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A real-time coastal ocean prediction experiment for MREA04

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Abstract

To provide a short-term ocean forecast for sea level variation, current, temperature, and salinity, an ocean nowcast/forecast system has been developed. The system is an integration of a data-assimilating, dynamical ocean model, a statistical data-analysis model, and various data streams for ocean bathymetry, climatological data, surface forcing, open boundary forcing, and observations. The system assimilates satellite data and in-situ measurements to produce an estimation of the current ocean state or nowcast and is forced with a meteorological forecast to produce an ocean forecast. During the MREA04 sea trial, the system was implemented for a region off the Portuguese coast with two-way nested grids and produced real-time ocean forecasts for the period of the experiment. The high density of real-time, in-situ observations during MREA04 provided a unique opportunity for the system to assimilate the in-situ observations in addition to satellite data and to perform a statistically meaningful evaluation of the system's forecast capability. The evaluation shows that the nowcast/forecast system has good skill in predicting the tide and fair skill in predicting the ocean temperature and salinity with overall rms errors of 0.5 °C and 0.15 psu for temperature and salinity, respectively. Assimilating in-situ CTD data produced a better nowcast/forecast than assimilating only satellite data. The forecast error increases as the forecast time increases, but the forecast error does not increase significantly over the nowcast error, which indicates that the error in the nowcast is the major source of the forecast error.
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Keywords: Ocean prediction; Data assimilation; Real-time ocean forecast

1. Introduction

The importance of predicting ocean current, temperature, salinity, and sea level in real-time has long been recognized (e.g., Mooers et al., 1981). Similar to weather prediction, ocean prediction consists of the use of dynamical and statistical models together with observations to produce nowcasts and forecasts. One difference between weather prediction and ocean prediction is that ocean prediction relies on weather prediction to provide air–sea fluxes, which are a major forcing for the ocean. Various ocean prediction systems based on different ocean models and data-analysis and data assimilation schemes have been developed (e.g., Robinson and Walstad, 1987).

Recently, a real-time ocean nowcast/forecast system (ONFS) has been developed at the Naval Research Laboratory (NRL). The NRL ONFS is intended for producing a daily, short-term (under a week) forecast of mesoscale ocean current, temperature, salinity, and sea level variation. The system is modularized so that each component, for example the ocean dynamic model, can be easily replaced. The system can be relocated to different locations and, once set up for a particular region, operates automatically.

The system is an integration of a data-assimilating, dynamical ocean model, a statistical data-analysis model,

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and various data streams for ocean bathymetry, climatological data, surface forcing, open boundary forcing, and observations for data assimilation. The NRL Modular Ocean Data Assimilation System (MODAS; Carnes et al., 1996; Fox et al., 2002) is used within the ONFS as the data-analysis model. MODAS uses satellite data, in-situ observations, and historical statistics to generate three-dimensional ocean temperature and salinity analyses. The analyses are then assimilated into the dynamic model to produce an ocean nowcast. From the nowcast, the forecast is conducted without data assimilation using a meteorological forecast.

The NRL real-time ONFS was first implemented for the North Pacific Ocean. This was called the North Pacific Ocean Nowcast/Forecast System (NPACNFS; Ko et al., 2003a) and operated in real-time from 1999 to 2004. The NPACNFS produced a nowcast and 72-h forecast every 24 h and the predictions were subjected to several evaluations and used for a number of studies (Ko et al., 2003a; Lee, 2003; Wu, 2003; Hwang et al., 2004; Ramp et al., 2004; Lin et al., in press). During 2000 and 2001, the ONFS was implemented in the Northern South China Sea (NSCSNFS) to provide mesoscale ocean descriptions for the Asian Seas International Acoustics Experiment in the South China Sea (Chapman et al., 2004; Weller, 2005). The NSCSNFS was coupled to the NPACNFS. The dynamical ocean model used in these two applications was based on the Princeton Ocean Model (POM; Blumberg and Mellor, 1987). POM is a primitive equation, sigma-coordinate ocean model with a mixed-layer model based on the Mellor–Yamada turbulence closure scheme (Mellor and Yamada, 1982).

Later the ONFS was implemented for several other regions including the Intra-Americas Sea (IASNFS; Ko et al., 2003b), which covers the Gulf of Mexico, Caribbean Sea, and Straits of Florida. The real-time IASNFS nowcasts and forecasts are available at the web site: http://www7320.nrlssc.navy.mil/IASNFS_WWW/. The ocean model applied in the IASNFS and later ONFS (e.g., Jacobs et al., 2005; Keen et al., 2006; Teague et al., 2006) is based on the Navy Coastal Ocean Model (NCOM; Martin, 2000). NCOM is similar to POM but has options to use hybrid vertical coordinates and multiple nesting.

In all these ONFS implementations, the real-time data for the data assimilation are from satellite altimeters and AVHRR. The surface forcing is either from the Navy Operational Global Atmospheric Prediction System (NOGAPS; Hogan and Rosmond, 1991; Rosmond, 1992) or from the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS, Hodur, 1997). The lateral open boundary conditions are either taken from a global ONFS or from a higher resolution regional ONFS if one is available. The NRL ONFS is fully automated in its daily operation once it is set up for a region.

