

ALTIMETRIC DATA ASSIMILATION FOR OCEAN DYNAMICS AND FORECASTING

Oceanic mesoscale variability is the “internal weather of the sea,” and its prediction is now feasible and interesting for scientific and practical reasons. A systematic approach in which observations are melded with dynamical model output (four-dimensional data assimilation) is critically relevant. The Gulf Stream region provides strong mesoscale signals and interesting dynamical phenomena. The Harvard Ocean Dynamical Group is producing weekly nowcasts and forecasts for the Gulf Stream in real time using satellite infrared, dedicated air-expendable bathythermography flights and the Harvard open-ocean model. The addition of sea-surface height from GEOSAT altimetric data will be powerful and effective.

The ocean is now known to have its own internal weather systems, the counterpart of atmospheric storms or meteorological synoptic-scale disturbances. The internal weather of the sea, generically categorized as oceanic mesoscale variability and commonly referred to as eddies, encompasses a wide range of phenomena including planetary waves, midocean eddies, current meanders, and intense (cast-off) ring vortices.¹ The physically coupled fields of current, pressure, density, salinity, and temperature are all implicated, and frontal phenomena abound. Recent progress in mesoscale variability research has been rapid, changing our picture of the structure of the ocean and providing for the first time a realistic kinematic basis for dynamical modeling and practical field descriptions. Ocean prediction, like meteorological weather forecasting, is now feasible and is being initiated.² It is interesting *as* scientific research (to test hypotheses), *for* scientific research (to locate future experiments in an intermittent turbulent environment), and for practical purposes involving marine operations and maritime environmental management issues. Forecasts benefit resource exploration and exploitation, including fisheries, energy, and dispersion studies associated with accidental or planned spills or disposals of cargo, chemicals, and nuclear wastes. Important for sub-surface naval operations, environmental forecasts of thermal fronts allow coupled forecasts of range-dependent acoustics.

The oceanic prediction problem is both similar to and different from the atmospheric one. The greatest similarity is for those oceanic regions, fortunately prevalent, in which the fields evolve according to internal sea dynamics rather than respond predominantly to direct and local surface wind forcing. Differences arise from the absolute phenomenological space and time scales of oceanic weather (tens to hundreds of kilometers and several days to months) compared with atmospheric scales (thousands of kilometers and hours to days). The

small size of ocean eddies puts such enormous demands on data sampling and computational resolution that a regional approach to accurate nowcasting and forecasting is necessary. Furthermore, the oceanic database is much sparser than the atmospheric one, and it will remain so for the foreseeable future. Data assimilation—the estimation of fields by the melding of observations and dynamical model forecasts—is naturally indicated. The relatively slow evolution of real oceanic time (on the eddy time scale) favors data assimilation procedures in real operational time.

Four-dimensional data assimilation is the backbone of contemporary weather-forecasting methodology³ and is akin to the optimal estimation techniques of modern en-

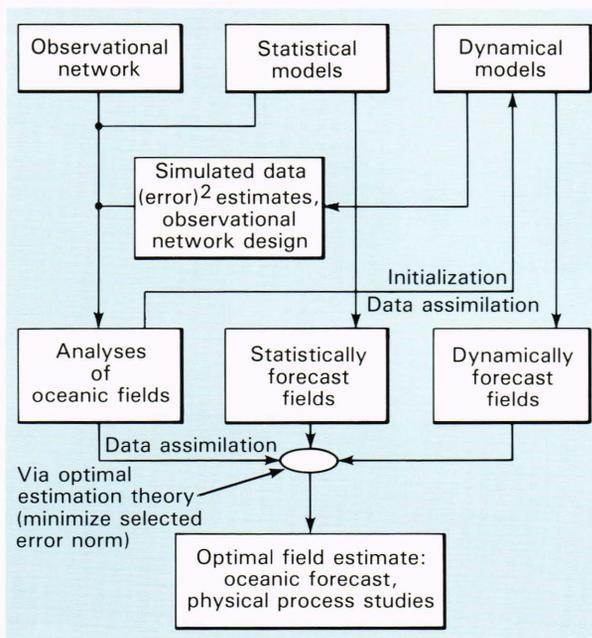


Figure 1—Schematic diagram of the Ocean Descriptive-Predictive System (from Ref. 5).

