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Chung-Chieng A. Lai
Los Alamos National Laboratory

Wen Qian
University of Southern Mississippi

Scott M. Glenn
Rutgers University

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Data Assimilation and Model Evaluation Experiment Datasets

Chung-Chieng A. Lai,*
Wen Qian,⁺ and
Scott M. Glenn^{**}

Abstract

The Institute for Naval Oceanography, in cooperation with Naval Research Laboratories and universities, executed the Data Assimilation and Model Evaluation Experiment (DAMÉE) for the Gulf Stream region during fiscal years 1991–1993. Enormous effort has gone into the preparation of several high-quality and consistent datasets for model initialization and verification. This paper describes the preparation process, the temporal and spatial scopes, the contents, the structure, etc., of these datasets.

The goal of DAMÉE and the need of data for the four phases of experiment are briefly stated. The preparation of DAMÉE datasets consisted of a series of processes: 1) collection of observational data; 2) analysis and interpretation; 3) interpolation using the Optimum Thermal Interpolation System package; 4) quality control and reanalysis; and 5) data archiving and software documentation.

The data products from these processes included a time series of 3D fields of temperature and salinity, 2D fields of surface dynamic height and mixed-layer depth, analysis of the Gulf Stream and rings system, and bathythermograph profiles. To date, these are the most detailed and high-quality data for mesoscale ocean modeling, data assimilation, and forecasting research. Feedback from ocean modeling groups who tested this data was incorporated into its refinement.

Suggestions for DAMÉE data usages include 1) ocean modeling and data assimilation studies, 2) diagnosis and theoretical studies, and 3) comparisons with locally detailed observations.

1. Introduction

The Data Assimilation and Model Evaluation Experiment (DAMÉE) was first conceptualized during the Institute for Naval Oceanography (INO) 1989 Summer Colloquium on Mesoscale Ocean Science and Prediction at the National Center for Atmospheric Research (NCAR). The idea was to help the navy

select an appropriate mesoscale ocean model and companion data assimilation scheme to be further developed into an operational forecast model system. After reviewing the inputs from the university ocean modeling community, the goals were changed to the following: 1) to foster *communication* between university ocean modeling groups and the navy ocean modeling group, 2) to provide an opportunity for university and navy research scientists to *evaluate* their work in ocean modeling and data assimilation, and 3) to *compare* the strength of different models under a uniform configuration. This concept is unique in the history of ocean modeling and data assimilation research.

In response to the need of supporting navy antisubmarine warfare, and because of the importance of understanding the Gulf Stream in oceanography research, the domain of the DAMÉE experiment was defined over the Gulf Stream region. Its eastern, western, southern, and northern boundaries were 47°W, 82°W, 27°N, and 47°N, respectively (see Fig. 1). Other reasons for choosing this domain were the distinctive features of the Gulf Stream, the availability of more observations over this region, and the existence of an operational ocean data analysis system—the Optimum Thermal Interpolation System (OTIS)—for this region. The DAMÉE was conducted in four phases, each based on different datasets (case studies) and each phase building upon the results from previous phases.

Four groups working on the development of mesoscale eddy-resolving models for the Gulf Stream region had participated in the experiment. These four models are 1) the Harvard Primitive Equation Ocean Circulation Model (FLEXCAST); 2) the Princeton Primitive Equation Data Assimilation Model (PEDAM); 3) the Rutgers Semi-Spectral Primitive Equation Model (SPEM), configured for the Gulf Stream region by the Massachusetts Institute of Technology (MIT) group; and 4) the Naval Research Laboratories (NRL) Data Assimilation Research and Transition (DART) Model. Readers are referred to the review paper by Leese et al. (1992) for attributes of those models. Table 1 illustrates the experimental plan of the four phases.

*Earth and Environmental Sciences Division, Los Alamos National Laboratory, Los Alamos, New Mexico.

⁺Center for Ocean and Atmospheric Modeling, University of Southern Mississippi, Stennis Space Center, Mississippi.

^{**}Institute of Marine and Coastal Sciences, Rutgers University, New Brunswick, New Jersey.

Corresponding author address: Dr. Chung-Chieng A. Lai, EES-5, MS D401, Los Alamos National Laboratory, Los Alamos, NM 87545.

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FIG. 1. The DAMÉE domain of studies. It is equivalent to the OTIS–Gulf Stream region and contains participating model domains.

This paper presents the preparation process and the product datasets of DAMÉE in the Gulf Stream region. The case studies in different phases are presented in section 2. Section 3 gives details about the DAMÉE data preparation. It describes 1) the tools used in data analysis, especially the OTIS package, 2) the data input to the OTIS and their qualities, 3) the data output from OTIS and their properties, and 4) the DAMÉE data archive. Section 4 suggests some uses for DAMÉE data; it is intended to communicate the experiences of existing users to new users in the community. Summaries of the data preparation pro-

cesses and the characteristics of datasets are given in section 5. For convenience, all acronyms and terms are listed in Table 2.

2. DAMÉE cases

The philosophy and the criteria for selecting DAMÉE cases evolved from phase 0 to phase III. A set of Gulf Stream analyses for May 1988, May 1987, and July 1987 cases (see Glenn et al. 1991a) was used in the phase 0 experiment. The criteria were good satellite Advanced Very High Resolution Radiometer (AVHRR) image coverage, the availability of the regional experiment's airborne expendable bathythermograph (AXBT) underflights of the Geodetic Earth Orbiting Satellite (Geosat), and the availability of Geosat altimetry for cross-checking. The intent was to provide analyses of an interest-

ing Gulf Stream evolution at 1-week intervals.

Feedback from those analyses from participating groups, after the phase 0 forecast experiment, was incorporated into the refinement of the analyses. Since the goal of phase I was to identify the effect of data assimilation on model forecast, the same cases as those for phase 0 were used for phase I. The results of phase 0 indicate that models initialized with OTIS analysis have shown forecast skill for at least a 2-week period (e.g., Ezer et al. 1992). To evaluate the capability to perform an extended forecast of a model with the aid of data assimilation, a 1-month case was proposed for phase II. This 1-month case consisted of a series of analyses from 30 May to 4 July 1988. The interval between two analyses varied from 5 to 9 days.

