1. Abstract

We propose to combine the expertise of the Partnership scientists in order to validate a Hybrid Coordinate Ocean Model with data assimilation capabilities. This Partnership effort accelerates and leverages both existing and planned efforts to develop a consortium for hybrid-coordinate data assimilative ocean modeling, which will be ready in 2003 to address both the US-GODAE (Global Ocean Data Assimilation Experiment) principal objective, *i.e.*, the depiction of the three-dimensional ocean state at fine resolution in near-real time, and the climate modeling objective of producing an unbiased estimate of the state of the ocean at coarse resolution for long-term climate variability research. The modeling component of the proposed research will be accelerated through the use of the TOPAZ programming tool for the automatic generation of efficient numerical code.

A detailed analysis of the mean and eddy transport of heat and salinity/freshwater, the climate variability on seasonal to multidecadal time scales, and the predictability of Lagrangian trajectories will be quantified. Model-based reanalysis of archived observational data will provide a comprehensive picture of the dynamics and thermodynamics of the global ocean during recent decades. A new web-based tool that allows quicker access to both data and software will facilitate the availability of those products to the user community.

2. Table of Partnerships

3. Relationship to NOPP Objectives

3.1 Support of Critical Research Objectives and Operational Goals

This Partnership effort accelerates and leverages both existing and planned efforts to develop a consortium for hybrid-coordinate ocean modeling, which will be ready in 2003 to address the US-GODAE (Global Ocean Data Assimilation Experiment) principal objective, *i.e.*, the depiction of the three-dimensional ocean state in near-real time. The hybrid model maintains the advantages of an isopycnal model in stratified regions while allowing more vertical resolution near the surface and in shallow coastal areas, hence providing a better representation of the upper ocean physics and biochemical processes. The effort contributes to the climate research goals of understanding, describing, and forecasting the global oceanic variability on long time scales by providing a data-assimilative depiction of the ocean state over the last fifty years. High-resolution basin simulations with data assimilation capabilities will increase our understanding of oceanic mesoscale variability and inertial western boundary currents and will be transitioned for operational use to the Fleet Numerical Meteorology and Oceanography Center (FNMOC). By these means, this effort contributes to the Partnership Act's goals of promoting economic growth, quality of life, and national security.

3.2 Broad Participation within the Oceanographic Community

This consortium represents a truly broad spectrum of the oceanographic community, bringing together academia, federal agencies, and industry/commercial entities, spanning modeling, data assimilation, and observational capabilities. Interests range from short-term forecasts for the operational Navy to seasonal, interannual, decadal, and centennial climate variability and forecasting for the Department of Energy (DOE) and the National Oceanic and Atmospheric Administration (NOAA).

3.3 Long-term Commitment of the Proposed Objectives

All of the institutions participating in this Partnership have long histories of supporting oceanographic research. Both the Naval Research Laboratory (NRL) and the University of Miami modeling groups have been working for about two decades with layer models (the NRL Layered Ocean Model - NLOM, and the Miami Isopycnic Coordinate Ocean Model - MICOM). The hybridization work of HYCOM (HYbrid Coordinate Ocean Model) was firmly embedded in the development effort of MICOM, carried out at the University of Miami and now also at the Los Alamos National Laboratory (LANL) in collaboration with NRL. All institutions are strongly committed to developing and validating an operational ocean model that combines the strengths of the vertical coordinates presently used in the current generation of ocean models by placing them where they perform best, *i.e.*, sigma in shallow coastal areas, z-level in the upper ocean, and isopycnal in the stratified interior. This commitment will lead to the transitioning of the validated hybrid-coordinate model (with data assimilation capabilities) to the Fleet Numerical Meteorology and Oceanography Center (FNMOC) (see attached letter from M. Clancy). Advanced and efficient data assimilation methodologies have been developed at the University of Miami, NRL, and NOAA, and are presently being implemented in HYCOM. Finally, model-data comparison (*i.e.*, the validation of the model's performance) is an integral part of the work presently performed with historical and real-time data at NOAA, NRL, the University of Miami, FNMOC, the U.S. Coast Guard (USCG), and the International Ice Patrol (IIP).

3.4 Resource Sharing

The key resources to be shared among the Partners are the HYbrid Coordinate Ocean Model, data assimilation capabilities, and data sets used for forcing, assimilation, and evaluation of the model. An additional important resource to be shared is scientific expertise, especially feedback among the Partners which will guarantee that the model addresses the needs of its diverse user community. Model code, data assimilation code, data sets, *etc.*, will be archived in an open access system and will be made available to the oceanographic community at large, with detailed instructions and manuals. Each institution is ready to share personnel and experience among the Partners. Computer time will be provided by the DoD High Performance Computing Modernization Program, in which two of the PIs are Grand Challenge users (H. Hurlburt and E. Chassignet), and by the Los Alamos National Laboratory (LANL) under the auspices of DOE's Climate Change Prediction Program (CCPP).

3.5 Degree of Cost-sharing by the Partners

Cost-sharing estimates from all Partners are listed in the table and detailed in section 8.1. Cost sharing amounts to approximately $6,072,362 for the five-year period, plus in-kind support from the FNMOC, the U.S. Coast Guard, and the International Ice Patrol.

4. Proposed Effort

We propose to combine the expertise of the Partnership scientists in order to validate a HYbrid Coordinate Ocean Model, hereafter referred to as HYCOM, with data assimilation capabilities. The 5-year goal of the consortium is to have the model operational and ready to address the principal objective of the U.S. Global Ocean Data Assimilation Experiment (GODAE) by 2003, namely the depiction of the three-dimensional ocean state in near-real time. Each participating institutions is presently working on at least one of the components that are necessary to achieve such a goal, *i.e.*, an operational model, data assimilation methodologies, model-data comparisons, understanding of ocean/model dynamics, scalable computers, code optimization, *etc.* As a scientific team, they complement each other and have the qualifications to form a "node" to the "central hub facility" [as defined by Powell (1998, U.S. WOCE Report)]. The main purpose of the "node" will be to build on and to coordinate effectively the efforts that are presently underway at each institution, and to provide the additional resources and incentives needed to achieve the principal objective. At the present time, our proposed "node" has the necessary computing facilities, data sets, and expertise to carry out the project. Our consortium will, however, actively participate in the establishment of the "central hub facility" to ensure that by 2003 GODAE will have (a) sufficient computing resources and (b) a smooth data flow from the observing system to the end-user.

4.1 Operational and Scientific Goals

In order to have the model ready to achieve the U.S. GODAE principal objective by 2003, several of the tasks to be performed will be of an engineering/operational nature. However, in addition to real-time forecasting of oceanographic Eulerian fields [*e.g.*, sea surface height (SSH), sea surface temperature (SST), mixed layer depth, and surface velocities] and Lagrangian trajectories, optimal estimates of the ocean state will also allow us to document and understand ocean structure and variability in comparison to observations, to perform ocean dispersion studies (*e.g.*, pollution pathways, search and rescue studies, ...) and to provide a state-of-the-art ocean model for coupling to atmospheric, hydrological, and biological models.

