CHARACTERIZING MAJOR FRONTAL SYSTEMS: A NOWCAST/FORECAST SYSTEM FOR THE NORTHWEST ATLANTIC

By Daniel N. Fox, Michael R. Carnes and Jim L. Mitchell

THE U.S. NAVY expends a considerable effort to determine the locations and properties of most major ocean frontal systems across the globe. This synoptic picture, called a nowcast, is partly constructed using expendable bathythermographs dropped from ships (XBTs) and airplanes (AXBTs). Such *in situ* measurements can give very detailed information, but the cost limits their utility to relatively localized and short-lived surveys. Fortunately, given an adequate database of earlier measurements, simply knowing the surface location of a front is often sufficient to reconstruct an accurate picture of the three-dimensional thermal structure of the water column to depths of thousands of meters. Obtaining that surface information is not a trivial task however.

Satellite infrared-radiometer (IR) images provide locations of important mesoscale features over large areas, but clouds can obscure important fronts for long periods, and the surface thermal structure is not always an accurate guide to the actual location of the predominant currents. An unknown geoid and other problems not withstanding (Mitchell *et al.*, 1990), satellite altimetry can provide accurate locations of currents and related features. In many areas of interest, the time and space scales on which the oceans evolve are not adequately sampled, however (Hurlburt, 1984; Kindle, 1986; Thompson, 1986). For example, the U.S. Navy's Geodetic Earth Orbiting Satellite (GEOSAT) (Born *et al.*, 1987) with its 17-day repeat cycle and equatorial track separation of less than 150 km was adequate to sample regions such as the Gulf of Mexico, but was not sufficient to provide a synoptic picture for the evolution of the Gulf Stream.

One approach to the sampling problem is to combine computer models of the oceans with data assimilation methods to extract the most information possible from the limited data available (Hurlburt, 1984 and 1992, this issue; Thompson, 1992, this issue). The design of an ocean observation, data assimilation, and forecasting system can be simplified by exploiting known characteristics of the ocean. As noted previously, the three-dimensional thermal structure of the ocean often can be reconstructed accurately given only information about fronts and eddies at the surface. Furthermore, the vertical structure of such quantities as temperature, salinity, density, and sound speed in the water column can be represented by a very small number of modes (two or three). These modes are basis functions that can be used to reconstruct the vertical profiles. Unlike arbitrary functions, such as polynomials or sines and cosines, these *empirical orthogonal functions* are derived from the thousands of profiles previously taken in the region using a method known as principal component analysis. This technique produces the smallest number of modes that are needed to reconstruct the original profiles to a user-controlled level of accuracy. The advantage of using these empirical orthogonal-function modes is that their amplitudes are related to surface properties such as dynamic height and temperature (deWitt, 1987; Carnes *et al.*, 1990). Thus, a surface measurement of sea-surface height (and ideally sea-surface temperature as well) will provide the amplitudes of the vertical modes, which in turn give us a complete vertical profile of temperature or salinity.

An example of how accurately subsurface temperature structure can be inferred from surface satellite altimeter measurements is shown in Figure 1. Finally, the shallow mixed layer at the surface is primarily driven by the interaction of the ocean with the atmosphere, which occurs on time scales very short compared with the relatively slower mesoscale meandering of fronts and propagation of rings. It is therefore possible to build a nowcast/forecast system that separates the surface mixed layer from the general circulation, which in turn can be represented by a computer model

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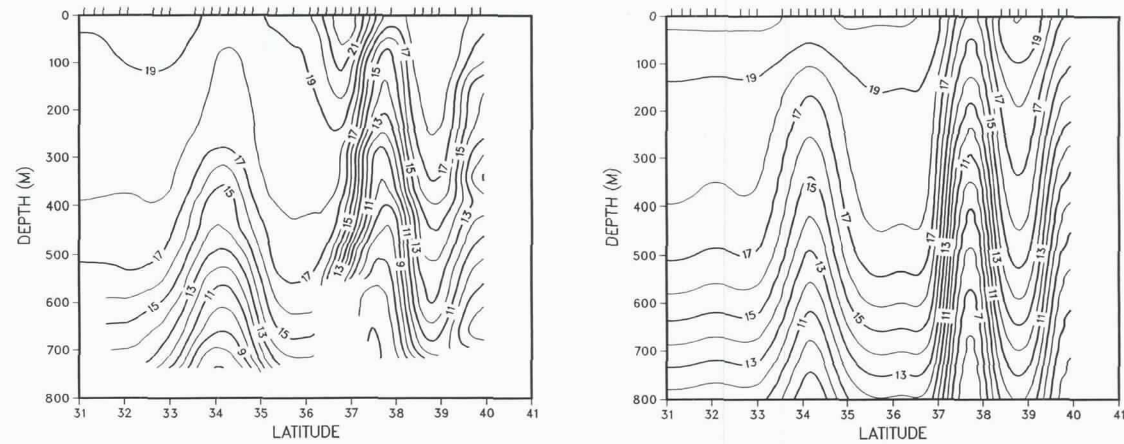