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gineering. Current research for the ocean includes the regular four-dimensional gridding of asynoptic “gappy” data, the construction of physical fields of interest from a collection of different sensors and sampling schemes, and the initialization, updating, and verification of numerical dynamical ocean models.⁴ Figure 1 is a schematic diagram of the Ocean Descriptive-Predictive System (ODPS),⁵ which was introduced for the implementation of regional oceanic field estimates and dynamical forecasts. The ODPS has been applied to studies in the POLYMODE region of the northwest Atlantic⁶ and the California Current System⁷ using real data initializations of the Harvard open ocean model,⁸ a quasi-geostrophic baroclinic model that now has an optional surface-boundary-layer component with higher order physics.⁹ An energy and vorticity analysis scheme¹⁰ called EVA uses dynamically filtered fields to provide the required consistency and accuracy for a balance-of-terms approach to local dynamical process studies.

The Gulf Stream meander and ring region in the northwest Atlantic is dynamically interesting and provides strong signals for satellite-borne sensors. The Gulf

Stream is a narrow (80-kilometer), intense (1-meter-per-second) current that leaves the Carolina coast and flows eastward to the Grand Banks. Meanders of the current propagate downstream and grow; deep meanders may separate from the stream, forming warm core rings to the north or cold core rings to the south. The rings tend to propagate to the west and frequently interact via intense (multiple) ring-stream and ring-ring interactions. The local dynamics of these intense, vigorous mesoscale flows is interesting, and the statistics of their processes strongly affects the general circulation. In addition, the propagation, evolution, and interaction of coherent vortices are vital research topics in geophysical fluid dynamics. The Gulf Stream has strong surface expressions in both sea-surface height (SSH) and temperature (SST). Typically there is a 1-meter change in the SSH across the stream (higher to the south) and a 5°C change in the SST. Rings formed from deep meanders show initial height changes of about 0.5 meter. The SST signal is quite variable, depending on the time of year and the age of the ring, because after a few weeks cold rings tend to be covered over with warm Sargasso Sea water.

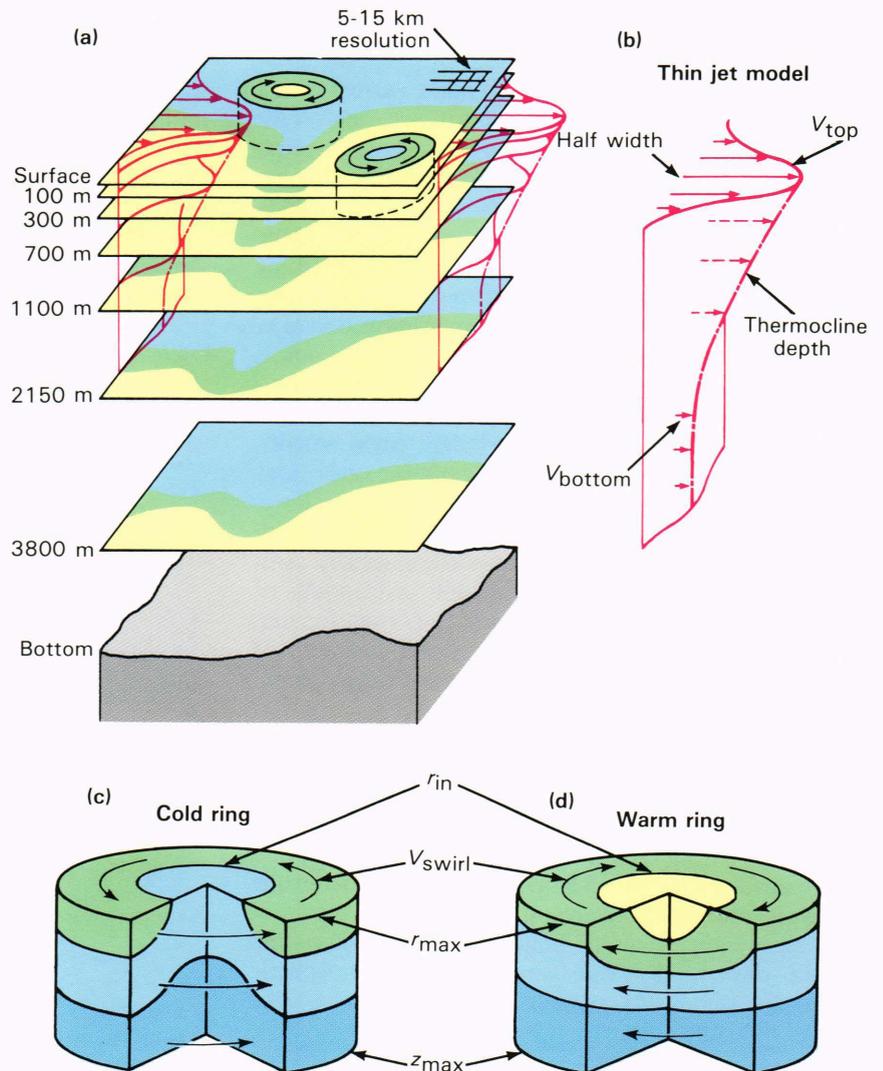


Figure 2—(a) Three-dimensional schematic diagram of the modeled region of the ocean. (b) Thin jet model for the stream. (c,d) Cold- and warm-ring models (from Ref. 11).