By performing detailed analysis of the mean and eddy transport of heat and salinity/freshwater in both global and basin-scale simulations, the climate variability on seasonal (especially for the high resolution experiments) to multidecadal (mainly with the global simulation) time scales will be quantified. The climate analysis will focus largely on modes of climate variability in which the ocean is known to play an active role, such as the El Niño-Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), Pacific North America Oscillation, and multidecadal variability involving changes in the global thermohaline circulation. Although these and other climate modes involve coupled interactions among the ocean, atmosphere, and other components of the climate system (land, cryosphere), a thorough characterization of the ocean's role will be necessary to understand these modes. We presently have a limited quantitative understanding of the oceanic contribution to these climate modes. This contribution involves processes such as baroclinic adjustment by the wind-driven gyres and changes in thermohaline circulation cells (the global overturning cell along with regional mode water overturning cells) in response to changes in air-sea fluxes of momentum, heat, mass, and energy. These processes in turn produce low-frequency variability in the distribution and transport of heat in the ocean, which feeds back to the atmosphere through the resulting anomalous patterns of SST. The improved quantitative understanding of these processes that we expect to achieve will document the ocean's role in the coupled climate system.

4.2 Roadmap

During the five year period, the "node" will work on both global and basin configurations, building on projects that are already in progress at the Partnership institutions. The node will have two primary foci:

1- Refinement and testing of the hybrid coordinate approach at low resolution (1^o) for the global ocean, with emphasis on mixed layer dynamics and water mass formation. Model-based reanalysis of archived observational data will provide a comprehensive picture of the dynamics and thermodynamics of the global ocean during recent decades (before and during the WOCE years).

2- Refinement and testing of the hybrid coordinate approach at high resolution [*i.e.*, eddy-resolving (grid spacing of less than 10 km)] for ocean basins, with an emphasis on data assimilation capabilities and the inclusion of coastal regions.

The global model configuration is the one adopted by the Los Alamos National Laboratory (LANL) in a comparison between HYCOM and POP (Parallel Ocean Program). Since POP will become the oceanic component in the next generation of the National Center for Atmospheric Research (NCAR) Climate System Model (CSM), this ensures that HYCOM's set-up and forcing parameterizations conform to the latest consensus on climate modeling. In its global configuration [which includes the LANL sea-ice model (CICE)], HYCOM will be forced by atmospheric state variables consisting initially of monthly climatological fields of radiative heat flux, atmospheric temperature, atmospheric relative humidity, precipitation, wind stress, and total wind speed from NCEP (National Centers for Environmental Prediction). Once the upper ocean has reached a stable seasonal cycle, the oceanic reanalysis (see section 4.5.1 for details) will be performed by replacing the climatological forcing fields with the NCEP atmospheric reanalysis fields (year 1946 to present). Initial simulations will be performed using monthly-averaged forcing fields, but later "production runs" will be performed using 6-hourly fields that resolve synoptic atmospheric forcing.

Expertise on the model's behavior with an eddy-resolving grid will be gained by running the model in basin-scale configurations using lateral boundary conditions provided by the global simulations. Because of its central role in the thermohaline circulation, we will initially focus our efforts on the Atlantic Ocean. In addition to the fact that it is the most densely sampled ocean, the PIs also have substantial experience in that region, especially with high resolution models (Chassignet *et al.*, 1998; Paiva *et al.*, 1999a; Hurlburt and Hogan, 1999; Fratantoni *et al.*, 1999; Murphy *et al.*, 1999) and with low-resolution model analysis of interannual to interdecadal climate variability (Jacobs *et al.*, 1994; Chassignet *et al.*, 1996; Halliwell, 1997a,1997b,1998; Paiva *et al.*, 1999b; Smith *et al.*, 1999). Both the 6-hourly NCEP (1946-present) and the 6-hourly ECMWF (European Center for Medium

Weather Forecasting) (1979-present) operational atmospheric data sets will be used to force the basin model (with and without data assimilation), and the model's response to these two forcing sets will be evaluated. Additional funding (Navy 6.4) will be sought in years 3-4 to transition the real-time data assimilative Atlantic model to operational use at FNMOC.

Most of the data that will be assimilated or used to evaluate the model results (global and basin configurations) are available at the home institutions, *e.g.*, near real-time satellite altimeter data from the Altimeter Data Fusion Center (ADFC) at the Naval Oceanographic Office, near real-time atmospheric forcing from FNMOC via NRL, near real-time sea surface temperatures from the RSMAS Remote Sensing Laboratory (O. Brown, R. Evans), the GDEM (Generalized Digital Environmental Model) dataset of edited hydrographic profiles, and the NOAA/AOML surface drifters and XBT data archive. Model diagnostics will consist of, but will not be limited to, water mass time evolution, strength and pathways of the thermohaline circulation, mean path and variance of western boundary currents, quantification of eddy activity (ring formation, eddy kinetic energy), Lagrangian pathways, *etc.*

4.3 HYCOM - HYbrid Coordinate Ocean Model: An Overview

Traditional vertical coordinate choices [z-level, terrain-following (sigma), isopycnic] are not by themselves optimal everywhere in the ocean, as pointed out by recent model comparison exercises performed in Europe (DYnamics of North Atlantic MOdels - DYNAMO) and in the U.S. (Data Assimilation and Model Evaluation Experiment - DAMÉE). Ideally, an ocean general circulation model (OGCM) should (a) retain its water mass characteristics for centuries (a characteristic of isopycnic coordinates), (b) have high vertical resolution in the surface mixed layer (a characteristic of z-level coordinates) for proper representation of thermodynamical and biochemical processes, (c) maintain sufficient vertical resolution in unstratified or weakly-stratified regions of the ocean, and (d) have high vertical resolution in coastal regions (a characteristic of terrain-following coordinates).

The hybrid coordinate, in the context of the proposed work, is one that is isopycnal in the open, stratified ocean, but smoothly reverts to a terrain-following coordinate in shallow coastal regions, and to z-level coordinates in the mixed layer and/or unstratified seas. The hybrid coordinate extends the geographic range of applicability of traditional isopycnic coordinate circulation models (the basis of the present hybrid code), such as the Miami Isopycnic Coordinate Ocean Model (MICOM) and the Navy Layered Ocean Model (NLOM), toward shallow coastal seas and unstratified parts of the world ocean. The theoretical foundation for implementing such a coordinate was set forth in Bleck and Boudra (1981) and Bleck and Benjamin (1993). In HYCOM, each coordinate surface is assigned a reference isopycnal. The model continually checks whether or not grid points lie on their reference isopycnals and, if not, tries to move them vertically toward the latter. However, the grid points are not allowed to migrate when this would lead to excessive crowding of coordinate surfaces. Thus, in shallow water, vertical grid points are geometrically constrained to remain at a fixed depth while being allowed to join and follow their reference isopycnals over the adjacent deep ocean.