Fig. 1: Comparison of temperature measured by an airborne expendable-bathythermograph survey (left), with that inferred from a coincident Geodetic Earth Orbiting Satellite (GEOSAT) altimeter pass (right) using the synthetic data algorithms. (From Carnes et al., 1990.)

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needing only a few degrees of freedom in the vertical.

A first-generation version of a nowcast/forecast system exploiting these observations has been constructed by the Data Assimilation Research and Transition (DART) group at the Naval Research Laboratory (NRL) and is now making operational forecasts of the Gulf Stream evolution for the Navy. This system has been shown (Fox *et al.*, 1992) to provide forecasts of Gulf Stream evolution that are better than persistence at both 1- and 2-week intervals, the first such system to do so using typical, operationally available data.

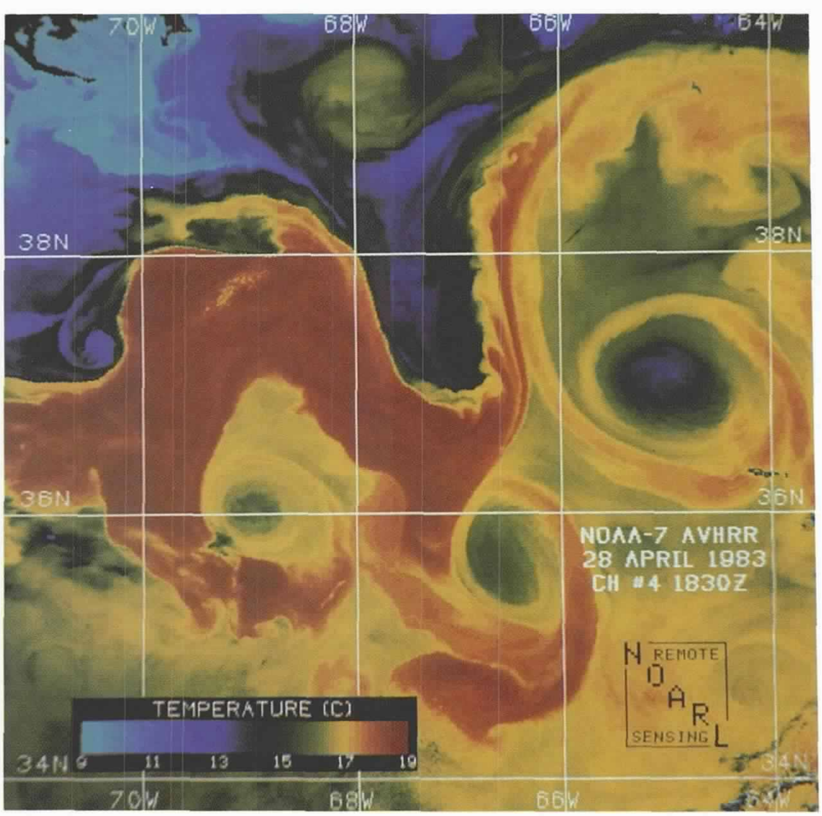

Fig. 2: Satellite infrared image for a cloud-free view of part of the ocean mesoscale field around the Gulf Stream on 28 April 1983. (From Hawkins et al., 1985.)

Estimating Initial Conditions

The procedure used to initialize and run a forecast begins with the subjective preparation of a Gulf Stream frontal-location map by the Naval Oceanographic Office. This manually prepared map blends ring- and frontal-location information obtained from satellite IR imagery (as shown in Fig. 2), satellite altimetry, and any available XBTs into a continuous depiction of the surface frontal location. On many days, portions of the Gulf Stream are obscured by clouds, so such gaps are filled using older data or previous forecasts.

