

# IMPLEMENTATION OF A NOWCAST/DATA ASSIMILATION CYCLE IN THE COASTAL OCEAN FORECAST SYSTEM

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## I. Introduction

NOAA's Coastal Ocean Forecast System (COFS) is run each day at the National Centers for Environmental Prediction (NCEP) to produce experimental nowcasts and 24-h forecasts of the physical state of the coastal ocean off the U.S. East Coast. Real-time information is important to a variety of users including search and rescue missions, fish recruitment, tracking of pollutants, commercial shipping, and to provide external forcing on the open boundaries of nowcast/forecast models being developed for estuaries (ex. Chesapeake Bay and Port of NY/NJ) by the National Ocean Service (NOS). COFS is a collaborative project between the National Weather Service (NWS), NOS, Princeton University and the U.S. Navy.

## II. Nowcast/Data Assimilation Cycle

A two cycle configuration of COFS, consisting of a nowcast/data assimilation cycle and a 24-h forecast cycle was implemented on April 1, 1998. The purpose of the nowcast/data assimilation cycle is to provide a 3-D nowcast for use as the initial conditions for the forecast cycle. Currently, COFS only assimilates sea surface temperature (SST) data. A description of the COFS nowcast/data assimilation cycle is given next. This includes a description of the ocean model, the SST data and quality control procedures, and the data assimilation procedure.

### A. Ocean Model

COFS is based on the Princeton Ocean Model (POM) (Blumberg and Mellor, 1987) which is a three-dimensional ocean circulation model. The model employs a free surface, has a turbulent closure submodel (Mellor and Yamada, 1982) to parameterize mixing, and includes tidal forcing (Chen and Mellor, 1998). POM uses a bottom-following sigma-vertical coordinate and a coastal-following, curvilinear orthogonal horizontal grid. The horizontal grid has a resolution of 10 km near the coast to 20 km offshore. There are 19 sigma levels in the vertical with increased resolution in the mixed layer and the upper thermocline. The levels are 0.0, 0.008, -0.0008, -0.0016, -0.0032, -0.0064, -0.0128, -0.0256, -0.0512, -0.1024, -0.2048, -0.4096, -0.8192, -1.6384, -3.2768, -6.5536, and -13.1072. The domain extends from the Florida Straits to Newfoundland and offshore to 50°W (Fig. 1). The model bathymetry is based on the U.S. Navy DBDB-5 (Digital Bathymetric Data Base; 5 minute gridded), modified over the continental shelf with the more accurate NOS-15 (15 second gridded bathymetry). At the shoreward boundary, the model's minimum depth is 10 meters.

Since there is currently no operational daily global basin-scale forecast model covering the Atlantic Basin, POM must be driven along its open southern and eastern boundaries by climatological estimates of temperature, salinity and transport. The temperature and salinity are based on the U.S. Navy's Generalized Digital



Environmental Model (GDEM) (Teague et al., 1990). For its coastal boundary, freshwater inflow is specified for 16 rivers, bays and estuaries along the East Coast with the monthly climatology of Blumberg and Grehl (1987) and Koutitonsky and Bugden (1991).

Surface boundary conditions, i.e. surface heat, moisture and momentum fluxes are derived from 3-hourly output from NCEP's high-resolution Eta atmospheric forecast model for the North America continent and adjacent waters (Black, 1994; Rogers et al., 1998). The Eta-32 model has a resolution of 32-km in the horizontal and 45 levels in the vertical. For its specification of SSTs, the Eta model uses NOAA's National Environmental Satellite, Data and Information

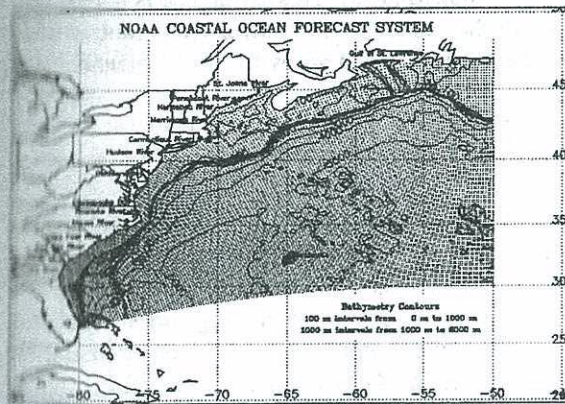


Fig. 1. COFS grid domain, bathymetry (m) and names of estuaries where monthly freshwater inflow are specified.

Service (NESDIS) 50-km resolution Multi-Channel Sea Surface Temperature (MCSST) Analysis that is updated approximately twice a week. The Eta-32 model is run four times a day at 0000, 0300, 1200 and 1800 UTC. Each run or cycle is preceded by the Eta Data Assimilation System (EDAS-32). COFS uses output from the 0000 UTC Eta-32 forecast cycle but has the backup capability to run with forecasts from previous 0000 and 1200 UTC cycles.

