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An operational Eddy resolving 1/16° global ocean nowcast/forecast system

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Abstract

The first real-time eddy resolving nearly global ocean nowcast/forecast system has been running daily at the Naval Oceanographic Office (NAVOCEANO) since 18 October 2000 and it became an operational system on 27 September 2001. Thirty-day forecasts are made once a week. The system, which was developed at the Naval Research Laboratory (NRL), uses the NRL Layered Ocean Model (NLOM) with 1/16° resolution and seven layers in the vertical, including a Kraus–Turner type bulk mixed layer. Sea surface temperature (SST) from satellite IR and satellite altimeter sea surface height (SSH) data from TOPEX/POSEIDON (T/P), ERS-2 and Geosat-Follow-On (GFO), provided via NAVOCEANO's Altimeter Data Fusion Center (ADFC), are assimilated into the model. The large size of the model grid ($4096 \times 2304 \times 7$) and operational requirements make it necessary to use a computationally efficient ocean model and data assimilation scheme. The assimilation consists of an optimum interpolation (OI) based scheme that uses an OI deviation analysis with the model as a first guess, a statistical inference technique for vertical mass field updates, geostrophic balance for the velocity updates outside of the equatorial region and incremental updating of the model fields to further reduce inertia–gravity wave generation. A spatially varying mesoscale covariance function determined from T/P and ERS-2 data is used in the OI analysis. The SST assimilation consists of relaxing the NLOM SST to the Modular Ocean Data Assimilation System (MODAS) SST analysis, which is performed daily at NAVOCEANO. Real-time and archived results from the model can be viewed at the NRL web site http://www.ocean.nrlssc.navy.mil/global_nlom. This includes many zoom regions, nowcasts and forecasts of SSH, upper ocean currents and SST, forecast verification statistics, subsurface temperature cross-sections, the amount of altimeter data used for each nowcast from each satellite and nowcast comparisons with unassimilated data. The results show that the model has predictive skill for mesoscale and other types of variability lasting at least 1 month in most regions and when calculated globally.

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1. Introduction

Adequate real-time data input, computing power, numerical ocean models and data assimilation capabilities are the critical elements required for successful eddy resolving global ocean prediction. Only recently, all of these elements have finally reached the status where this is feasible. In recognition of this, a multinational Global Ocean Data Assimilation Experiment (GODAE) is underway and will continue through 2007. GODAE is designed to help justify a permanent global ocean observing system by demonstrating real-time global ocean products in a way that will provide wide utility and availability for maximum benefit to the community. As outlined in the GODAE Strategic Plan (International GODAE Steering Team, 2000), it is currently in the development phase (2000–2002) to be followed by a demonstration phase (2003–2005) and a consolidation and transition phase (2006–2007).

In this paper, we discuss the first real-time, eddy resolving (1/16°) global ocean prediction system. It has been running continuously in real-time at the Naval Oceanographic Office (NAVOCEANO), Stennis Space Center, MS, since 18 October 2000 and it became an operational system on 27 September 2001. This system contributes to the GODAE goals and, consistent with those goals, extensive real-time results are viewable on the web at http://www.ocean.nrlssc.navy.mil/global_nlom. This is a first generation system and as in weather forecasting, there will be future upgrades and improvements as permitted by advances in the critical elements.

The amount of data available to oceanographers has increased dramatically during the 1990s. The launch of Geosat, ERS-1 and TOPEX/POSEIDON (T/P) started a new era in oceanography, in part because they represent the first observing system with the potential to permit eddy resolving global ocean prediction (Hurlburt, 1984). For the first time, it was possible to observe the near global synoptic sea surface height (SSH) field starting with usably accurate multiyear data from Geosat and more accurate continuous data starting in 1992 with ERS-1 and T/P. Dynamically, SSH is an important oceanic observable because it is closely related to the geostrophic component of surface currents and to subsurface thermohaline structure, including the depth of the main thermocline (Hurlburt, 1984; Carnes et al., 1990, 1994).

Assimilation of altimetric SSH data by the ocean prediction model is critical in mapping the evolution of oceanic features that are not a deterministic response to the atmospheric forcing, such as mesoscale flow instabilities, and it can be used to improve the model's depiction of many features that are. With T/P, ERS-2 and Geosat-Follow-On (GFO), the amount of satellite altimeter data is at an unprecedented level and currently it is normally available within 2 days or less. The follow-ons to T/P (JASON I) and ERS-2 (ENVISAT) were launched December 2001 and March 2002, respectively, and future satellite altimeter missions are planned. Unfortunately, only oceanic surface data are available from most space-borne sensors with sea surface temperature (SST) the one presently used for global ocean prediction in addition to SSH. Other observing systems, such as the ARGO profiling floats, are planned to increase the availability of subsurface observations as well, profiles of temperature and salinity in the case of ARGO. This will be an important addition of data, but there is no prospect on the horizon for sufficient subsurface data to constrain the evolution of mesoscale variability in a data-assimilative, eddy resolving global ocean model. For example, 3000 profiling floats spaced 50 km apart along T/P altimeter tracks, each providing one profile every 10 days, is the equivalent of 5.4 T/P revolutions per 10-day repeat cycle in terms of surface data. Since T/P makes 127 revolutions per repeat cycle (Fu et al., 1994), 3000 profiling floats would provide only about 4% as much surface data as a T/P altimeter (but throughout the stratified water column in most locations). Fortunately, the statistics from historical hydrographic databases are valuable in generating synthetic temperature and salinity profiles from real-time SSH and SST (Carnes et al., 1990, 1994, 1996; Fox et al., 2002). The ARGO profiling float data could greatly enhance this capability.

A major component of the Naval Research Laboratory's (NRL) ocean modeling program has been a detailed study of the model resolution required for ocean prediction. There is strong evidence that the NRL Layered Ocean Model (NLOM) with an embedded mixed layer sub-model (Wallcraft et al., submitted for publication) and other popular ocean models need to use grid cells for each prognostic variable that are at most about 7 km across at mid-latitudes. NRL experiments with NLOM have shown that doubling the horizontal resolution to 3.5 km per cell gives substantial improvement but doubling again to 1.7 km gives only modest additional improvement (Hurlburt and Hogan, 2000). For the NLOM grid, these resolutions translate to 1/16°, 1/32° and 1/64°, respectively. This is for the global and basin-scale. Much finer resolution is needed for coastal models. So far, 1/16° is the finest resolution computationally feasible for global ocean prediction and then only when using an extremely efficient ocean model, such as NLOM (see Section 2).

At 3.5 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 (based on a ratio of 20–30 for the first internal mode radius of deformation, atmosphere/ocean). More specifically, our research has shown that fine resolution of the ocean eddy scale is required to obtain coupling between upper ocean currents and sea floor topography via turbulent flow instabilities, a mechanism which occurs without direct contact between the upper ocean currents and the topography. 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 (Hurlburt et al., 1996; Hurlburt and Metzger, 1998). The high resolution is

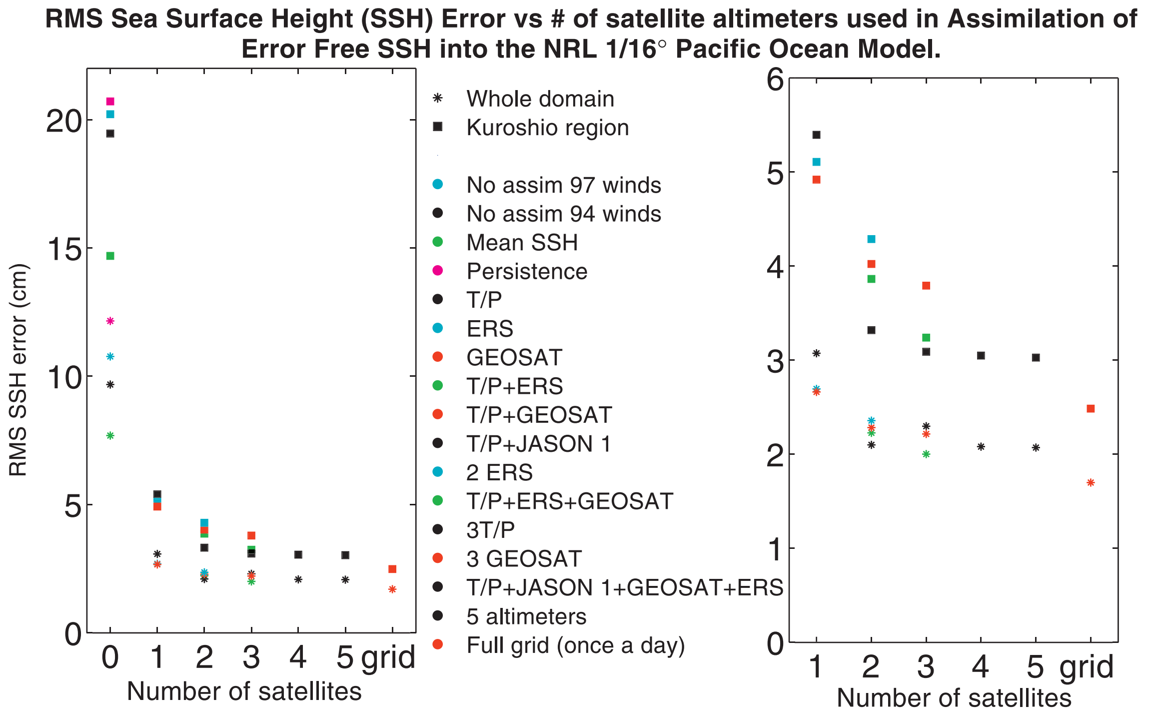


Fig. 1. Test of altimeter data capability to constrain a realistic highly eddy resolving ocean model using altimeter data simulated by the NRL 1/16° Pacific Ocean model. Satellite names refer to simulated data sampled like the altimeter named or a defined offset. ERS has a 35-day repeat orbit with 80.0 km spacing between parallel ground tracks at the equator; Geosat has a 17-day repeat orbit with 164.2 km spacing between parallel ground tracks at the equator and T/P and Jason 1 have a 10-day repeat orbit with 315.5 km spacing between parallel ground tracks at the equator. A control run (CR) was forced in 1990–1998 using 12-hourly FNMOC winds. Starting from a 1997 CR initial state, 1994 wind forcing and simulated CR altimeter data from 1994 were assimilated for 80 days to make the model in 1997 look like the model CR in 1994. Many features take more than 80 days to respond to wind forcing or are a nondeterministic response to forcing. SSH RMS error is the value over the last 30 days of assimilation. The right panel is the same as the left except that "0" satellites is omitted and the ordinate is expanded to better show the impact of increasing the number of satellites. The two ERS are for altimeters covering the same ground tracks 1/2 a repeat cycle apart, while the T/P + Jason 1 are for altimeters offset by 5 days and 1/2 the equatorial T/P track spacing. These plus Geosat are the five-altimeter configuration. The three T/P and three Geosat are for simultaneous equatorial crossings 1/3 the equatorial track spacing of each altimeter apart. Adapted from Hurlburt et al. (2000, 2001) with additional altimeter configurations.

