EXPERIENCE GAINED DURING THE IMPLEMENTATION OF NOAA'S COASTAL OCEAN FORECAST SYSTEM[1] [2]

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ABSTRACT

A Coastal Ocean Forecast System (COFS) is being developed at NCEP, in collaboration with NOS and Princeton University, to forecast the physical state of U.S. coastal waters. It is based on a state-of-the-art ocean circulation model which is forced at the surface by heat, momentum, and moisture fluxes provided by a high-resolution atmospheric forecast model. The present version of COFS has been running off the U.S. East Coast since 8/93 and has been providing 24-hour forecasts of surface elevation, and temperature, salinity, and currents for the entire water column.

During the past four years, we have gained considerable experience in the development and implementation of COFS. We have encountered problems as well as successes during this period. Model predictability has been examined and is relatively high near the coast. With respect to the problems, some have been solved and some remain to be solved. These problems include the specification of appropriate surface fluxes from the atmosphere, how to specify realistic forcing along the open boundaries of the model domain, and the specification of realistic freshwater fluxes along the coastal boundary in order to generate representative salinities where the salinity gradients are strongest. Another problem that appears to be generic to ocean circulation models which include the Gulf Stream, is how to generate the correct pattern of flow near Cape Hatteras where the Gulf Stream separates from the coast. Finally, a number of problems arise with respect to ocean data assimilation which have yet to be satisfactorily addressed, ranging from data availability and distribution, to the appropriate methodologies to be employed. Following a brief description of the COFS, model predictability together with other positive results are discussed. Then the problems indicated above are discussed along with the solutions that have been found, or, in some cases, are still being sought.

I. THE COASTAL OCEAN FORECAST SYSTEM

COFS will provide regional ocean forecasts for coastal waters around the continental U.S. on an operational basis (Kelley et al., 1997). It is based on a three-dimensional ocean circulation model called the Princeton Ocean Model (Blumberg and Mellor, 1987). This model is based on the primitive equations, employs a free upper surface, and has a second order turbulence closure submodel to parameterize mixing (Mellor and Yamada, 1982). The model employs a terrain-following sigma coordinate system in the vertical, and a coastline-following curvilinear grid in the horizontal. The model has 18 layers with increased vertical resolution in the mixed layer and the upper thermocline. The spatial resolution increases from 20 km offshore to 10 km near the coast. The coastal boundary corresponds to the 10 m isobath. The model bathymetry is based on the U.S. Navy's digital bathymetric database (DBDB-5) with 5-minute resolution. The COFS domain for the U.S. East Coast extends from 27° to 47°N, and from the coast out to 50°W (Fig.1). COFS is coupled to a high-resolution regional atmospheric forecast model called the ETA model (Black, 1994) which provides surface fluxes of heat, moisture and momentum. Coupling between the atmosphere and ocean is presently one-way, i.e., there

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is no feedback from the ocean to the atmosphere. Tidal forcing for six tidal constituents is included in the model (Chen and Mellor, 1998). The model is forced along its open boundaries using climatological estimates of temperature and salinity, and volume transports which are specified separately. Freshwater inputs are specified for 16 rivers, bays and estuaries along the U. S. East Coast and are based on monthly climatological data (Blumberg and Grehl, 1987).

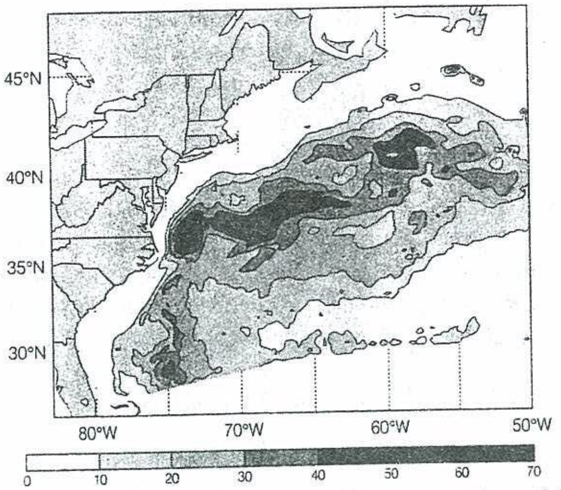

Fig. 1. Model domain for the east coast version of the COFS showing model predictability in terms of the root-mean-square difference in surface velocity between a control run and a parallel run using slightly different initial conditions (see text for details).