During the 2004 Maritime Rapid Environmental Assessment (MREA04) sea trial off the Portuguese coast, a test of the rapid relocatability of the NRL ONFS was carried out. The system was set up with a two-way nested grid and forced with air–sea fluxes from the COAMPS Europe meteorological forecast model. During MREA04, near real-time in-situ CTD temperature and salinity profiles collected from the Navy Undersea Research Center's (NURC) R/V Alliance and a French Research Ship were used for data assimilation in addition to assimilation of satellite altimeter data (Chapman et al., 2004) from JASON-1, GFO, and ENVISAT and MCSST data from AVHRR. The CTD data also were used for the evaluation of the ocean nowcasts and forecasts.

The details of the implementation of the NRL ONFS for MREA04 are described in Section 2. The evaluations of the ocean nowcasts and forecasts against in-situ observations are shown in Section 3. A conclusion is provided in Section 4.

2. Implementation of NRL ONFS for MREA04

2.1. Model setup

The NRL ONFS was implemented for the Portuguese coastal waters for the MREA04 sea trial. The area of coverage extended from 8° to 11° W and from 36° to 40° N. The ocean model operated with a 4-km resolution main grid and a 1-km nested grid covering the central coastal region of the main grid. The vertical grid consisted of 40 layers with 19 sigma layers from the surface down to 140 m and fixed-depth layers from 140 m to the bottom. Model bathymetry was first interpolated from the NRL DBDB2, a global 2-min ocean bathymetry data base (http://www7320.nrlssc.navy.mil/DBDB2_WWW/), and then combined with additional data from several sources with spatial resolutions ranging from 2 min to 6 s. The model land–sea boundary was adjusted based on the coastline from the Generic Mapping Tools (GMT) software (Wessel and Smith, 2006). Figs. 1 and 2 show the model grid and bathymetry, respectively, used during MREA04.

2.2. Initial and open boundary conditions

The model was initialized with temperature, salinity, sea surface elevation, and current interpolated from the 1/8th degree global NCOM (Rhodes et al., 2002; Barron

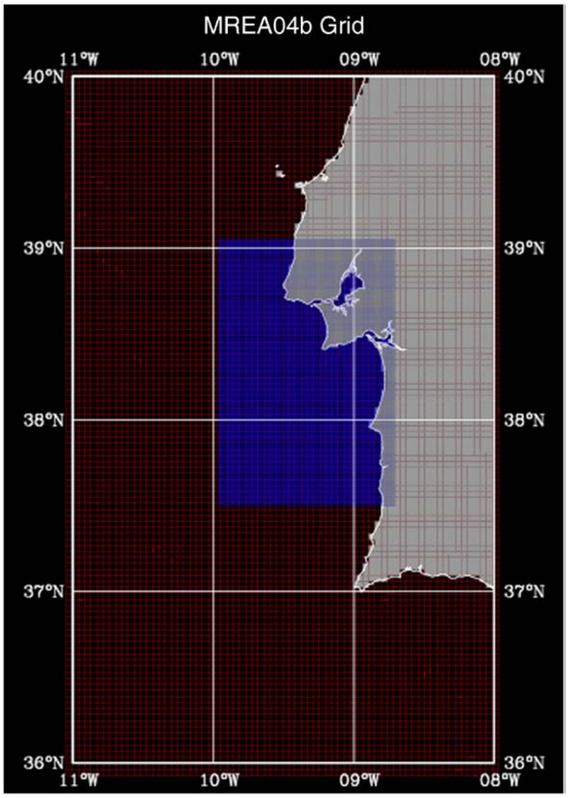

Fig. 1. A nested grid system was applied to the MREA04 sea trial region off Portuguese coast. The host grid (in red) has a 4-km resolution and the nested grid (in blue) a 1-km resolution.

et al., 2004). Global NCOM also provided the open boundary conditions (BC) for the main grid. Two-way coupling was applied between the main grid and the nested grid. The main grid provided BCs of sea surface elevation, current, temperature, and salinity for the nested grid and the temperature and salinity from the nested grid were averaged and returned to the main grid. The barotropic tidal forcing was applied to the main grid by superimposing tidal elevation and transport for 8 tidal constituents (K1, O1, P1, Q1, K2, M2, N2, and S2) on the (non-tidal) BC from global NCOM using a forced radiation BC. The tidal data were from the OSU global tidal data base (Egbert et al., 1994; Egbert and Erofeeva, 2002). Tidal potential forcing was applied over the interior of the model domain of both grids. Freshwater discharge was provided for the Mondego, Tagus, Tamega, Sado, and Odelonga Rivers based on monthly climatological river runoff. The rivers are prescribed by specification of the river temperature (monthly climatology), salinity (freshwater), and discharge as a function of depth.

2.3. Surface forcing

Atmospheric forcing consisted of 3-hourly fields of sea level air pressure, wind stress, solar radiation, and surface heat flux from the 27-km resolution COAMPS Europe analysis/forecast model on the original COAMPS computational grid (provided by the NRL Marine Meteorology Division). The meteorological fields are interpolated to the ocean model grids using a cubic spline (Akima, 1970). An advantage of having meteorological fields on their original computational grid is that contamination of values interpolated to the ocean model grid by values at land points on the meteorological grid can be avoided. There are often large differences in the air–sea fluxes between land and sea (Fig. 3).