also required to obtain sharp fronts that span major ocean basins (Hurlburt et al., 1996) and for adequate representation of straits and islands (Metzger and Hurlburt, 2001). It can even affect the large-scale shape of ocean gyres such as the Sargasso Sea in the Atlantic (Hurlburt and Hogan, 2000).

Hurlburt et al. (2000) presented a feasibility demonstration of ocean model eddy resolving nowcast/forecast skill using satellite altimeter data. This study used a 1/16° Pacific Ocean model north of 20°S and a 1/4° global ocean model to assimilate satellite altimeter data and then to perform month-long forecasts initialized from the data assimilative states. Some parts of the study used real altimeter data from T/P and ERS-2 while others used simulated altimeter data from the eddy resolving 1/16° Pacific Ocean model. The results demonstrated (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 dynamical 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. These capabilities were demonstrated by the 1/16° model but at mid-latitudes not by the 1/4° model.

Even one altimeter gave large error reduction for the mesoscale when an eddy resolving 1/16° model with dynamical interpolation skill was used to assimilate the data. That was true even though one nadir beam altimeter cannot resolve the observed space scales of mesoscale variability (Jacobs et al., 2001). However, using simulated data, Hurlburt et al. (2000) found that the error in depicting the mesoscale was greatly reduced when data from three nadir beam altimeters in ERS, GFO and T/P orbits were used. Here, we have added results for other satellite configurations (Fig. 1). Of the tested three altimeter configurations, the three parallel T/P configuration gave the lowest root-mean-square (RMS) error (~ 3.1 cm) in the Kuroshio region, a region of very high mesoscale variability (Hurlburt et al., 2001).

This paper presents the results from the operational near global NLOM nowcast/forecast system. In Section 2, the ocean model, the nowcast/forecast system and the data assimilation scheme are described. In addition, the forcing fields and the altimeter and SST observations are described. Results from the real-time assimilation system are discussed in Section 3. A summary and conclusions are presented in Section 4.

2. The nowcast/forecast system

2.1. The NRL layered ocean model

The model component of the ocean prediction system is the NLOM. It is based on the primitive equation model of Hurlburt and Thompson (1980) but with greatly expanded capability (Wallcraft, 1991; Wallcraft and Moore, 1997; Moore and Wallcraft, 1998; Wallcraft et al., submitted for publication). Wallcraft et al. (submitted for publication) discuss the formulation of the global NLOM version used here but without data assimilation and they discuss testing of a climatological simulation at much lower resolution. The data-assimilative operational model has a nearly global domain that extends from 72°S to 65°N (Fig. 2). The horizontal resolution of each model variable is 1/16° in latitude by 45/512° in longitude or ~ 7 km at mid-latitudes, which is eddy resolving. The model has lateral boundaries, which follow the 200 m isobath. It has six dynamical layers plus the mixed layer and realistic bottom topography, which is confined to the lowest layer of the model. At the solid boundaries, kinematic and no-slip boundary conditions are used. Much of the deep-water formation in the far north Atlantic is parameterized via observationally based flows through northern boundary ports at the Davis Strait and the three straits between southern Greenland and Scotland. The flow is northward near the surface and southward below. This includes transport contributions due to entrainment as dense water from the Nordic Seas sinks after passing southward through the straits. Thus, the model includes a contribution to meridional overturning from outside the model domain, a contribution which affects the strength and pathway of some upper ocean and abyssal currents (see Shriver and Hurlburt, 1997 for detailed discussion).

In the NLOM, prognostic variables are layer density, layer thickness, layer volume transport per unit width (layer velocity times layer thickness), SST and mixed layer depth (MLD). The model has a free

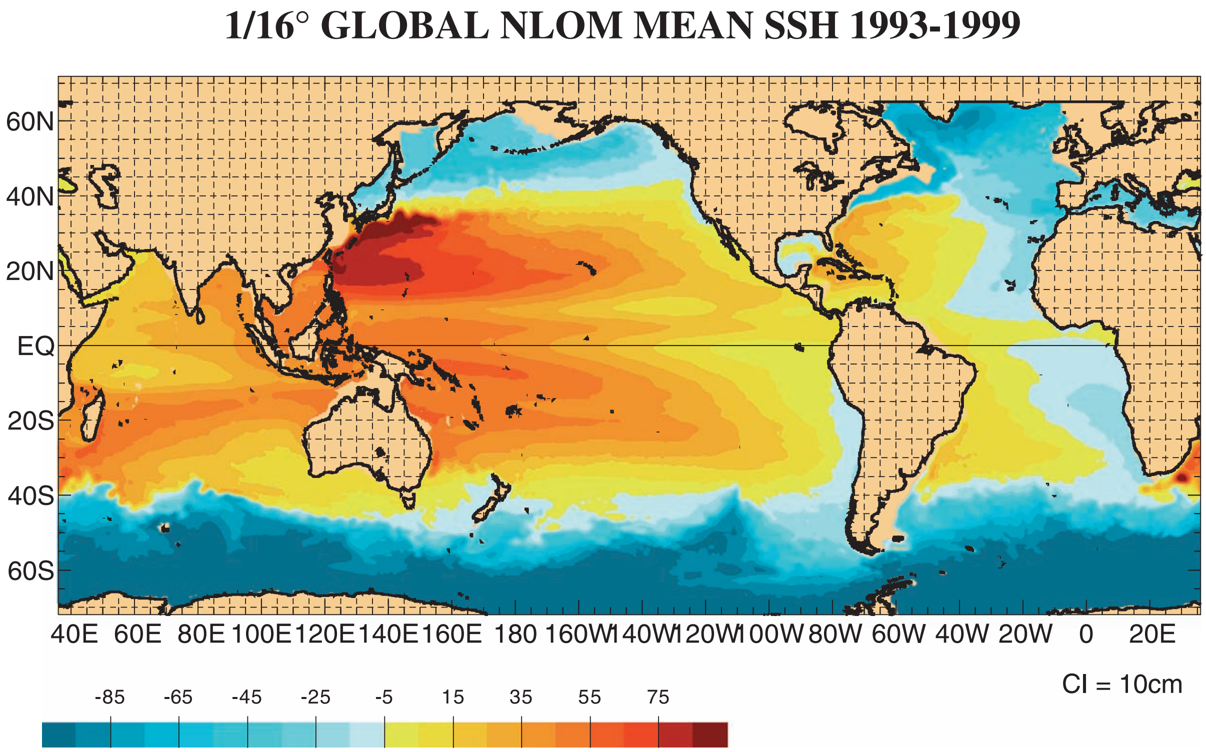


Fig. 2. Slightly modified model mean sea surface height (SSH) over the time period 1993–1999 showing the geometry of the ocean model. The grid resolution is 1/16° in latitude and 45/512° in longitude. This SSH field was added to the altimeter SSH deviations from a temporal mean.

surface, corresponding to SSH (a variable observed by satellite altimetry). The Kraus–Turner type mixed layer is not confined to be within the upper dynamical layer (i.e., floating mixed layer). It is to some extent independent of the dynamical layers; however, it is not entirely passive. In particular, (1) a deep mixed layer distributes surface forcing across the multiple dynamical layers, (2) thermal expansion is based on the mixed layer temperature (T_m) rather than layer 1 temperature, and (3) surface heat flux depends on T_m. All three factors can change the steric sea surface height anomaly. The embedded mixed layer model employed here carries prognostic equations for the SST and MLD and is discussed in detail by Wallcraft et al. (submitted for publication).

Below the mixed layer, the density of the top 5 dynamical layers is relaxed toward the annual mean climatological density of that layer except for layer 1, which is relaxed toward a monthly mean climatology due to the significant seasonal cycle within that layer. Unlike other models with fixed levels in the vertical, such relaxation does not significantly damp the anomalies because in NLOM most of the information about circulation anomalies is carried by layer thickness variations, not density variations. For example, NLOM maintained a Rossby wave generated by the 1982–1983 El Niño for at least a decade (Jacobs et al., 1994) without oceanic data assimilation except for the relaxation to climatological density within layers.

