes. NRL research has shown that doubling the horizontal resolution to 4 km per cell gives substantial improvement but doubling again to 2 km gives only modest additional improvement (Hurlburt and Hogan, 2000). For the Navy Layered Ocean Model grid these resolutions translate to 1/16°, 1/32° and 1/64°, respectively. This is for the global and basin-scale.

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. It can even affect the large scale shape of ocean gyres such as the Sargasso Sea in the Atlantic.

The need for high horizontal resolution is highlighted in Figure 2 that shows sea surface height snapshots for the Atlantic basin from four non-data assimilative Navy Layered Ocean Model simulations at 1/8°, 1/16°, 1/32° and 1/64° resolution. The 1/8° model shows two unrealistic Gulf Stream pathways that are consistent with linear dynamics. Higher horizontal resolution is required in order to get into a more non-linear flow regime, and this occurs at 1/16° resolution. Note the explosion of eddies between the 1/8° and 1/16° models. There is now one Gulf Stream pathway that separates from the U.S. coast at Cape Hatteras, although it does not exhibit a strong inertial character as far into the basin as is observed. In the 1/32° model, it penetrates farther into the interior, changing the large scale shape of the subtropical gyre (Sargasso Sea) in comparison to the 1/8° model. The 1/64° model provides modest improvement over the 1/32° model.

