Operational Circulation Forecast Systems in NOAA

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Abstract

Several ocean and estuary/bay/lake circulation forecast systems are running operationally at NOAA's National Weather Service (NWS) and National Ocean Service (NOS) computing facilities to provide real-time ocean conditions and forecast guidance to users in the commercial industry, educational institution, and other government agencies for navigational safety, emergency response, and research development and applications. Base on numerical ocean models, these forecast systems focus on short term and real time operational forecasts up to weekly time scales with domains ranging from basin, region, to estuarine and lake. The numerical model resolution is designed to be capable of resolving mesoscale eddies or small scale coastal features.

The basin-scale ocean forecast system, Real Time Operational Forecast System (RTOFS - Atlantic), based on the HYbrid Coordinate Ocean Model (HYCOM) has been running operationally at NWS since 2006. This eddy resolving model system replaces the previous Princeton Ocean Model (POM) based Coastal Ocean Forecast System (COFS). RTOFS emphasizes on the coastal ocean, the loop current and the Gulf Stream regions and provides nowcasts and forecasts of sea level, current, temperature, and salinity for the entire North Atlantic Ocean.

There are nine operational forecast systems, based on POM and others, running operationally at NOS since 2002. During the system development, the core models are evaluated by NOS standard skill assessment procedures to ensure the model performance quality. The Coastal Ocean Model Framework (COMF) has been implemented to standardize all model operations including data ingestion and product dissemination. Under the NOS's Physical Oceanographic Real-Time System (PORTS) and monitored by the Continuous Operational real-Time Monitoring System (CORMS), these operational forecast systems provide nowcast and forecast guidance of water level, current velocity, temperature and salinity for mariners navigating in the Chesapeake Bay, New York Harbor, Galveston Bay and Channels, St. Johns River, and all five Great Lakes (Erie, Ontario, Huron, Michigan, and Superior). Currently, three estuarine forecast systems are under development using Regional Ocean Model System (ROMS) for Delaware Bay, Chesapeake Bay (2nd generation), and Tampa Bay. Future development will be focused on a regional scale with sufficient detail in the estuary.

1. Introduction

One of NOAA's missions is the protection of life and property and to support environmental management and economic development in the coastal domain. The objective for developing and implementing ocean and estuarine circulation forecast model systems is to fulfill this critical mission within NOAA. These forecast systems, consists of a general circulation model and forced with surface and lateral boundary conditions, provide near real-time ocean conditions and short term (with time-scale 2 to 3 days) forecast guidance to the users. The information provided by circulation forecast systems includes sea surface height (water elevation) and three-dimensional current velocity, temperature and salinity. A control framework processes the input/output datasets required by the forecast system and controls operational sequences.

This paper presents an overview of the development procedure for operational circulation forecast systems (OFS) within NOAA. These systems include the basin-scale Real-Time Operational Forecast System (RTOFS) at NWS and nine estuarine/bay/lake operational forecast systems at NOS. Modeling framework designed to standardize model system development and operations under operational environment are discussed. The evaluation of the forecast system core model performance is based on their hindcast and semi-operational skill assessment.

2. Basin Scale Forecast System RTOFS

RTOFS (Atlantic) (Spindler, et. al., 2006) is a basin-scale ocean forecast system based on the dynamical model HYDCOM, jointly developed by the University of Miami, the Naval Research Laboratory (NRL), and the Los Alamos National laboratory (LANL). The system has been running operationally at NWS's National Centers for Environmental Prediction (NCEP) for the Atlantic Ocean (Fig. 1) covering from about 30^0 S to 70^0 N. The bathymetry is shown in Fig. 2.

The goals of RTOFS are: (1) to establish operational high resolution (eddy resolving) ocean forecast system for short-term forecasts (about 7 days) of the Atlantic Ocean with US deep and coastal waters well resolved, (2) to provide nowcasts and forecasts of sea levels, currents, temperatures, and salinity, emphasizing on the coastal ocean, the Loop Current and the Gulf Stream regions, (3) to provide seamless boundary and initial conditions to regional ocean physical and biogeochemical models, (4) to enable the coupling of circulation-wave ocean models with one-way and two-way interactions, and (5) to couple with atmospheric-ocean hurricane forecast.