In the mixed layer, grid points are placed vertically so that a smooth transition of each layer interface from an isopycnic to a constant-depth surface occurs where the interface outcrops into the mixed layer. HYCOM therefore behaves like a conventional sigma model in very shallow and/or unstratified oceanic regions, like a z-level coordinate model in the mixed layer or other unstratified regions, and like an isopycnic-coordinate model in stratified regions. In doing so, the model combines the advantages of the different types of coordinates in optimally simulating coastal and open-ocean circulation features. Of particular interest to the Navy is the fact that the present procedure of driving high-resolution coastal models (which invariably use fixed vertical grids) with output from a basin-scale isopycnic model will be streamlined, since HYCOM will be able to provide the required near-shore data at fixed depth intervals.

The feasibility of the hybrid coordinate approach for handling both deep and shallow regions, throughout the annual heating/cooling cycle, has recently been demonstrated for a North Atlantic basin configuration by the University of Miami modeling group (Halliwell *et al.*, 1998) in collaboration with the NRL modeling group. The basin model has performed well both in terms of numerical stability and physical realism in a series of multi-decade simulations. Two vertical cross sections through hybrid model fields, depicting winter and summer conditions respectively, are used here to illustrate the structure of the hybrid model, the properties of the solutions obtained with it, and the model's handling of seasonal changes in the thermocline, *i.e.*, the point at which the isopycnals become constant depth coordinates. Fig. 1 shows the stratification of the model ocean along a 500 m deep meridional section in the eastern Atlantic in winter. Features to note are the coincidence of layer interfaces and isopycnals in the stratified interior, the vertical orientation of isopycnals in the mixed layer (a feature dictated by the Kraus-Turner paradigm), and the transition of layer interfaces to constant-depth surfaces near the point where they enter the mixed layer. The flattening of the interfaces well below the mixed-layer bottom near 45°N illustrates the point at which the minimum layer-thickness constraint overrides the tendency of a coordinate surface to remain attached to its reference isopycnal. Fig. 2 shows conditions along the same meridional section in summer. At this time, the seasonal thermocline extends upwards to within a few tenths of meters of the surface. This allows several coordinate surfaces at mid to high latitudes, which in Fig. 1 are shown to reside in the mixed layer, to attach themselves to their reference isopycnals. In order to extend the isopycnal coordinate domain upward during the warm season, the minimum layer thickness

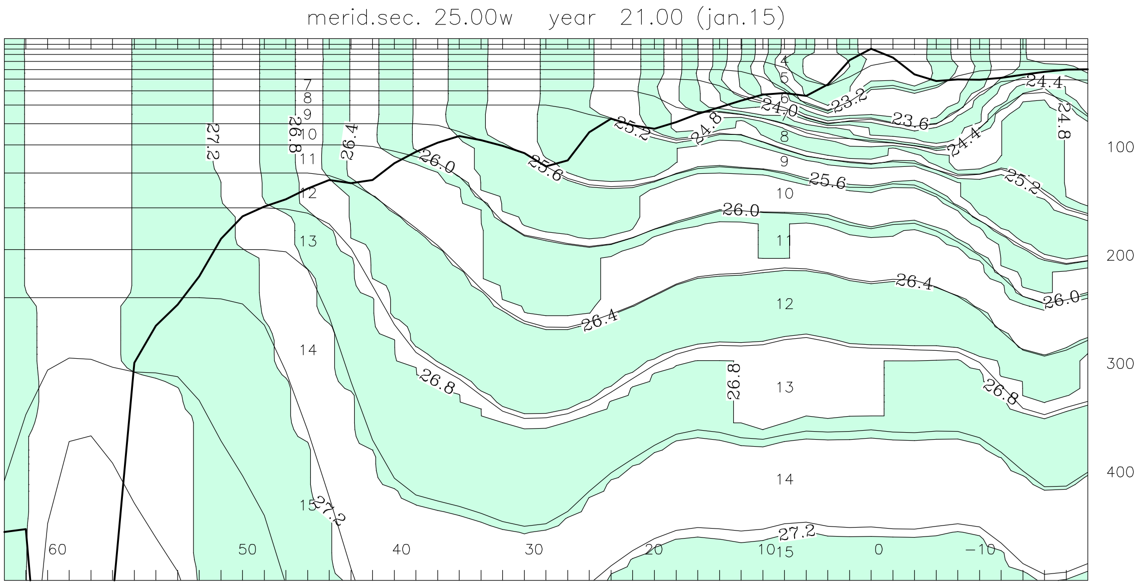

Figure 1: HYCOM vertical section at 25°W in January of year 21. Shaded field: density. Thin solid lines; layer interfaces. Thick line: mixed-layer depth. Depth range: 500 m. Numbers along bottom indicate latitude. Tick marks at the top and bottom indicate horizontal mesh size.

is allowed to be smaller in summer than in winter.

The capability of assigning additional coordinate surfaces to the oceanic mixed layer gives us the option of replacing the present slab-type Kraus-Turner mixed layer by a more sophisticated closure scheme, such as K-Profile Parameterization (KPP) (Large *et al.*, 1994, 1997). Development of such a new surface boundary scheme is presently underway. The KPP model is particularly attractive for several reasons. It contains improved parameterizations of physical processes in the mixed layer, including non-local effects. It actually calculates the mixing profile from the surface to the bottom of the water column, and thus provides an estimate of diapycnal mixing beneath the mixed layer. It has also been designed to run with relatively low vertical resolution, and is thus substantially more efficient than turbulent closure models. Finally, such a model can simulate the vertical structure of dynamical and thermodynamical variables along with biochemical constituents[1] (especially important for connectivity to the biochemical "node").

The hybridization work is firmly embedded in MICOM's development effort carried out at the University of Miami and now also at the Los Alamos National Laboratory. The freedom to adjust the vertical spacing of coordinate surfaces in HYCOM will simplify the numerical implementation of some physical processes (mixed layer detrainment, convective

[1]Collaborations are anticipated with T. Peng (CO_2, NOAA), R. Fine (tracers, RSMAS), and D. Olson (biological models, RSMAS).

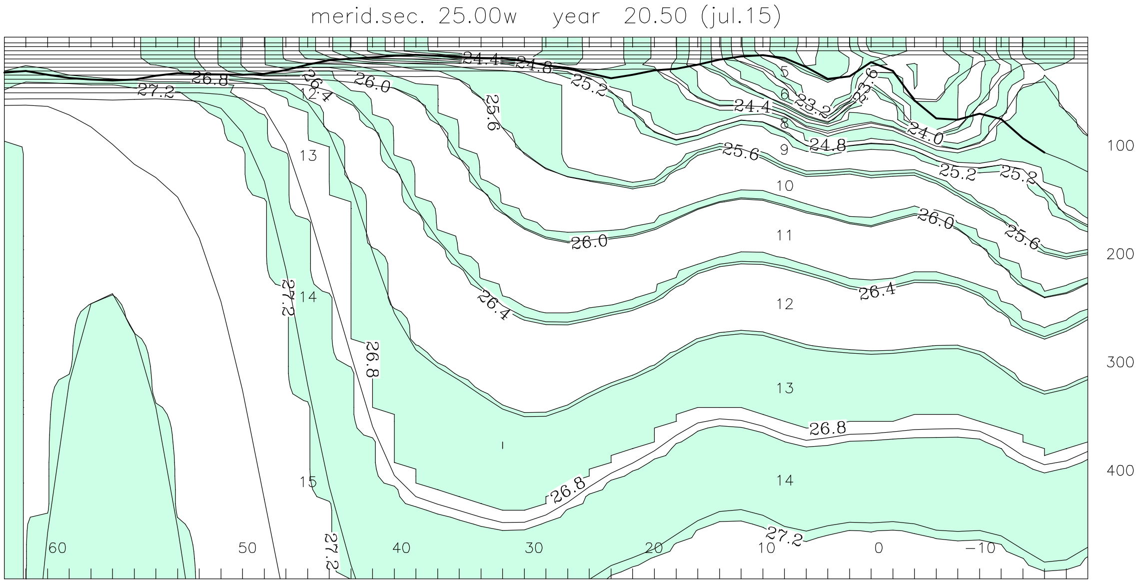

Figure 2: As in Fig. 1, but for July of year 21.

