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Reprinted from Eos, Transactions, American Geophysical Union

Eos, Transactions, American Geophysical Union, Vol. 75, No. 34, August 23, 1994, Pages 385, 391, 394

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Using data sets of known quality as the basis for comparison, a recent experiment explored the Gulf Stream Region at 27°-47°N and 80°-50°W to assess the nowcast/forecast capability of specific ocean models and the impact of data assimilation. Scientists from five universities and the Naval Research Laboratory/Stennis Space Center participated in the Data Assimilation and Model Evaluation Experiment (DAMEÉ-GSR).

DAMEÉ-GSR was based on case studies, each successively more complex, and was divided into three phases using case studies (data) from 1987 and 1988. Phase I evaluated models' forecast capability using common initial conditions and comparing model forecast fields with observational data at forecast time over a 2-week period. Phase II added data assimilation and assessed its impact on forecast capability, using the same case studies as in phase I, and phase III added a 2-month case study overlapping some periods in Phases I and II.

The Navy's Optimum Thermal Interpolation System (OTIS 3.0) was used to grid data and geographical area. OTIS functions in an analysis-prediction data assimilation cycle with an ocean mixed-layer model using an optimum interpolation formulation. Climatology serves as the first-guess field for the analysis of ship, bathythermography, buoy, satellite data, and the mixed- layer model predictions. DAMEÉ-GSR assessment data include OTIS historical temperature and salinity; multichannel sea surface temperature (MCSST), sea surface height (SSH) (Geosat altimetry), and temperature and salinity observations made during the case study periods.

The measure of performance was based on the best-available analysis of the location of the North Wall of the Gulf Stream. The model-generated versus the best available analysis of the position of the Gulf Stream (surface North Wall) is used to assess performance. The best available analyses were provided from advanced very high resolution radiometer imagery, and each group projected the surface location to 200 m or the 200-m model position to the surface. The same procedure was used to determine the average offset between model-generated location and analyzed position. The average offset is the area between the curves representing the predicted and observed Gulf Stream North Wall divided by their average North Wall length calculated between 52°–73°W.

Case Study Development

Satellite infrared imagery, Geosat altimetry, and numerous air-expendable bathythermographs (AXBTs)/conductivity temperature depth profiles (CTDs) were overlaid in a Geographical Information System for the Gulf Stream region to develop a high-quality 8-week case study of Gulf Stream meander and ring evolution. The new study, which covered the time period May 25–July 4, 1988, took advantage of the most cloud-free satellite infrared coverage of the Geosat Exact Repeat Mission and the overlap of several in situ observation programs.

The evolving location of the Gulf Stream North Wall and its warm and cold rings were determined at weekly intervals using an improved geoid and a new image-patching technique that fills cloud gaps in an image using cloud-free pixels from other images close in time.

Figure 1 illustrates the patched composite, the nearly concurrent Geosat and AXBT/CTD data, and the analysis for June 13, 1988. The nearly straight white lines show all Geosat ground tracks within 2 days. The along-track dynamic topography is plotted perpendicular to the ground tracks, with positive to the right and the zero crossing at the Gulf Stream maximum velocity axis. The ascending track in the middle of the image captures a local low associated with a cold ring, a 1-m drop across the Gulf Steam, and a local high associated with the edge of a warm ring. AXBT/CTD locations are shown in yellow, with the temperature at 200 m coded by shape. The Gulf Stream North Wall, ring edge, and ring center locations for June 13 are marked in black.