The surface forcing on the model includes atmospheric fluxes from 3-hour NCEP Global Forecast System (GFS). Open boundaries are relaxed to temperature and salinity climatology. River discharges from US Geological Survey (USGS) are specified as inflows. Body and boundary tides are included. Eight tidal constituents (M2, S2, N2, K1, P1, O1, K2, and Q1) are used. Data ingested during the nowcast data assimilation cycle includes: SST from GOES AVHRR and in-situ data; SSH from JASON GFO; and S and T from ARGOS, XBT, and CTD.

The model system is run once a day starting with a 24 hours data assimilation to update the ocean condition. The model then makes a 120 hours forecast. Examples of RTOFS forecast SST, SSH, surface salinity, and surface current velocity are shown as Fig. 4.

NCEP will establish a RTOFS global model system to provide boundary conditions to other basin or regional models such as RTOFS-Atlantic and future RTOFS-Northeast Pacific and RTOFS-Hawaii. This global forecast system will server as a backbone for all other NCEP requirement such as Hurricane Weather Research and Forecasting (HWRF) and ecological modeling requirement.

3. Estuaries/Bay/Lakes Forecast Systems

There are nine estuarine/coastal/lake operational forecast systems (Fig. 3) currently running at Centers for Operational and Oceanographic Product and Services (CO-OPS) within NOAA's NOS. They are: Chesapeake Bay, New York Harbor, Galveston Bay and Channels, St. Johns River, and all five Great Lakes (Erie, Ontario, Huron, Michigan, and Superior). Three others are under development and scheduled to become operational in 2009: Delaware Bay and Tampa Bay forecast systems and retrofitting Chesapeake Bay forecast system.

Except at the Great Lakes where the primary circulation driven force from wind and fresh river flow, the NOS estuarine forecast systems take observed water level as open boundary conditions for the nowcast. Tidal predictions added to the wind driven water level forecast from NWS's operational Extra Tropical Storm Surge (ETSS) model are specified at the estuary/bay entrance for the model to produce 30 hours forecast guidance of water level, current velocity, and salinity and temperature. Surface elevation forecasts from other basin scale models are also under consideration for open boundary condition including NWS's RTOFS and Navy Coastal Ocean Model (NCOM). The nowcast and forecast guidance from these estuaries/lakes forecast systems are then disseminated on the Internet as station time series, vector plots, and contours.

The first operational forecast system, Chesapeake Bay Operational Forecast System (CBOFS, Fig. 4) was implemented in 2002 (Gross, 2000). This forecast system, based on Model for Environmental Circulation and Assessment (MECCA, Hess, 2000) model runs four times a day and provides water levels over the entire Chesapeake Bay for promoting navigation safety. Water surface elevations from tidal predictions and subtidal water level at Chesapeake Bay Bridge Tunnel are specified as the lateral boundary conditions. Observed (met pack at NOS water level stations) and model forecasted winds (North American Mesoscale, NAM) are used for surface forcing.

The New York Operational Forecast System (NYOFS), based on Princeton Ocean Model (POM, Blumberg and Mellor, 1987), was implemented in 2003. A higher resolution fine grid, covering inland navigational channels, is nested within a coarser grid which covers the entire New York Harbor nearby estuary (Fig. 5(a)) (Wei and Chen, 2002). The fine grid model receives boundary conditions from the coarse grid is capable of providing detail current velocity on navigational channels shown in Fig. 5(b). These current velocity fields are critical for Coast Guard to determine the "right-of-way" for vessel navigating in a narrow waterway. In addition to the observed and forecasted surface elevations specified at Sandy Hook, NY and Kings Point, NY, winds and the river inflows are also input to the model.

The Galveston Bay Operational Forecast System (GBOFS) was developed with POM model (Schmalz, 2000) for Galveston Bay and Houston Channel, Texas. A fine grid covers the navigation channel through the Galveston Bay is nested in the coarse grid as shown in Fig. 6(a). The surface current velocity forecast is shown in Fig. 6(b).

The St. John's River (SJROFS) Operational Forecast Systems developed with Environmental Fluid Dynamic Code (EFDC) model (Zhang, et al., 2006) was implemented in 2005. Fig. 7(a) shows the model grid. Fresh river inflow from upstream reservoir and run off from hydrological watershed to the St. John's River, Florida meet the sea water intrusion at the coast is clearly indicated in a snapshot of salinity forecast contour shown in Fig. 7(b).