Using monthly climatological atmospheric forcing, Wallcraft et al. (submitted for publication) and Kara et al. (submitted for publication) discuss global NLOM performance at 1/2° resolution in predicting SST and MLD. These were atmospherically forced, free running simulations with no assimilation of SST and the testing includes numerous comparisons with observational data sets. Global NLOM has also been run interannually 1979–2001 using 6-hourly ECMWF forcing, again with the Kara et al. (2002) formulation for surface wind stress and latent and sensible heat flux, including effects of SST (no assimilation of SST observations or analyses). Fig. 3 shows SST verification statistics for global NLOM at 1/8° resolution in comparison with 442 yearlong daily SST time series from moored buoys over the time frame 1980–2001. The median RMS difference is 0.86 °C and the median correlation is 0.89. The low correlations are for time series in the western equatorial Pacific region where the SST variability and the RMS errors are small. These results and the results of the two climatological studies strongly suggest that NLOM is suitable for assimilation of SST data. Additional details concerning NLOM can be found in Hurlburt et al. (1996), Metzger and Hurlburt (1996), and Shriver and Hurlburt (1997). Shriver and Hurlburt (1997) discuss the ability of global NLOM to simulate the global overturning circulation, including the cross-interfacial mixing scheme based on oxygen saturation. Mixing also occurs when there is model layer outcropping.

It should be noted that NLOM is a single efficient portable and scalable computer code that can run any of the model configurations on a variety of computing platforms (Wallcraft and Moore 1997). 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. We are solving the problem on today's systems capable of only a few percent of this performance by taking a multifaceted approach to cost minimization.

One facet is the use of 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 (Wallcraft and Moore, 1997). NLOM's performance is due to a range of design decisions; the most important of which is the use of Lagrangian layers in the vertical rather than the more usual fixed depth cells. This allows seven layers in NLOM vs. the 40 fixed levels used in 1/8° global NCOM (Rhodes et al., 2002). However, due to these design decisions NLOM excludes the Arctic and most shallow water regions and cannot be used for applications requiring high vertical resolution in and near the surface mixed layer. High vertical resolution 3-D temperature (*T*) and salinity (*S*) can be obtained via post processing as discussed in Section 3.3.

2.2. The assimilation scheme

Another facet of our efficiency drive is the use of an inexpensive data assimilation scheme. The intense computational requirements of mathematically sophisticated approaches to data assimilation preclude their use for practical assimilation into models with the large domain and high horizontal resolution of the NLOM global system (4096 × 2304 × 7). This is especially true in an operational setting where limited computer time is available for the daily model run. The assimilation technique presently used with NLOM increases the model run time by about 1/2 compared to running the model without assimilation. More sophisticated techniques like the ensemble Kalman filter (Evensen, 1994) may require up to 100 times more computer time.

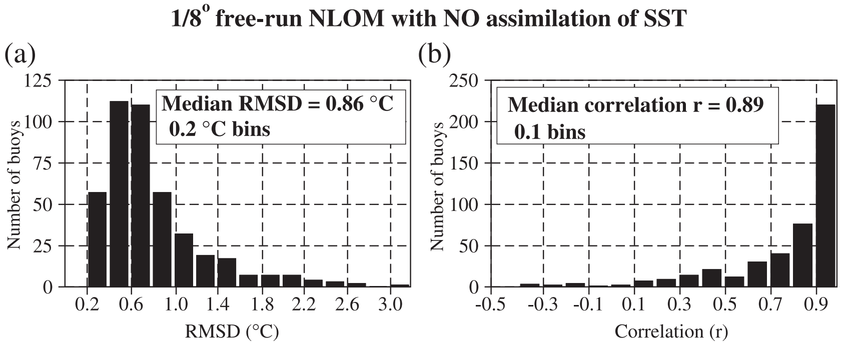


Fig. 3. (a, b) Histograms of RMS difference and correlation between a 1/8° nearly global NLOM simulation with no assimilation of SST and 442 yearlong daily SST time series from moored buoys over 1980–2001.

The assimilation scheme is similar to the incremental updating technique described in Smedstad and Fox (1994). The SSH data assimilated into the model consist of the altimeter SSH deviations from a temporal mean plus the mean SSH discussed in Section 2.3. The first step of the assimilation is an optimum interpolation (OI) analysis of the SSH data deviations from a model forecast of SSH valid at the analysis time, a technique known as an OI deviation analysis using the model forecast as a first guess. A 3-day window is used for the altimeter data. Anisotropic, spatially varying mesoscale covariance functions, determined from altimeter data (Jacobs et al., 2001), are used in the deviation analysis. Satellite altimetry gives information only about the SSH. Previous studies have shown that it is important for the assimilation scheme to transfer the surface information to the lower layers as fast as possible (Hurlburt, 1986; Hurlburt et al., 1990; Haines, 1991; Haines et al., 1993; Smedstad and Fox, 1994; Smedstad et al., 1997). The statistical inference technique of Hurlburt et al. (1990) is used to update the pressure fields in all layers below the surface. There is only a weak correlation between the upper and abyssal-layer pressure fields at each point of the model, a much higher one between the surface layer pressure field and the intermediate-layer pressure fields. Hurlburt et al. (1990) showed that the abyssal layer pressure fields could be better inferred by relating them to empirical orthogonal functions derived from an array of SSH points. This approach has been extended to all of the subsurface layers. The velocity fields in all layers are updated using a geostrophic correction calculated from the pressure changes. The velocity correction is not performed within 5° latitude of the equator. Between 5° and 8°, the correction is gradually increased to full strength using a hyperbolic tangent function. These corrections are then used to incrementally update the model variables so that the creation of inertia–gravity waves is minimized.

The SST assimilation consists of a relaxation toward the Modular Ocean Data Assimilation System (MODAS) MCSST analyses operational at NAVOCEANO (Fox et al., 2002; Section 2.5 of this paper) using a 3-h e-folding time scale. During the forecast period, it is relaxed toward climatologically corrected persistence of the nowcast SST with a relaxation time scale of 1/4 the forecast length (i.e., 1 day for a 4-day forecast and 1 week for a 4-week forecast). This is a necessary step for the long-term (30-day) SST forecasts because the forecast atmospheric thermal forcing is only available out to 4 days. Experience at NRL has shown this method produces a more accurate SST forecast. During a 30-day forecast, the position of oceanic fronts, current/frontal meanders and eddies can change substantially. The SST relaxation is weak enough that it allows the model to keep the SST forecasts of these features in better phase with the forecasts of SSH and surface currents than climatologically corrected persistence. There is no relaxation for SSH because forecasts are generally dominated by the movement of fronts and eddies due to flow instabilities and by free waves. These are more sensitive to initial conditions than to atmospheric forcing (Section 3.4).

2.3. The mean sea surface height

In order to assimilate the anomalies determined from satellite altimeter data into a numerical model, it is necessary to know the oceanic mean SSH over the time period of the altimeter observations. Unfortunately, the geoid is not known accurately on scales important for the mesoscale. Several satellite missions are underway or planned to try to determine a more accurate geoid, but until this becomes accurate to within a few centimeters on scales down to approximately 30 km, another approach must be taken. The approach taken here is to use a model mean SSH. It is necessary to have the mean of major ocean currents and associated SSH fronts more sharply defined than is feasible from hydrographic climatologies, a major advantage of this approach. This requires a fully eddy resolving ocean model which is consistent with hydrographic climatologies, but with sharper features. Additionally, fronts must be in the correct position for this approach to be successful. The model mean, which is over the period of the satellite data, is therefore compared to other sources of information. This includes the mean dynamic height calculated from available temperature and salinity measurements modified with data over the period of the satellites. To help determine the position of the fronts, mean frontal positions from satellite IR plus the variability from satellite altimeter data are also used. Following this effort to accurately determine the mean position of the front, the model mean is modified as needed using a collection of computer programs specifically designed to operate on SSH fields. It includes methods to move SSH features in an elastic way (rubber sheeting) (Hord, 1982; Clarke, 1992; Carnes et al., 1996), merge data, overlay contours from a second reference field and raise or lower the values of a region. Fig. 4 is an example of the modification done to the model mean in the Gulf Stream region.

When the model is run in assimilative mode, either hindcast or real-time, the positions of fronts are compared with independent observations, especially in the Gulf Stream region, the Gulf of Mexico, the northwest Pacific and the Japan/East Sea. The comparisons are mainly with satellite IR and hydrographic cross-sections as discussed in Section 3.

2.4. The wind and thermal forcing

A hybrid approach is used for the wind stress forcing in the model. It is a combination of Fleet Numerical Meteorology and Oceanography Center (FNMOC) Navy Operational Global Atmospheric Prediction System (NOGAPS) (Hogan and Rosmond, 1991) and Hellerman and Rosenstein (HR) (1983) surface stresses where the long-term mean (August 1990–July 1999 for FNMOC) is subtracted from the FNMOC stresses and replaced with the HR annual mean. This hybrid approach has been used successfully with the HR and European Centre for Medium-range Weather Forecasts (ECMWF, 1994) 1000 mb winds (Metzger et al., 1992, 1994; Hurlburt et al., 1996). From this wind product, we get the analysis quality forcing up to the nowcast time plus a 5-day forecast. The atmospheric forcing for the 30-day forecasts gradually reverts toward climatology after 4 days. The last forecast record is weighted with the contemporaneous climatological values over a 10-day time span. Over that time, a linearly decreasing (increasing) weight (1-weight) is used for the forecast (climatology). In Section 3.4, we discuss effects of this on ocean forecasts. The thermal fluxes also come from FNMOC NOGAPS, but with the formulation for latent and sensible heat flux replaced by that of Kara et al. (2002). The sensible and latent heat fluxes are strongly dependent on SST, and they are calculated every time step using the model SST. Radiation fluxes also depend to some extent on SST but FNMOC values are used for these because they are strongly dependent on cloudiness, which is less readily available. Basing fluxes on model SST automatically provides a physically realistic tendency towards the “correct” SST. If the model SST is too high/low, the flux is reduced/increased relative to that from the correct SST. The trend towards reality is typically not sufficient on its own to keep the model SST on track, but it is sufficient if we also have an “accurate enough” characterization of the temperature just below the mixed layer. In addition to applying the heat flux, the latter temperature is kept on track in NLOM by relaxing the dynamic layer densities back towards climatology (monthly in layer 1, annual otherwise). Kara et al. (submitted for publication) describes experiments showing the ability of NLOM to accurately predict SST over most of the global ocean without relaxation/assimilation of SST data. These experiments show that NLOM predicts annual mean SST with an RMS error of < 0.5 °C for the nearly global model domain in comparison to the Comprehensive Ocean-Atmosphere Data Set (COADS) SST climatology.