The strong surface frontal signals, together with historical knowledge of subsurface flow structures in the Gulf Stream meander and ring region, have led to a special and powerful way to initialize a dynamical model called feature-model initialization. Historical knowledge indicates that when it is viewed in its instantaneous axis coordinates, the Gulf Stream always appears remarkably the same. Although there may be young, old, shallow, and wide rings, nevertheless a ring is a ring! The method involves (a) locating the stream-axis front and ring fronts by some means (e.g., satellite infrared images), (b) fixing a standard-model stream and model rings in the location, and (c) running the dynamical model forward in time. The dynamical model first adjusts and interacts the features and interpolates among them, and then physically evolves the system in a forecasting or hindcasting mode. Figure 2 is a schematic diagram of the feature models and their parameters, including the width, maximum velocity, and depth of the stream and the radius, swirl speed, and depth of the rings. The ring radius is generally estimated from the imagery when a ring is newly formed; later, the estimate is based on the historical evolution of rings. The remaining parameters are based on historical data and a tuning of the model in the Gulf Stream meander and ring region. A major numerical experiment designed to calibrate and to establish sensitivity was based on satellite infrared data taken from November through December 1984.¹² The positions and parameters of the features were varied consistently with available historical and infrared data, and a matrix of model runs was analyzed. Figure 3a indicates a particular initial condition; Fig. 3b is the model-estimated field after five days of integration. The initialization shown evolves in agreement with all available data throughout the 25 days of integration, including the births of major warm and cold rings that were analyzed with EVA.

A Gulf Stream version of the ODPS has been implemented and is now producing weekly nowcasts and forecasts in a project called Gulfcasting.¹¹ Components of the system are satellite observations (currently infrared) for locating fronts with good data coverage, critical in-situ data (air-expendable bathythermography—AXBT—flights) for locating selected features, and dynamical model runs, including sensitivity experiments. In a research mode, the operational forecasting procedure involves the production of a central forecast, with new initial conditions based on the available infrared, the AXBTs, and the most recent previous forecast, as well as combining model and data.¹³

The sensitivity experiments involve varying the positions of features and their associated parameters consistently with available data and reinitializing the model. Those variations that result in significant alterations in the evolution of the stream and rings are identified, and an AXBT flight is directed to determine more accurately the parameters to which the forecast is sensitive. Typically this involves determining the separation between a ring and the stream. The procedure maximizes the value of the AXBT flight or minimizes the number of AXBTs needed to produce a satisfactory estimate of the