The five Great Lake Operational Forecast Systems (GLOFS, including Lakes Erie, Ontario, Huron, Michigan, and Superior) were original developed by NOAA's Great Lake Environment Research Laboratory (GLERL) and Ohio State University (Schwab and Bedford, 1994). The systems were running at GLERL since 1997. They were transferred to NOS and became operational in 2006 (Kelley, et. al., 2007).

GLOFS is designed to provide improved predictions of water levels, water currents and water temperatures in the Great Lakes for commercial recreation and emergency response. There is no tide and salinity in the Great Lakes, the hydrodynamic circulation in the lakes is driven by wind set-up and the temperature gradient induced by river inflow, the wind and heat flux exchange with atmospheric at the surface.

Nowcast and forecast guidance produced from each of five Great Lakes OFS are graphically disseminated on the Internet. Fig. 8 shows the surface temperature of Lake Erie and the surface current velocities of Lake Huron produced by the GLOFS.

4. Modeling Framework

The operation and maintenance of all NOS forecast systems require a comprehensive and integrated management system to ensure the integrity and the production quality of forecast system operation procedure. The Coastal Ocean Model Framework (COMF) (Gross, et. al., 2006) at NOS has been developed for this purpose. COMFS is a set of standards and tools for developing and maintaining NOS's OFS. The goal of COMF is to provide a comprehensive software infrastructure to increase ease of use, performance, portability, interoperability, and reuse in forecast models of estuaries, coastal ocean and Great Lakes. COMFS also provides a software framework for individual scientists, model production, and the critical operational environment.

The COMF consists of several logically and simply defined modules. Each module is composed of Unix scripts, FORTRAN programs, Perl scripts, and graphic routines to perform various tasks. A main shell script in each OFS provides the primary interface and controls the timing, acquisition of data, running of the models, generation of site specific output, generation of graphics and dissemination of results via a web interface.

Module functionality and sequential execution of COMF are: (1) set environment variables for directories, (2) test computer system, (3) create the start and end times of each designed simulation run, (4) acquire input data, (5) reform and quality control input data, (6) perform hydrodynamic simulation, (7) archive simulation input and output data, (8) generate graphics, (9) create run flags, and (10) purge old files.

These modules provide standardization to the operational forecast systems and simplify their creation. Among all modules, the unified data access and quality control modules are the most significant and complicated. A complete collection of data access tools are provided to grab data of water level, wind, river discharge, salinity and temperature from several data sources including NOS' National Water Level Observation Network (NWLON) or Physical Oceanographic Real-Time System (PORTS) stations, US Geological Survey (USGS) rivers, and National Data Buoy Center (NDBC) Coastal Marine Automated Network (C-MAN). NOAA forecast model guidance from North American Mesoscale atmospheric model (NAM) and Extra Tropical Storm Surges (ETSS) model are also accessed with the same routines.

Model forecast run flags produced from Module 8 contain information for NOS's 24x7 Continuous Operational Real-Time Monitoring System (CORMS) to display on Internet web page (Fig. 9). This color display shows the forecast system operational status of input data acquisition, model runs, graphic generation, and archive process. The information provides CORMS operators who monitor the real-time data and forecast system operational status.

All forecast systems developed and transferred to NOS operational status will be standardized within COMF. The time and cost efficiency for forecast system development and production will be increased under COMF. Effort to improve the accuracy and efficiency of OFS process will be a continuous development task by infusing new methods.

5. Operational Forecast System Evaluation

In developing and implementing forecast models to support navigational and environmental applications in coastal waters, the policies and procedures for the evaluation of NOS nowcast/forecast models are required in order to ensure that these models have been developed and implemented in a scientifically sound and operationally robust way (Hess, et al., 2003). The complete forecast system evaluation includes: (1) standardization of model output and products, documentation, and skill assessment and operation procedures, (2) periodic review, (3) skill assessment, and (4) product quality control, and (5) documentation. Since the primary user of the products is the navigational community, and their concerns are under-keel clearance and maneuvering in port areas, the primary variables to be evaluated are water levels, currents, and water density. The skill assessment of model system performance becomes the focus point for the evaluation. The components of skill assessments include: (1) the quantities relevant to navigation, (2) the time series of observed and predicted variables, (3) data processing techniques, (4) the model run scenarios, (5) the comparison statistics or quantities, (6) the target values, (7) comparison of forecast method, and (8) acceptance criteria.