## B. Data and Quality Control Procedures

Currently, COFS assimilates SST data including in-situ and remotely-sensed observations. The in-situ observations are obtained from a variety of platforms including fixed and drifting buoys, Coastal-Marine Automated Network (C-MAN) stations, and ships participating in the Voluntary Observing Program. Within the COFS domain there are usually 27 fixed buoys and C-MAN stations that measure SSTs

and approximately 5-10 drifting buoys on any given day.

The remotely-sensed observations consists of MCSST retrievals. These retrievals are derived from multi-channel data from the Advanced Very High Resolution Radiometer (AVHRR) on board NOAA's operational polar-orbiting satellites, NOAA-12 and NOAA-14. Separate MCSST equations are used for day and night data. Each retrieval represents an approximate 8 x 8 km area. The retrieval is based on an average of four AVHRR Global Area Coverage (GAC) spots arranged as a 2 x 2 unit array. Each GAC spot in the unit array is an approximate 4 x 4 km square of 1 km horizontal resolution AVHRR data. The number of retrievals in the COFS domain on a given day ranges from 400 to 7000.

In addition to the quality control that is performed by the National Data Buoy Center prior to the in-situ fixed buoy data being received at NCEP, a gross check is done to remove data less than 1°F and greater than 33°F. These limits will be modified after quality control checks for missing data and geographic positional error are implemented in COFS.

## C. Data Assimilation Procedure

The data assimilation procedure is based on two assimilation schemes, the optimal interpolation scheme of Behringer (1994) and the mixed-layer assimilation scheme of Chalikov et al. (1997). The optimal interpolation is used to determine a correction field of the model's top layer temperature. The mixed-layer assimilation technique is used to project the surface data into the model's mixed-layer. A similar approach has been used in the United Kingdom Meteorological Office's Forecasting Ocean Atmosphere Model for the Arctic and Atlantic Oceans (Forbes, 1995).

The surface correction field is calculated by an objective analysis of the MCSST and SST observation increments or observation-minus-background differences at the observation sites. In other words, the purpose of the objective analysis is to spread out the differences at the observation sites into the model grid domain. Thus, the correction field is an analysis of the observation increments. In this scheme, the objective analysis equation is solved using an equivalent variational formulation (Derber and Rosati, 1989). In this formulation, the goal is to minimize the objective function or functional which consists of two terms. The first term is a measure of the fit of corrected temperature field to the uncorrected model temperature field and the second is a measure of the fit of the corrected temperature field to the observations. The form of the functional is



$$I = \frac{1}{2} T^T E^{-1} T + \frac{1}{2} (D(T) - T_o)^T F^{-1} (D(T) - T_o) \quad (1)$$

where  $T$  is an  $N$  component vector of the corrections to the model temperature field,  $E$  is an approximation to the  $N \times N$  model error covariance matrix,  $T_o$  is an  $M$  component vector of differences between the observations and model temperatures,  $D$  is an interpolation operator from grid points to observation locations, and  $F$  is an approximation to the  $M \times M$  observational error covariance matrix. The error covariance matrices are poorly known and thus are specified in a simple manner.

The observational error covariance matrix,  $F$  is estimated at the present time only from measurement errors. These errors are treated as if they were uncorrelated and thus the matrix is diagonal. Thus  $F$  and its inverse  $F^{-1}$  are diagonal matrices whose elements are the observation error variances and their inverses, respectively. We note that the implicit assumption of independence of observation errors that makes the error covariance matrix  $F$  diagonal, is undoubtedly not valid. Especially, we expect it to be invalid for the MCSST retrievals which generally contribute the greatest numbers of temperature values to the analysis. Often the retrievals are relatively dense and analyzed values at individual grid points may be influenced by several retrievals at once. Therefore, the retrievals have significant potential for creating errors in the analysis from errors in the specification of the spatial covariances. The variances are specified by observational type and are similar to those in NCEP's basin-scale climate ocean models (Derber and Rosati, 1989; Ji et al., 1995).

The first-guess error covariance,  $E$  is modeled by repeated applications of a Laplacian smoother. This results in a first-guess error covariance,  $E(r)$  between any two points on a model layer that is approximated by a Gaussian function

$$E(r) = a \cdot e^{-\left(\frac{r}{b}\right)^2} \quad (2)$$

where  $a$  is the first guess error variance,  $r$  is the horizontal distance between two model grid points, and  $b$  is the estimate of the correlation spatial scale of the model error. The error variance,  $a$  controls the relative weight between the observations and the first guess. The value of  $b$  was arbitrarily set to 30 km.

The correction field is added to the model first guess field. This corrected top layer temperature field serves

as the target for the mixed-layer extrapolation scheme to estimate a new subsurface temperature structure.

