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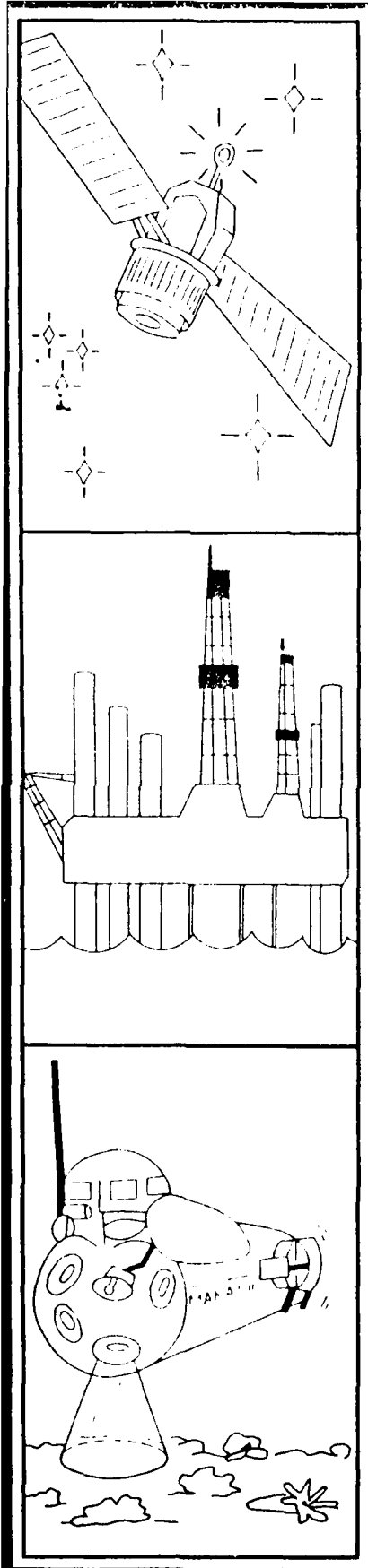**15. Number of Pages.**
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OBJECTIVE USE OF SATELLITE ALTIMETRY AND IR IN SIMULATIONS OF WESTERN BOUNDARY CURRENT DYNAMICS

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Abstract

A series of numerical experiments to predict the evolution of the Gulf Stream have been performed. The forecast system uses a primitive equation model of the north western Atlantic Ocean and assimilation schemes which employ both a feature model and statistical correlations derived from the regional climatology of in situ data and long time-base numerical simulations. The evaluation criterion is the mean absolute distance between forecast locations of the Gulf Stream front and actual locations as verified from extensive satellite and in situ data. Eight one-week and five two-week evaluation intervals during 1986-1988 were selected to represent a variety of both active and inactive Gulf Stream regimes. To insure objectivity, hindcasting was disallowed. The resulting forecasts were significantly better than persistence at both one- and two-week intervals. This study indicates the feasibility of Gulf Stream forecasting using assimilation schemes which provide adequate deep information and numerical models which are designed to be consistent with available data.

1 Introduction

The western boundary current regions of the oceans represent domains of high variability and considerable eddy activity. They are not adequately sampled by in situ measurements or by satellite altimetry [10,13] to permit accurate, instantaneous estimates of sea surface topography. They are also regions of significant strategic importance. The development of numerical models of the North Atlantic [15] capable of reproducing the measured variabilities, large scale circulations, and eddy activity has given us the confidence to proceed with the construction of a system which will use such models to dynamically interpolate the asynoptic measurements available and thereby provide both improved nowcast and forecast capabilities.

A system for constructing initial state estimates and performing forecasts was constructed for the region of the North Atlantic by the Data Assimilation Research and Transition (DART) team at the U. S. Navy's Naval Oceanographic and Atmospheric Research Laboratory.