adjustment, sea ice modeling, ...) without robbing the model of the basic and numerically efficient layer architecture that is characteristic of MICOM and NLOM throughout most of the ocean's volume. The latter aspect is important as the Partnership can therefore build on the expertise acquired over the years with both MICOM and NLOM in the effort of validating HYCOM.

4.4 Data Assimilation Techniques

A hierarchy of data assimilation techniques starting with (a) simple nudging (*e.g.* Verron, 1992), (b) the Parameter Matrix Objective Analysis algorithm, hereafter PMOA (Mariano and Brown, 1992), (c) a Singular Evolutive Extended Kalman Filter, hereafter SEEKF (Pham *et al.*, 1998), and (d) a Markov Random Field Information Filter, hereafter MRFIF (Chin *et al.*, 1999), will be evaluated as a function of computational resources and prediction accuracy. The computational overhead for this hierarchy of data assimilation techniques varies from 10% to 2000%. The goal of the evaluation is therefore to determine which of the above techniques gives us the most "bang for the buck". Techniques (c) and (d) will only be applied to sea surface height anomaly (SSHA) data because of their large computational overhead. The first two techniques will be evaluated for all variable types. A brief description of each technique is presented in this section. The basic experimental strategy will be presented in the following section (4.5).

A given set of observations (subscript o) can be decomposed into three components,

$$\mathbf{T}_o(x, y, z, t) = \mathbf{T}_f(x, y, z, t) + \mathbf{T}_c(x, y, z, t) + \mathbf{e}_s(x, y, z, t),$$

where the first term is the model forecast, the second term is the true correction to the model forecast, and third term incorporates the errors. All of our assimilation techniques essentially take a weighted sum of the data residuals, $\mathbf{T}_o - \mathbf{T}_f$, and the model forecast, $\mathbf{T}_f$, to produce the "best" analysis for the next forecast cycle. The nudging technique,

$$\hat{\mathbf{T}}(x,y,z,t) = \mathbf{T}_f(x,y,z,t) + \mathbf{w}(\mathbf{T}_o(x,y,z,t) - \mathbf{T}_f(x,y,z,t)),$$

uses weights that are usually static. The Gauss-Markov theorem tells us that the optimal set of weights, in a least-squares sense, is given by the covariance between the observations and forecast normalized by the inverse covariance function of the observations. Assimilation methods (b)-(d) differ from each other in the updating of these covariance functions.

The PMOA is a data-driven analogue of a Kalman filter that uses an assumed horizontal covariance model with nine adjustable parameters that can vary in space-time. One of the main reasons for evaluating this technique is that results from the DAMÉE 0.5° resolution North Atlantic experiments clearly indicate a much improved representation of the model's surface circulation after assimilating SST with the PMOA. For an overhead of 25%, the Gulf Stream, located too far north in the original simulations, was moved toward the correct position, and the strength of the meridional overturning circulation was increased, thus bringing the meridional heat flux closer to observed values. The estimation of the nine adjustable parameters from the data is done by a contour-based technique described in Mariano and Chin (1996). A multi-variate version of the PMOA based on geostrophy will be used for the coarse resolution reanalysis.

Both SEEKF and MRFIF are especially suited for the large dimensional EKF problems (Chin *et al.*, 1999). The two methods assume a tangent linear approximation of the system dynamics, and both factor the covariance functions into horizontal and vertical components. The SEEKF algorithm was developed for MICOM by a team of scientists in France; it reduces the computations by approximating the covariance functions by singular low rank matrices. The novel aspect of this method is the evolution of the singular matrices starting with an initial guess of the covariance matrix given by Empirical Orthogonal Functions (EOFs). The details of this method can be found in Pham *et al.* (1998).

Chin *et al.* (1999) outline the use of a second-order Gauss-MRF model for parameterizing the spatial covariances in an Extended Kalman Filter based on an information filtering algorithm. This parameterization allows us to reduce the $O(n^2)$ covariance information needed to $O(10n)$ for an ocean circulation model with a state-space of size n. The MRF is the spatial analogue of an Auto-Regressive time-series model. The primary reasons for selecting this methodology are its ability to grow as computational power grows, and also that the MRF model allows a large degree of flexibility in its use. The GMRF model and information filter determine the horizontal correlation structure and the correlations between the state variables for each isopycnal layer. The vertical correlations are based on ensemble averages of the vertical covariances between layer thicknesses in the model and SSHA. Subsurface projection methods based on the pressure field (Hurlburt *et al.*, 1990; Smedstad and Fox, 1994) and "synthetic" profiles (Carnes *et al.*, 1990, 1994, 1996) will also be evaluated. Synthetic profiles have been constructed from the GDEM data set as a function of variable type (salinity or temperature), SST, latitude, longitude, and time of the year. The profiles are calculated from the EOFs of the relationship of each variable type to dynamic height. Synthetic profiles allow the updating of subsurface temperature and salinity fields directly from satellite measurements of SST and SSHA.

We will also use an EKF for the assimilation of Lagrangian data into a random-flight (or higher-order) trajectory model that will be based on the study of Özgökmen *et al.* (1999). The prediction of Lagrangian trajectories has a number of important applications such as search and rescue, predicting the pathways of pollutants, and mine warfare. The U.S. Coast Guard, the International Ice Patrol, and FNMOC will evaluate our trajectories for their operational needs.

4.5 Evaluation of the Model Outputs

4.5.1 Evaluation of Coarse Resolution Global Simulations

A major objective of this project is to guarantee that the model's depiction of the global general circulation is in agreement with observations. To achieve this objective requires, first, a careful model-data comparison to determine the nature of the modeling errors, and second, the assimilation of data to compensate for uncertainties in initial conditions and boundary fluxes. The error analysis will be used to identify deficiencies in the model formulation, which will be corrected to remove systematic model-data discrepancies. It will also provide a statistical basis for assimilating data. The result of assimilating the data will be a model-based reanalysis of archived oceanographic data, which should give the best possible depiction of the ocean's circulation over the past fifty years together with a careful accounting of errors. Not only will such a reanalysis be useful in its own right for studying ocean dynamics, it will also contribute to the high-resolution, near-real-time objective of this project by providing boundary conditions for higher resolution regional and basin models and by providing a good estimate for the initial conditions. Furthermore, the global low-resolution data-assimilating model can be used as the oceanic part of a short-term climate-forecast model similar to the one used operationally by NCEP.