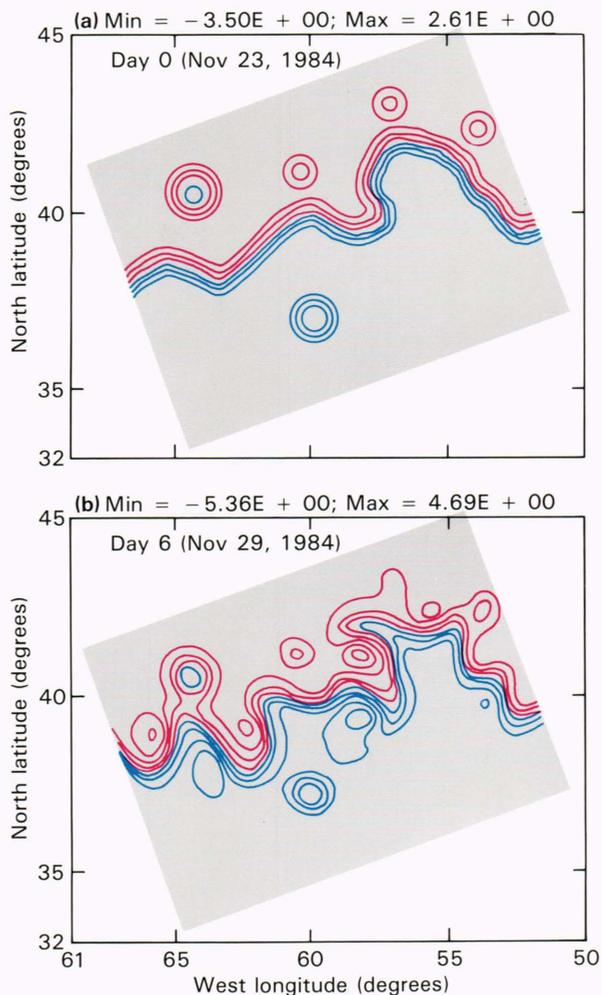


Figure 3—Streamfunction (or pressure field) at 100 meters from run 4 of Ref. 12.

three-dimensional temperature fields in the region. An example of frontal positions digitized from the NOAA/NWS oceanographic analysis charts is shown in Fig. 4a. Note that this image is exceptional because there are very few cloudy regions, and the warm core ring at 67°W is unusually large. The locations of AXBT data are also shown in Fig. 4a. From this information and from the most recent forecast, feature positions are determined and an initial field is calculated, as seen in Fig. 4b. The forecast in Fig. 4c compares well with the infrared image taken a week later (Fig. 4a, right). Also, while sitting in a comfortable chair in an office that rarely moves enough to cause seasickness, one may produce vertical sections of temperature, velocity, etc. for anywhere in the region (Fig. 4d).

The addition of SSH from GEOSAT altimetric data (see the article by Calman elsewhere in this issue) to Gulfcasting for the associated dynamical process studies will be very powerful and effective. Conversely, the Gulfcasting environment provides an almost ideal opportunity to exploit systematically the potential GEOSAT data for practical forecasting of ocean dynamics. Because infrared imagery is frequently obscured by clouds and the