Solar radiation was input separately from the rest of the surface heat flux since solar radiation penetrates below the ocean's surface. An adjustment of the surface heat flux was applied proportional to the difference between the multi-channel sea surface temperature (MCSST) analysis and the model sea

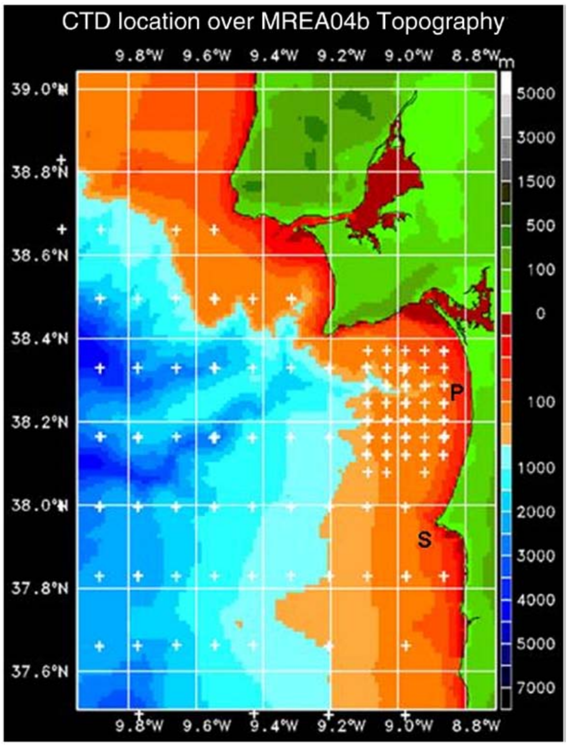

Fig. 2. The model topography is shown with color contours. The locations of the CTD stations are indicated by "+". The sea level measurements at buoys near Sines (S) and near Pinheiro da Cruz (P) are used to evaluate the model SSH prediction.

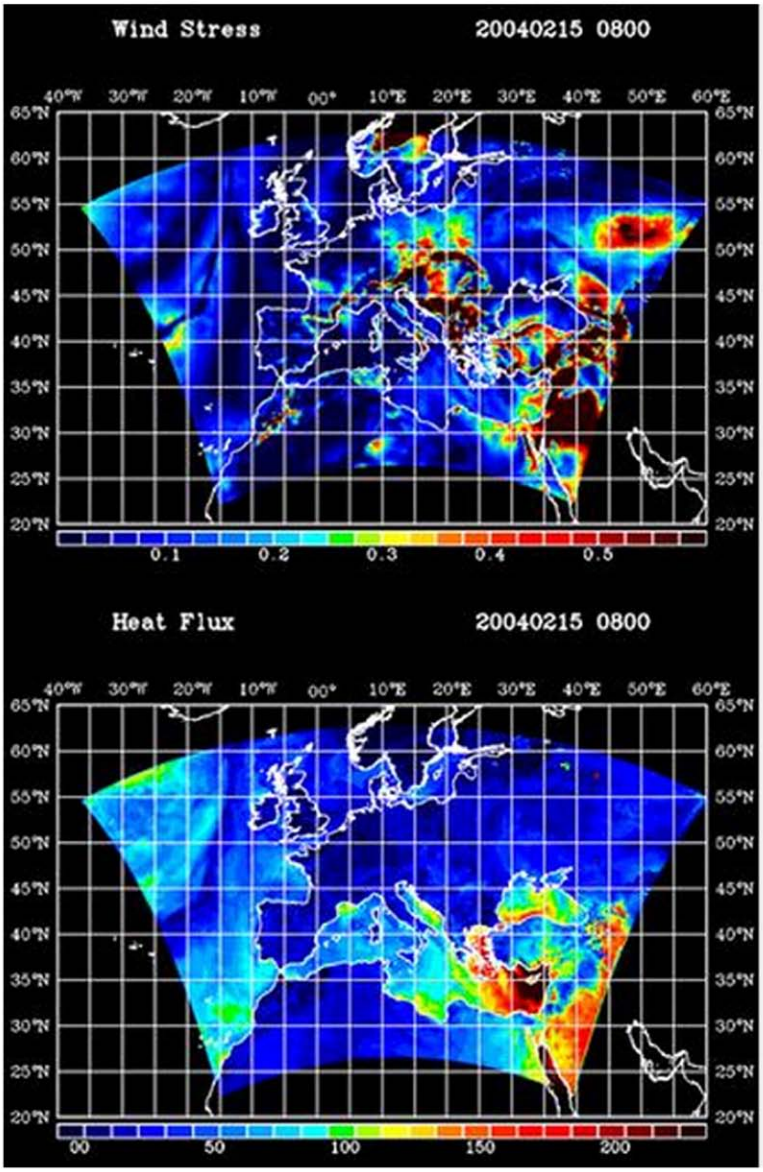

Fig. 3. The magnitude of wind stress (top) and heat flux (bottom) on the COAMPS (Europe) original computational grid for 0800 GMT, Feb. 15, 2004. The plots show large differences between land and sea.

surface temperature (SST). In addition, a weaker correction was applied based on the difference between the monthly climatological SST and the model SST.

The surface salinity flux was computed based on the difference between the MODAS surface salinity analysis (see Section 2.4) and the model sea surface salinity (SSS) and on the difference between the monthly climatological SSS and the model SSS.