Computational Requirements

As far back as 1989, the President's Office of Science and Technology recognized

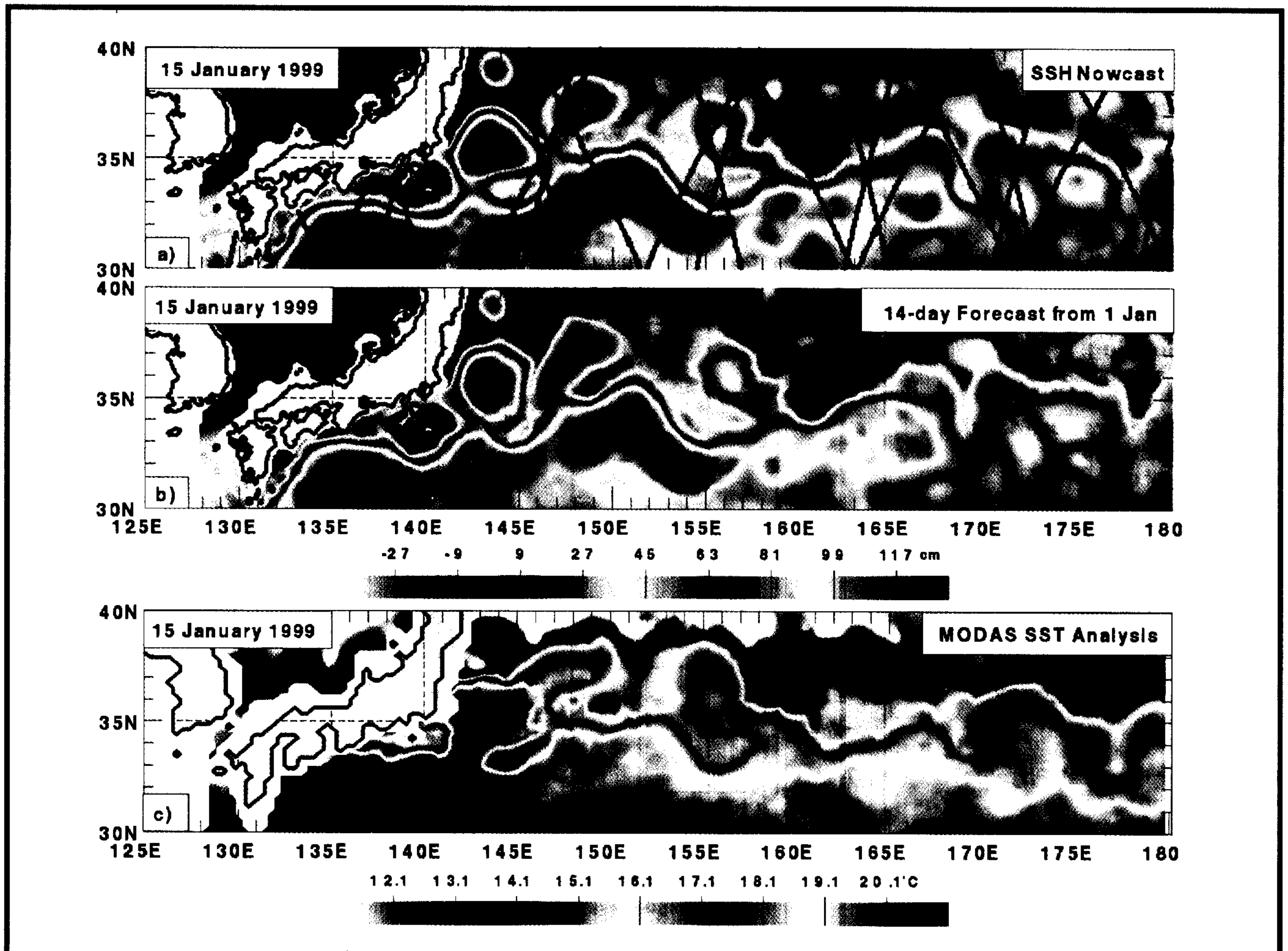

Figure 3. *Zoom on the Kuroshio south and east of Japan. (a) SSH (sea surface height) for 15 January 1999 from the 1/16° global nowcast/forecast system with assimilation of satellite altimeter data from Topex/Poseidon and ERS-2. The altimeter tracks with data available for this update cycle are overlaid. (b) The corresponding SSH snapshot from a 14 day forecast initialized from 1 January 1999. (c) The MODAS 1/8° SST analysis from satellite IR imagery. The MODAS SST product was developed by C. Barron at NRL and is an operational product at NAVO. The SST color bar is designed to highlight the Kuroshio pathway.*

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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. We are solving the problem on today's systems capable of only a few percent of this performance by taking a multi-faceted approach to cost minimization.

One facet is the use of the Navy Layered Ocean Model (Wallcraft and Moore, 1997) 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. The Navy Layered Ocean Model'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 Navy Layered Ocean Model layers to replace the 100 or more fixed levels that would be needed at 1/16° resolution.

Another facet of our efficiency drive is the use of an inexpensive data assimilation scheme backed by a statistical technique for relating surface satellite 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.

The initial goal of this research has been a fully eddy-resolving, data assimilative global ocean prediction system with 1/16° horizontal resolution and this is currently being transitioned to NAVO. An upgrade to the desired resolution of 1/32° is planned for 2003.