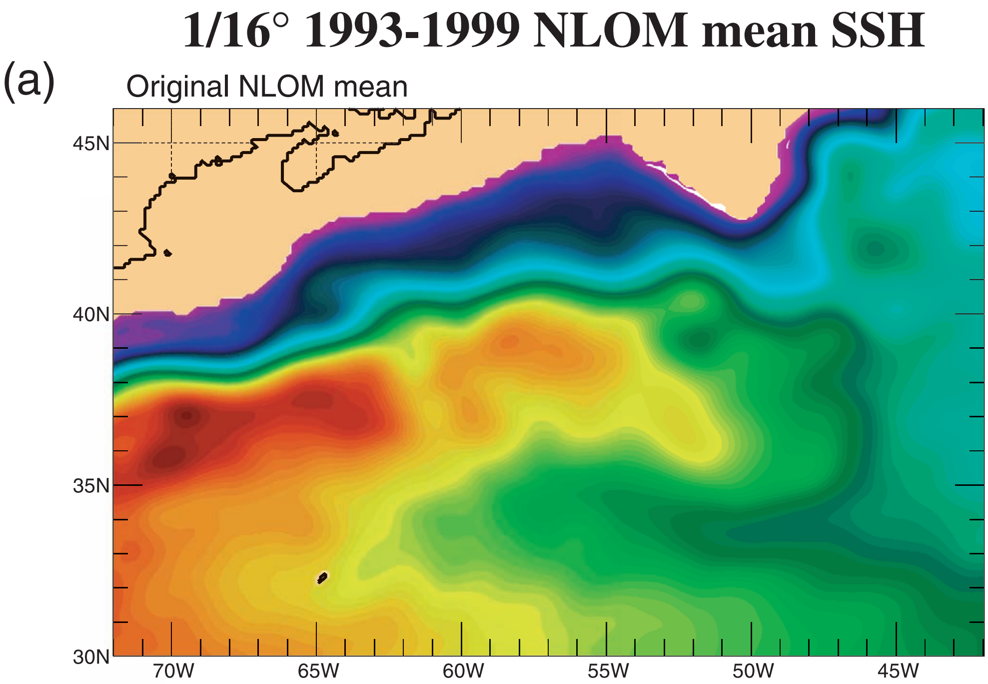
2.5. The altimeter and SST data

The altimeter data assimilated into the model are delivered via NAVOCEANO’s Altimeter Data Fusion Center (ADFC). The observations are available in near real time. Both ERS-2 and T/P data are available within 24 h and the GFO data within 48 h. Better orbit corrections are available with a slightly longer delay. This is one reason why the assimilation cycle of the nowcast/forecast system restarts 3 days prior to the nowcast time.

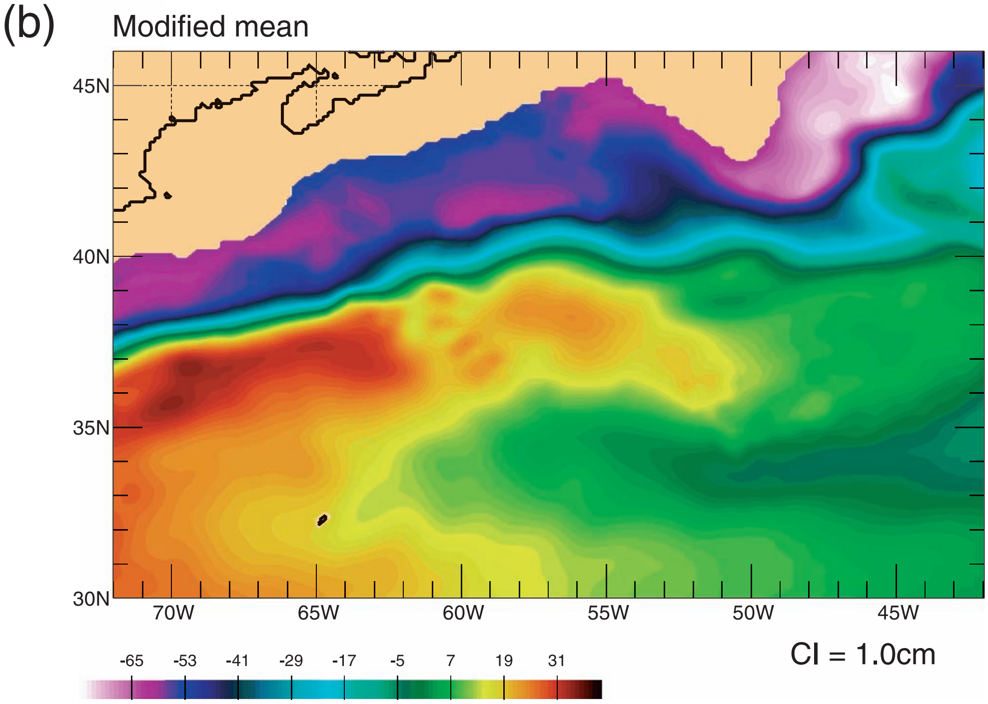
The MODAS system is also operational and running daily at NAVOCEANO (Fox et al., 2002). It produces an OI analysis of SSH observations from the available satellite altimeter data as well as an OI analysis of available MCSST observations. The daily MODAS SST analysis is used as data for the SST relaxation in the NLOM system.

2.6. The operational cycle

The operational nowcast/forecast system was running on 216 Cray T3E processors at the NAVOCEANO Major Shared Resource Center (MSRC) until 1 May 2002. It is now running on 132 processors



(a) Original NLOM mean



(b) Modified mean

Fig. 4. The NLOM mean SSH in the Gulf Stream region over the period 1993–1999. (a) The mean SSH from the model forced with the 6-hourly winds but without any assimilation. (b) The modified mean SSH for the same time period. Available observations of the position of the Gulf Stream were used to determine the mean position of the stream and then a rubber sheeting technique and other techniques described in Section 2.3 were used to modify the model mean.

of the IBM SP3 at the MSRC. The data assimilation cycle for the system restarts the model 3 days prior to the nowcast time to pick up newly received data and altimeter data with improved orbits. It uses analysis wind and thermal forcing while SSH and SST data are assimilated up to the nowcast time (see Fig. 5). This 3-day approach improves the accuracy of nowcasts used to initialize model forecasts. The system performs a daily 4-day forecast, except on Wednesdays when a 30-day forecast is made.

The scripts controlling the operational run have been written to minimize the need for human intervention. A typical daily run starts with the creation of the wind and thermal forcing fields. The SST fields from the MODAS run are processed as well as the latest altimeter data. If the forcing fields are not received by a prescribed time, the previous day's forecast is automatically used and then extended with climatology. When the model is finished with the daily run, the necessary fields are extracted from the model archive files and the plots that can be seen on the web page are created. The SSH and SST fields are copied to local workstations where the statistical calculations are performed to evaluate the forecast skill. The performance statistics for each forecast are updated daily for the duration of the forecast.

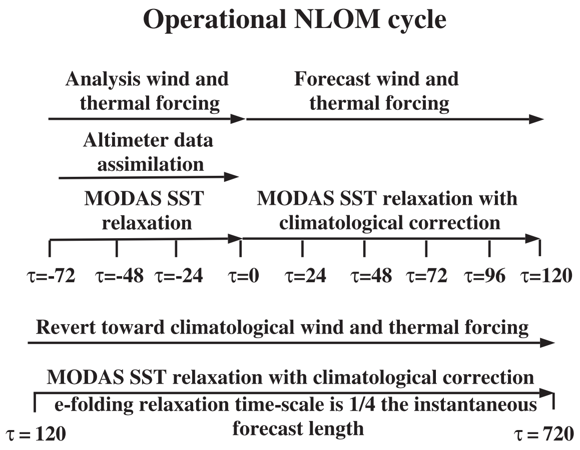


Fig. 5. The operational cycle of the NLOM nowcast/forecast system. The model restarts 72 h prior to the nowcast time every day in order to pick up newly received satellite data. A 30-day forecast is performed every Wednesday. At the end of the available meteorological forecast, the forcing fields gradually revert toward climatology. The MODAS SST relaxation includes a climatological correction to the latest SST analysis.

3. Evaluation of nowcast/forecast skill

Several types of monitoring/evaluation of the nowcast/forecast system are performed on a daily basis. This section describes the different types of statistics and model/data comparisons available on the real-time web site.

3.1. RMS error, anomaly correlation and skill score

The forecast skill of the model is routinely monitored by calculating different types of statistics between the forecast and the final analysis from the model. RMS error, anomaly correlation and climatological skill score are calculated for both SSH and SST. The statistics are calculated for the global domain as well as numerous subregions of the world ocean. The RMS error is calculated as

$$\mathrm{RMS}(f,x) = \frac{1}{N-1}\sqrt{\sum (f-x)^2} \tag{1}$$

where f represents the forecast and x represents the analysis.