Since both the 4 May–18 May 1988 analyses and the 30 May–4 July 1988 analyses were exceptionally good cases, the DAMÉE participants decided to experiment with a 2-month case in phase III. This 2-month case was formed by combining the two cases with a bridging date on 25 May 1988. The intent of this choice was to use the best available analyses for long-term forecast. This 2-month case also provided DAMÉE experimenters a chance to investigate whether the model and data assimilation combination extended the forecast ca-

TABLE 1. DAMÉE experimental plan.

Phase	Forecast lengths	Initialization/data assimilation
0	6 1-week forecasts	OTIS initialization, no data assimilation
I	6 1-week forecasts 3 2-week forecasts	OTIS initialization, with data assimilation
II	1 1-month forecast	OTIS initialization, with data assimilation
III	1 2-month forecast	OTIS initialization, with data assimilation
Group	Model	Data assimilation
Harvard	FLEXCAST	Intermittent data assimilation
Princeton	PEDAM	Optimum interpolation data assimilation
Rutgers/MIT	SPEM	Nudging data assimilation
NRL	DART	Rubber sheeting

pability beyond 1 month. Table 3 gives a list of analysis dates for the four phases of DAMÉE.

The case selection for phase II was meant to take advantage of the good coverage of observations near the Gulf Stream during the Synoptic Ocean Prediction (SYNOP) field program (supported by the Office of Naval Research). The spatial domains of the SYNOP experiment and the DAMÉE overlap. Thus, the datasets from SYNOP that fell within the time period of the DAMÉE phase II case is of great value when generating a comprehensive dataset. The SYNOP datasets included observations from arrays of current meters and inverted echo sounders, moored acoustic Doppler current profilers (ADCP), shipboard hydrography, conductivity–temperature–depth sensors (CTD), expendable bathythermographs (XBT), dropsondes, expendable current profilers, RAFOS floats, and satellite infrared imagery.

The Gulf Stream surface north wall, as derived from AVHRR imagery data, is defined as the maximum temperature gradient on the north side of the stream except for shingles. Figure 2 illustrates the Gulf Stream surface north wall position for the six 1-week cases (cases 1a, 1b, 2a, 2b, 3a, and 3b). The six 1-week cases (for phases 0 and I) can also be used as three 2-week cases (cases 1a + 1b, 2a + 2b, and 3a + 3b). The solid line is the initial path, the long-dashed line is the 1-week path, and the short-dashed line is the final 2-week path of the surface north wall. Circles, squares, and triangles denote the initial, 1-week, and final positions of the rings, respectively.

a. Cases 1a and 1b: 4, 11, and 18 May 1988

Figure 2a is an overlay of the Gulf Stream surface north walls and rings for all three analyses to illustrate the time history of the May

FIG. 2. Time series of Gulf Stream surface north wall and rings: (a) 4–18 May 1988; (b) 6–20 May 1987; (c) 7–21 July 1987. The solid line is the initial path of the surface north wall, the long-dashed line is the 1-week path, and the short-dashed line is the final 2-week path. Circles, squares, and triangles denote the initial, 1-week, and final positions of rings, respectively (Glenn et al. 1991a).

TABLE 2. Acronyms and terms.

Acronyms	Terms
ADCP	acoustic Doppler current profiler
AVHRR	Advanced Very High Resolution Radiometer
AXBT	airborne expendable bathythermograph
CTD	conductivity–temperature–depth sensor
DAMÉE	Data Assimilation and Model Evaluation Experiments
DART	Data Assimilation Research and Transition
FLEXCAST	Harvard Primitive Equation Ocean Circulation Model
FNOC	Fleet Numerical Oceanography Center
GEOSAT	geodetic earth orbiting satellite
GDEM	Generalized Digital Environmental Model
INO	Institute for Naval Oceanography
JPL	Jet Propulsion Laboratory
MCSST	multichannel sea surface temperature
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
NAVEASTOCEANCEN	Naval Eastern Oceanographic Center
NAVOCEANO	Naval Oceanographic Office
NCAR	National Center for Atmospheric Research
NCDC	National Climatic Data Center
NOAA	National Oceanic and Atmospheric Administration
NODC	National Oceanic Data Center
NRL	Naval Research Laboratories
OTIS	Optimum Thermal Interpolation System
PEDAM	Primitive Equation Data Assimilation Model
SPEM	Semi-Spectral Primitive Equation Model
SST	sea surface temperature
SYNOP	Synoptic Ocean Prediction field program
XBT	expendable bathythermograph

1988 case. During these two weeks, a small wavelike meander near 69°W propagated downstream, a warm ring formed near 65°W, the cold lobe meander near 63°W approached pinch-off, the warm lobe meander near 62°W grew bigger, the small trough near 60°W propagated eastward, and the meander crest near 54°W underwent an apparent relaxation. The day-to-day evolution of this meander crest near 54°W is uncertain between 11 May and 18 May. The scenarios consistent with available data include the following: 1) simple relaxation of the meander crest to form a straight Gulf Stream, 2) formation of a new warm ring that merges with the old warm ring already located near 54°W, or 3) absorption of the old warm ring

followed by formation of a new warm ring.

b. Cases 2a and 2b: 6, 13, and 20 May 1987

For the May 1987 case (see Fig. 2b), the initial Gulf Stream on 6 May has a large meander trough near 68°W and a large meander crest near 57°W. By 13 May, these meanders formed a cold and a warm ring, respectively. The existing cold ring near 63°W propagated toward the Gulf Stream. Over the next week, the Gulf Stream interacted with the cold ring near 63°W, which was advected downstream and almost absorbed. The Gulf Stream also interacted with the newly formed warm ring near 57°W.