In order to provide a 'level playing field' in the arena of ocean forecasting, a set of reference data (i.e., Gulf Stream frontal locations) was created for a subset of the Gulf Stream region. Before any forecasts had been done, data over the preceding three years was examined to attempt to define several periods for which accurate positions of the Gulf Stream axis and eddies could be constructed for at least two weeks. Clear satellite IR imagery was required, and in most cases XBTs and GEOSAT altimetry [3] was used to refine the locations of the features. Four time periods were chosen in 1986 through 1988 which permitted eight 1-week forecast and verification experiments and five 2-week experiments.

The primary evolution criterion was the mean absolute distance between forecast locations of the Gulf Stream front and the actual (or verification) locations. Forecast error was computed as the *average absolute offset* between the forecasted position of the axis with the position given in the verification state. *Persistence*, the assumption of no motion over the forecast interval, was used as a comparison in judging forecast skill. For a model to have any significant skill in forecasting, the error in its forecast (the *forecast error*) must be less than the error computed by simply using the initial state as the forecast (the *persistence error*).

To examine the degree to which this small number of states was representative of the Gulf Stream as a whole, persistence errors were computed both from these states and from a year of the operationally produced front locations. The distributions were compared to verify that the cases chosen were representative.

The domain was divided into three subregions: a Western Region, extending from 73°W to 66°W longitude, a Central Region, extending from 66°W to 59°W longitude, and an Eastern Region, extending from 59°W to 53°W longitude. The average absolute offset error of each of these subregions was computed, as well as the overall region, extending from 73°W to 53°W longitude.

2 Forecast Experiment Results

Figure 2 presents the results from one of the 2-week forecast experiments. Measuring the errors in the overall region from 73°W to 53°W longitude, persistence represents an error of 50 km at 1-week and 65 km at 2-weeks. By comparison, the forecast provided errors of only 26 km and 39 km at 1- and 2-weeks respectively. When all eight 1-week and five 2-week cases are examined, it was found that the system provided forecasts which were better than persistence by approximately 6 km at 1-week and 10 km at 2-weeks. Standard statistical techniques were used to verify the significance of these results.

3 DART End to-End Nowcast/Forecast System

In this section, we provide a detailed description of the DART Gulf Stream run stream. The procedure used to initialize and run the DART forecasts begins with the subjective preparation of an initial Gulf Stream frontal location map. This manually prepared map blends frontal location information contained in satellite IR imagery, satellite altimetry, and any available BTs into a continuous depiction of the surface frontal location. The resulting continuous depiction of North Wall location is then run through a feature model algorithm in the OTIS computer program which provides an initial state estimate of the dynamic height, which is then converted to an upper layer pressure anomaly (p1) in the NOARL primitive equation circulation model. Scaling between OTIS dynamic height and model p1 is necessary to correctly represent the transport in the model's thick upper layer. This initial p1 field is instantaneously converted in an accompanying lower layer pressure field (p2) using a statistical inference technique based upon the circulation model's climatology. Together, p1 and p2 are then used to provide for geostrophic initialization of the circulation model. For a brief interval immediately following these "cold start" initializations, a filter is applied in the circulation model run to nearly eliminate gravity waves. Finally, the $p1=0$ contour in the model's forecast state is used to define the forecast frontal location for direct comparison with independent verification frontal location maps.

Much of the success in these "cold start" DART forecasts is a result of the several techniques used to directly (and instantaneously) transfer upper layer information into the lower layer of the circulation model. These techniques are described chronologically in the following sections.

3.1 OTIS Feature Model

Maps of surface topography used to initialized the circulation model and to verify the forecasts were prepared using the regional OTIS, devel-oped primarily at the Fleet Numerical Oceanography Center (FNOC) [5] with contributions from the Naval Oceanographic Office (NOO) and the Naval Oceanographic and Atmospheric Research Laboratory [1,2] OTIS is a data quality control and interpolation system which combines climatology, maps of front and eddy boundaries, MCSSTs (satellite IR multi-channel sea surface temperatures), and measured temperature profiles to form gridded three-dimensional synoptic thermal analyses for selected ocean regions. A reduced set of the OTIS system capabilities was used in this study: the surface topography maps were produced using maps of front and eddy positions as the only data source. The OTIS software interprets these maps and applies models for the Gulf Stream front and eddies to form a gridded three dimensional field of temperature. 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.