The correction with climatological SST and SSS is to prevent bias that may exist in the COAMPS heat fluxes and SST and SSS analyses.

2.4. Data analysis

The model assimilated temperature and salinity analyses that were generated from satellite altimeter sea surface height (SSH), AVHRR MCSST, and CTD temperature/salinity profiles collected during the MREA04 cruise. The satellite altimeter (JASON-1, GFO, ENVISAT) SSH anomaly and AVHRR MCSST data were gridded using an optimal interpolation (OI) scheme. A 15-day correlation time scale and a correlation length scale computed from along-track altimeter data were used in the OI (Jacobs et al., 2002).

The barotropic signal in the altimeter SSH anomaly that is not related to the ocean temperature variation is substantially reduced in the gridded SSH anomaly (Chapman et al., 2004). A mean SSH computed from temperature climatology was added to the altimeter SSH anomaly. A 3-D temperature estimation was produced from the altimeter SSH and the MCSST data based on historical statistical correlations between the sea surface height and sea surface temperature and the sub-surface temperature (Carnes et al., 1996; Fox et al., 2002). The salinity was estimated from the temperature analysis based on *T*–*S* correlations based on historical data. The CTD profiles were combined with satellite estimates using OI. A 5-day correlation time scale and a baroclinic Rossby radius-based length scale (63–75 km) estimated from the temperature and salinity climatology of the area were used for the OI.

2.5. Real-time nowcast/forecast

Both the main and nested ocean model grids were initialized from global NCOM fields on January 1, 2004 and were run with all forcings and with data assimilation for two months to provide a spinup of the ocean fields. Starting on March 1, 2004, real-time nowcasts and forecasts were conducted daily during the period of MREA04. Each day at 00 GMT, daily temperature and salinity analyses for the previous 3 days were produced from satellite data and all the available CTD data. The ocean model was then restarted from its own fields at minus 72 h (i.e., at 72 h before the nowcast time). During the 72 h leading up to the nowcast time, the temperature and salinity analyses were continuously assimilated into the model fields by an incremental adjustment. A vertical weighting function based on the estimation of the relative errors of the model prediction and the analyses was applied with a 5-day relaxation time scale for the adjustment. After the nowcast was completed, a 72-h forecast was generated without the data assimilation. Once the daily nowcast and forecast were completed, all the fields were transmitted to a server at the NATO NURC for evaluation and application by other researchers. The daily nowcasts and forecasts were also made available on a website: http://www7320.nrlssc.navy.mil/MREA04/. A sample nowcast field for March 14, 2004 at 1800 GMT is shown in Fig. 4. In this instance, the model predicted a coastal upwelling event, which was also observed in the AVHRR data.

To estimate the impact of the in-situ CTD data on the nowcast/forecasts, a parallel run that assimilated

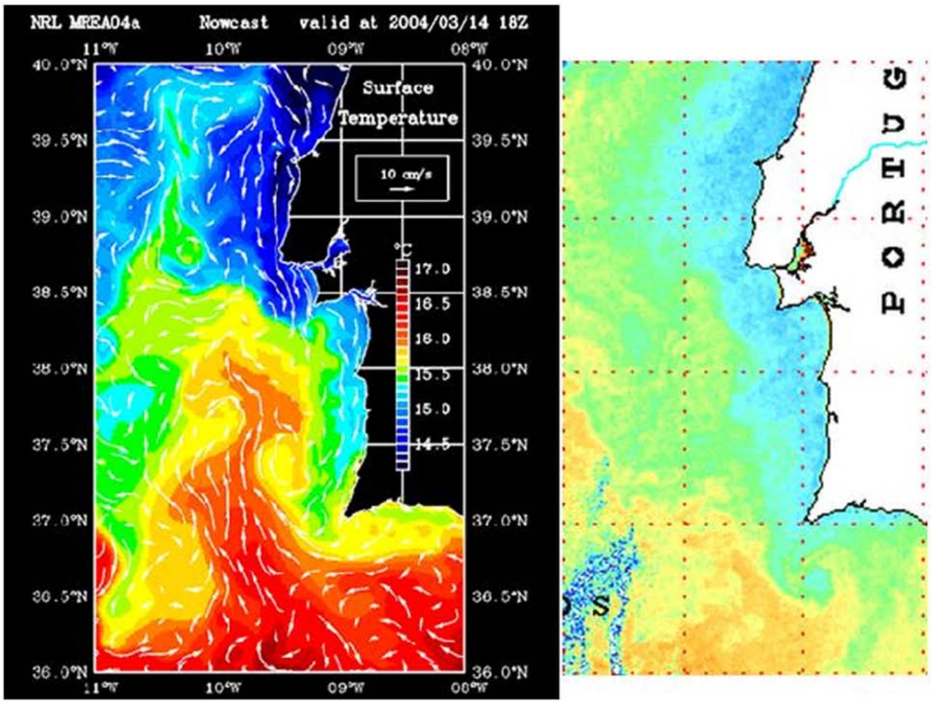

Fig. 4. Model nowcast of surface temperature and current on March 14, 2004 at 1800 GMT (right). Model SST shows coastal upwelling, which is also indicated by the AVHRR image (left) (The color palette for the model SST is not applicable to the AVHRR image).

temperature and salinity analyses produced with only satellite data (i.e., without the CTD data) was also conducted.