The anomaly correlation is calculated as

$$\mathrm{AC}(f,x) = \frac{\sum (f-\bar{f})(x-\bar{x})}{\sqrt{\sum (f-\bar{f})^2}\sqrt{\sum (x-\bar{x})^2}} \tag{2}$$

where $\bar{f}$ is the model mean and $\bar{x}$ is the mean of the analysis. In this case, the SSH mean of the model and the analysis is the model mean over 1993 to 1999 with the modifications described in Section 2.3. The SST mean is the monthly model mean over 1999 and 2000 interpolated to daily values. The climatological skill score (Murphy and Epstein, 1989) is calculated as

$$\mathrm{SS}(f,c,x) = 1 - \frac{\mathrm{MSE}(f,x)}{\mathrm{MSE}(c,x)} \tag{3}$$

where c represents the climatology as described above, $\mathrm{SS}(f, c, x)$ is the climatological skill score, $\mathrm{MSE}(f, x)$ is the mean square error between the forecast and the analysis and $\mathrm{MSE}(c,x)$ is the mean square error between the climatology and the analysis. If the forecast is perfect, its mean square error ($\mathrm{MSE}(f, x)$) is zero, and the score is one. If the forecast error equals that of climatology ($\mathrm{MSE}(c, x)$), the score is zero. A negative score means that the forecast error is larger than the error obtained using climatology as the forecast.

The forecast statistics for SSH and SST are calculated for each day of the weekly 30-day forecasts. A mean forecast skill over all the available 30-day forecasts is also calculated. Fig. 6 shows the mean SSH and SST statistics for the global domain. The mean is for sixty-four 30-day forecasts over the period from 20 December 2000 to 3 April 2002. Fig. 7 shows the same statistics for the Gulf Stream region, (76–40°W and

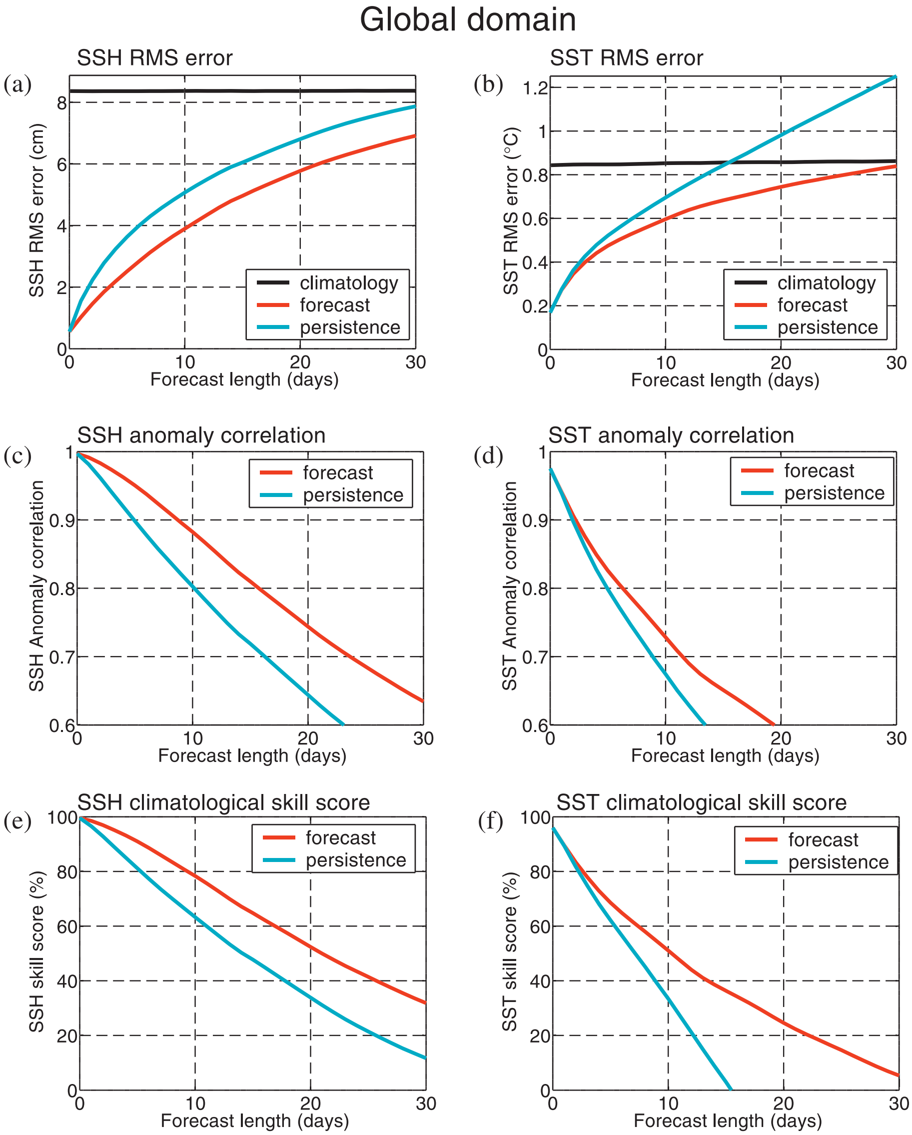


Fig. 6. The 1/16° SSH forecast verification against the model with T/P, ERS-2 and GFO altimeter data assimilation over the global domain. Shown are the different types of statistics calculated for each of the 30-day forecasts. The plots show the mean statistics over sixty-four 30-day forecasts for the period 20 December 2000 to 3 April 2002. (a) The SSH RMS error, (b) the SST RMS error, (c) SSH anomaly correlation, (d) SST anomaly correlation, (e) SSH climatological skill score and (f) SST climatological skill score. The red curve is the NLOM forecasts; the blue curve is the forecasts of persistence (i.e., no change from the initial state) and the black curve in the RMS plots is climatology (modified model annual mean SSH and a monthly SST mean interpolated to daily values, see text).

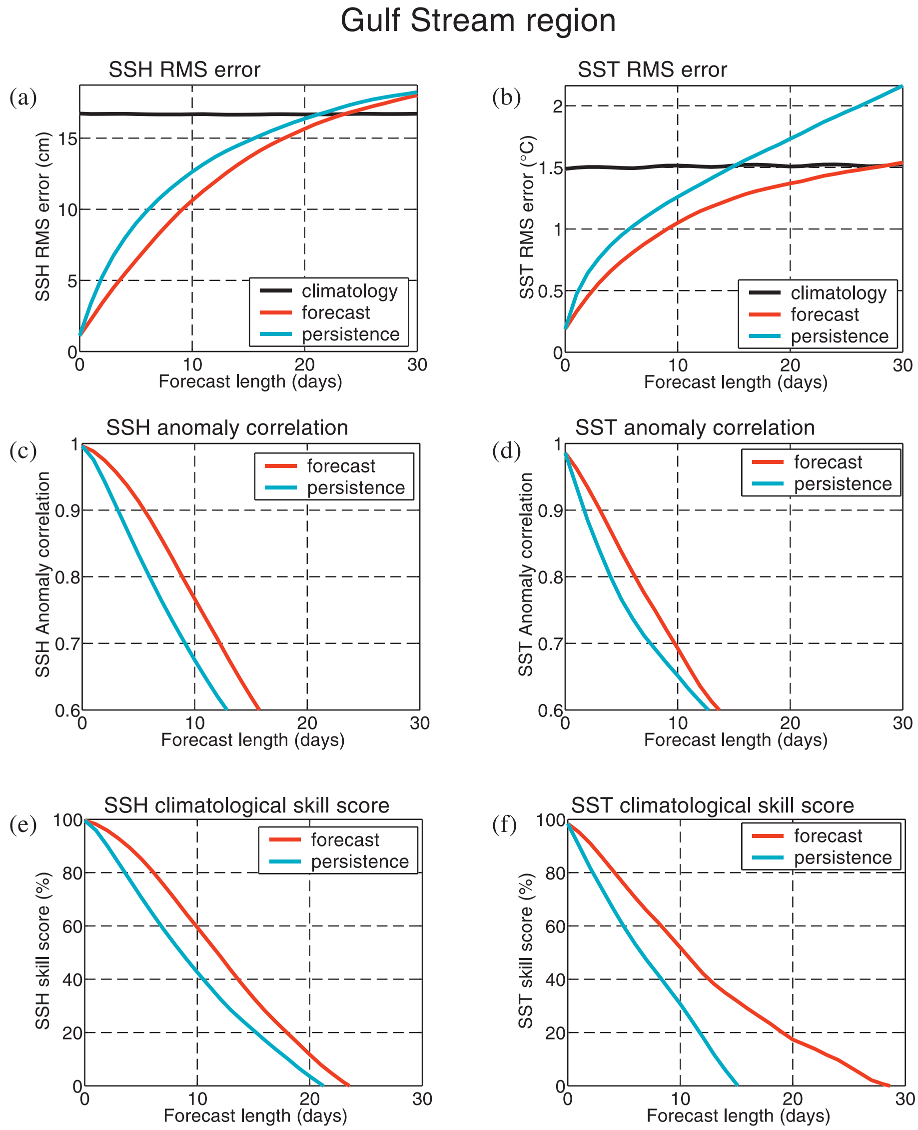


Fig. 7. Same as Fig. 6 except the plots show the results from the Gulf Stream region.

35–45°N). Nowcast/forecast results and verification statistics for many regions are available on the NRL public web page, http://www.ocean.nrlssc.navy.mil/global_nlom.