All data for each analysis date were combined onto a single map consisting of frontal path segments from IR, locations of front and ring crossings from altimetry, and AXBT locations coded according to water type. An unbroken frontal path, from the western to the eastern boundaries of the model domain, was drawn by hand through the composite data set and then digitized, and ring radii and center locations were extracted.

OTIS uses parametric models of the Gulf Stream front, eddies, and the ambient background which have been developed from a combination of historical observations, simple dynamical models, and information obtained from published studies.

The OTIS system assimilates synthetic observations, true observations taken at irregular times and positions, and climatology to form synoptic maps using optimum interpolation [7,4] 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 provide subsurface information, whereas most measurements are made only at the surface from satellites. This study uses only synthetic profiles to construct the final field of temperature.

The optimum interpolation results in a three-dimensional grid of temperature covering the domain of the grid of the circulation model. Since salinity is not available from this analysis, dynamic heights at the surface are computed from the same relationships between dynamic height and temperature used in modeling the structure of rings. The root-mean-square error in dynamic height computed by this method is about 0.065 dynamic meters.

3.2 Circulation Model

The circulation model used in this study is documented in Thompson and Hurlburt [14], Hurlburt and Thompson [9] and Thompson and Schmitz [15]. It is an *n*-layer, primitive equation model covering the region from 78°W to 45°W longitude and 30°N to 45°N latitude. 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. Figure 1 shows a plot of weekly axis locations taken from a year of NEOC boguses. The outlined box in the plot represents the circulation model domain. The relatively small variability in the position of the Gulf Stream axis where it enters the model domain permits the inflow to be specified at a fixed location south of Cape Hatteras. The version of the model used in this evaluation included two layers, with a deep western boundary current [15] supplied by an inflow port in the north eastern part of the lower layer. The model used in these experiments is on a spherical grid with a resolution of 1/6 degree in longitude and 1/8 degree in latitude, which represents a spatial sampling of approximately 14 km in each direction at the center of the grid.

Since layer thickness is included among the model variables, fluctuations of the pycnocline can be modelled 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 which uses fixed thickness *levels*. This was deemed of particular importance in these experiments, due both to the manner in which we initialize the lower layer (described in detail in the next section) and the number of experiments contemplated.

3.3 Statistical Inference of Subthermocline Information

Information on the subthermocline has been shown to be extremely valuable in forecasts based on numerical simulations of the Gulf of Mexico [8,11] and the Gulf Stream [6,12].

Long model simulations are used to derive statistical relationships between the subthermocline pressure (p2) at any given grid point in the model and the surface pressure (p1) at an array of grid points. Parameters which 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.

Figure 3 shows an example of using these coefficients to estimate the lower layer pressure for the Gulf Stream. Note that while the pat-

tern correlation between p1 and p2 on this model day is only .26, the correlation exceeds .9 between p2 and the estimate of p2 computed from p1 by the statistical inference technique. The coefficients derived from these lengthy model simulations are applied to the surface height fields produced by the thermal analysis to provide an estimate of the lower layer pressure field, and thus the pycnocline depth anomaly for each of the forecast dates. The absolute accuracy of this estimate of the depth of the pycnocline has not been quantified, but for the purposes of initializing the circulation model, it represents lower layer information which is *dynamically consistent* with the upper layer information provided by OTIS.

To calculate the contribution to the forecast skill of including this deep pressure information, forecasts were made using the present reference datasets and using three alternatives for defining the lower layer pressure field in the initial states. Forecasts made using either a reduced gravity initialization or using the model's climatological lower layer pressure field resulted in a larger error than those made with the statistical inference initialization, generally by about 5 km.