The surface front and ring information is extrapolated downward into a three-dimensional thermal volume using an Optimal Thermal Interpolation System (OTIS) computer program (Clancy *et al.,* 1988; Cummings *et al.* 1991; Clancy, 1992, this issue). OTIS combines simple structural models of fronts and rings with optimal interpolation to reproduce such attributes as the sloping of the front with depth, the warm core of the Gulf Stream, and the subsurface structure of eddies.

A primary function of OTIS is to supplement real temperature observations with synthetic profiles to sufficiently resolve the mesoscale structure in the final gridded analysis. These synthetic profiles are derived from models of the Gulf Stream, its rings, and the background water structure using a front and eddy map as a guide. Most synthetic profiles are positioned in the stream, the eddies, and in a band on either side of the stream. The distance between profiles is roughly proportional to the expected temperature-covariance length scales at each position.

OTIS assimilates the synthetic observations together with true observations to form synoptic maps using optimum interpolation (Gandin, 1963; Bretherton *et al.,* 1976). The synthetic observations provide a high-spatial-resolution data set within and near fronts and eddies, where observational data is often too sparse to resolve these features. Also, the synthetic profiles constructed from satellite surface data provide subsurface information, whereas the direct measurements made by satellites are of surface parameters only.

Dynamic height at the sea surface (used to initialize the circulation model) must be computed from the analyzed temperatures. Because salinity is not available from the OTIS analysis, dynamic heights at the surface are computed from regression relationships between dynamic height and temperature profiles. The root-mean-square error in dynamic height computed by this method is ~0.07 dynamic meters (Carnes *et al.,* 1990). Relative dynamic height at the surface is then computed directly from the grid of temperature profiles using relationships derived from analysis of regional historical temperature and salinity data sets.

Although the work described here focuses on western boundary currents (and the Gulf Stream, in particular), interest is certainly not limited to these regions. Positions of all the major fronts in the northern hemisphere are routinely determined operationally (see Fig. 3) by the Naval Oceanographic Office. We are already extending the synthetic data approach used in the Gulf Stream to the region of the Kuroshio Extension and, in a coarser implementation, to the entire world's ocean. In general, the approach of fitting satellite surface data (e.g., analyzed frontal location maps or even direct satellite measurements such as sea-surface topography from an altimeter) to low-vertical-mode temperature structure should work well in all western-boundary-current regimes. This approach seems to work at least equally well in atmospherically forced planetary-wave regimes such as the equatorial Pacific (Maul *et al.,* 1988). Recently, we have begun to examine the utility of our synthetic data approach in the more challenging regions of temperature-salinity compensated fronts (e.g., Iceland-Faroes).

Circulation Model

The circulation model used in the operational forecasts is documented in Hurlburt and Thompson (1980) and Wallcraft (1991). Applications of the model are described in Thompson and Hurlburt (1982), Hurlburt and Thompson (1984), and Thompson and Schmitz (1989). It is an *n*-layer, primitive-equation model covering the region from 78°W to 45°W longitude to 30°N to 45°N latitude (roughly from Cape Hatteras to the Grand Banks). It includes large-amplitude bottom topography. The model domain was chosen so that the variability in the location of the Gulf Stream entrance into the domain would be small. The version of the model used in the present system includes two layers, with a deep western boundary current (Thompson and Schmitz, 1989) supplied by an inflow port in the northeastern part of the lower layer. The model is on a spherical grid with a resolution of $\frac{1}{6}$° in longitude and $\frac{1}{8}$° in latitude, which represents a spatial sampling of ~14 km in each direction at the center of the grid. Because layer thickness is included among the model variables, fluctuations of the pycnocline can be modeled by changes in the depth of the interface between the upper and lower layers. This permits a more efficient representation of the dominant dynamical modes in the domain than is possible with a model that uses fixed thickness levels.

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Subthermocline Initialization

Information about the subthermocline has been shown to be extremely valuable in forecasts