Semispectral Primitive Equation Model

The semispectral primitive equation model (SPEM) was used to achieve a better understanding of the dynamical processes characterizing the Gulf Stream system and better predictions of the Gulf Steam frontal evolution. The model domain covers 50°W to 75°W and 29°N to 46°N. The OTIS fields provide the three-dimensional distributions of temperature and salinity from which the density is evaluated. The surface height generated by OTIS was used as surface pressure

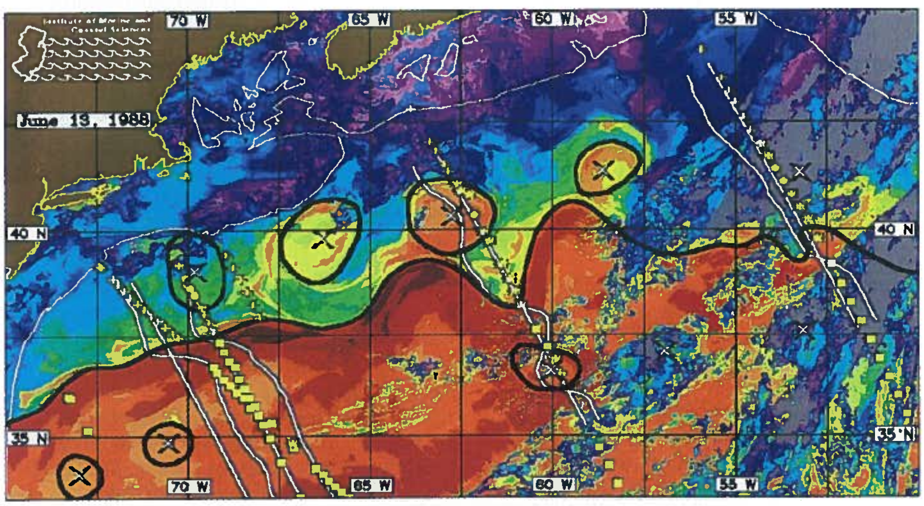

Fig. 1. Composite remote sensing/in-situ data set and the locations of the Gulf Stream North Wall and rings for June 13, 1988. Key: 200-m isobath, white; Geosat groundtracks and dynamic topography, white; AXBT/CTD locations, yellow/purple symbols; Gulf Stream North Wall and ring edges, black; ring centers, black/white cross. AXBT/CTD temperature at 200 m: ≤12.50°C, plus; 12.50–15.0°C, star; 15.0–17.50°C, circle; >17.50°C, square.

For more information, contact Robert C. Willems, Center for Ocean and Atmospheric Modeling, The University of Southern Mississippi, Building 1103, Stennis Space Center, MS 39529