c. Cases 3a and 3b: 7, 14, and 21 July 1987

At the beginning of the July 1987 case (see Fig. 2c), two large meander troughs developed at 61°W and 58°W, and a large meander crest appeared near 52°W. By 14 July, the western meander trough narrowed considerably, and the eastern meander trough formed a cold ring. The large meander crest formed a warm ring that remained close enough to the Gulf Stream to continue interacting. The Gulf Stream interacted with the warm ring near 62°W and advected it downstream. By 21 July, the western trough formed a cold ring near 58°W that was so close to the cold ring formed during the previous week that the two rings interacted and apparently merged. There was evidence of only one large ring in this region after this event.

d. Cases 4: 30 May–4 July 1988

1) GULF STREAM MEANDER

DAMÉE phase II had a 1-month case to test the forecast capability of the model–data assimilation combination. The series of events represented by the Gulf Stream path and rings (see Crowley 1993) are illustrated in Fig. 3. On 30 May, the beginning of the case, the Gulf Stream had a few shallow troughs and weak crests. The trough at 66.5°W moved steadily eastward while decreasing its amplitude. The shallow trough at 62°W, on the contrary, developed into a deep trough at 61°W on 22 June. The location of the developed trough was right above the New England seamounts (see Fig. 1). After 22 June, the axis of the

FIG. 3. Composite analysis of surface north wall and ring history: 30 May–4 July 1988. Crosses denote ring centers. Circles denote ring edges. Surface north walls are denoted by curves extending from west to east (Crowley 1993).

trough tilted along the seamount orientation. The tilting may also have been caused by the Gulf Stream interaction with the preexistent cold ring at 60°W. By 4 July, the deep trough formed a cold ring and a huge ridge existed over the seamounts area.

The trough on the east lee (at 58°W) of the New England seamounts had moderate development between 30 May and 22 June. It had been locked into the same longitude, while the immediate upstream crest

grew. The growth of the crest may have been associated with the warm ring near 58.5°W.

The two short waves at 72°W and 70°W on 30 May quickly disappeared before 13 June, but the short wave at 53.5°W on 30 May had a complicated life. By 13 June, it eroded part of the crest immediately downstream. On 22 June it dug out a moderate trough at 51°W, and the ridge downstream evolved into an appendix shape. At the end of the period, the crest extended northwestward to absorb the warm ring at 53°W, 41.5°N.

TABLE 3. DAMÉE case study dates. Numbers in parentheses are case numbers.

OTIS initialized forecast	OTIS initialized forecast with data assimilation		
Phase 0	Phase I	Phase II	Phase III
(1a) 4–11 May 1988	4–11 May 1988	(4) 30 May →	(5) 4 May →
(1b) 11–18 May 1988	11–18 May 1988	5 June →	11 May →
(2a) 6–13 May 1987	6–13 May 1987	13 June →	18 May →
(2b) 13–20 May 1987	13–20 May 1987	22 June →	25 May →
(3a) 7–14 July 1987	7–14 July 1987	29 June →	30 May →
(3b) 14–21 July 1987	14–21 July 1987	4 July 1988	5 June →
			13 June →
			22 June →
			29 June →
			4 July 1988

2) RINGS AND RING–STREAM INTERACTION

There were five warm rings and five cold rings at the beginning of the case. The warm rings are labeled W1–W5, and the cold rings C1–C5, from west to east.

Rings W1 and W2 moved steadily toward west-southwest throughout the whole period and did not interact with the Gulf Stream. Ring W3 was a very interesting

ring; it influenced the growth of the crest that was moving from 65°W to 62°W. At the beginning, W3 moved westward, approaching the upcoming and amplifying crest. Then, it was pushed (or steered) eastward. By 4 July, it resumed a west-southwest motion. Ring W4 was weaker than W3; it also began drifting westward but, after 22 June, it encountered the same fate as W3, being pushed back. The event occurred a bit later when the crest and W4 were close enough. Ring W5 had been drifting eastward since the beginning; it was absorbed into the Gulf Stream crest around 51°W and formed a larger meander.

Ring C1 appeared stagnant throughout the whole period. Ring C2 moved slowly and steadily toward the west. Ring C3 had been absorbed by the deep trough at 61°W when it was wandering above the New England seamounts between 13 June and 29 June.

The optimum interpolation technique combines the observed and synthetic temperature anomalies with a first-guess field provided by GDEM to produce the final analysis.

By 4 July it re-formed on top of the seamount at 60.5°W, 37.7°N with renewed strength. Rings C4 and C5 were not much affected by the Gulf Stream. Ring C4 had a steady westward motion throughout. It was close to the deep trough at 60°W, yet remained a distinct entity. Ring C5 moved along a steady southward path at a relatively fast pace.

3) MAJOR EVENTS

Major events during this 1-month case were 1) the dramatic deepening of the trough between 62°W and 60°W and the breaking off of the trough into a cold ring, 2) the growth of the crests immediately upstream and downstream of the deep trough, 3) the interaction between W3 and the crest, 4) the absorption of C3 by the deep trough, and 5) the absorption of W5 by the crest at 51°W. The first four events occurred geographically around the New England seamounts.

e. Case 5: 4 May–4 July 1988

This 2-month case was completed by combining case 1, case 4, and a bridging date on 25 May 1988 (Crowley 1993). During the first 2 weeks (4 May–18 May), a segment of Gulf Stream meander consisting of a large crest and deep trough near the New England seamounts evolved into a new warm ring and a new cold ring. By 25 May (see Fig. 3), the growing warm

lobe near 62.5°W absorbed the warm ring to the north, and the newly formed cold ring merged with a nearby cold ring to the east. By 30 May, the enlarged warm lobe at 62.5°W pinched off to form a warm ring, so the Gulf Stream returned to a more relaxed jet, flanked by five warm rings and five cold rings. The evolution of Gulf Stream during the next month was described earlier. It was another cycle of meandering and ring-stream interaction.