As can be seen in Fig. 6, the model has at least 30-day forecast skill over the global domain. In the Gulf Stream region (Fig. 7), the model typically has useful forecast skill for about 17 days based on anomaly correlation >0.6 (Murphy and Epstein, 1989). Atlantic Ocean simulations with different resolutions (Hurlburt and Hogan, 2000) have shown that the resolution of the 1/16° nowcast/forecast system is the minimum for a realistic Gulf Stream pathway between Cape Hatteras and the Grand Banks, but more robust results are obtained with 1/32° resolution. In addition, the mean baroclinic Gulf Stream transport is greatly increased east of the New England Seamount Chain (~ 65°W), 43 Sv at

1/16° and 78 Sv at 1/32° vs. 70 Sv estimated from observations south of the Grand Banks (~50°W), and the associated nonlinear recirculation gyre is much stronger and penetrates farther to the east in accord with hydrographic climatology and the pattern of SSH variability from T/P altimeter data (Hurlburt and Hogan, 2000; Hurlburt et al., 2001). See Schmitz (1996) for a summary of transport and other observations in the Atlantic. At 1/32° resolution model simulation improvements are also seen in other regions, but some regions show no significant improvement.

3.2. The Kuroshio extension/Gulf Stream frontal position

An error in the position of the Gulf Stream and the Kuroshio axes is calculated from the model forecast and the analysis. The error is calculated as the area between the frontal position in the forecast and the analysis divided by the length of the front in the analysis. Since we are using the model analysis as the "truth", we use several different SSH contours to represent the front and calculate an average error for these contours. Fig. 8a is an example of the axis error for the Gulf Stream. It is the mean error over sixty-four 30-day forecasts over the period from 20 December 2000 to 3 April 2002.

The position of the Kuroshio and the Gulf Stream is also being compared to the analyses of IR frontal positions performed at NAVOCEANO. The IR frontal analyses are performed using high-resolution MCSST data. These analyses are overlaid on the model SSH. An example can be seen in Fig. 8b. The example illustrates the correspondence between an IR analysis of the Gulf Stream north wall (a sharp front in SST) and the Gulf Stream axis marked by an arrow ribbon of sharp gradient in SSH. This example for 11 June 2001 is a situation where there was recent clear IR imagery along the entire Gulf Stream pathway through the region (not a common event) and a nearly full complement of satellite altimeter data from three satellites (ERS-2, GFO and T/P). Note some of the smallest scale features in the IR frontal analysis are shallow shingles of water from the Gulf Stream which have an SST signature but little SSH signature.

3.3. Model-data comparisons using moored buoys and tide gauges

Real-time SST observations and temperature profiles from the Tropical Atmosphere Ocean and Triangle Trans-Ocean Buoy Network (TAO/TRITON) array in the equatorial Pacific (Hayes et al., 1991; McPhaden, 1995), the Pilot Research Moored Array in the Tropical Atlantic (PIRATA) (Servain et al., 1998) and NDBC buoys (http://www.ndbc.noaa.gov) are used to monitor the performance of the SST and the subsurface temperature in the model. These observations are not used in the NLOM data assimilation and are therefore an independent check of model performance. Time series comparisons of SST from the model and these buoys are available on the web page in real time, http://www.ocean.nrlssc.navy.mil/global_nlom. Fig. 9 shows the daily time series for four different locations. Fig. 9a is from one of the PIRATA buoys in the equatorial Atlantic Ocean. It is located at (0°N, 23°W). The time series in Fig. 9b and c are from the TAO array in the equatorial Pacific at (0°N, 110°W) and (2°N, 125°W), respectively, while Fig. 9d is from one of the NDBC buoys near the Alaska coast in the North Pacific Ocean at (56°N, 148°W). The correlation and RMS error for the model in comparison with the four buoys are shown on the plots. For the 84 daily SST time series from the moored buoys in comparison to the model nowcast, the median correlation and RMS difference are 0.93 and 0.36°C, respectively (Fig. 9e, f). Again, the low correlations are in the western equatorial Pacific where the variability and the RMS differences are small. The largest RMS difference (2.1°C) is for a buoy located at 38°N, 71°W near a strong SST front at the north wall of the Gulf Stream where the correlation is 0.91.

Fig. 10a illustrates the value of using an ocean model to assimilate altimeter data in a western boundary current region. It shows a comparison of SSH time series at Mera, Japan (marked by a star in Fig. 10b) between tide gauge data, operational NLOM and the operational MODAS2D SSH analyses (Fox et al., 2002). Matching this tide gauge is especially challenging because it is located at the southeast corner of Japan near the Kuroshio separation from the coast (Fig. 10b). This tide gauge time series is not a deterministic response to atmospheric

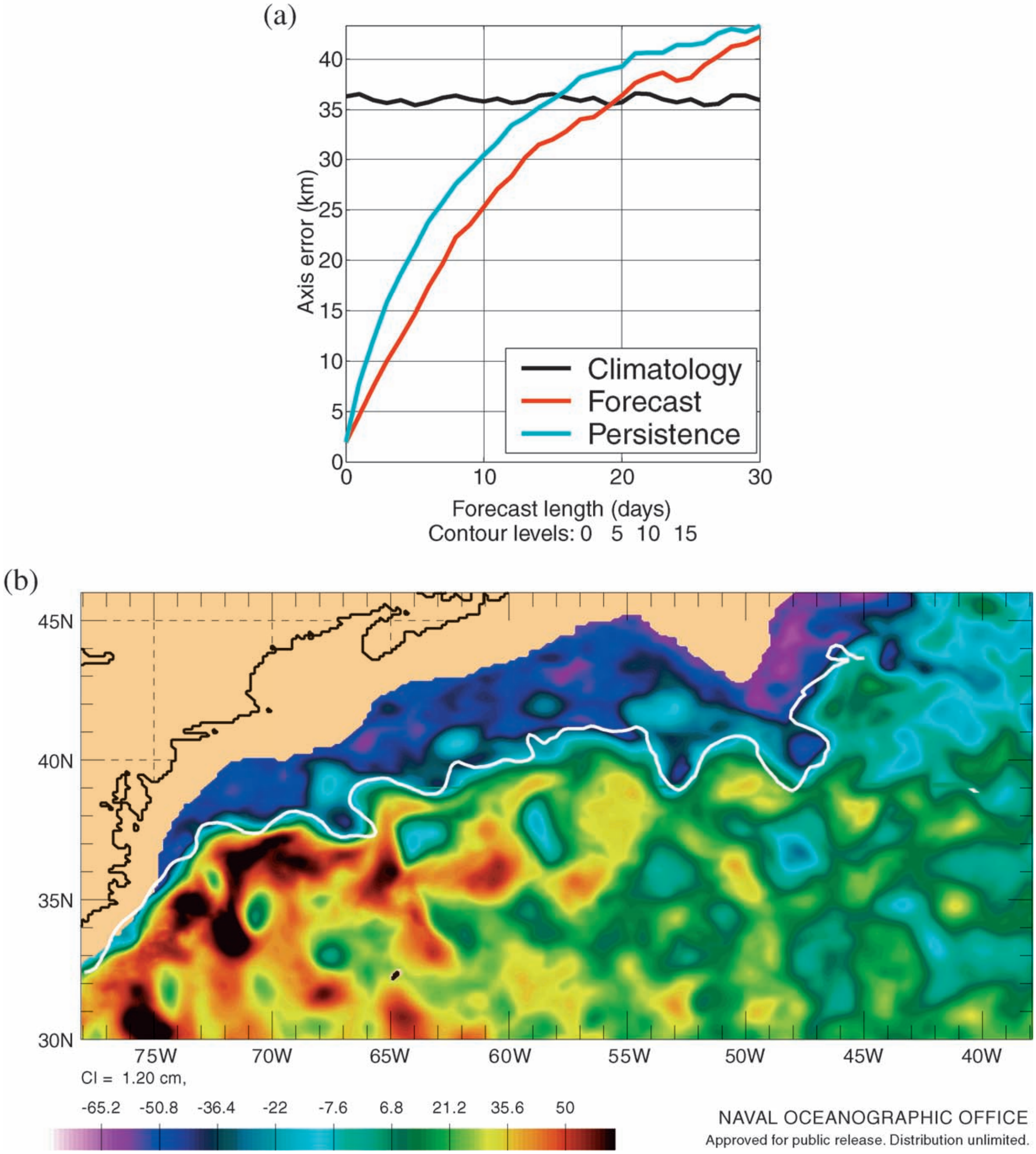


Fig. 8. (a) Axis error for the Gulf Stream. The error is the mean error over sixty-four 30-day forecasts covering the period 20 December 2000 to 3 April 2002. (b) The Gulf Stream IR North wall for 11 June 2001 vs. the Gulf Stream SSH pathway from the 1/16° global NLOM with real-time assimilation of T/P, GFO and ERS-2 altimeter data. The IR north wall pathway is from an independent operational analysis of unusually cloud free satellite IR imagery performed by Naval Oceanographic Office at Stennis Space Center, MS, USA.