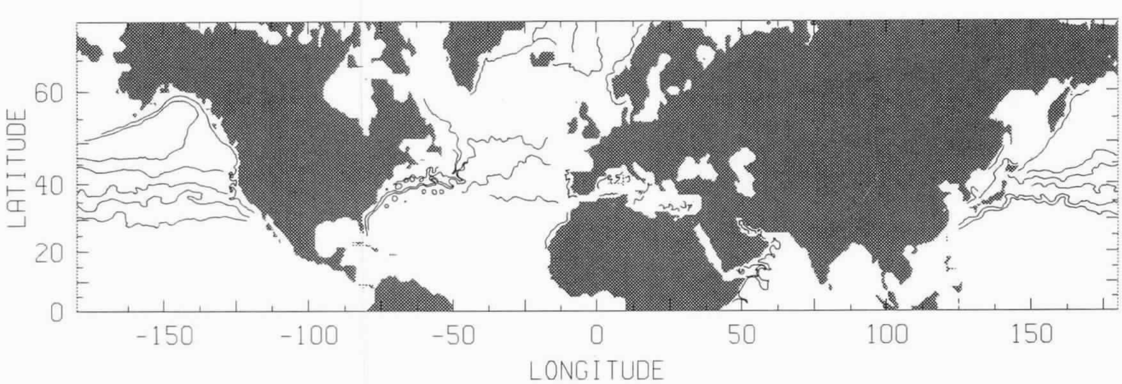

Fig. 3: A world map of many of the standard operational fronts. Positions are derived mostly from satellite infrared-radiometer imagery, which is often obscured by clouds.

based on numerical simulations of the Gulf of Mexico (Grant and Hurlburt, 1985; Hurlburt, 1986 and 1987) and the Gulf Stream (Fox *et al.*, 1988; Hurlburt *et al.*, 1990). The OTIS analysis can provide reasonable estimates of temperature in the water column, and this information can be converted into dynamic height, free-surface anomaly, or surface-pressure anomaly directly. The circulation model requires layer-thickness anomalies or (equivalently) pressure anomalies for all its dynamically active layers. Rather than attempting to extract subsurface pressure or layer thickness information directly from the OTIS analysis, we derive a statistical relationship between the surface pressure field and the pressure anomaly in the subthermocline layer. The lower-layer pressure field is only weakly correlated with the upper-layer pressure (sea-surface topography) at the same geographic location. Long model simulations are therefore used to derive statistical relationships between the subthermocline pressure at any given grid point in the model and the surface pressure at an array of grid points. To accomplish this, the model is spun up from rest for 17 model years, at which time both layers have reached statistical equilibrium as measured by the potential and kinetic energies. Five years of monthly fields are then used in the derivation of regression coefficients. Parameters that control this derivation are chosen to maximize the skill in estimating the lower-layer pressure in an independent dataset. That is, coefficients are derived from one run of the model and are used to estimate the lower layer in an independent run. In the cases of the Gulf of Mexico (Hurlburt *et al.*, 1990) and the Gulf Stream (Fox *et al.*, 1988), the lower-layer pressure anomaly from the model simulations can be accurately estimated by such techniques. The pattern correlation between upper and lower pressure anomaly is low (typically 0.2 to 0.3). The correlation exceeds 0.9 between the true lower-layer pressure fields and that estimated from the upper layer by the statistical inference technique, which uses spatial empirical orthogonal functions of the sea-surface topography as predictors. Alternate methods for initializing the lower-layer pressure field, such as using the reduced-gravity approximation (setting the pressure anomaly to zero) or climatology (setting it to the mean derived from a long circulation model simulation), produce significantly worse forecasts (Fox *et al.*, 1992).

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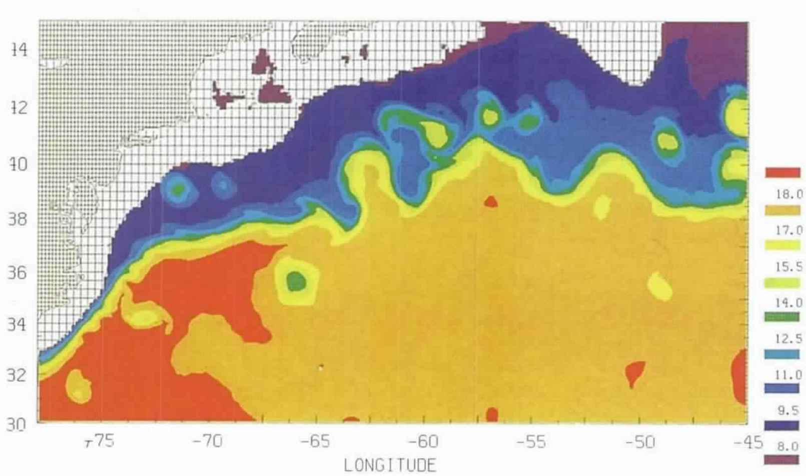

Fig. 4: Temperature at 200 meters from a 1-week run of the coupled hydrodynamic and thermodynamic computer models.