3. Evaluation against observations

3.1. Tidal prediction

The model hourly SSH prediction was compared to the measurements at the buoy near Sines (97 m water depth) and at the buoy near Pinhiero da Cruz. As shown in Fig. 5, the sea level variation in the region is dominated by the tide, which has a 3-m range. The model-predicted SSH showed good agreement with the in-situ measurements at both locations with an rms error less than 10 cm. The accuracy of this prediction is mostly due to the fairly deep water in the region, even near the coast (Fig. 2), which results in only small variations in the tidal amplitude and phase, except in the bay areas, as shown in the model SSH predictions (Fig. 6).

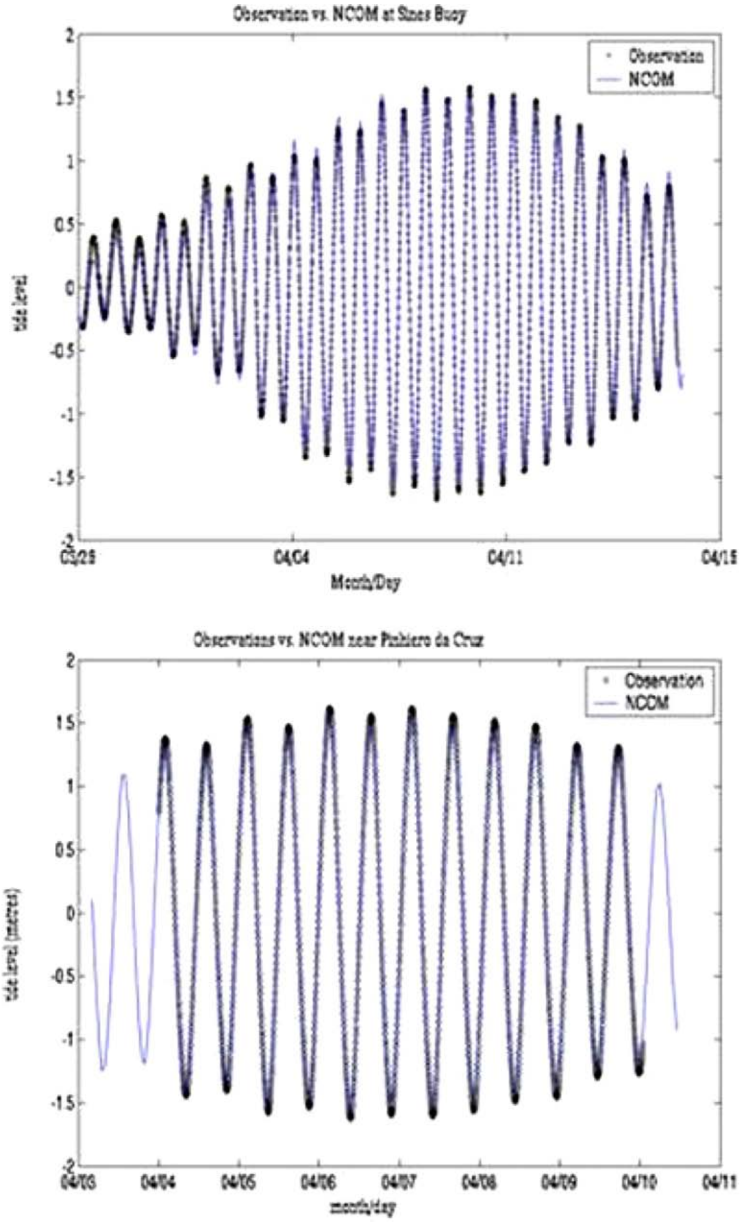

Fig. 5. Comparison of the model sea level prediction to the buoy measurements at Sines (top) and near Pinhiero da Cruz (bottom).