The first step in the mixed-layer scheme is to calculate the depth of the mixed-layer using the model's thermal profile. Next, the scheme checks to see whether the corrected surface temperature is warmer or cooler than the model's first guess. When the corrected field is warmer than the first guess, the surface temperature difference is distributed throughout the mixed layer. When the corrected field is colder than the first guess, the corrected field replaces the model temperatures down to the depth where they become equal.

Finally, the difference between the model and the estimated temperature is calculated at each model grid point in the mixed layer. This difference is then slowly applied to the model's mixed layer temperatures using simple Newtonian relaxation with a coefficient equal to  $10^{-5} \text{ s}^{-1}$ .

### III. Daily Operations

The execution of COFS at NCEP involves the following steps: 1) extraction and archiving of in-situ SST observations and MCSST retrievals within the COFS region; 2) extraction, archiving and interpolation of Eta-32 model output to the COFS domain; 3) execution of POM; 4) post-processing of COFS output; and 5) launch and post-processing of the COFS 24-h forecast cycle.

Marine observations are decoded from the Binary Universal Form for Representing Meteorological Data (BUFR) files located on NCEP's Cray C-90 supercomputer. The observations are contained in five separate files for U.S. and Canadian fixed buoys, C-MAN stations, ships, drifting buoys, and surface aviation routine weather reporting stations located near the coast. These files are combined into a file containing on- and offshore marine observations for the East Coast and Gulf of Mexico for one day. Next, MCSST retrievals are decoded from BUFR files located on the Cray C-90.

SST observations and MCSST retrievals within the COFS domain are selected and combined into one file. In addition, the model coordinates of the retrievals and in-situ SST observations are calculated and added to the data record. Each data record contains the time, date, latitude and longitude coordinates, model coordinates, sensor ID, observation type, water temperature, and the estimated reciprocal of the error variance. The file for the previous day is created at approximately 0015 UTC.

The surface forcing fields from the 0000 UTC Eta-32 model forecast cycle are extracted from its original GRIdded Binary (GRIB) formatted file and archived by COFS following the completion of the Eta-32 model



cycle usually at 0300 UTC. Once the Eta-32 model output has been archived, the COFS nowcast/data assimilation cycle is submitted to the Cray C-90 for execution.

COFS software performs a data availability analysis of the archived Eta-32 output to determine whether there is any missing forecast projection. If there are missing projections, COFS will attempt to fill the gap with forecasts from other Eta-32 forecast cycles using a priority table (Lobocki, 1996). The availability analysis is done in conjunction with the degribbing and interpolation of the Eta-32 output to the COFS domain. Once the Eta-32 output is ready, POM is submitted to the Cray C-90.

After POM completes its 24-h nowcast/data assimilation cycle, post-processing programs are executed to perform various tasks. These include the encoding of the native-model grid output into GRIB format, the interpolation and encoding of output to a standard grid in GRIB format, the transfer of output to the COFS archives at NESDIS' National Oceanographic Data Center (NODC), the generation and display of COFS on NCEP's restricted World Wide Web (WWW) site, and the submittal of the COFS 24-h forecast cycle to the C-90. A sample COFS nowcast of SST and currents is depicted in Fig. 2.

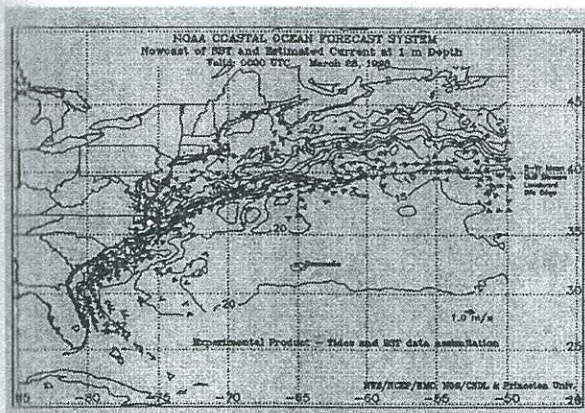


Fig. 2. Nowcast of SST and surface currents valid at 0000 UTC March 28, 1998.

The forecast cycle performs similar pre- and post-processing activities as those executed by the nowcast/data assimilation cycle. Monthly updates of COFS nowcasts and forecasts can be seen at NCEP's unrestricted WWW Site, <http://polar.wwb.noaa.gov/cfs/Welcome.html>.

#### IV. Plans

Assimilation of SST data into COFS has improved prediction of surface temperatures and of subsurface temperatures through the mixed layer in most locations. However, additional work is required to further improve COFS nowcasts. Planned improvements include the use of 3-hourly analyzed fields from EDAS-32 in COFS nowcast/data assimilation cycle. This is considered important because experiments using analyzed winds from EDAS-48 suggest an improvement in the coastal water level simulations of ~20% (RMSE) (Aikman et al, 1998). In addition, more realistic specifications of error covariance matrices, and the assimilation of subsurface temperature reports into COFS are planned.

#### V. Acknowledgments

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