The U.S. Navy's Generalized Digital Environmental Model (GDEM) is used to provide the model's initial state for temperature and salinity when it was initially started from rest (Teague et al., 1990). Subsequently, the initial conditions for the model are provided each day by advancing the previous day's initial conditions using analyzed atmospheric forcing fields from the previous 24-hours and the assimilation of available data during this period. The data assimilation procedure for the present version of COFS uses *in situ* SSTs and satellite retrievals of SST from the Advanced Very High Resolution Radiometer (AVHRR). The assimilation procedures *per se* are based on the assimilation scheme of Derber and Rosati (1989) and Behringer (1994). The influence of the SST data are projected below the surface using a mixed layer adjustment procedure (Chalikov and Peters, 1997). Preliminary evaluations of COFS which include data assimilation have shown a significant improvement in model performance (Kelley et al., 1997).

II. MODEL PREDICTABILITY AND OTHER POSITIVE RESULTS

In 1994, a model predictability experiment was performed using COFS (Sheinin and Mellor, 1994). The results from two, three month-long model integrations were compared. A control run using initial conditions from climatological data was compared with a second run where the initial conditions were "perturbed". The perturbed initial state for the second run was obtained from the control run after it had run for approximately five weeks. The same surface forcing was used in each case and there was no data assimilation. At the end of the three-month period, output fields from both runs were compared. Model predictability (e.g., root mean square differences between the fields for each run) was calculated for surface elevation, surface velocity, and SST. For surface elevations and velocities, in particular, model predictability was relatively high everywhere except for the Gulf Stream region (Fig. 1). Because of the inherent instability of the flow in this region, data assimilation is required in order for the model to realistically portray this feature. Our experience with COFS since this experiment was conducted has generally confirmed these results.

Consistent with the above, COFS has shown considerable skill in predicting waters levels at the coast with, and without, tidal forcing (e.g., Aikman et al., 1998). The highest skill has been achieved for the subtidal water levels which are strongly influenced by the wind-driven set-up and set-down at the coast. The wind-driven influence, of course, also reflects on the quality of the wind forcing which is provided by the ETA model. Additional improvements in wind forcing are also being incorporated into COFS using surface winds from the ETA nowcast cycle which will replace the use of previous day's forecast to provide today's initial conditions for COFS. Comparison of subtidal water levels at two locations along the East Coast over a 6-month period showed that using the nowcast winds from ETA did, in fact, improve the subtidal response of the model (Aikman et al., 1998).

The bathymetry for COFS is based on the Navy's DBDB-5 bathymetric database (5-minute resolution). However, certain deficiencies were found in the Navy database, particularly along the continental shelf and slope between the Florida Straits (~28°N) and approximately 44°N. As a result, the existing bathymetry in this region was replaced with more recent, higher-resolution (15-second) bathymetry from National Ocean Service (NOS). Details of the replacement procedure are given in Wei (1995). Parallel model runs using both databases showed that flow in the Gulf Stream, particularly near Cape Hatteras, was more realistic in the case where the new NOS bathymetry was included (Wei, 1995). The modified bathymetric database which includes the higher-resolution bathymetry from NOS has since been incorporated into the operational version of COFS.

III. PROBLEMS ENCOUNTERED

During the development and implementation of COFS, a number of problems have been encountered. In some cases we have found solutions, or partial solutions, to these problems, and in other cases we are still seeking solutions. We discuss these problems in this section.

A. Anomalous increases in SST

During the spring and summer of 1994, daily model runs indicated an increasing anomaly in SST over the model domain with temperatures in the top layer of the model at least 5°C higher than observed values. Two possibilities for this behavior were initially examined: a lack of vertical mixing during periods of increased stable stratification, and unrealistically high heat fluxes from the atmospheric model. Although insufficient vertical mixing may have been a contributing factor in the anomalous buildup of heat in the model's top layer, it was found that the net heat flux into the ocean from the atmosphere was significantly higher than what one would expect by a comparison with the Comprehensive Ocean Atmosphere Data Set (COADS) climatology (Woodruff et al., 1987). We, indeed, found that the latent and sensible heat fluxes, and the incoming short wave radiation, in the ETA model were much larger than those conventionally accepted as representative over a wide range of atmospheric conditions. To provide a temporary solution to this problem, an adjustment factor was applied to COFS to reduce the overall net heat flux in order to insure closer agreement with the COADS climatology. The net effect of this adjustment has been to effectively eliminate the surface overheating problem in the model.