An approximate initial state for the low-resolution global-ocean model can be achieved by holding the temperature and salinity fields at their climatological mean values and forcing the momentum equations with the climatological mean wind-stress field. Then, the climatological annually varying surface fluxes can be used to force the model until unforced transients in the water-mass properties and circulation die out. At this point, the model state reflects the characteristic oceanic gyres, the ventilation of the thermocline, and the global conveyer-belt circulation. However, it does not represent the state of the ocean at any particular time. That would require actual rather than climatological surface forcing. Roughly fifty years of meteorological reanalyses are available for estimating the actual surface-forcing fields. Continuing the model integration with this forcing produces a time-varying model state that can be compared to actual observations.

Errors in the simulated circulation stem from two sources: (1) The climatological spin-up procedure described above produces a rather crude approximation to the ocean state of fifty years ago, before estimates of actual forcing were available, and the surface-flux fields used subsequently to drive the model are based on very sparse data; (2) furthermore, as is the case with all OGCMs, the treatment of sub-grid scale processes (*i.e.*, mixing) is problematic, and the 1° resolution used here cannot capture the detailed structure of fronts and eddies. Still, the resolution of the model exceeds that of existing hydrographic data. These data are subject to sampling errors due to inadequate coverage, which complicates the comparison of individual observations with the model state. Nevertheless, our objective is to make detailed comparisons in order to understand and to quantify errors.

We intend to study error characteristics on a region-by-region basis and for spatial scales ranging from local to global. In particular, systematic model-data differences will be identified. An ongoing effort will be made to identify their causes, *e.g.*, the extent to which disagreements can be attributed to problems with the initial state or with forcing fields that can be improved via data assimilation, or to problems with mixing that require improvements to the model's formulation. As the improvements are made, the model-data comparisons will continue with the objective of achieving an unbiased estimate of the actual oceanic state. In addition, error covariances will be examined and parameterized for subsequent assimilation procedures used for constructing model-based reanalyses of the data.

The reanalysis will be achieved by assimilating the data into a model state initialized to reflect the climatological seasonal cycle and forced by estimates of the actual surface forcing (initially monthly, then 6-hourly). The procedure will be sequential and will be based on optimal estimation theory as discussed in section 4.4. Spatial error covariances of the temperature field allow the SST and XBT data to be used to improve the temperature field. An important point is that the error covariances will be empirically determined from the model-data comparisons rather than through the assumption of a smoothing scale.

Cross-field error covariances are more difficult to estimate, so care is needed to see that the salinity and momentum fields properly reflect the changes in temperature. Specifically, adjustments in temperature and salinity should preserve observed T-S correlations, while adjustments in density (through temperature and salinity) and momentum should preserve the geostrophic balance. In regions of well-defined water-mass properties, the assumption can be made that the temperature and salinity errors exhibit the same T-S relationships as the corresponding water masses, which can be estimated from the CTD data. If model layers correctly depict observed T-S relationships, temperature and salinity adjustments can both be made simply by adjusting the depth of layer interfaces. Near the surface, where stable T-S relationships do not exist, the problem is more difficult and deserves attention. As estimates of evaporation and precipitation are error prone and the model's mixing processes should be regarded with caution, it is important to insure that the resulting estimate for salinity is within the error limits of climatological estimates (Hansen and Thacker, 1999).

Hardly any data exist for estimating temperature-momentum error covariances. It is reasonable to assume that corrections to the momentum field should be in geostrophic balance with those to the density field. When temperature and salinity are adjusted, this will be accomplished by running the model diagnostically, holding the mass field fixed at the corrected values long enough for them to cause the momentum field to adjust. By sequentially assimilating the data in this way, an estimate of the time-varying state of the ocean for the past fifty years will be produced.

Comparing the actual observations to the reanalysis will give a quantitative characterization of the reanalysis errors. Systematic differences will indicate modeling biases or failures to correct correlated errors when assimilating data. Once these problems are identified and corrected, the procedure can be repeated to produce an unbiased reanalysis. The size of the remaining random differences and their correlations provide estimates of the uncertainties of the estimated model state.

The low-resolution global reanalysis will be strongly linked to the high-resolution data-assimilation component of this project. First, it will provide boundary conditions for the open boundaries of the basin model and a realistic approximate initial state. Second, comparisons with the high-resolution estimate will quantify the influence of the real-time data and identify the influence of eddies and fronts at depths. Error-covariances estimated using the different approaches will be compared to gain an improved understanding of the accuracy of the model-based estimates. Thus, this part of the project contributes directly to the examination and understanding of the errors and improvements to the high-resolution model and its data-assimilation system that are to be used for the GODAE near-real-time estimates of the three-dimensional ocean state.

4.5.2 Evaluation of Fine Resolution Basin Simulations

The evaluation of the fine resolution basin simulations will consist of a suite of data-model comparisons and diagnostics similar to the one described in the previous section for the global simulations, augmented by more direct and detailed comparisons to observational datasets of comparable resolution (temporal and spatial) to the resolution of the model runs.

Examples include a thorough analysis of the rate/mechanism of ring formation in the Gulf Stream and in the Brazil Current retroflection, the path and predictability of Lagrangian trajectories as a function of oceanic regime (*e.g.*, interior vs. western boundary regions) and data density, the meridional migration of the Gulf Stream on seasonal to decadal time scales and its relationship to thermal and wind forcing, the nonlinear dynamics of Gulf Stream separation/recirculation/bifurcation, equatorial upwelling rates, and convection rates in the subpolar and polar seas. Covariance functions calculated from the model will be compared to those calculated from the observational data for a better identification of the error and for a better parameterization of the covariances needed for data assimilation and for the design of sampling strategies.

The data assimilation component in the high-resolution simulations will first use simple nudging, and then the PMOA algorithm. In order to evaluate the impact of each data type [*i.e.*, SST, SSH, near-surface drifter velocities, P-ALACE measurements, and hydrographic data (CTD/XBTs)], the sequence of experiments will consist of assimilating (1) SST only (both satellite and in-situ), (2) SSH only, (3) both SST and SSH, (4) SST, SSH, and drifter velocities, and finally (5) all available data. Furthermore, this approach will also provide the information needed for the design of efficient ocean observing strategies through observing system simulation experiments. For each of the first four data groupings, the data not being assimilated will serve as truth for evaluations. For example, for experiments (1)-(3), the drifter velocities will serve as truth, and for experiment (4), the hydrographic data will serve as truth. In all experiments, forecast skill will also be used to evaluate assimilation skill by calculating the lagged forecast errors for all variables.