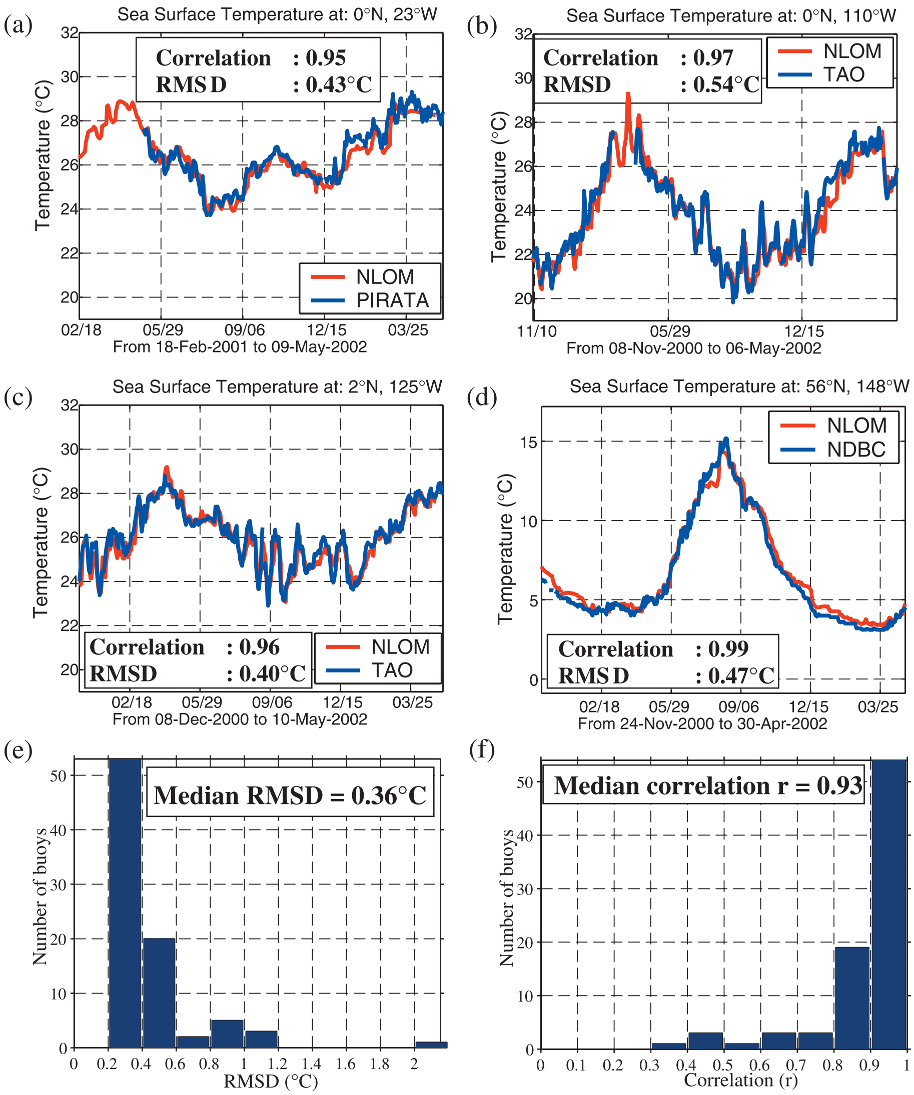
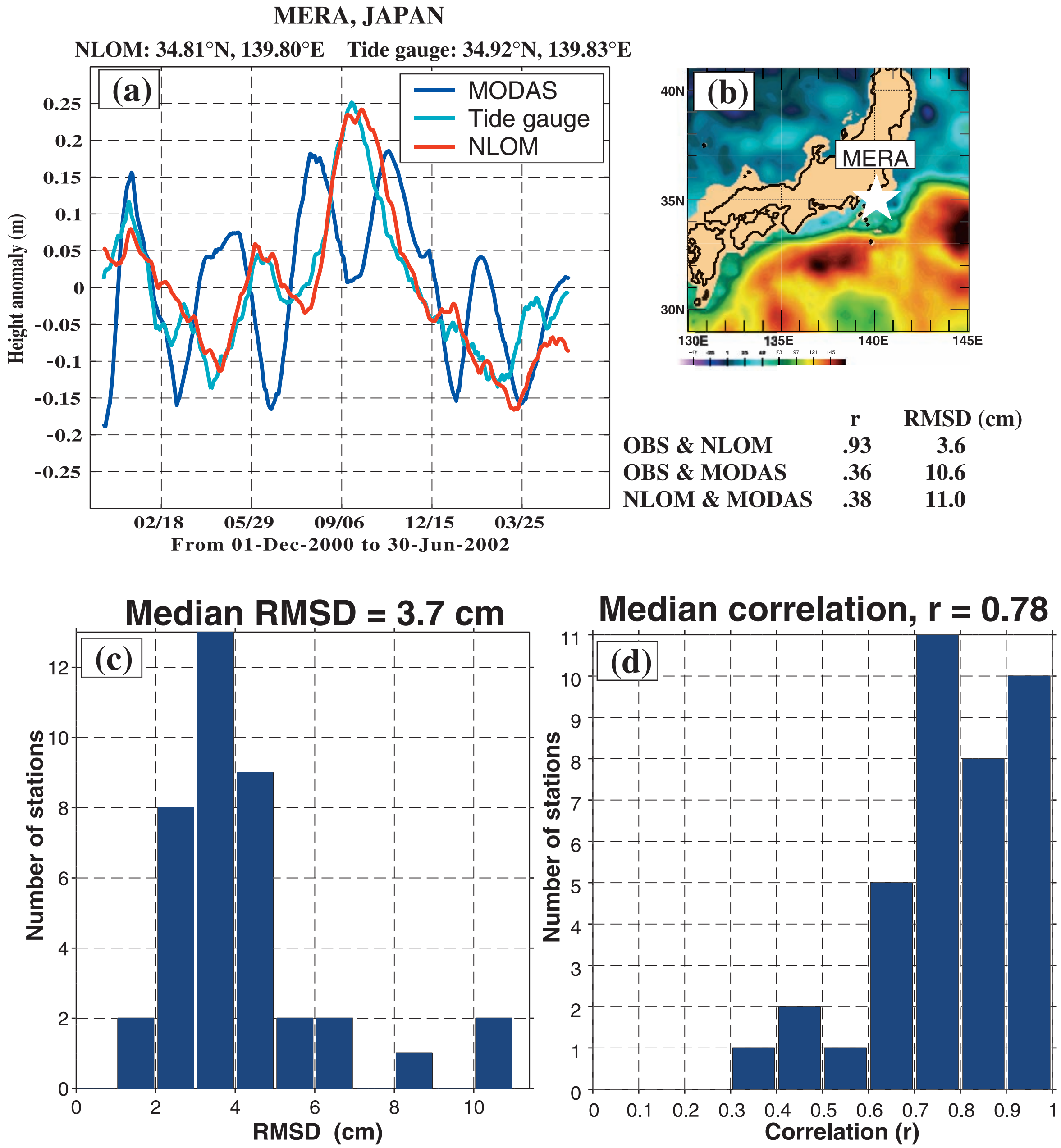


Fig. 9. Daily time series of observed SST from buoys and nowcast SST from the 1/16° global NLOM system. The red line is the time series from NLOM, while the blue line is the observed SST. The buoys are located at: (a) 0°N, 23°W, (b) 0°N, 110°W, (c) 2°N, 125°W and (d) 56°N, 148°W. (e, f) Histograms of RMS difference and correlation between the operational real-time NLOM and daily SST time series from 84 moored buoys over the time frame 8 November 2000 to 31 August 2002.

forcing as demonstrated by minimal correlation between SSH time series from interannual identical twin, eddy resolving simulations which differed only in initial state details several years earlier, and by minimal correlation between either free-running model simulation and the tide gauge time series. Thus, the 0.93 correlation and 3.6 cm RMS difference between operational NLOM and the Mera tide gauge data are due entirely to assimilation of altimeter data by an ocean model. The SSH analysis product gave a correlation of only 0.36 and an RMS difference of 10.6 cm. The concatenated correlation between operational NLOM and 39 tide gauge time series around the world (28 island, 11 coastal) is 0.78 and the concatenated RMS difference is 4.7 cm. For the MODAS2D SSH analyses the



	r	RMSD (cm)
OBS & NLOM	.93	3.6
OBS & MODAS	.36	10.6
NLOM & MODAS	.38	11.0

Fig. 10. (a) Comparisons of SSH vs. time off Mera, Japan: NLOM and MODAS2D vs. tide gauge data, all with a 30-day running mean. MODAS2D is a 1/4° NAVOCEANO operational, model-independent analysis of SSH from altimeter data (Fox et al., 2002). Both NLOM and MODAS used altimeter data from T/P, GFO and ERS-2. (b) SSH analysis for 9 September 2002 from operational NLOM in the Kuroshio region near Japan. The star marks the location of the Mera, Japan tide gauge. (c, d) Histograms of RMS difference and correlation between real-time, operational NLOM and 39 tide gauge time series around the world (28 island, 11 coastal) over the time frame of 1 December 2000 and 30 June 2002. All of the time series were filtered using a 30-day running mean with the time series mean removed.

concatenated correlation and RMS difference are 0.67 and 5.7 cm. Unlike Mera, some of the coastal stations are in harbors a degree or more from the NLOM time series taken at the shelf edge. All the statistics with tide gauge data used 30-day running means between 1 December 2000 and 30 June 2002 and the mean over the same time period was removed from the time series at each location. The filtering is an attempt to remove time scales not well resolved by the altimeter repeat cycles, especially high frequency non-steric components. Fig. 10c, d shows the distribution of RMS difference (median = 3.7 cm) and correlation (median = 0.78) between the filtered time series.

The NLOM SSH and SST values are used to calculate vertical temperature profiles using the MODAS 3-D system. MODAS 3-D is a reanalysis of historical temperature and salinity profiles producing a variable-resolution climatology plus statistical regressions to relate subsurface temperature and salinity to surface temperature and sea surface height. Fig. 11a shows the temperature profile at 8°N, 180°W and Fig. 11b the profile at 5°S, 140°W on 1 December 2001. The plots show the MODAS climatology (black line), the NLOM profile (blue line) and the buoy observed profile (red line). As shown by Rhodes et al. (2002), profiles of temperature vs. depth obtained from the NLOM nowcasts using this methodology gave lower RMS error than climatology in comparison to numerous O (10^3) unassimilated XBT profiles.