Several refinements have since been made to the heat flux-related parameterizations in the ETA model which have reduced the net heat flux. Improvements in the surface layer parameterizations for the latent and sensible heat fluxes have been made, as well as a reduction in the incoming short wave radiation (Black et al., 1997). For the incoming short wave radiation, several new features were added including the introduction of atmospheric absorption by ozone and aerosols, and the replacement of a circular orbit for the earth by an elliptical orbit. The inclusion of these factors has reduced the incoming short wave radiation by approximately 10%. As these improvements to the ETA model have been incorporated, the magnitude of the adjustment factor in COFS for the net surface heat flux has been reduced accordingly.

B. Specification of lateral boundary conditions

As shown in Fig. 1, the model domain for COFS has large open boundaries along its southern and eastern extremities. Adoption of a limited-area model was, of course, dictated by the need for higher spatial resolution inside the model domain. However, adequate specification of the temperature, salinity and transport along these lateral boundaries has been, and continues to be, a serious problem. At the present time, climatological values of temperature and salinity are specified for transport into the model domain along the open boundaries. For this purpose, the monthly climatology from GDEM is used. Estimates of the volume transport into and out of the model domain have been obtained from at least two sources including Worthington (1976) and Hogg (1992). Unfortunately, climatological values of temperature, salinity and transport are not necessarily representative of the actual conditions that exist in these regions since, by definition, climatological data have been averaged extensively in space and time and so do not contain much of the important mesoscale structure and variability which should be important to the model.

One of the problems evident in the forecast fields produced by COFS is the consistent lack of flow to the southwest in the Slope Water region that lies between the continental shelf and the Gulf Stream. This deficiency is clearly related to the boundary condition prescribed along the eastern extremity of the COFS domain. Trajectories from drifters and warm core eddies in this region consistently indicate flow to the SW at speeds of up to 10 cm/sec. In an effort to produce more realistic southwestward flow in this region, sensitivity studies were conducted in 1995 to determine if enhanced, persistent flow to the SW could be produced by modifying inflow conditions along the eastern boundary north of the Gulf Stream.

As transport across the boundary was increased[3], most of the additional inflow which initially entered the domain, turned to the south and then to the east, finally exiting the domain just south of the region where it had been injected, i.e., just north of the Gulf Stream. This experiment showed that intuition does not always lead to the desired results!

An alternate approach to specifying the lateral boundary conditions is to imbed or nest the regional model within a global or basin-wide model. One-way or two-way coupling between the models along their common boundaries then provides the regional model with the required information on lateral forcing. We are presently exploring the possibility of nesting COFS or some other similar regional mesoscale model inside a global ocean model. Such a global ocean model is currently under development at NCEP (Chalikov and Peters, 1997). As discussed in Warner et al., (1997), however, model nesting also has a number of limitations generally related to mispecification of the lateral boundary conditions. They include changes in spatial resolution at the boundary between the models, poor initial information from the global model, differences in the process parameterizations between the models that can lead to spurious property gradients at the boundary interface, and, finally, the generation of transient disturbances at the interface that may interact with the desired solution on the interior of the regional model domain.

Of particular concern in our case, is how to properly specify inflow from the Florida Current on the southern boundary near the coast. Because the Gulf Stream in this area is narrow and jet-like, the ability of any global-scale ocean model to adequately resolve the spatial structure of the Gulf Stream at this location is doubtful. Clearly, a poorly-resolved inflow for the Gulf Stream on the southern boundary will most likely result in an unrealistic Gulf Stream further downstream inside the model domain. One solution to this problem is to relocate the southern boundary of the COFS domain to a position further away from the coast. Within the next year or two, the COFS domain will be extended to include the Gulf of Mexico. At that time the model will have only one major open boundary which will be located at approximately 50°W. The Gulf Stream will then be generated completely within the model domain itself, with little, if any, influence from the external (i.e., lateral) boundary.