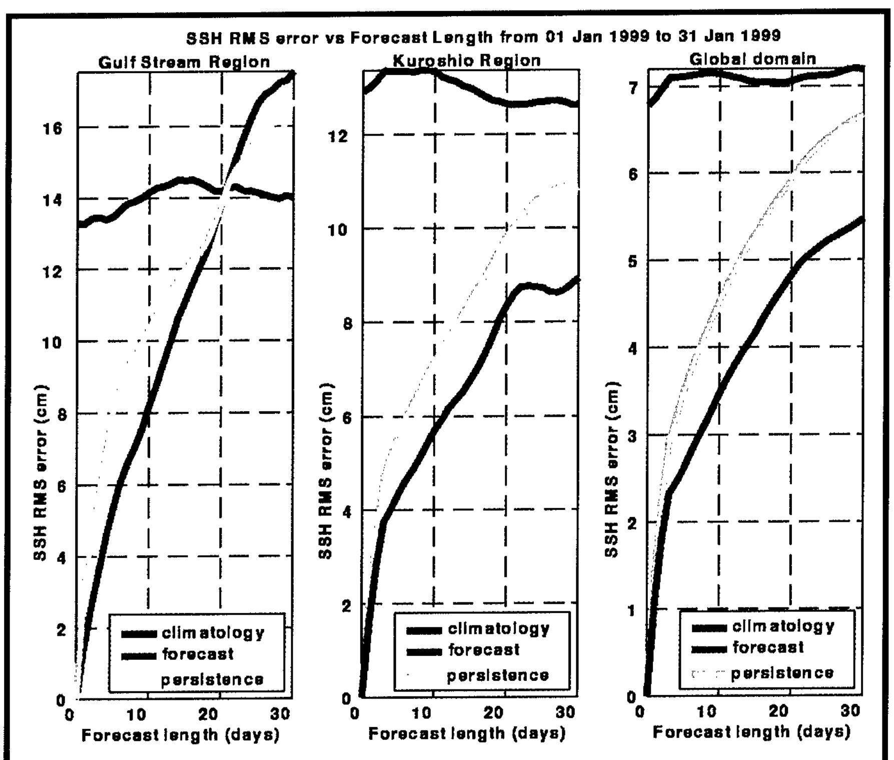

Figure 4. *The 1/16° global SSH (sea surface height) forecast verification against the model with Topex/Poseidon and ERS-2 altimeter data assimilation for the period 1-31 January 1999. Shown is RMS error (cm) versus forecast length (days) for the Gulf Stream (left), the Kuroshio (middle) and the whole domain (right). The red curves are the Navy Layered Ocean Model forecasts; the blue curves are forecasts of persistence (i.e. no change from the initial state) and the black curve is from climatology.*

Predictive Skill

Figure 3 depicts a sea surface height nowcast and 14 day forecast valid on 15 January 1999 from the 1/16° global system. An independent 1/8° SST analysis from the Modular Ocean Data Assimilation System (MODAS) is also shown for comparison. The SST analysis shows good correspondence between the Kuroshio pathway and some of the eddies seen in the simulated SSH (sea surface height) field. The global system consistently produces a skillful regional and basin-wide forecast of oceanic fronts and eddies. Figure 4 shows forecast verification from the period discussed above. Compared to forecasts of climatology and persistence (no change), the operational system shows forecast skill for more than one month over the entire model domain and Kuroshio region, and 21 day forecast skill in the Gulf Stream region in this instance.

The results have shown that altimeter data alone is sufficient to produce an accurate nowcast when a high resolution ocean model is in the loop to act as a dynamical interpolator to fill in the space-time gaps in the altimeter data. The simulation skill of the model also leads to skillful forecasts of a month or more in many regions.

The World Wide Web

To view real time Navy Layered Ocean Model results on the world wide web, start at the NAVOCEANO homepage (http://www.navo.navy.mil) and click on "operational products". In the sub-window click on "product search form". In the next sub-window click on the "product type view" button and in the lower window scroll to "Model Navy Layered Ocean Model" and highlight it. This causes several region indicators to appear in the upper window and these should be highlighted. Finally, click on the "Submit Query" button. The analysis and forecast plots and animations are then viewable. Near the top of the page is a hyperlink to aid in book marking references.

Acknowledgments

This work is a culmination of many projects over many years. Individuals who have made significant contributions toward this final operational product include Jay F. Shriver (NRL), A. Birol Kara (Sverdrup Technology Inc.), and Jean-Francois Cayula (Planning Systems Inc.). This is a contribution to the 6.2 Basin-scale Ocean Prediction System project funded by the Office of Naval Research under program element 62435N and to the 6.4 projects Large Scale Ocean Modeling and Ocean Data Assimilation funded by the Space and Naval Warfare Systems Command under program element 63207N. The numerical model was run on the Cray T3Es at the Naval Oceanographic Office, Stennis Space Center, Mississippi and at the U.S. Army Engineer Research and Development Center, Vicksburg, Mississippi. Both are part of the Defense Department's High Performance Computing Initiative. ■

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Ocean Color Spectrum

Photo of dolphins. A school of short-beaked common dolphins, the most abundant small cetacean in offshore waters of the Galápagos Archipelago. The typical size of these schools is about 270 animals, but they can aggregate in groups of 3,000 or more.
Photo courtesy of Daniel Palacios

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*This month's Ocean Color Spectrum features a host of interesting contributions from around the world. The featured contribution is provided by **Daniel M. Palacios**, with co-authors Karin A. Forney and Gene Feldman.*

Cetaceans (whales and dolphins) are at the top of the oceanic food chain. From this perspective, it is important to augment our understanding of the influence of oceanographic phenomena on cetacean patterns of occurrence. On the western side of the Galápagos Islands, strong environmental gradients result from the interaction between tropical and equatorial surface waters with the upwelled waters of the Equatorial Undercurrent. GalCet2K was a cruise designed to investigate mesoscale physical/biological interactions influencing the distribution and abundance of cetaceans in this region. The 15 day survey took place 5 to 19 April 2000 aboard R/V Odyssey, as a collaborative effort between the authors and the Ocean Alliance, a non-profit whale research and conservation organization (www.oceanalliance.org).