3.4 Geostrophic Velocity Initialization

The remaining model variables, the *u* and *v* components of velocity for each of the two layers are computed geostrophically. For example, in the upper layer:

$$\hat{k} \times f\vec{v}_g = -g\nabla\eta$$

where *f* is the Coriolis parameter ($f = 2\omega \sin\theta$, where ω is the angular velocity of the earth's rotation and θ is the latitude), $\hat{k}$ is a unit vertical vector, $\vec{v}_g$ is the geostrophic component of the current and η is the free surface anomaly.

3.5 Gravity Wave Filter

Despite the statistical inference of the lower layer and the geostrophic velocity initialization, there will inevitably still be some dynamic imbalances in the initial state. One advantage of the primitive equation model approach is that such imbalances will be converted to short-period gravity waves, which can easily be removed by selective filtering. For the particular domain of this model, the dominant gravity wave period is approximately 8 to 9 hours. These waves are attacked in the NOARL circulation model by a time-domain running average with a length of 8.5 hours which is applied once at +12 hours into the forecast and again at +24 hours, after which no further filter is done during the remaining two weeks.

4 Summary

A series of numerical experiments to predict the evolution of the Gulf Stream have been performed. The nowcast/forecast system developed by the DART team at NOARL is the first such system to show significant skill in forecasting the evolution of the Gulf Stream frontal axis, providing estimates of the front that are (on average) 6 km better than persistence at 1-week and 10 km better at 2-weeks.

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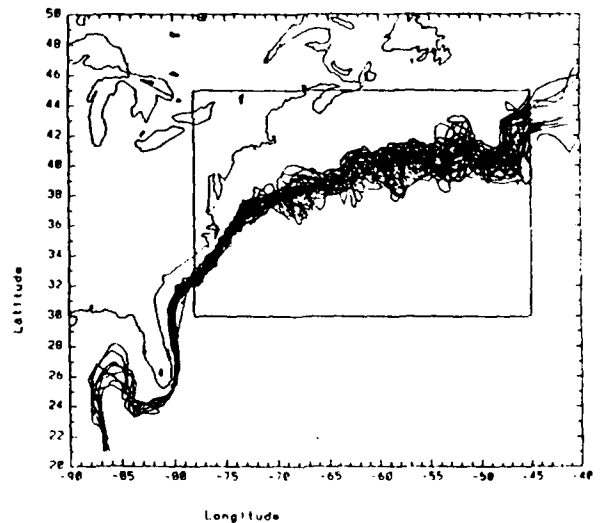
Figure 1 -- One year of weekly Gulf Stream axis positions. Inner box represents the domain of the forecast system.