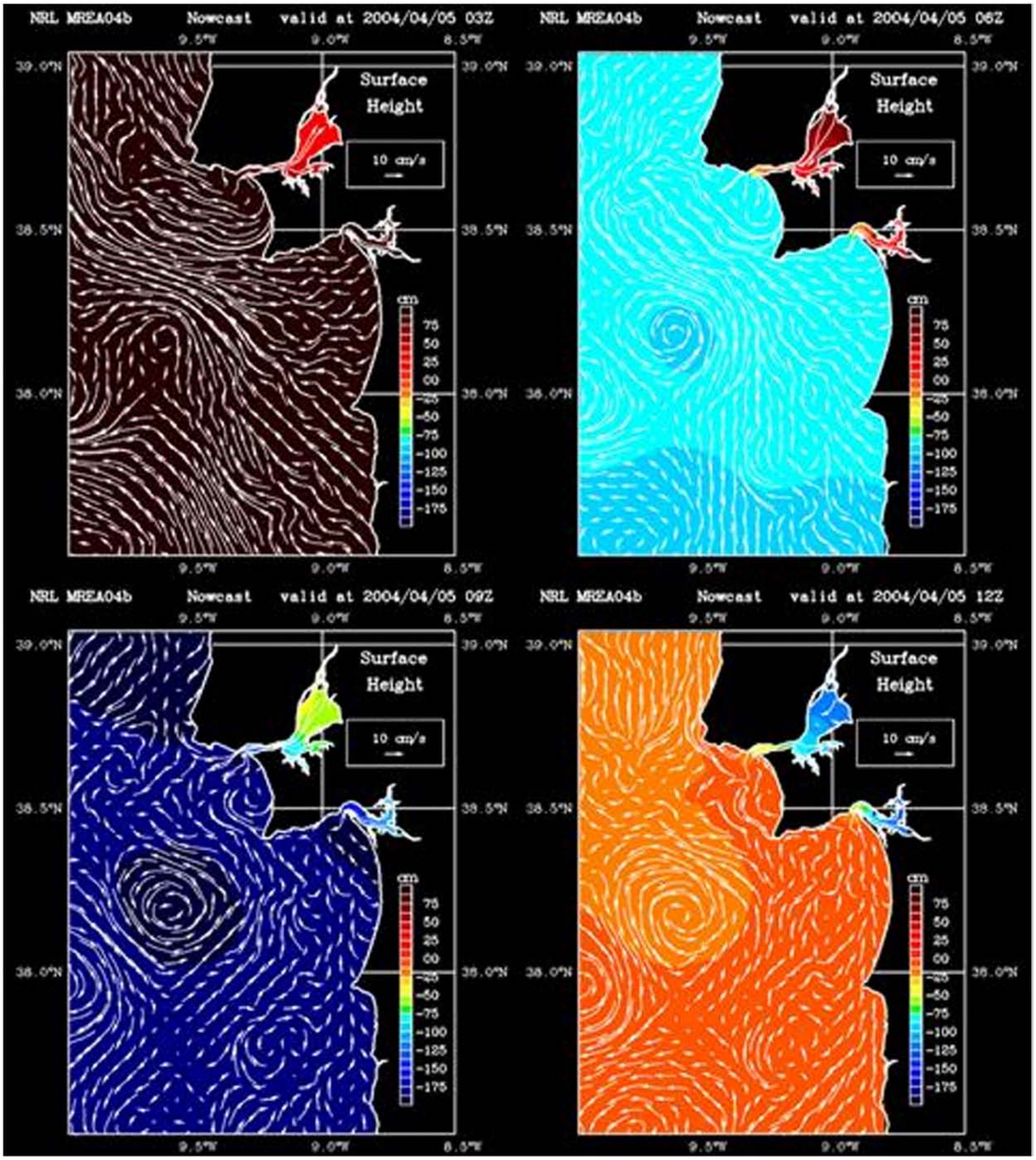

Fig. 6. The model sea level predictions at 3-h intervals (in color) show the tidal phase to be quite uniform for the region except in the bay areas. The model surface current vectors are overlaid.

3.2. Temperature and salinity prediction

Daily model temperature and salinity nowcasts and forecasts from the 1-km resolution nested grid were compared with the CTD measurements. The model and CTD profiles were interpolated to the standard depths used by the Naval Oceanographic Office. An example from these comparisons is shown in Fig. 7. There were about 200 CTD profiles collected during MREA04. The locations of the CTD stations are shown in Fig. 2. The

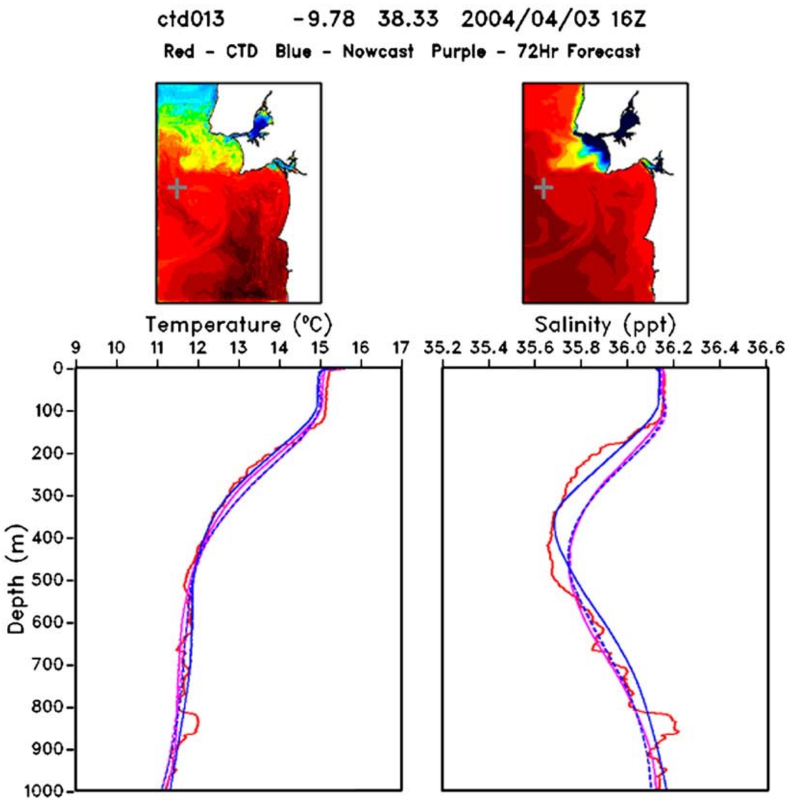

Fig. 7. Comparison of the nowcast/72-h forecast temperature and salinity profiles to the CTD measurement. The solid lines are from the run with the CTD data assimilated and the dotted lines are from the run assimilating only the satellite data. The location of profiles indicated by "+" are superimposed over the model SST and SSS predictions.

root-mean-square (rms) errors were computed at the standard depths for all the nowcasts and forecasts over the 2-week period of the MREA04 sea trial. The overall rms temperature error is about 0.5 °C (Fig. 8) and the overall rms salinity error is about 0.15 psu (Fig. 9). The error varies with depth. The larger error below 600 m is likely due to the internal waves generated by the tides, which the model did not predict well (see the comparison of the temperature and salinity profiles between the CTDs and the model in Fig. 7). In an evaluation of the NSCSNFS predictions in the South China Sea, Chapman et al. (2004) found that the high-frequency, small-scale oceanic variations in the ONFS tend to be damped by the assimilation of temporally and spatially smoothed analyses.