C. Freshwater influxes and coastal salinities

Along the western boundary of the COFS, i.e., the U.S. East Coast, 16 bays, rivers, and estuaries discharge fresh water into the model domain and thus are expected to have a major impact on the distribution of salinity near the coast. As a result, in many coastal areas, the circulation may be primarily governed by salinity and not by temperature. This was clearly shown to be the case for the low salinity plume off the Chesapeake Bay (Breaker et al., 1998), for example. Since no salinity data are available for assimilation into the model at this time, the salinity field initially is based on the GDEM climatology and is modified over time through river input plus the difference between precipitation and evaporation at the surface predicted by the ETA model[4].

At the present time, the specification of freshwater discharge for the 16 entry points is based on the monthly climatology of Blumberg and Grehl (1987). Climatological data contain no information on major events such as tropical storms and hurricanes, or periods of drought, which may lead to significant departures from the climatology in outflow. Also, the natural day-to-day variability in outflow is lost. In order to improve this situation, we are in the process of replacing the monthly climatological outflows presently in the model with observed daily values obtained from the U.S. Geological Survey's network of gauges that measure streamflows for all of the major rivers in the U.S. In some cases, readings from one gauge may be representative of the actual outflow into the model domain. However, in cases like the Chesapeake Bay, estimating the total outflow at the mouth of the bay is problematic since at least nine rivers discharge waters into the bay, and the time required for these waters to circulate through the bay is difficult to estimate. In some cases, groundwater contributes to the outflow, further complicating the problem. Starting with Chesapeake Bay, we will simply sum up the various river inputs to Chesapeake Bay and assume that there are no delays involved, as a first approximation. The remaining rivers and bays will be upgraded in the model in a similar fashion, with the highest priorities given to the rivers, etc., with

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[3] The distribution of the inflow north of the Gulf Stream was also varied.

[4] Of course internal processes in the model also affect the distribution of salinity such as gravitational instabilities that may result from the assimilation of temperatures that lead to negative density gradients.

the highest outflows, i.e., New York Harbor, Delaware Bay, the Connecticut River, and so on.

Although improved freshwater fluxes along the coastal boundary of the model domain may contribute to more realistic salinities near the coast, the availability of salinity distributions from direct measurements would obviously be enormously helpful. Unfortunately, there are currently few, if any, observations of surface salinity available anywhere around the world on a real-time basis. As a result, new approaches to acquiring information on salinity are required. Remote sensing techniques may offer at least a partial solution to this problem. Microwave remote sensing of surface salinity is now being conducted experimentally from aircraft (Miller et al., 1998). A second possibility is through the use of Color Dissolved Organic Matter (CDOM), which can be derived from ocean color satellite data. CDOM has been shown to be inversely related to salinity under certain conditions, based on ocean color data acquired aboard a NASA aircraft (Carder et al., 1993). Previous results have demonstrated that the spectral absorption at 415×10^{-9} m due to dissolved organic matter in coastal regions where river effluent is present is inversely related to salinity. Although this relationship has only been verified in certain coastal regions, and will most likely be location-specific, it may be possible to use ocean color data from SeaWiFS to derive a proxy for salinity in areas where such relationships can be established and validated. With the availability of salinity data, appropriate methods of data assimilation will have to be developed to incorporate this new source of information into COFS.

D. Ocean data assimilation

Perhaps the most difficult problem that we face in creating a true ocean forecast system is that of ocean data assimilation. Without a major ocean data assimilation component it will be impossible to forecast the state of today's ocean. At the present time we are assimilating SSTs based on satellite retrievals and from *in situ* reports and projecting their influence down through the depth of the mixed layer. Obviously, the vast majority of SST data come from satellites and so their availability depends on cloud cover. In the Gulf Stream region, a primary area of interest, cloud cover is a persistent problem. The time scales of variability for the Gulf stream are as short a day or two, and frequently, several days or more may elapse before new coverage can be acquired in this region. (A similar problem arises for the west coast model domain where fog and stratus frequently obscure the coastal ocean during spring and summer.) The fact that the distribution of available satellite-derived SST's is cloud cover-dependent, presents a major limitation for ocean data assimilation.