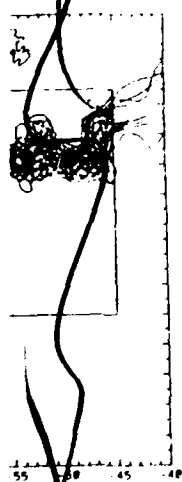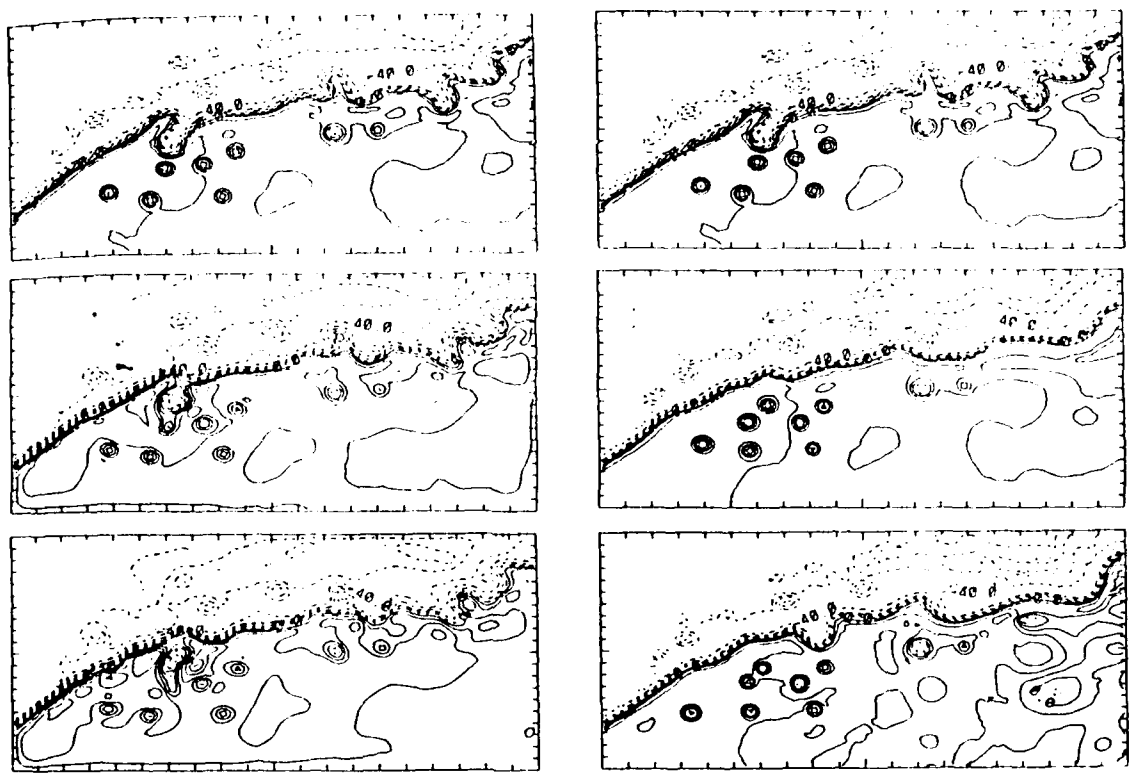Figure 2-- Sample forecast (left) and verification (right) initialized on 6 May 1987 (top) and forecasted for 13 May (middle) and 20 May (bottom).
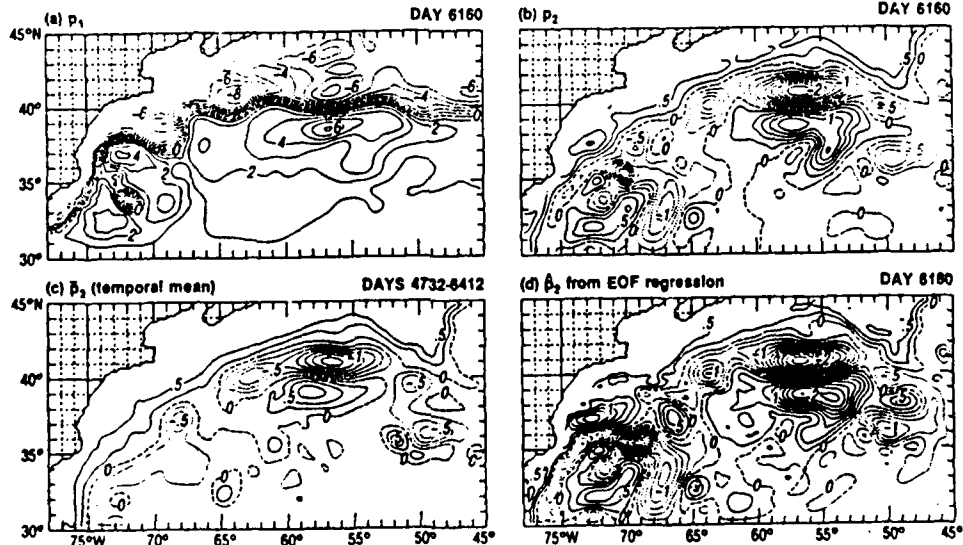
(a) p_1 DAY 6160

(b) p_2 DAY 6160

(c) $\bar{p}_2$ (temporal mean)   DAYS 4732-6412

(d) $\bar{p}_2$ from EOF regression   DAY 6160

Figure 3-- Statistical estimation of subthermocline pressure ($p2$) from surface pressure ($p1$) for the Gulf Stream.