The forecast error increases with forecast time as expected, but it does not increase much over a 72-h forecast. The small increase in the forecast error is mainly due to the short length of the forecast relative to the mesoscale time scale of 30 days or more. The main source of forecast error for the temperature and salinity is the error in the nowcast field.

Figs. 10 and 11 show a comparison of the rms nowcast and 72-h forecast errors from the run that did not assimilate the CTD data with the errors from the run that assimilated the CTD data. The rms errors for temperature and salinity are significantly smaller for the run with the assimilated CTD data, which illustrates the impact of assimilating in-situ data. The forecast error for the run without assimilation of CTD data, however, did not increase over the nowcast error. This is because a longer relaxation time scale (15 days versus 5 days) was used for the run without CTD assimilation. A longer relaxation time may allow the model fields to become more fully adjusted to the changes in the model temperature and salinity from the data assimilation, and therefore allow a better forecast when the model is not constrained by the data.

4. Conclusion

An ocean nowcast/forecast system has been developed at NRL. The system integrates dynamical and statistical models together with oceanic observations

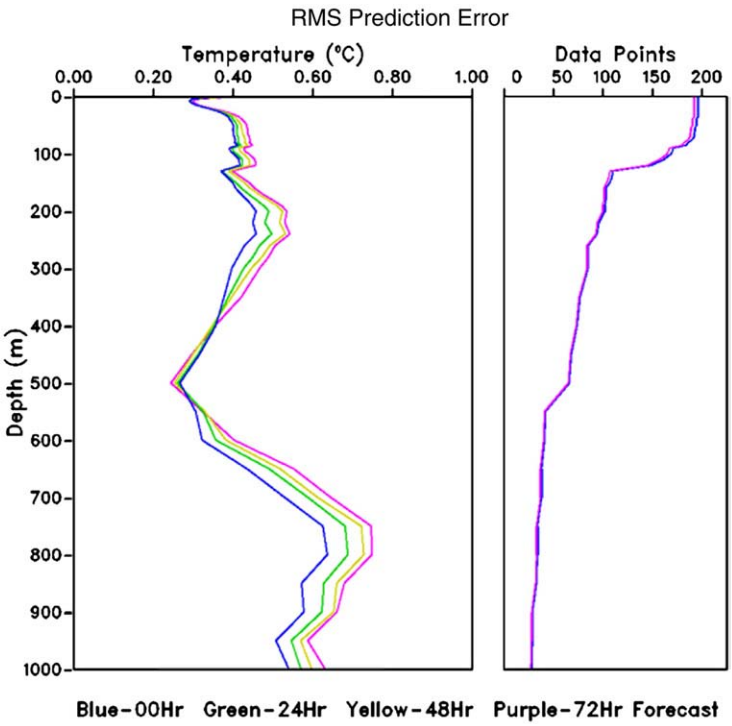

Fig. 8. The rms error for the temperature predictions as function of depth. The CTD data points at various depth used for the evaluation are shown on the left. The plot shows an overall rms error of about 0.5 °C.

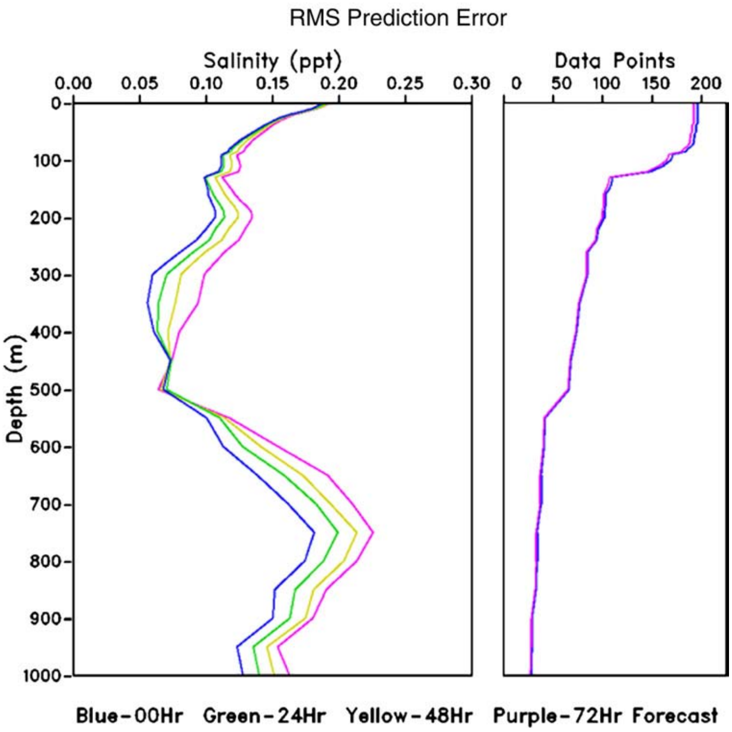

Fig. 9. The rms error for the salinity prediction compared to the CTD measurement. The overall rms error is about 0.15 ppt.