At this time we are working on the problem of assimilating data at levels below the surface. Experience has shown that it is imperative that we assimilate information at deeper levels, particularly in the area of the Gulf Stream, if we hope to reproduce surface (and subsurface) flow fields which are realistic. The only options available at this time to obtain subsurface data are expendable bathythermograph (XBT's) and surface elevations from altimeter data acquired by the TOPEX/POSEIDON and the ERS-2 satellites. With respect to XBT's, often there are less than 10 XBTs available within our model domain on any given day and their distributions are usually unfavorable for resolving the features of interest. Altimeter data is expected to provide a significant amount of useful information on the flow structure within the region of interest. For high-resolution models that will be used to make forecasts in real time, however, altimeter data have some important limitations. For the TOPEX/POSEIDON satellite, for example, adjacent track lines are approximately 250 km apart and repeat coverage over the same area can be obtained only once every 10 days. It is also not clear what technique is best-suited for projecting the altimeter surface measurements into the interior of the ocean domain. A number of possibilities exist including the extraction of synthetic profiles of temperature and salinity, which can be assimilated into the model (Carnes et al., 1996), to the direct assimilation of surface elevation where the model itself makes the necessary internal adjustments to the vertical structure of temperature and salinity. Other methodologies are also being explored including the use of correlations between surface elevation and subsurface temperature structure obtained directly from the model itself (Mellor, personal communication).

Another source of available data that could be used in ocean models is the information gathered and/or produced by satellite-tracked drifting buoys. Small numbers of drifters frequently traverse the COFS domain. These tracks can be used to calculate the trajectories of the drifters or the velocities at the flotation depth of the buoy. Both pieces of information are potential candidates for assimilation into COFS. Unfortunately, the use of these types of data for assimilation has not received much attention yet.

Finally, a number of mathematical techniques exist for assimilating data into ocean models. For their implementation, most require information on the error statistics and spatial covariance structures for the model-minus-observation increments for each ocean parameter of interest. Unfortunately, this information is poorly-known for COFS at the present time. As a result, parallel model runs have been initiated to determine the sensitivity of the model to variants of the default values which are presently being used to represent these statistics which may lead to improvements in the existing data assimilation package.

E. Problems in reproducing a realistic Gulf Stream

A problem in Gulf Stream separation occurs frequently off Cape Hatteras. A persistent anticyclonic meander develops just north of the Cape where the Gulf Stream separates from the coast. This problem arises in other largescale and mesoscale ocean circulation models as well. Although SST data assimilation appears to significantly reduce this artifact, the unrealistic meander gradually reforms when SST data are not available in this region for several days. Hence, SST data assimilation alone does not provide a permanent solution to this problem. A number of explanations have been proposed but our experience indicates that several factors may contribute to this behavior. First, speeds in the core of the Gulf Stream at this location (and elsewhere in the Gulf Stream as well) are usually somewhat lower than observed (up to 50% lower in some cases). Second, because the Gulf Stream is jet-like, relatively high spatial resolution is required to retain this jet-like structure. In the region of Cape Hatteras, the spatial resolution of the model is approximately 10 km which may not be high enough to maintain the necessary jet-like structure. Without sufficient resolution, there may be a tendency for the momentum associated with the Gulf Stream to spread laterally which could contribute to the formation of the anomaly. Finally, the bathymetry is very complex near Hatteras, and higher resolution bathymetry may be required locally to provide the correct topographic influence in this region.

IV. CONCLUSIONS

Some successes and a number of problems have occurred in the development of the COFS. Model performance near the coast, at least in terms of water level, was expected to be good and observations have shown that to be the case. For some of the problems which have been identified, solutions or at least partial solutions have been found or are close at hand. Problems related to the specification of the lateral boundary conditions along the two large open boundaries, for example, may be significantly reduced when the model domain is expanded to include the Gulf of Mexico since there will only be one open boundary at that point which may be located as far east as 50°W. The possibility of extracting information on coastal salinities from ocean color satellite data is exciting and should be pursued. Better methods need to be developed to estimate the inflows into the domain from the connecting rivers and estuaries. In the case of ocean data assimilation, however, serious problems remain. The availability and distribution of oceanographic data are poor compared to the atmosphere. For real time applications, the only data types which are routinely available are SSTs, vertical temperature profiles from XBTs, and altimeter data. The availability of satellite-derived SSTs depends on cloud cover, the number of XBTs which are available are usually small in number and poorly distributed, and the utility of altimeter data for assimilation into COFS is still open to question with regard to the space/time coverage it provides. Finally, it is imperative that advanced three-dimensional multi-variate analysis techniques be developed to assimilate all types of available ocean observations to improve our ability to specify the initial state of the ocean.

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