In conducting habitat assessments for cetaceans, a compromise was made between the requirements necessary to obtain precise estimates of abundance, and an environmental sampling design that will resolve the scales of interest. This is complicated by the fact that, at the higher trophic levels, species-environment relationships are a function of complex trophic and life-history dynamics that are not easily measured. Therefore, we must rely on proxy variables that can be readily measured within the scope of a typical cruise. Our approach consisted of an intensive visual survey for cetaceans along the track of the vessel, while stopping two to three times per day to sample the upper 150 m of the water column with a small CTD instrument with an attached fluorometer. Along-track measurements of sonar intensity were also collected at two frequencies (50 and 250 kHz), as a bulk index of biomass of zooplankton and nekton (which are potential

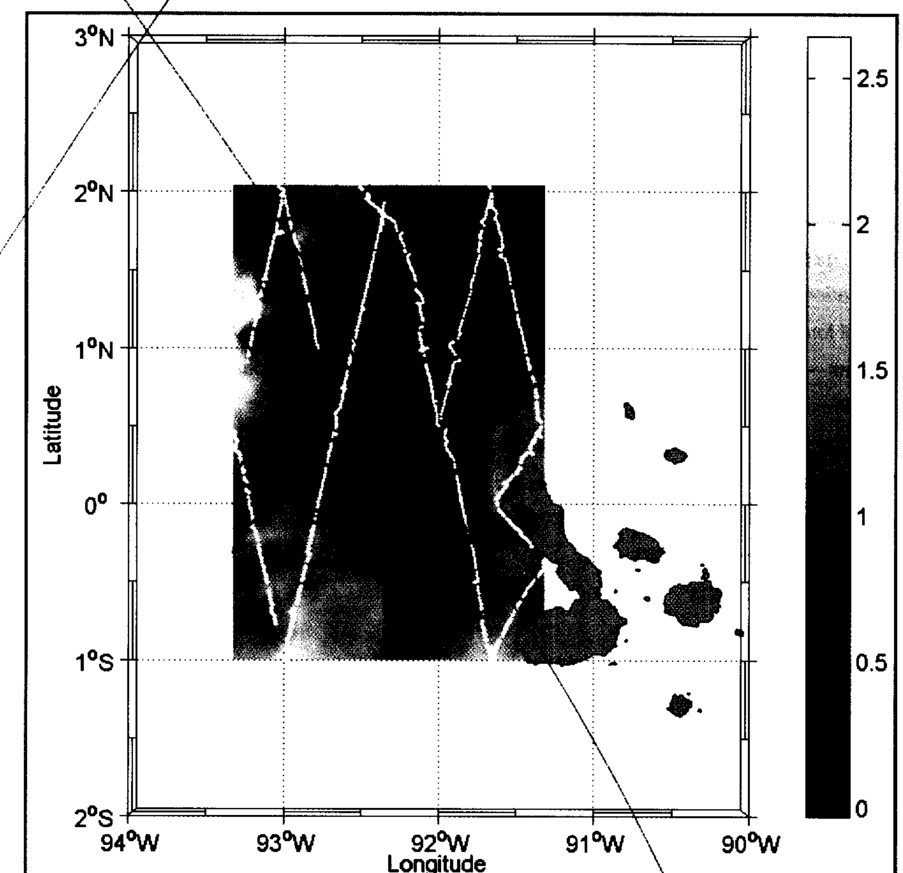

Figure 1. ***Water column zooplankton/nekton biomass index integrated to 150 m, as derived from sonar returns (50 plus 250 kHz). Scale is arbitrary. Dotted white line depicts measurement locations and red contour indicates a biomass index of one.***