3. DAMÉE data preparation

To properly initialize the primitive equation models and provide boundary conditions, a high-quality analysis of some of the primitive equation variables has to be carefully prepared. Ideally, we wish to obtain a high density of observations of all primitive equation variables (temperature, salinity, and horizontal velocity) in three dimensions and two dimensions (dynamic height). In reality, there are only sparse observations of temperature, salinity, and horizontal velocity from XBT, mooring, inverted echo sounder, etc. The most abundant datum is the multichannel sea surface temperature (MCSST), which is derived from the satellite AVHRR remote sensing. The next one is the satellite altimetry data. However, the AVHRR data is two-dimensional and the altimetry is along track; they are not enough to properly initialize primitive equation models.

The INO chose OTIS (Clancy et al. 1990; Cummings and Ignaszewski 1991), developed by the Fleet Numerical Oceanography Center (FNOC), to prepare DAMÉE datasets because it blends several available kinds of information and provides 3D temperature and salinity datasets, 2D dynamic height fields, and more for model initialization and verification.

a. OTIS package

Version 3.0 of the OTIS is the most technically advanced ocean thermal structure analysis model now operational at the FNOC. It has been tested by scientists from FNOC, the Naval Eastern Oceanography Center, the Naval Postgraduate School, and the NRL. It implements the optimum interpolation data assimilation technique to assimilate real-time ship, bathy, buoy, satellite MCSST, and “synthetic” data into a complete 3D surface to 5000-m representation of ocean thermal structure. Using empirical techniques, it also derives a full 3D salinity representation, consistent with the analyzed temperature. Due to sparse subsurface data, OTIS 3.0 relies heavily on “synthetic” bathythermograph data to supplement the “real” observations. The OTIS produces the synthetic data internally from 1) an empirical orthogonal func-

tion representation of individual water masses, with all available sea surface temperature (SST) data at synthetic data locations; 2) ocean “feature models” (Bennett et al. 1988; Robinson et al. 1989) describing the transitional structure of front and eddies between water masses; and 3) the information contained in the Naval Oceanographic Office (NAVOCEANO) ocean “Bogus map,” which depicts the surface positions and other characteristics of fronts and eddies. The synthetic data are voluminous and concentrated in the vicinity of the mesoscale ocean features delineated in the NAVOCEANO Bogus map, which is based primarily on a subjective interpretation of satellite imagery. The synthetic data provide far more information on subsurface thermal structure than would otherwise be available.

Sophisticated and rigorous quality control on all incoming observations are performed by OTIS 3.0 to ensure that spurious reports are omitted and good reports are retained in the analysis. To do this, all observations are compared with the Generalized Digital Environmental Model (GDEM). GDEM, prepared by the navy, is a set of four seasonal climatological vertical profiles of temperature and salinity at a 30-min resolution grid. Anomalies between the synthetic temperature profile derived from accepted temperature observations and that in the GDEM climatology, interpolated in time to the day of the observation, is defined as the “synthetic temperature anomalies.” A new and complete set of synthetic temperature anomalies are calculated each day based on the latest NAVOCEANO Bogus map and stored in a running time window for up to 60 days.

The optimum interpolation technique combines the observed and synthetic temperature anomalies with a first-guess field provided by GDEM to produce the final analysis. The technique assigns the weighting of each piece of data (both real and synthetic) received in the final analysis based on the time–space distribution of the data, their assumed error variance, and standard optimum interpolation statistical parameters describing the nature of the thermal variability in the analysis region. The resulting product gives an accurate 3D representation of the temperature and salinity structure, including a realistic depiction of the fronts and eddies identified and tracked in the NAVOCEANO Bogus map.

The following is a list of the OTIS input–output packages and analysis procedure.

1) INPUT DATA:

- Information from Bogus maps
- Satellite-derived MCSST fields
- XBT data
- GDEM climatology

- Ships’ observations
- Fixed and drifting buoy data
- Coastal marine station data

2) OUTPUT DATA:

- 3D temperature fields
- 3D temperature error fields
- 3D temperature anomaly fields
- 3D salinity fields
- 2D dynamic height field
- 2D mixed-layer depth field

3) ANALYSIS PROCEDURE:

(a) Observations are classified according to their water mass of origin by a multivariate Bayesian analysis. Water mass class parameters (mean, variance, probability) are determined from historical data.

(b) Satellite and buoy data are reduced by spatially averaging the observation anomaly and location within a correlation length scale to form superobservations. A “superobservation” is an areal assignment of temperature based on input-observed temperature.

(c) Mesoscale eddies are identified from Bogus maps.

(d) Eddy fringe locations are fit, in a least-squares sense, to an ellipse with output in the form of eddy center, major and minor axis lengths, and major axis orientation.

(e) Bogus data are incorporated into feature models to generate synthetic observations at an adequate resolution:

- Given a feature location and frontal path, compute the orthogonal distance to the front and the orthogonal crossing point on the frontal path.
- Compute expected property difference (temperature or salinity) across the front using bilinear interpolation of water mass–based temperature and salinity climatology.
- Interpolate the property difference across the front to the feature location forming the frontal gradient by solving for the width and slope of the front.
- Integrate the gradient current relationship to give an estimate of absolute dynamic topography at any arbitrary position within the eddy ellipse.
- Thermal and salinity structure at the feature locations is estimated using the first two EOFs that relate surface dynamic height and sea surface temperature.

(f) The resultant synthetic profiles from the front and eddy models are referenced to the GDEM climatology and added to the observational database for the data assimilation.

(g) The observational database is quality controlled prior to the assimilation.

(h) Variability is parameterized in terms of space-time covariance functions.

(i) Gaussian covariance models are fit to the data using least-squares procedures.

(j) The influence radius for the distance-weighted scheme is specified by the e -folding water mass correlation length scales derived by a bin average approach.