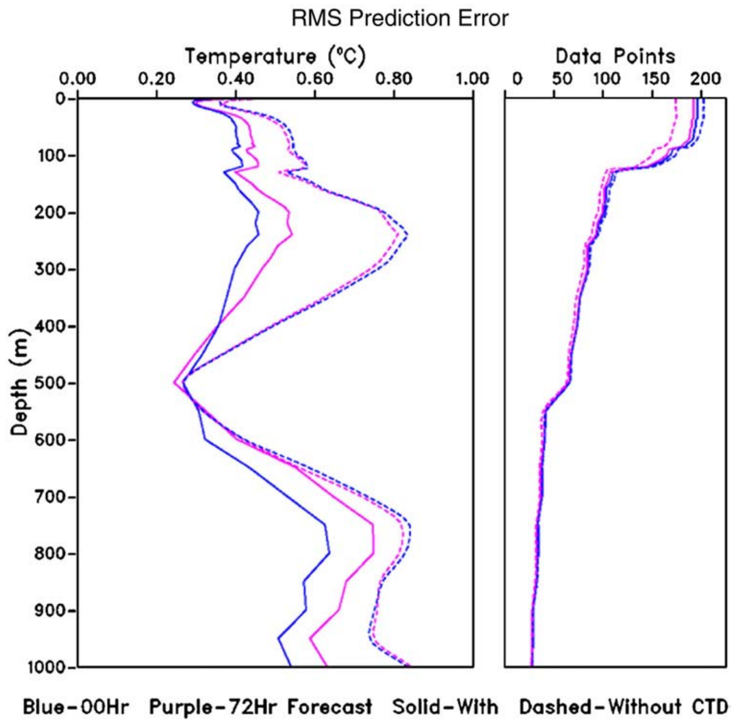

Fig. 10. Comparison of the rms errors for the temperature predictions with (solid lines) and without (dashed lines) assimilating CTD data. The plot shows the improvement of the prediction assimilating CTD data.

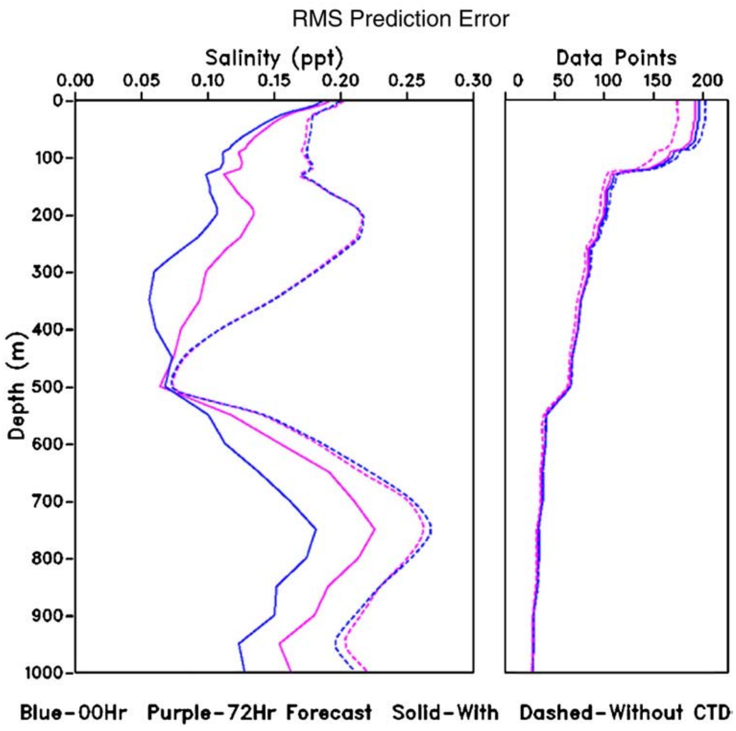

Fig. 11. Comparison of the rms errors for the salinity predictions with (solid lines) and without (dashed lines) assimilation of CTD data. The plot shows the improvement of the prediction assimilating CTD data.

and meteorological forcing to nowcast and forecast sea surface elevation, ocean current, temperature, and salinity. During the NATO MREA04 sea trial, the NRL ONFS was implemented in an area off the Portuguese coast to perform real-time ocean nowcasts and forecasts with a 4-km main and 1-km nested grids. Surface forcing of sea level pressure, wind stress, and heat fluxes was taken from the NRL COAMPS Europe meteorological forecast model. Satellite altimeter data, MCSST data, and in-situ CTD temperature and salinity profiles were used for the data assimilation.

The system performance in predicting SSH and temperature and salinity was evaluated against observations. The evaluation shows that the nowcast/forecast system has good skill in predicting the tide and fair skill in predicting the ocean temperature and salinity. The accurate prediction of the tide is due to fairly uniform tidal amplitude and phase for the region. Assimilating in-situ CTD data produced a better overall nowcast/forecast than assimilating only the satellite data. The forecast error increases as the forecast time increases, but the forecast error does not increase significantly over the nowcast error, which indicates that the error in the nowcast is the major source of the forecast error.

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