3.4. Sensitivity of forecast skill to the forcing fields

A significant question is the sensitivity of the ocean model forecast skill to the use of climatological atmospheric forcing fields beyond the end of the forecast available from an atmospheric model. Since many aspects of the ocean circulation evolve much more slowly than the atmosphere (~ 10 × slower for mesoscale variability than atmospheric weather systems), they should be predictable for much longer. To investigate forecast sensitivity to the quality of atmospheric forcing, initial states used to make the 30-day forecasts during the operational run were archived. Later, they were used to make new 30-day forecasts (actually hindcasts), but this time with analysis quality atmospheric forcing for the duration. This applies both to the wind and thermal forcing and to the SST fields used in the SST relaxation. As discussed in Hurlburt (1984), we would anticipate high sensitivity for oceanic features that respond strongly to atmospheric forcing on time scales less than a month, such as the oceanic mixed layer/SST, wind-driven coastal upwelling, the Ekman component of surface currents, the onset of some equatorial and coastal trapped waves, and ocean circulation in shallow coastal regions (not included in NLOM). We would anticipate low sensitivity for non-shelf free waves (e.g., Kelvin, Rossby and Yanai waves) already in existence at the initial time, on products of mesoscale flow instabilities (e.g., current/frontal meanders and eddies) which are nondeterministic in relation to forcing, and for phenom-

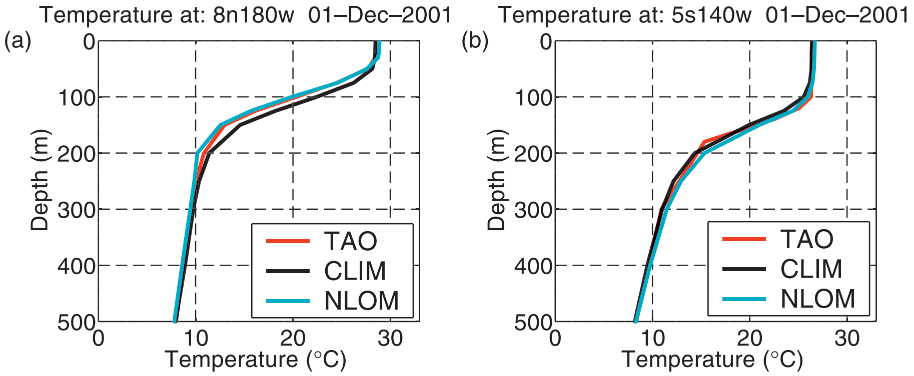


Fig. 11. Vertical temperature profiles at (a) 8°N, 180°W and (b) 5°S, 140°W. The black line is the MODAS climatology; the blue line is the NLOM profile and the red line is the observed profile from the buoy.

ena which are an integrated response to forcing on time scales longer than a month (e.g., many ocean gyres). Fig. 12 shows that globally and in many regions of the world the 30-day SSH forecasts are not very sensitive to the difference between climatological and analysis quality forcing fields. This is especially true in regions where the response of the ocean model is nondeterministic in relation to the forcing, such as the Gulf Stream and Kuroshio regions (Fig. 12b, c). In other regions, like the equatorial Pacific (Fig. 12d) and equatorial Atlantic the model response to the atmospheric forcing is more deterministic and improved oceanic predictive skill is observed when the analysis quality forcing fields are used. Note that these results are means for eight 30-day SSH forecasts performed early in 2001. Similar results are found for the other statistical performance measures used, RMS error and the climatological skill score.

4. Summary and conclusions

The world's first real-time, eddy resolving (1/16°) nearly global ocean prediction system is now operational. It has been running continuously at Naval Oceanographic Office, Stennis Space Center, MS since 18 October 2000 and it became an operational system on 27 September 2001. Developed by the Naval Research Laboratory at the Stennis Space Center, it uses the NRL Layered Ocean Model (NLOM) with

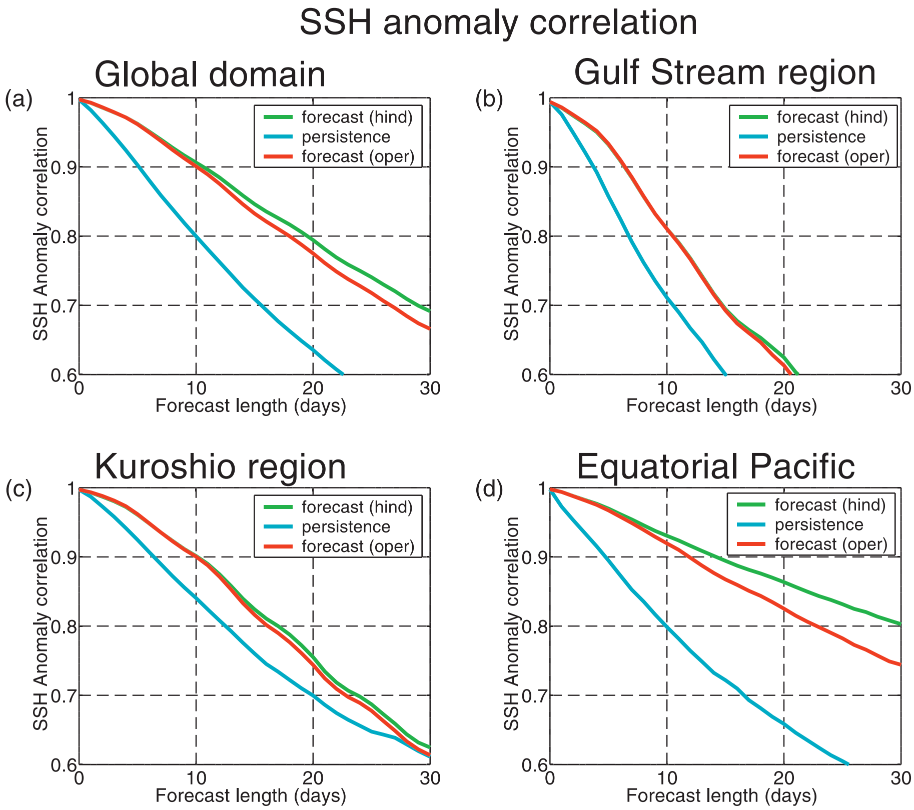


Fig. 12. The 1/16° global NLOM 30-day SSH forecast verification against the model with T/P, ERS-2 and GFO altimeter data assimilation. These results illustrate the impact of using analysis quality fields for wind and thermal forcing and for SST relaxation during the forecast. (a) The whole domain, (b) the Kuroshio, (c) the Gulf Stream and (d) the equatorial Pacific region. The red curve is for the real-time NLOM forecasts; the blue curve verifies forecasts of persistence (i.e., no change from the initial state), and the green curve verifies the forecasts (actually hindcasts) which used analysis quality wind and thermal forcing and SST fields. The results are means for eight forecast periods early in 2001.

assimilation of sea surface height data from satellite altimeters and sea surface temperature from multichannel satellite infrared radiometers. This system clearly demonstrates the ability to track the evolution of many ocean features, including ocean eddies and the meandering of ocean currents and fronts, which have space scales of ~ 100 km. It also shows that skillful 30-day forecasts are possible for many regions of the world ocean. Detailed results, including many zoom regions, can be viewed on the web at http://www.ocean.nrlssc.navy.mil/global_nlom.

An eddy resolving global ocean model and prediction system such as this one has a wide range of civilian and military applications and it is a contribution to the Global Ocean Data Assimilation Experiment (GODAE) goal to have data-assimilative global ocean models that provide useful real-time global ocean products with wide availability to a broad community of potential users around the world. Applications include assimilation and synthesis of global satellite surface data; ocean forecasting; optimum track ship routing; search and rescue; fisheries and marine resource management; anti-submarine warfare and surveillance; tactical planning; high resolution boundary conditions that are essential for even higher resolution coastal models; input to ice, atmospheric and biochemical models and shipboard environmental products; environmental simulation and synthetic environments; ocean research and education; observing system simulation and assessment; impact on ocean structures such as oil rigs; pollution and tracer tracking and inputs to water quality assessment.

The following are examples of applications reported by users in the community. NLOM results are routinely used by fishing service companies in preparation of fishing forecasts in many regions of the world ocean. They are being used to study the location of blue whales in relation to ocean features such as cold eddies and ocean fronts in the northwest Pacific (Moore et al., 2002) and in fishery studies of swordfish north of Hawaii. In the New Caledonia region of the South Pacific, they are being used to investigate blooms of cyano bacteria in relation to ocean eddies and to increase scientific knowledge for exploitation and protection of marine resources. SSH anomalies from a hindcast run were used for an educational television program to illustrate Kelvin and Rossby waves in the tropical Pacific in relation to the 1997–1998 El Niño. An oil company is using real-time nowcast/forecast results to monitor currents and ocean features that could affect deep oil rigs in the northern Gulf of Mexico and off Brazil. NLOM results were used to monitor ocean features and currents in the vicinity of the Hawaiian Islands during the raising of the Ehime Maru by the US Navy. They are being used to monitor the confluence of the Benguela Current and the Atlantic South Equatorial Current, particularly in relation to variations in tropical convection across the equatorial Atlantic. A field program in the Arabian Sea/Gulf of Aden used the results from the system as a guidance for their cruise. Results from the operational system were used as boundary conditions for a model off the west coast of the United States by Kindle (NRL, personal communication). His results show that the use of a high-resolution model as a source for boundary conditions for the coastal model is far superior compared to using results from a coarser (1/4°) global model. He has also looked at the positioning of eddies in the Arabian Sea and compared them to observed filaments in Sea-viewing Wide Field-of-view Sensor (SeaWifs) ocean color imagery. Striking agreement in the position of eddies along the Oman coast and the filaments could be observed. The model revealed that the filament was generated by the interaction of two counter-rotating eddies with the coastal circulation during an upwelling-favorable wind event.

As computer power increases, more sophisticated systems, which are impossible to run on today's computers, will be implemented as soon as they demonstrate improved capability/skill and that they can run within operational time requirements. Current plans for the system running at NAVOCEANO include an upgrade of the NLOM system to 1/32° resolution in 2003 and then in 2006 to upgrade the system with the Hybrid Coordinate Ocean Model (HYCOM) now under development in collaboration with a multi-institutional consortium.

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