(k) Perform assimilation and verification statistics.

b. Data input to OTIS

In DAMÉE, data input to OTIS include Bogus information, MCSST, XBT, and GDEM. They are prepared from several observational data. These include 1) Bogus information prepared jointly by DAMÉE participants (S. Glenn, M. Crowley, L. Perkins, A. Lai, and W. Qian) and NRL employees; 2) MCSST fields obtained from the National Aeronautics and Space Administration (NASA) Physical Oceanography Distributed Active Archive Center at the Jet Propulsion Laboratory (JPL); 3) MCSST regions 6 and 7 obtained from the National Climatic Data Center (NCDC) of the National Oceanic and Atmospheric Administration (NOAA); 4) XBT/AXBT data obtained from NAVOCEANO, the NRL Regional Experiment field project, the Harvard Gulf Stream Forecast Project, and SYNOP; 5) NAVOCEANO GDEM coefficients set; 6) NAVOCEANO Gulf Stream infrared imagery; 7) Geosat altimetry provided by the Applied Physics Laboratory at Johns Hopkins University; 8) ocean frontal analysis provided by the Naval Eastern Oceanographic Center (NAVEASTOCEANCEN); and 9) the Gulf Stream surface north wall analyzed by the University of Rhode Island.

1) MERGING AND QUALITY CONTROL OF OBSERVED DATA

Because there are only sparse observations, merging of different kinds of observed data is necessary in order to prepare an analysis for the required domain. However, it takes extra effort to prepare reliable analysis of data for OTIS from spatially and temporally inhomogeneous observations. Different sources and different types of information also make the judgment of quality difficult.

The preparation of OTIS input data had gone through several iterative stages. The first stage was to prepare Bogus maps, MCSST data, XBT casts, and GDEM climatology. Bogus maps prepared in this stage contained warm and cold ring centers, sizes, temperatures, and Gulf Stream surface north wall locations to the north of Cape Hatteras and to the west of 50°W only. Before OTIS was run, a mean Gulf Stream surface north wall from 27°N to Cape Hatteras (Auer 1987) was added. The OTIS outputs were used in the phase 0 experiment.

The OTIS outputs at this stage had three problems. First, models initialized with this dataset tended to forecast a major ring formation event too late or with unrealistic size. Second, the temperature and salinity fields had a contrast that was too strong across the Gulf Stream. Third, there appeared to be a shift of surface north wall by OTIS.

The second stage of data preparation, basically, was to correct the problems discovered in the results from the first stage. It included 1) the comparison of Bogus maps prepared in house with other analyses by NRL and the modification of some segments of Gulf Stream surface north wall, and 2) the communication with an FNOC scientist (Jim Cummings) and applying the correct frontal structure to the Gulf Stream and slope front. The OTIS outputs based on those modified Bogus maps gave more realistic fields. This dataset was used in the phase I experiment.

The next stage was to compare the Bogus maps with other independent analyses and to merge them into a complete analysis of the Gulf Stream system. The independent analyses used in this stage included 1) the Ocean Frontal Analysis charts prepared by the NAVEASTOCEANCEN and 2) the Gulf Stream surface north wall analysis prepared by the University of Rhode Island (see Fig. 4). In this stage, the mean Gulf Stream surface north wall between 27°N and Cape Hatteras, used in the first stage, was replaced with the analysis shown on the NOAA/National Ocean Services Ocean Frontal Analysis chart for the date. The Gulf Stream surface north wall analysis was also extended to 45°W. This provided better temperature and salinity fields near the eastern boundary (at 47°W). The warm and cold rings interacting with the Gulf Stream were checked carefully to ascertain their identities. Some elongated crests and troughs were checked to make sure a misinterpretation was not made of warm or cold rings near the Gulf Stream. The central temperature and size of rings were also checked to attain continuity and be comparable to AVHRR analysis. The OTIS outputs based on Bogus maps of this stage demonstrated very good spatial and temporal continuity. This dataset includes all cases for phases I, II, and III.

The last stage of preparation was to check the OTIS output fields with input XBT data. This resulted in the finding of an incorrect temperature unit used in some AXBTs. Therefore, OTIS fields were regenerated and plotted.

2) INFORMATION FROM BOGUS MAP

The most important and sensitive dataset among all inputs to OTIS was the Bogus information. A Bogus map is a subjective interpretation of the Gulf Stream system. Data used in obtaining this analysis, however,

FIG. 4. Time series of Gulf Stream surface north wall from day 161 to 180, 1988.

are objectively analyzed quantitative information, for example, AVHRR field, Geosat altimetry data, XBT casts, etc. The information contained in the Bogus maps are 1) the Gulf Stream surface north wall and 2) the warm and cold ring locations, sizes, central temperatures, ages, swirl velocities, etc.

To analyze the surface north wall, defined earlier, one must first identify the Gulf Stream before finding the maximum gradient of temperature, because sometimes the temperature gradient between shingles and slope water is stronger than that between the Gulf Stream and shingles. The surface north wall was also obtained from the Geosat data. It is defined as the location at which the sea surface height begins to level off after crossing the Gulf Stream. The estimated errors in location of the surface north wall from these two data types are 15 and 14 km, respectively.

The archived FNOC and National Oceanic Data Center (NODC) AXBTs were also used in the final preparation of the Bogus maps for cases 1, 2, and 3. Because some rings can remain unobserved in AVHRR

imagery for weeks, the historical Geosat Ocean Application Program and the geoid provided by the Johns Hopkins University/Applied Physics Laboratory (see Glenn et al. 1991b) were used to obtain historical interpretations of the warm and cold ring locations. Since relatively few data are available on the ring swirl velocities, the estimates were based largely on estimates of ring age. Although individual datasets can be patchy in regions, an aggregate dataset may cover the entire domain. Figures 2a–c are examples of Bogus maps showing the smoothed surface north wall and the ring locations for 4–18 May 1988.