The more expensive and optimal methods SEEKF and MRFIF will then be evaluated using SSHA altimeter data. The different factorizations and vertical covariance schemes presented in section 4.4 will be evaluated against each other using the model results from the simpler data assimilation methods as a reference, the suite of model diagnostics described in section 4.2, and the prediction errors calculated as a function of temporal lag. The trade-off between accurately reproducing the observed ocean data and computational resources will be documented. We will investigate the ability of data, especially altimeter data, and the different assimilation techniques to help the model map and track the evolution of mesoscale variability, including oceanic eddies and the meandering of currents and oceanic fronts. J.F. Cayula (Planning Systems Inc.) has considerable expertise in automated frontal analysis (Cayula and Cornillon, 1995, 1996).

Once these techniques are transitioned to the production component, our consortium will concentrate on contour-based assimilation techniques (Mariano and Chin, 1996), such as rubber-sheeting (Carnes *et al.*, 1996), and the use of a MRF model for characterizing fronts and eddies. We strongly believe that this approach can lead to a new paradigm for assimilating data into models because it preserves the strengths of fronts and vortices. A major scientific issue that needs to be constantly addressed is the specification of the mean SSH field to be added to the SSH anomalies determined from the altimeters (Topex/Poseidon, ERS1, *etc.*). The present geoid has errors as large as the signal of interest. As a first step, a blend of historical and model SSH fields will be evaluated for different sets of weights. O.M. Smedstad and J.F. Cayula (Planning Systems Inc.) are currently investigating the use of a rubber-sheeting technique to use the information contained in both the model and data-derived mean SSH fields, in order to prevent the smearing of strong jets and mesoscale features. For example, the positions of strong oceanic fronts like the Gulf Stream or the Kuroshio in the mean SSH fields are isomorphically mapped onto a set of new positions given by satellite and in-situ data for each estimation time (Mariano, 1990; Carnes *et al.*, 1996).

4.6 Computational and Communications Facilities

4.6.1 Code Portability and Performance

There is a shared dedication of the Partners to the development of highly accurate, efficient, parallel, global ocean circulation models. Collaboration between the University of Minnesota parallel software team and the University of Miami ocean modeling team began in 1993 and yielded the first massively parallel version of MICOM (originally developed as a vector code) in early 1994 (Bleck *et al.*, 1995; Sawdey *et al.*, 1996). This highly successful effort yielded several firsts:

- the first thermodynamically-active, $1/12^o$ basin-scale ocean circulation calculation performed over the North Atlantic, showing a strong correlation to the observed Gulf Stream (Sawdey *et al.*, 1996; Bleck *et al.*, 1995; Chassignet *et al.*, 1998); this code now runs in production on the NAVO CRAY T3E;
- the first use of the "shrink-wrapping" technique to remove redundant calculations over land points in parallel ocean circulation simulations (Bleck *et al.*, 1995);
- the first two-level, domain-decomposed, parallel ocean model to run successfully on a cluster (Sawdey *et al.*, 1996), this code now runs in production on the ASCI Blue Mountain SGI Origin 2000 cluster in Los Alamos (Bleck, 1998);
- the first Web-based tool for interactively producing smooth-motion animations of ocean circulation calculations;
- the first automatic program analysis for parallelizing ocean codes using domain decomposition.

Concurrently, the NRL modeling group has developed a portable, scalable version of NLOM that can run efficiently on most computers, from local workstations to MPPs (Wallcraft and Moore, 1997, 1998; Wallcraft, 1999). A. Wallcraft (NRL) is presently working with M.

O'Keefe (University of Minnesota) on a CHSSI project to extend the scalability of the production system by adding support for two-level parallelization, where appropriate, with one level taking advantage of high-bandwidth low-latency local memory and the other suitable for lower-bandwidth higher-latency remote memory or networked node accesses. One of the important byproducts from the University of Miami/University of Minnesota/NRL collaboration has been the development of the TOPAZ programming tool (O'Keefe *et al.*, 1998), which performs compiler analysis on programs that are self-similar (all ocean circulation codes and many data assimilation techniques).

TOPAZ allows scientists to develop the numerical kernels and physics in their models while isolating them from most of the unpleasant details involved with exploiting parallel computers. It performs program analysis and includes libraries for more efficiently exploiting parallel machines. TOPAZ will allow our NOPP consortium to parallelize HYCOM in all stages of its development, and it will greatly aid our efforts to port HYCOM to different parallel architectures that may be used operationally by FNMOC. In this effort, TOPAZ will be extended to analyze and parallelize the data assimilation codes. Fast, effective data assimilation codes are crucial to the success of our enterprise: our Partnership has years of of experience in developing efficient, parallel ocean and atmospheric codes. M. O'Keefe and A. Wallcraft will take the lead in this activity.

4.6.2 Educational and Community Outreach

A critical problem in ocean modeling and data assimilation is making both the observational data and model output available to:

- the members of our consortium for HYCOM and data assimilation code development;
- the wider oceanographic and scientific communities, including climate and ocean ecosystem researchers;
- students in elementary and high school education, to more widely disseminate our research, and to encourage students to consider careers in science and engineering.

In an earlier effort to meet these goals, MPEG animations (movies) of the parallel MICOM simulations were placed on the Internet (http://www-mount.ee.umn.edu/˜okeefe/micom). This effort was quite successful, as the files were downloaded several thousand of times, but there were a number of limitations. For example, the resolution of the full datasets had to be reduced by a factor of 100 to allow reasonable download time. Even worse, there was no way for the user to interactively specify that (1) only a limited portion of the whole domain should be animated, and (2) only a limited time period should be animated. These two capabilities would allow an interested dataset user to custom build animations for only those regions of interest, at whatever resolution is required (subject to the current bandwidth limitations on the Internet).

A first prototype of a Web tool, named "Rennell" after the pioneering English oceanographer James Rennell, has recently been developed at the University of Minnesota and allows just this type of customization. Like the three-tiered Web database architecture now popular in the business world, Rennell consists of an underlying archive and database containing observations and model outputs; an intermediate software layer written in Java that accepts user requests from a client program for animations and graphs from a particular dataset, and generates movies based upon these requests; and a standard browser such as Netscape and Internet Explorer (or possibly a custom Java client) capable of executing Java applets. This software solves the problem of porting the client-side user interface among multiple platforms. Movie and graph generation control is carried out in this portable interface. At the present time, the Rennell movie generator prototype works well for medium-size datasets, but needs to be extended to work with the Terabyte archives that will be generated by parallel HYCOM calculations. The work performed at the University of Minnesota in fast, scalable mass storage systems will help to solve this problem. Rennell will also be extended to provide a web interface to popular plotting packages such as NCAR or GMT graphics. It should also provide an interface into the raw datasets themselves. Rennell has great potential to exploit new wideband capabilities as they develop on the Internet to support applications such as digital video to the home.

4.7 Anticipated Results and Timetable

The primary computational goal is the establishment of a global real-time ocean forecast system based on a hybrid-coordinate ocean model with sophisticated data assimilation techniques that can be efficiently executed on massively parallel computers. Fine resolution subdomains will be embedded in the coarse resolution global model starting with the North and Equatorial Atlantic. As computational power grows in conjunction with more efficient algorithms, the fine resolution domain will be expanded to encompass the South Atlantic first, then the Indian Ocean, and finally the Pacific Ocean.