Surface Mixed Layer

A central assumption of our approach to ocean modeling has been that the differing time scales of the thin surface mixed layer and the mesoscale dynamics permit the separation of the prediction problem into two regimes that are united later. Significant progress has been made in achieving this reconnection. Experiments so far show that combining the geostrophic vertical shear (derived from the mass field of the mixed-layer thermodynamic model; Clancy, 1979, 1981, and 1983) with the surface geostrophic velocity and depth-independent ageostrophic velocity (from the circulation model) provides an advection field, which can synchronize the two models for the operationally required time period. Figure 4 shows an example of the temperature field at 200 meters from a 1-week coupled forecast.

Forecast Skill

The measure chosen to evaluate the performance, or skill of the forecast system depends on the interests of the particular user. Operationally, the system was needed to forecast the absolute position of the Gulf Stream, so the measure chosen to evaluate the skill is an estimate of the average absolute offset between the true stream location and that forecast by the system. It is useful to compare the performance of the model forecast to the alternatives of persistence and climatology. In the case of persistence, we compute the error between the initial conditions and the final state 1 or 2 weeks later, without running any model forecast at all. This also is also called the assumption of no motion. In the case of climatology, the final state is compared against an average state. Figure 5 summarizes the performance of the system in the region from 73°W to 53°W longitude. The results for climatology (the uppermost, horizontal line) are computed from a year of daily analyzed Gulf Stream paths prepared at the Naval Oceanographic Office. The data is binned in $\frac{1}{2}$° increments and a mean path is computed. This average state is then compared against all the original data to compute the average offset error. Now if we are asked to estimate the location of the Gulf Stream on a day when cloud cover com-

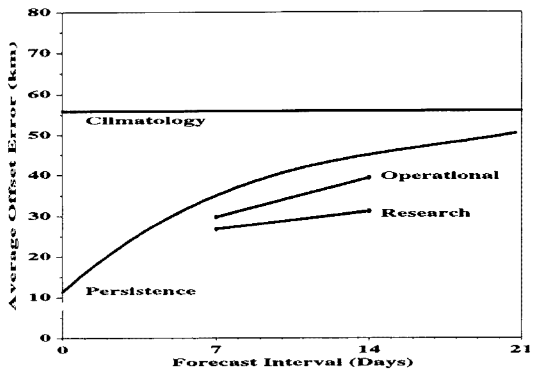

Fig. 5: Error in absolute position of the Gulf Stream using climatology, persistence, and the DART forecast system. Forecasts using 6 months of standard operational data and a small research-quality dataset are contrasted.

pletely obscures it, we could fall back on the climatological mean path, but Figure 5 shows that we will make an error of 50 to 60 kilometers by doing so.

The same data used to prepare the line for climatology can be used to estimate the results for persistence. Figure 5 shows that if the stream has been obscured for a week and we are forced to use data from 7 days ago as our estimate of today's stream location, we should expect to make an error of 35 km, on average. If we must go back 14 days to find a clear image of the stream, using this old data as our estimate of today's stream location would produce an expected error of ~45 km. It is interesting to note that the persistence curve does not pass through the origin. There are many sources of small errors in the analysis technique that are used to produce an estimate for the location of the Gulf Stream. These conspire to produce an overall error in any particular analysis of ~10 km.

Finally, we can choose to use the forecast system to project old data into an estimate of where the Gulf Stream is today. The two bottom curves in Figure 5 represent results from applying the forecast system to two different datasets. The curve labeled "Operational" is a summary of 6 months of forecast skill using the standard, operationally available Gulf Stream analyses. The curve labeled "Research" is a much smaller dataset of very high grade analyses that were prepared for the Data Assimilation and Modeling Evaluation Experiment (DAMEE) being coordinated at the Institute of Naval Oceanography. Figure 5 shows that using the forecast system with very good data produces an error of ~27 km at 7 days and 31 km at 14 days. In each case, this estimate is 20–25% better than using persistence as the forecast and far better than using climatology. Using the standard operational estimates of Gulf Stream location, the skill is still better than persistence, but not by so great a margin.

Summary

An initial version of a complete nowcast/forecast system for the Gulf Stream has been developed and successfully tested at the Naval Research Laboratory by the DART Project team, and is now used in daily Naval operations. The development of the first such system to show skill relative to persistence using routine operationally available data is a significant step toward the eventual goal of a global ocean nowcast and forecast capability.

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