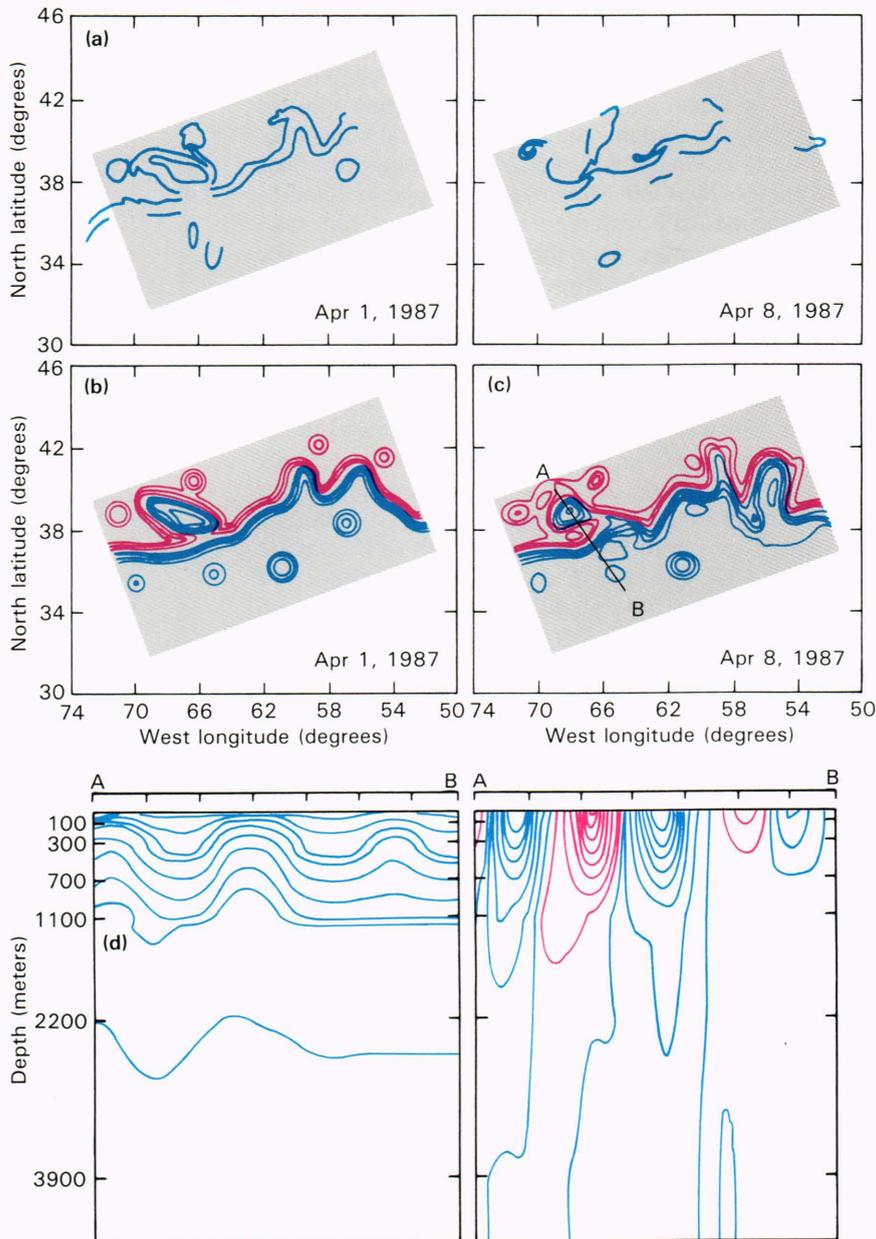


Figure 4—Gulf Stream operational research forecast for April 1–8, 1987, from Ref. 13. (a) Digitized fronts from the NOAA/NWS Gulf Stream Analysis. (b,c) The streamfunction at 100 meters. (b) The initial field as indicated by the infrared and the feature models. (c) The forecast 7 days later. (d) The temperature and velocity along a section through the forecast as indicated by the line A-B.

signal is only qualitatively related to the flow in the upper ocean, there are two important advantages to altimeter data: the effect of clouds is eliminated, and the SSH is directly related to the geostrophic velocity in the upper ocean. We have initiated studies of altimeter data assimilation involving both actual and simulated satellite data. By developing techniques for assimilating simulated data sets, procedures for assimilating actual data can be developed. We treat the integrated fields from the model as a data set representative of the ocean and then sample the SSH along the altimeter tracks as seen in Fig. 5. The advantage of using such simulated data (i.e., perfect SSH from model-adjusted fields) is that the difference between a forecast made with altimeter data and one made with the simulation may be attributed to

the errors induced by sampling and assimilation only. It is then possible to study the effect of other error (geoid, atmospheric, etc.) corrections to the SSH measurement by adding appropriate error fields to the simulated SSH data set. Upper bounds on the quantitative utility of the data can be established

These studies are part of a cooperative Harvard/APL project that plans first to use GEOSAT data in the Gulf Stream region and then to apply our experience to the use of GEOSAT data in other regions for mesoscale forecasting and dynamical studies. GEOSAT also provides the opportunity to prepare for the use of future altimetric data sets (Navy Remote Ocean Sensing Systems, Topography Experiment, etc.). Simulations will constitute an important part of such research.

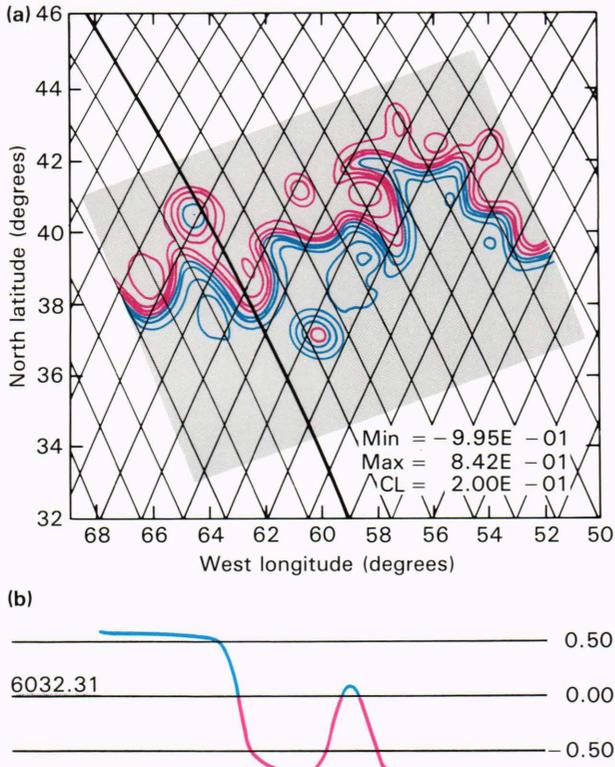


Figure 5—Altimeter assimilation simulation. (a) The SSH from day 6 of run 4 of Fig. 3. Overlaid curves are the GEOSAT tracks for the 17-day repeat orbit. (b) The height in meters along the bold track from south to north. The first decrease is the stream crossing; the bump is a warm core ring.

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