The primary scientific goals are (i) to produce a 50-year coarse resolution reanalysis to study low-frequency global oceanic mass, heat, and salt flux variability from 1946 to the present that will also serve as boundary-conditions for atmospheric models and for the fine resolution ocean simulations in selected basins and coastal regions, (ii) to study in detail regional oceanic fluxes and the strongly nonlinear dynamics that naturally arise in fine resolution model simulations (such as the Gulf Stream separation, recirculation, and bifurcation), and (iii) tp make ongoing improvements to model physics and assimilation methods based on the model-data comparison studies.

The computations will either be performed at Los Alamos on the SGI/Cray Origin 2000 Blue Mountain cluster under the auspices of DOE's Climate Change Prediction Program (CCPP), or at NAVO MSRC on the T3E (soon to be upgraded to 816 processors) under

H. Hurlburt and E. Chassignet DoD Grand Challenge projects. The numerical codes will continually be optimized to run with maximum efficiency on the various platforms (M. O'Keefe, A. Wallcraft). A yearly 5-day workshop will be held in rotation at Miami, the Stennis Space Center, or Los Alamos, for progress status reports, communication, and integration of the scientific objectives in this effort. The PIs tasks are summarized in the table of section 2, and the anticipated timetable is as follows:

<u>For the Global Simulations:</u>

Year 1: Model configurations, comparison of mixed-layer models, and data archiving. Enhancement of present websites with our new products for the research and educational communities.

Year 2: Climatological simulations driven by monthly forcing and evaluation of the reanalysis fields and methodology. Calculation of oceanic fluxes.

Year 3: Global ocean reanalysis with 6-hourly forcing fields (last 50 years) and evaluate the impact of different forcing products.

Year 4: Assimilation of SSHA, SST, P-ALACE float profiles, and surface drifters, producing a new reanalysis product spanning the last two decades (the WOCE years).

Year 5: Comparison of the reanalysis products and their fluxes as a function of forcing and assimilation data. Diagnostic studies of seasonal to multi-decadal ocean climate variability.

<u>For the Fine Resolution Simulations:</u>

Simulations at the resolution of interest (less than 10 km) are computer intensive. Based on the experience gained with the $1/12^o$ North Atlantic MICOM, we should be able to integrate HYCOM forward 30 years in the first year and 120 years in the fifth year, given the computer time that we presently have at our disposal and anticipating a fourfold increase in computer power over the next 5 years. A fair amount of computer time will actually be used for the data assimilation, and correspondingly, forward integrations will likely not exceed 40 years during a given year, especially in the years when the more expensive SEEKF and MRFIF data assimilation algorithms will be implemented.

Year 1: North and Equatorial Atlantic high resolution simulations using two wind stress climatologies (ECMWF and NCEP). Model-data comparisons as outlined in section 4.2. Implementation and testing of nudging as a data assimilation scheme with simulated altimeter data, SSTs and hydrographic profiles. Comparison of different methods for the projection of the SSH information downward. Evaluation of climatological boundary conditions from the global simulations.

Year 2: Interannual simulation forced using the 1979-2000 6-12 hourly ECMWF reanalysis and monitoring of the performance using both climatological and time dependent model-data comparisons. Addition of PMOA as a data assimilation technique and comparison of the performance with the nudging approach. Evaluation of the mixed-layer formulations and of the boundary conditions from the global simulations. Initial evaluation of predicted Lagrangian trajectories for operational needs.

Year 3: Multidecadal simulation forced using the 1946-2001 6-hourly NCEP reanalysis with the same suite of diagnostics as for the ECMWF run. Comparison to the ECMWF run and the coarse resolution global run.

Year 4: Evaluation of the SEEKF data assimilation algorithm. Study of nonlinear dynamics in selected regions such as the Gulf Stream and the Brazil Current retroflection. Initiation of real-time model runs with real-time atmospheric forcing from FNMOC, and assimilation of real-time altimeter data from the Altimeter Data Fusion Center at the Naval Oceanographic Office (NAVO), real-time SST from O. Brown and R. Evans (RSMAS) (or alternatively from NAVO), and real-time hydrographic data from FNMOC (including P-ALACE float data). Perform month-long forecasts at 2 week intervals. The real-time data assimilation will be evaluated mainly though forecast verification.

Year 5: Evaluation of the MRFIF algorithm. Final evaluation of predicted Lagrangian trajectories for operational use. Improved oceanic budgets of mass, heat, and salt. Continue real-time run with data assimilation upgrades as warranted.

5. Research Tasks and Team Qualifications

5.1 University of Miami/RSMAS

The RSMAS team consists of E. Chassignet (ocean modeling, also a member of the U.S. GOADE steering committee), T. Chin (data assimilation), G. Halliwell (climate-oriented ocean modeling), and A. Mariano (data assimilation/Lagrangian prediction). This team has been working together for eight years on ocean modeling, data assimilation, oceanic predictability, and the study of ocean dynamics and variability from both Eulerian and Lagrangian viewpoints. We actively interact with many of our colleagues in the division of Meteorology and Physical Oceanography: O. Brown (satellite oceanography), R. Evans (satellite oceanography), A. Griffa (Lagrangian prediction), W. Johns (model-data comparison), D. Olson (coupling to biological models), T. Özgökmen (Lagrangian prediction), C. Rooth (theory), and N. Shay (air-sea interaction). These collaborations will strengthen the proposed research and the research of our colleagues.

5.2 NRL

The NRL team has had a commitment to ocean prediction research, ocean modeling, and data assimilation for about two decades. Currently, team leader H. Hurlburt is a member of the international and U.S. Scientific Steering Teams for the Global Ocean Data Assimilation Experiment (GODAE). The team effort ranges from basic research (6.1), with an emphasis on the dynamics of eddy-resolving global and basin-scale ocean models, to transition of ocean prediction systems to operational use at FNMOC (efforts led by team member R.

Rhodes). It includes a wind-forced 1/4 degree global ocean model with assimilation of real-time altimeter data from Topex/Poseidon (T/P) and ERS-2, a model which followed the evolution of the 1997-98 El Niño and transition to La Niña while running in real time at FNMOC (Metzger *et al.*, 1998).

The NRL effort is co-located at Stennis Space Center with the Naval Oceanographic Office, which hosts a DoD Major Shared Resource Center (MSRC) for High Performance Computing (home of an 816 processor Cray T3E and other supercomputers), and the Altimeter Data Fusion Center (ADFC), which provides real-time altimeter data from T/P and ERS-2. Team member G. Jacobs, who is experienced in satellite altimeter data processing and analysis, was instrumental in the development of the ADFC. In general, the NRL team has ready access to real-time and archived data at FNMOC and NAVO, including real time atmospheric forcing from FNMOC (6-hourly, 1990-present), real-time SST analyses from NAVO, plus real-time and archived hydrographic, drifter, and other data. The NRL team has already acquired additional complete sets of atmospheric analyses needed to force the ocean model, including the 6-hourly reanalysis and 12-hourly archived operational analyses from ECMWF (1979-mid 1998), and the 6-hourly atmospheric reanalysis by NCEP (1958-97). Finally, the NRL team is a leading user of DoD High Performance Computing, including large DoD Challenge grants of computer time, and has considerable experience in developing scalable, portable ocean model computer code (team member A. Wallcraft).