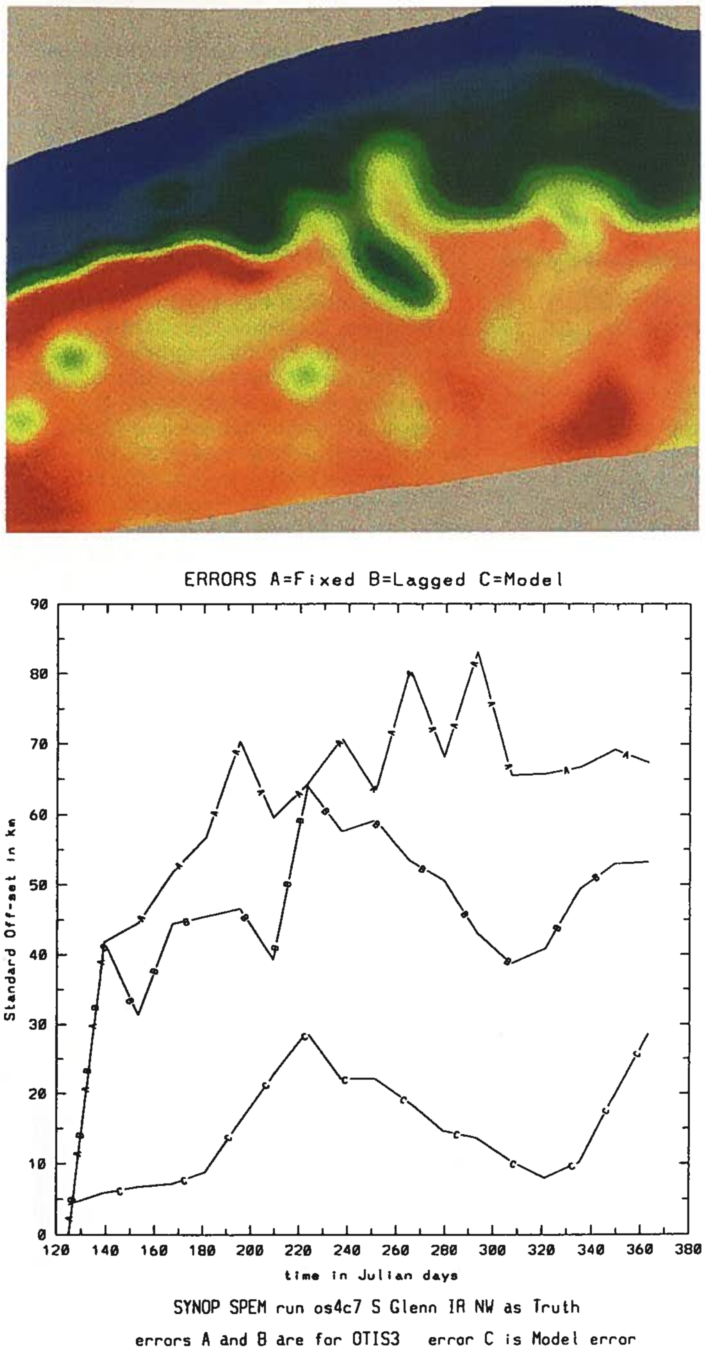

Fig. 2. a) Upper panel: Density field at 200 m depth at day 62 of the hindcast experiment starting on May 4, 1988, and ending on December 28, 1988, with biweekly assimilation of OTIS 3.0 fields. b) Time evolution over 6 months of the North Wall offset. Line A, using simple persistence of initial conditions; Line B, persisting OTIS over a 2-week period; Line C, biweekly OTIS assimilated into SPEM. Line C shows the offset for the prediction experiment in which biweekly OTIS maps are assimilated into SPEM in a time dependent fashion.

and the three-dimensional pressure field was obtained by integrating downward using the hydrostatic relationship, from which geostrophic velocities are evaluated, both for initialization and assimilation.

The model fields are adjusted (nudged to OTIS) to the OTIS biweekly data set fields for 2 days prior and one day after. The rest of the time, the model runs unconstrained outside of this time window. In Figure 2a, the density field is shown at 200 m depth at day 62, starting from May 4, 1988, in a 6-month-long hindcast experiment in which the OTIS fields are intermittently assimilated into SPEM. The zero line marks the Gulf Stream North Wall. A cold core ring has just pinched off from the Gulf Stream indicating a ring for the birth event. Other ring structures are evident in the far field.

To assess the success of the assimilation, we use the offset between the model representation of the Gulf Stream North Wall and the North Wall locations provided as best available analysis. As shown in Figure 2, the model evolution with biweekly assimilation dramatically improves the simulation of the Gulf Stream North Wall over long time intervals, reducing its mean offset from the IR North Wall to fall within the error bar associated with the IR imagery location of the North Wall.

Princeton Ocean Model

The Princeton ocean model (POM), when applied to the Gulf Stream region, has been shown to simulate realistic Gulf Stream separation, and has compared well with the observed seasonal climatologies of this region. Figure 3 shows an example of the model fields at the surface and at 500 m.

The initialization includes an interpolation of temperature and salinity fields from the OTIS analysis into the model grid and diagnostic calculations to produce a dynamically balanced velocity field and surface elevation. Prognostic calculations following the initialization show a forecast skill for at least a 2-week period and demonstrate the sensitivity of the forecast to initial conditions and model parameters.