The skill assessment statistics that can quantify model performance are easily calculated quantities that provide relevant information on the important categories of model behavior. The standard suite of statistics gives a global assessment of errors, and includes: (1) series mean (SM), (2) root mean square error (RMSE), (3) standard deviation (SD) of error, (4) central frequency (CF), i.e., the frequency the errors lie within specified limits, (5) positive outlier frequency (POF), i.e., the frequency of model outliers higher than the observed, (6) negative outlier frequency (NOF), i.e., the frequency of model outliers lower than the observed, (7) maximum duration of positive outliers (MDPO), and (8) maximum duration of negative outliers (NDPO).

The primary variables for the standard suite statistics in terms of importance for navigation in U.S. coastal waters and ports are: (1) for under-keel clearance - the magnitude of water levels, the times and amplitudes of high and low water; (2) for vessel maneuvering - the speed and direction of the currents, the time, amplitudes, and direction of the maximum flood and ebb currents, and the starting times and end times of slack water; and (3) for density - salinity and temperature.

The target criteria for those statistic parameters are set based on user requirements. For example, for most of the vessels navigating in coastal waterways and channels, the target criteria for water level prediction error threshold is 15 cm and the central frequency is 90%. This means that 90% of the time the water level forecast errors, when compared with observations, should be less than 15 cm for the system to meet NOS implementation standard.

The skill assessment will apply to model data, at locations where observations are available, from five model simulation scenarios during the model development. They are: (1) astronomical tide only simulations, (2) hindcast, (3) semi-operational nowcast, (4) semi-operational forecast, and (5) persistence forecast. These simulation scenarios are designed not only to ensure the accuracy of model calibration and verification process ((1) and (2)) but also to measure the model system nowcast/forecast performance capability under the operational environment ((3) to (5)).

A software package (Zhang, et. al., 2006) has been developed at NOS to compute the standard suite statistics automatically using data files containing observed, nowcast, and forecast variables. Based on the requirement of the forecast system model application, this skill assessment software acquires the observations and/or NOS standard tide predictions from available NOS database. Observations are quality controlled with gap filled to match with model data time series. The model data from each model simulation scenario are read in and compared with observations to calculate skill assessment statistics in tables which can be incorporated into model evaluation reports. The skill assessment results provide the System Design and Implementation Team (SDIT) the information to determination of the system status from development to implementation.

6. Summary

Operational circulation forecast systems in NOAA provide valuable ocean condition information of water levels, currents, salinity and temperature to the marine community for navigation safety, commercial cargo efficiency, emergency response, and ecological and environmental studies. The development and implementation of those forecast systems require standardized framework to manage a unified process for efficient operation and maintenance. The performance of the core model within the forecast system needs to be evaluated by a standard skill assessment procedure to ensure the quality of the forecast system products.

7. References

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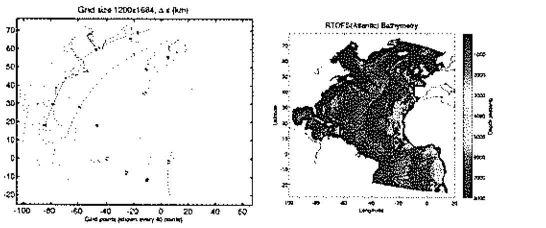


(a) (b)

Fig. 1 RTOFS HYCOM (a) model grid, (b) model bathymetry.

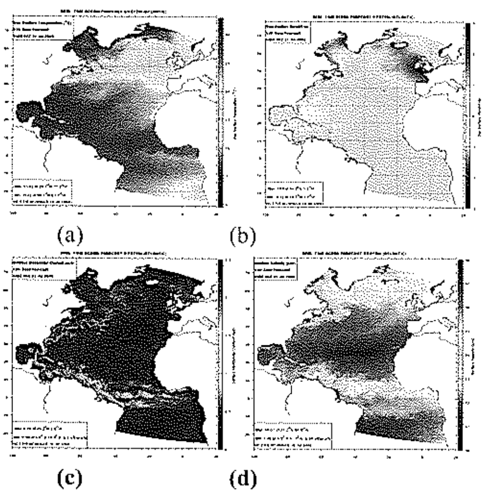


Fig. 2 RTOFS forecasts of (a) SST, (b) SSH, (c) surface current velocity, and (d) surface salinity.