5.3 NOAA/AOML

The Atlantic Oceanographic and Meteorological Laboratory (AOML) is one of the Environmental Research Laboratories of the National Oceanic and Atmospheric Administration (NOAA), a part of the US Department of Commerce (DOC). AOML's mission is to conduct a basic and applied research program in oceanography, tropical meteorology, atmospheric and oceanic chemistry, and acoustics. The program seeks to understand the physical characteristics and processes of the ocean and the atmosphere, both separately and as a coupled system. The principal focus of these investigations is to provide knowledge that will ultimately lead to better understanding of the factors affecting both climate and environmental quality, to better utilization and management of marine resources, to improved prediction and forecasting of severe storms, and to improved ocean and weather services for the nation. The model-evaluation/data-reanalysis effort of this project draws upon the expertise of AOML's scientists and staff, especially those associated with AOML's Global Ocean Observing System (GOOS) Center. Dr. Thacker, AOML's PI for this project, has over ten years experience with data-assimilation methodologies and has been an invited speaker at international workshops and colloquia addressing this topic.

5.4 University of Minnesota

Professor O'Keefe's research group specializes in the development of efficient software for massively parallel machines and a new storage architecture, the Global File System, for distributed computing environments. A new message-passing version of MICOM called MP-MICOM that uses SHMEM on the Cray T3D/T3E and MPI on other machines has been developed. They also have a shared-memory, multi-threaded version (SC-MICOM) for SMP clusters and the SGI Origin2000 that uses MPI to communicate between machines and direct shared memory within each machine. In addition, a new Web-based tool for quicker user access that is needed for the community to routinely access the large amounts of information generated by ocean models was developed.

5.5 Planning Systems, Inc.

Planning Systems Inc. (PSI) is a small business which provides high technology scientific and engineering services to government and industry customers. Products include performance prediction systems for undersea warfare, precision measurement instrumentation for underwater acoustic ranges, and manufacturing facilities producing digital hydrophones, underwater acoustic arrays, and ATM telemetry systems. The company has a broad range of expertise in data assimilation techniques, image processing, and visualization. PSI has supported the Naval Research Laboratory effort in implementing data assimilation techniques used in operational ocean models. Software to automatically detect fronts from satellite imagery and the ability to combine this information with ocean model outputs have also been developed.

5.6 Los Alamos National Laboratory

Los Alamos is home to a group of geophysical fluid dynamics modelers whose principal mission, funded in the past by DOE's CHAMMP program and now by DOE's Climate Change Prediction Program (CCPP), has been the development and validation of massively parallel ocean and sea ice model codes and their application as components of fully coupled climate models. With the recent hiring of R. Bleck, LANL now supports two different ocean models – MICOM and an offspring of the GFDL MOM code named the Parallel Ocean Program (POP). Hybridization of POP is underway, using design criteria that differ somewhat from those used in HYCOM, and there is institutional commitment to incorporate HYCOM into the supported model suite as well. LANL intends to capitalize on the in-house availablity of several models by conducting focussed intercomparison studies that will shed light on model strengths and weaknesses and thereby drive further model development. DOE's computers, recently upgraded to meet research needs created by the international nuclear test ban treaty, are deemed powerful enough to allow ocean and climate modeling to proceed in this direction.

5.7 Orbital Image Corp.

Orbital Imaging Corp. is the leading commercial source of ocean information for use by the world's major fishing fleets. Orbimage will (i) evaluate the model-generated upper ocean temperature, salinity and velocity fields for improving our fishing forecasts and (ii) the consistency of the model data with OrbView-2 imagery products with respect to the location of major fronts and circulation features.

5.8 U.S. Coast Guard

The USCG's Operational System Center in Martinsburg, VA, and the International Ice Patrol in Groton, CT, will evaluate our product for their operational Search and Rescue and iceberg tracking work, respectively. The work performed by these agencies is vital for safe and efficient maritime operations. The primary goals are to improve the 80% success rate of global search and rescue missions to save more lives and property at sea, and to make shipping lanes safer.

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6.2 Vitaes

7. Budgetary Information

The proposed research is labor intensive and $O(85\%)$ of the budget is for salaries and associated costs. $O(10\%)$ budget is for computer maintenance and software licensing costs, computational costs such as node charges at each home institution, and hardware upgrades, most notably a new server for the interactive Web-site to be located in Miami (see enclosed letter of support from Silicon Graphics). The remaining budget will facilitate once a year workshops at the University of Miami, NRL, and LANL on a rotating basis, domestic travel for presenting scientific results at national meetings, and publication costs.

In addition to PIs salaries, two post-doctoral positions are requested, one from the University of Miami to work in collaboration with R. Bleck in Los Alamos and one at AOML/NOAA to work with C. Thacker.

8. Supporting Information

8.1 Cost Sharing Information

RSMAS: The RSMAS team has several proposals with ONR, NSF, and NOAA which will provide concurrent support to the proposed work (approximately equivalent to $455,000/year; see present and pending support pages). In addition, the network of 10 DEC alpha workstations will be made available for code development and model evaluations.

NRL: The projected cost sharing is 300K/year FY00-04 from the 6.1 project "Thermodynamic and topographic forcing in global ocean models" and a closely collaborative follow-on project, 50K/year for FY00-02 from Alan Wallcraft's CHSSI proposal, and for FY03-04, NRL will seek 6.4 funding (250K/year) to transition the data-assimilative HYCOM Atlantic model to FNMOC.

NOAA: NOOA will provide 9 months of C. Thacker's salary, This will bring his participation level in the project to 12 months. Details can be found on his budget page.

U. of Minnesota: M. O'Keefe has several proposals which will provide concurrent support for this work (total of 4 months = $72,800/year). They are part of the DoD HPCMO Programming Environment and Training program; the DoD CHSSI program; and of a NASA effort to create a file system capable of processing massive data sets.

Planning Systems Inc.: The projected cost sharing is 50K/yr for FY00 from the NRL Contract N00014-97-C-6014 entitled "Ocean Dynamics and Prediction (Ocean Modeling)" and a similar amount from follow-on contracts during the period FY01-04.

LANL: R. Bleck anticipates spending 2.5 months per year on consortium-related work (approximately $50,000/year; see letter of support).

Orbital Imaging Inc.: Orbital Imaging Corp. will (i) evaluate the model-generated upper ocean temperature, salinity and velocity fields for improving our fishing forecasts and (ii) the consistency of the model data with OrbView-2 imagery products with respect to the location of major fronts and circulation features (see letter of support).

The U.S. Coast Guard (Search and Rescue, International Ice Patrol: The USCG's Operational System Center in Martinsburg, VA, and the International Ice Patrol in Groton, CT, will evaluate the model outputs for their operational Search and Rescue and iceberg tracking work, respectively (see letters of support). The primary goals are to improve the 80% success rate of global search and rescue missions to save more lives and property at sea, and to make shipping lanes safer.

8.2 Letters of Support

8.3 Present and Pending Support

8.4 Certifications