A continuous data assimilation scheme, based on an efficient three-dimensional optimum interpolation approach, was tested, first with simulated data and then with Geosat altimeter data. Data along satellite tracks are continuously interpolated horizontally and then projected vertically into the model grid and assimilated into the model prognostic fields. Preprocessed correlations are used to relate surface elevation anomalies and subsurface temperature and salinity anomalies in the deep ocean. Estimated model and data errors are also taken into account in the assimilation process. Higher nowcast skill has been achieved during periods of good coverage of the altimeter in 1987 compared to periods of poorer coverage in late 1988.

Extension of the assimilation scheme to include other data sources such as SST and surface Gulf Stream position show promising results. However, differences in the variability and errors of each data type should be considered.

Harvard Ocean Forecast System

Several Gulf Stream hindcast experiments have been carried out using the Harvard Generic Oceanic Estimation System. These numerical simulations are performed with Harvard's open ocean primitive equation model, which includes open boundary conditions, hybrid coordinates in the vertical following the bottom topography, eddy viscosity parameterization in terms of a Shapiro filter, and arbitrary domain configuration. The model is initialized and updated using the three-dimensional temperature and salinity fields derived from OTIS. It is updated via an optimum interpolation data assimilation scheme, in which the model and observation fields are combined together, taking into account the errors of prediction and observation. The assimilation strategy is

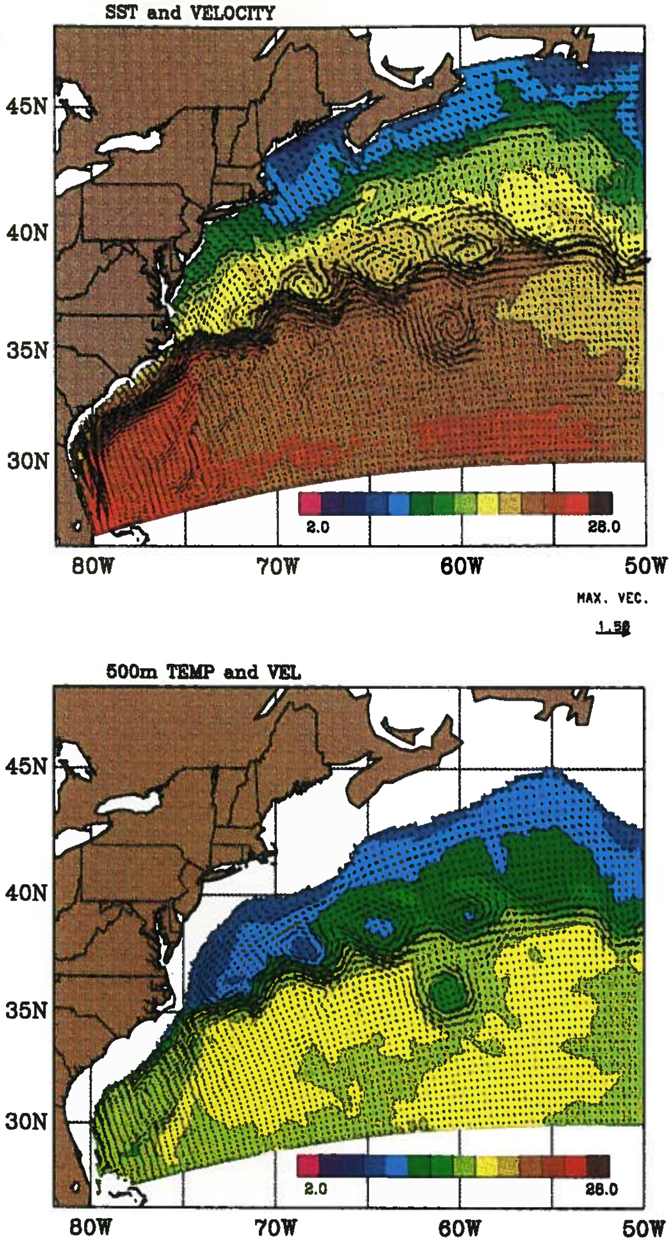

Fig. 3. Temperature and velocity vectors calculated by the Princeton Gulf Stream model forced by monthly averaged heat flux and wind stress data, during a particular day in November. Fields are shown at the surface (upper panel) and at 500 m (lower panel).