The preparation of Bogus maps for cases 4 and 5 was independent from any earlier analysis. When Bogus maps for cases 1, 2, and 3 were being prepared, climatology was used to fill in data gaps in order to force the analyses to be at 1-week intervals. This was a bad assumption because that favored persistence during times of patchy data. So, for the 1-month case (case 4), days with very clear imagery were chosen as central days for composite analysis. In this

FIG. 5. Composite satellite AVHRR image, Geosat satellite altimetry analysis, AXBT/CTD data, and resulting Gulf Stream analysis for 13 June 1988 (Crowley 1993).

analysis, a thresholding and patching technique, rather than the customary warmest pixel technique, was used to composite infrared images. The result was less smearing of features than warmest pixel composites. Images within ± 2 to 3 days of each central day were processed. First, pixels with temperatures below a specified threshold were assumed to be contaminated by clouds and were deleted from each image. The remaining pixels from each image were then patched together, one image at a time. The image-by-image patching process involves replacing pixels in the composite with the remaining pixels in each threshold image. The composite was patched together with the images furthest in time from the central day substituted first and the central day image substituted last.

Besides infrared imagery, Geosat altimetry and XBT/CTD temperature profiles from a variety of sources were used in determining the Gulf Stream surface north wall, the ring centers, and the ring edge. For each ring, the time series of observed ring parameters (central location, size, and strength) were interpolated to the central days. Figure 5 is a composite satellite image, Geosat altimetry analysis, and Bogus analysis for 13 June 1988. The 2-month case is a hybrid analysis of cases 1 and 4. The main thrust in preparation was to attain a consistency and continuity of the

Gulf Stream system.

The 4 May 1988 Bogus map is shown in the lower-left panel of Fig. 6. The yellow line represents the surface north wall. The vertical crosses represent the warm and cold rings. The size of the cross is proportional to the size of ring and the temperature at the center of the ring is color coded.

3) MCSST

MCSST is the most abundant data among OTIS inputs. The NASA/JPL datasets were used in preparing the MCSST data for OTIS and the NCDC's data were used as a countercheck. NASA/JPL's MCSST dataset has a resolution of approximately 0.175° in latitude and longitude. Every analysis is a weekly composite of the field. To obtain the MCSST for OTIS, data were first interpolated from NASA/JPL's grid into the OTIS grid using bilinear interpolation. Then, the weekly composite was interpolated in time to the date of each case using a cubic spline fit. The upper-right panel of Fig. 6 shows the MCSST for 13 June 1988. The color bar at the bottom of the figure gives the color-coded temperature range. The Gulf Stream surface north wall can be roughly defined at the sharp transition zone from yellow pixels to blue pixels.

The MCSST field provides some mesoscale tex-

ture inside the Sargasso water mass. Since MCSST is used in OTIS to create superobservations, its mesoscale texture reflects on the OTIS analysis of SST.

4) XBT

The only in situ data used as input to OTIS in this DAMÉE is the XBT (AXBT, CTD). Even after collecting all NAVOCEANO, NRL Regional Experiment, and special Geosat ground track AXBTs, there were still only a few XBTs available near the date of each

DAMÉE case. Because XBT data usually contain many errors, vigorous quality control was necessary before they could be used in the analysis. NODC XBTs during those DAMÉE cases were available but were not used in the OTIS analysis because a high percentage of XBTs were not good. The rest of the good NODC profiles are redundant with those collected from special field programs. Therefore, the way to supply enough XBTs to OTIS was to widen the temporal window. A 60-day temporal window, centered at

FIG. 6. OTIS3 SST and input data for 13 June 1988: OTIS-analyzed SST, upper-left panel; MCSST, upper-right panel; Bogus information (surface north wall and ring centers), lower-left panel; XBT locations and surface temperatures, lower-right panel. Temperature ($^{\circ}\text{C}$) is coded in the color bar at the bottom.

Fig. 7. XBT locations and temperatures ($^{\circ}\text{C}$) at 200-m depth during June 1988 (Crowley 1993).

the central date of each case, was used in the OTIS analysis. However, a narrower window was used to check the Gulf Stream front location. A large portion of XBTs used in DAMÉE are Geosat ground track AXBTs. If the analysis of Geosat altimetry is reliable, the AXBTs become redundant in the process of identifying the Gulf Stream location.

Because of the sparseness of XBT, the horizontal temperature field was mostly influenced by MCSST. However, XBTs helped to construct the vertical structure of front when they were close to the Gulf Stream.

Figure 7 shows the locations of all XBTs during June 1988. The temperature at 200 m of the profile is color coded. All of these XBTs and other XBTs that fell within the 60-day window were used in the OTIS analyses of Phase II cases. The lower-right panel of Fig. 6 shows the locations and surface temperatures of XBTs used in each OTIS analysis.

5) GDEM CLIMATOLOGY

GDEM climatology supplies OTIS with a 3D background (first guess) on which new observations are added before optimum interpolation is executed. If no other information is provided to OTIS, the analysis looks like a climatology of the Gulf Stream.

GDEM climatology provides vertical profiles of temperature and salinity that bear the characteristics of

the mixed layer and thermocline for the top 400 m of water. The top 400-m vertical profile can be reconstructed from the coefficients of a polynomial stored in the GDEM climatology datasets. The rest of the profile is stored with values at standard levels.

To prepare the GDEM climatology field for OTIS, one had to first interpolate the coefficients of the polynomial and the values at standard levels from GDEM grid and levels to OTIS grid and levels. In this process, bilinear and linear interpolations were used. Since there are only four seasonal means (representing 15 February, 15 May, 15 August, and 15 November), linear interpolation is used in time. Monthly SST was also linearly interpolated to the date of OTIS analysis.

In summary, inputs to OTIS include Bogus information, MCSST, XBTs, and GDEM climatology. Figure 6 shows the data of those types except GDEM climatology for the 13 June 1988 OTIS analysis date. OTIS-analyzed SST is presented at the upper-left panel of the same figure to facilitate the comparison between input and output temperatures. A complete set of figures for all DAMÉE cases is presented in Lai and Qian (1993).

c. Data output from OTIS

Outputs from OTIS include 3D temperature, salin-

ity, temperature error, temperature anomaly fields, and 2D surface dynamic height field. Temperature and salinity are the product of assimilating the observed data into a first guess (GDEM) field. The temperature error is essentially the Gaussian covariance field and the temperature anomaly is the difference between the analysis and the climatology. Surface dynamic height is computed from the analyzed temperature and salinity profile. The level of no motion is set at 2000 m.