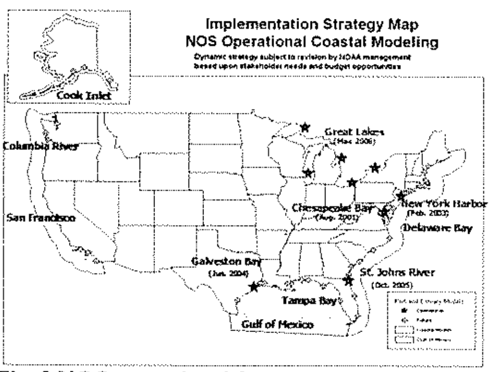
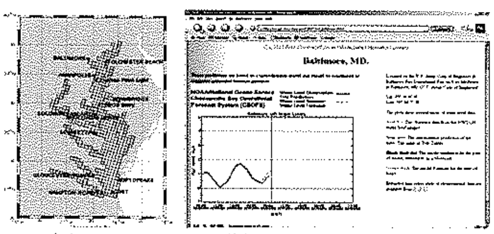


Fig. 3 NOS operational forecast systems.



(a) (b)

Fig. 4 CBOFS: (a) model grid, and (b) water level nowcast and forecast at Baltimore Harbor.

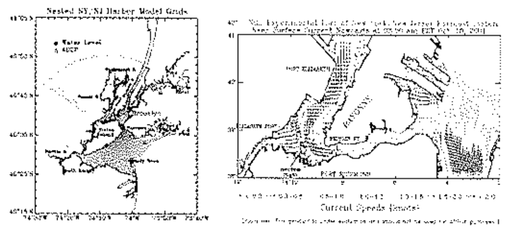
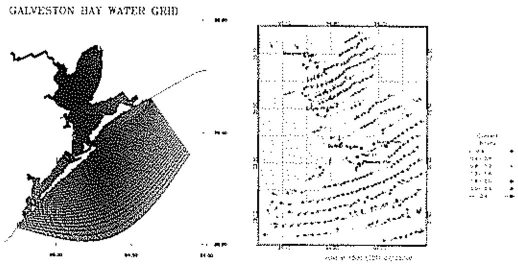
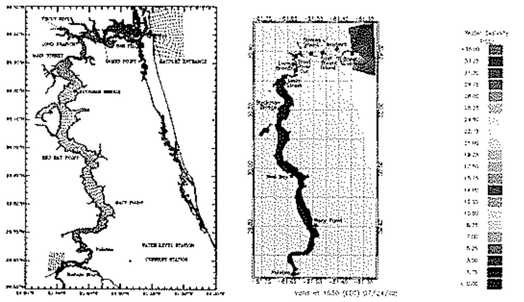


Fig. 5 NYOFS: (a) nested model grids, (b) surface current velocity within the nested fine grid.



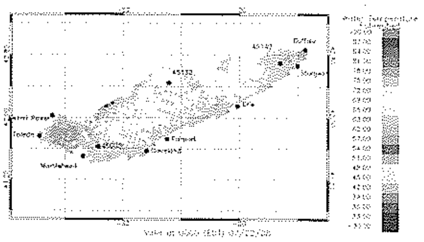
(a) (b)

Fig. 6 Galveston forecast system (a) model grid, and (b) current velocity forecast.

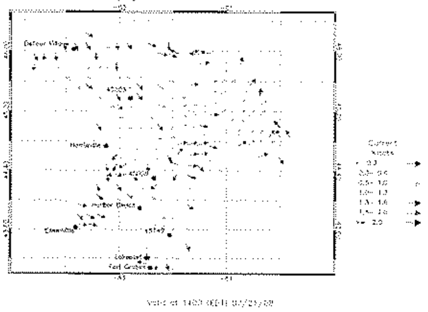


(a) (b)

Fig. 7 St. John's River forecast system (a) model grid and (b) surface salinity forecast.



(a)



(b)

Fig. 8 (a) Surface temperature forecast at Lake Erie and (b) Surface current forecast at Lake Huron.

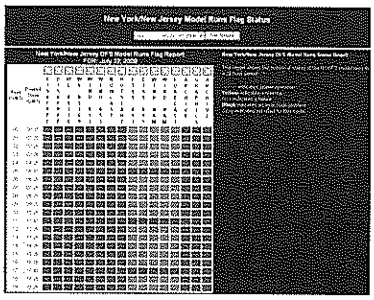


Fig. 9 CORMS model status display for Lake Huron OFS.