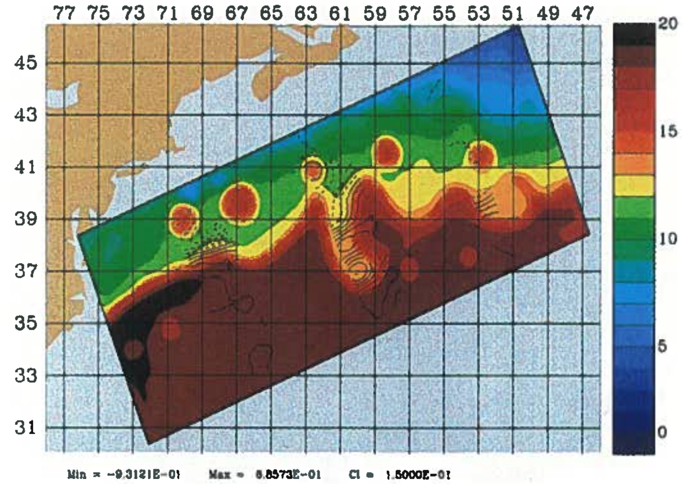

Fig. 4. Temperature map at 200 m and sea surface height (in centimeters) contours derived from Geosat for June 15, 1988.

to gradually incorporate the new data into the model a day before and a day after an assimilation cycle to minimize shock to the system. The model performance is measured in terms of the Gulf Stream North Wall average offset.

Results

The 2-week forecast experiments during the DAMEÉ phase II show between 11–37% improvement over persistence in the location of the Gulf Stream when the OTIS analysis for day 7 is gradually assimilated. For example, the hindcast beginning on May 4, 1988, has a North Wall offset of 25.7 km, 37% better than persistence at 40.6 km. On average, the temperature normalized root-mean-square difference between forecast and analysis at 500 m is in 90% agreement at day 14 for these cases.

In other words, these results show that assimilating data (OTIS analysis) into the solution (hindcast) gives an improvement of 11–37% when measured against persistence—no change from initial conditions—for a 2-week period. Also, there is a 90% agreement between observations (OTIS analysis) and model solution (hindcast) at day 14. The significance of these results is quantifying the improvement of a hindcast cycle by assimilating data (observations) and the accuracy of the hindcast solution when compared to the best available analysis of observations.

During DAMEÉ phase III, a continuous 2-month state of the Gulf Stream meander and ring region was estimated by assimilating all the available OTIS analyses between May 6 and July 4, 1988. The gradual assimilation cycles were approximately 7 days apart.

This experiment clearly illustrated the corrections to the predicted field in light of new available OTIS analyses. The temperature map at 200 m for June 15, 1988, is shown in Figure 4 and illustrates the formation of a cold core ring near 60°W. We evaluated the model performance in this case using the Gulf Stream location derived from Geosat data. The objectively analyzed sea surface height of the Geosat data is overlaid on the temperature map. The average offset is about 5 km in the areas of available Geosat tracks. There is also excellent agreement on the positions of warm core rings to the north of the Gulf Stream and on the formation of a cold core ring near 37°N, 60°W.

Acknowledgments

We thank Carlos J. Lozano for providing objectively analyzed Geosat data; Ziv Sirkes and D.-S. Ko for providing and assisting with data; Jim Cummings for comments on OTIS applications and results and Wen Qian for producing verified OTIS runs for case study periods; Louise Perkins and Dick Crout for impartial analyses of case study data; Namsoug Kim for graphics help; and Susan Sprouse and Marti Lyle for their administrative and editorial talents. DAMEÉ-GSR is supported by the Office of Naval Research, Navy Ocean Modeling Program; the Princeton group was also supported by the National Ocean Service and Geophysical Fluid Dynamics Laboratory.