There are 34 levels in the vertical for each OTIS output profile. The depths of those levels are listed in Table 4. Regardless of the actual bathymetry, all profiles are extended to 5000-m depth. The domain of OTIS output is bounded by 47°W and 82°W in the east–west direction, and by 47°N and 27°N in the north–south direction. Because the resolution is 12 min, there are 176 x 101 sets of temperature and salinity profiles in one OTIS analysis. Every set of profiles is labeled with its grid numbers, location (latitude and longitude), surface dynamic height, and mixed-layer depth. The sequence of the profiles is temperature, salinity, temperature error, and temperature anomaly.

1) 3D TEMPERATURE AND SALINITY FIELDS

In most cases, the OTIS-analyzed SST (see upper-left panel of Fig. 6) resembles the input MCSST field. However, when there was a long period of extensive cloud coverage over a certain Gulf Stream area and the MCSST was obtained through horizontal and temporal interpolations, the two fields can be quite different. Under this situation, the feature model built in OTIS constructs a temperature field according to the Bogus information primarily. The SST also reflects the Gulf Stream meanders and warm/cold rings. The input XBT surface temperature is not always the same as the SST at the XBT's location because OTIS does internal adjustment.

Usually, it is quite easy to identify the Sargasso water area to the west of 50°W. The boundary between the slope water area and shelf water area is not clear on the SST field. The shelf water to the south of Cape Hatteras sometimes reaches a high temperature. This could be real, but caution is needed when OTIS SST is used.

Figure 8 shows the OTIS analyses of temperature (in °C) and salinity (in ppt) at 50 m (level 9), 200 m (level 15), 500 m (level 18), and 2000 m (level 30) depths for 13 June 1988. The temperature field is presented with color-coded pixels and salinity is pre-

TABLE 4. Depths (m) of OTIS levels.

Level	Depth	Level	Depth	Level	Depth	Level	Depth
1	0	10	62.5	19	600	28	1500
2	2.5	11	75	20	700	29	1750
3	7.5	12	100	21	800	30	2000
4	12.5	13	125	22	900	31	2500
5	17.5	14	150	23	1000	32	3000
6	25	15	200	24	1100	33	4000
7	32.5	16	300	25	1200	34	5000
8	40	17	400	26	1300		
9	50	18	500	27	1400		

sented with contours. The fields at the 50-m level show the properties in the mixed layer. In the Sargasso water area, the gradient of salinity is very weak. Some very cold water (slightly below 0°C) can be found in the Labrador area in spring. At the 200-m level, the salinity gradient is very strong across the Gulf Stream but the temperature gradient is slightly weaker than at the 50-m level. The “subsurface north wall” is usually defined as the 15°C isotherm at the 200-m level. Cornillon and Watts (1987) compared the subjectively determined surface north wall (given in Bogus maps) with the subsurface north wall and found that the surface north wall was, on average, offset 9 km shoreward with a rms variability of 14.3 km. At the 500-m level, the temperature in the Sargasso water area and in slope water area is quite uniform. But, there is a clear jump from slope water temperature to Sargasso water temperature. The salinity gradient is concentrated at the Gulf Stream front. The 12°C isotherm at the 500-m level is usually used as the “subsurface axis” of the Gulf Stream. It is well correlated with the maximum velocity axis. Submerged cold rings usually stand out at 200- and 500-m levels through salinity change. Both the temperature and salinity fields at the 2000-m level are very uniform. However, the Gulf Stream and warm/cold rings still can be recognized by a very tiny change of salinity. The same color code is used for all temperature fields at 50-, 200-, 500-, and 2000-m levels. This facilitates the comparisons between levels. However, the contour intervals for salinity fields are adjusted in the vertical to reflect the change of the magnitude of variation.

2) SEA SURFACE DYNAMIC HEIGHT AND MIXED-LAYER DEPTH

OTIS calculates sea surface dynamic height after the vertical profiles of temperature and salinity are obtained. The reference level (level of no motion) is set at 2000-m depth. This value is given to every OTIS grid

FIG. 8. OTIS3 temperature (°C, colorcoded) and salinity (ppt, contours) at 50-, 200-, 500-, and 2000-m levels for 13 June 1988.

point and forms a 2D field. The field is used in the initialization of an NRL layered model. Since much of the continental shelf is less than 2000 m deep, the sea surface dynamic height obtained this way is not reliable there. Another version of OTIS is used by NRL to correct the problem. No sea surface dynamic height and mixed-layer depth fields are presented in this paper.

A better source of sea surface height is the Geosat altimetry data. The Exact Repeat Mission data give reasonable coverage for the Gulf Stream area every 17 days. Optimum interpolation is usually used to

generate a 2D field from data along a set of ascending and descending arcs. The Geosat derived fields and OTIS-analyzed fields around Gulf Stream have been compared (Ezer et al. 1993) to be in fair agreement, although there are obvious differences.

d. DAMÉE data archive

All DAMÉE data files have been archived in a directory in the ocean datasets of the National Center for Atmospheric Research and a directory residing in an optical storage device belonging to the Center for Ocean and Atmospheric Modeling of the University of

Southern Mississippi. Users are referred to Lai and Qian (1993) for the data structure, sample pieces of data, and software packages (FORTRAN programs) for accessing and manipulating DAMÉE datasets. Navy standards in formatting OTIS input and output are followed in order to facilitate the comparison between these *research quality* datasets and *operational quality* datasets.

4. Suggestions for the use of DAMÉE data

The DAMÉE datasets are an extensive collection of observed data (XBT, MCSST, altimetry), subjective analysis (Bogus information), climatology (GDEM), and objective analysis (OTIS output) for several case studies of different lengths. The main thrust in the preparation of DAMÉE data was "iterative quality control." The subjective Bogus information for cases 1, 2, and 3 had a long history of analysis and verification from navy study to DAMÉE. All cases had been tested by participating models to be dynamically reasonable scenarios. On the other hand, extensive effort had also been devoted to the quality control of in situ data like XBT data and remote-sensing data like MCSST data. The previous 1-month case (case 4) was thoroughly checked from initial patching of AVHRR imagery, analysis of surface north wall, and rings through dynamical testing by models. Case 5 provided a continual series of good analyses with superior consistency and continuity of the Gulf Stream system.

By combining the high-quality analyses of observations with the most technically advanced ocean thermal structure analysis system (OTIS), we obtained an excellent 3D data product for mesoscale ocean modeling that had not been obtained before. Therefore, this dataset is worth making available to the oceanography community for modeling, observation, and theoretical research.

In the Gulf Stream modeling aspect, this dataset gives a modeler tremendous help in model initialization. The high-resolution 3D temperature and salinity fields can be used in model spinup. Of course, a model should obtain dynamical balance before any forecast run is attempted. During the course of model simulation or forecast, other data (including XBT, Geosat, or even Bogus information) can be used in data assimilation. The method of data assimilation depends on the properties of model and the data being assimilated.

Although tremendous effort had been devoted to

the datasets, no one can ascertain how close the analysis is to the truth. On the other hand, although much effort had been spent in developing dynamical models, they are still limited by the numerics used, the scale, and the physics involved. Therefore, caution is needed when comparing the DAMÉE analysis data and the model simulation results.

Most of the DAMÉE data are temperature and salinity. It is very desirable to include velocity fields in the dataset. However, it is almost impossible to get enough current meter observations to perform an objective analysis of velocity fields for the entire Gulf Stream region. One alternative is to take the velocity field from model simulations and compare with as many in situ measurements of currents as possible. If

By combining the high-quality analyses of observations with the most technically advanced ocean thermal structure analysis system (OTIS), we obtained an excellent 3D data product for mesoscale ocean modeling that had not been obtained before.

a majority of velocity measurements agree with simulated velocity data at the corresponding model grid points, and the in situ and remote-sensing data of temperature agree with the model temperature field, the model's velocity field may be considered useful. To achieve this, an iterative process is necessary and is described below.

The spatial and temporal domains of the SYNOP experiment and DAMÉE overlap. Thus, the datasets from SYNOP that fall within the DAMÉE time period and inside the DAMÉE spatial domain will be of great value in generating a comprehensive dataset for modeling and theoretical study. Three moored ADCPs near 37.5°N, 68.5°W were part of the SYNOP central array at sites H3, H4, and I2 (Johns and Zantopp 1991). Measurements were taken from 10 June 1988 through August 1990. They provide monthlong continuous measurements of near-surface current for the width of the Gulf Stream for DAMÉE case 4. RAFOS float data were collected from April 1988 to March 1990 (Anderson-Fontana and Rossby 1991). Thus, it also provides Lagrangian velocity data for DAMÉE cases 1, 4, and 5. An assimilation of SYNOP type velocity measurements have been tested successfully by Malanotte-Rizzoli and Young (1992).

If an appropriate model is initialized with the OTIS temperature and salinity fields of case 4 (begins 30 May 1988) and then assimilates the 5 June OTIS new analysis and all XBTs data collected in DAMÉE and

SYNOP datasets, the model velocity field should be ready to compare with ADCP data and Rafos float data mentioned earlier by the next OTIS analysis date, 13 June 1988. If both the temperature field and velocity data agree well with observations, this model simulation may be used as a starting point. If not, both the OTIS analysis on 30 May and 5 June need to be adjusted by a trial and error approach, using intermittent or adjoin data assimilation of velocity to get the simulated velocity on 13 June close to observation. If this is achievable, this model can continuously assimilate new XBT, ADCP, and RAFOS float data between OTIS analysis dates and verify with all observations and OTIS analysis on subsequent OTIS analysis dates. Every preceding OTIS analysis may need adjustment before the next cycle. After the whole series of trial and error adjustments from 30 May through 4 July are completed, a continuous simulation is necessary to create a comprehensive dataset of all variables.

This kind of complete dataset can be used to pursue theoretical study of the dynamics involved in the growth of the Gulf Stream meanders and the formation of rings. Remember, this approach is taken for convenience; the findings should always be cross-checked with detailed study through analysis of real data. By examining the 3D comprehensive dataset, the different spatial and temporal scales of Gulf Stream variation can be detected and the instruments in future field programs can be arranged accordingly.

5. Summary

The concept of DAMÉE is unique in the history of ocean modeling and data assimilation research. Due to limitations in time and manpower, not all interesting topics in the experiment were thoroughly studied at the conclusion of DAMÉE. However, the dataset prepared for DAMÉE will prove to be a major asset to the community for future research.

The preparation of the DAMÉE dataset consisted of a series of processes: 1) collection of observational data, 2) analysis and interpretation, 3) interpolation using the OTIS package, 4) quality control and re-analysis, and 5) data archiving and software documentation.

The data products from these processes include a time series of 3D fields of temperature and salinity, 2D fields of surface dynamic height, 2D Bogus information of the Gulf Stream and rings system, 2D MCSST fields, 2D Geosat altimetry fields, and XBT profiles. To date, they are the most detailed and high-quality data for mesoscale modeling, data assimilation, and forecasting research. By skillfully applying these datasets

to data assimilation, using the appropriate models, they can generate a comprehensive dataset of model variables that may be treated as close to observations and used in future theoretical research and observation plans.

Based on the experiences of participating groups, it is realized that the success of applying a primitive equation model in forecast mode is determined, in large part, by how the model is initialized, which data are assimilated, and how the subgrid-scale processes are parameterized. Toward this end, the DAMÉE demonstrated that the preparation of a best-possible nowcast (analysis) is a key component of forecast ability.

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