HYCOM Consortium for Data Assimilative Ocean Modeling

Eric P. Chassignet, Toshio M. Chin, George R. Halliwell, and Arthur J. Mariano
Meteorology & Physical Oceanography
University of Miami/RSMAS
4600 Rickenbacker Causeway,
Miami, FL, 33149-1098
Phone: (305)361-4041 Fax: (305)361-4696 Email: echassignet@rsmas.miami.edu

Award #: N00014-99-1-1066
http://panoramix.rsmas.miami.edu/hycom_nopp

LONG-TERM GOALS

Development of 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.

OBJECTIVES

The primary objective 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.

APPROACH

- 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;

- Coarse resolution model-based reanalysis of archived observational data will provide a comprehensive picture of the dynamics and thermodynamics of the global ocean during recent decades;

- 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.

WORK COMPLETED

a) Release of HYCOM 1.0

b) Global and basin-scale simulations

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **SEP 2000**	2. REPORT TYPE	3. DATES COVERED **00-00-2000 to 00-00-2000**
4. TITLE AND SUBTITLE **HYCOM Consortium for Data Assimilative Ocean Modeling**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Meteorology & Physical Oceanography,,University of Miami/RSMAS,4600 Rickenbacker Causeway,,Miami,,FL,33149**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**10**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

b) Data assimilation capabilities

RESULTS

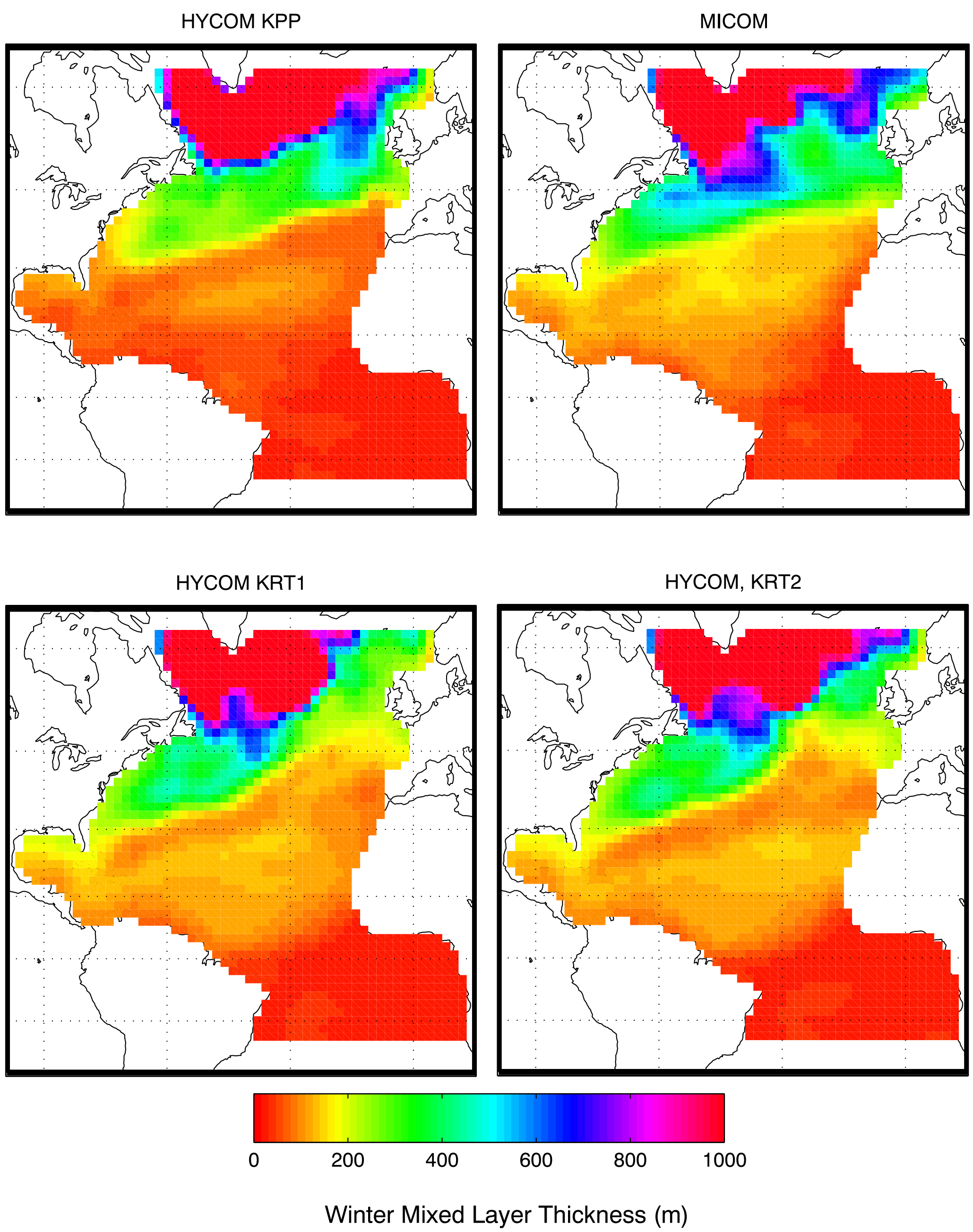

Figure 1: Winter mixed-layer thickness for HYCOM 1.0 KPP (upper left panel), MICOM (upper right panel), HYCOM 1.0 KT1 (lower left panel), and HYCOM 1.0 KT2 (lower right panel).

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 adopted in HYCOM (HYbrid Coordinate Ocean Model) is one that is isopycnal in the open, stratified ocean, but smoothly reverts to a terrain-following coordinate in shallow coastal regions, and to pressure-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.

HYCOM 1.0 was recently released and is the result of collaborative efforts between the University of Miami (Halliwell, Chassignet), the Los Alamos National Laboratory (Bleck), and the Naval Research Laboratory (Wallcraft). The capability of assigning additional coordinate surfaces to the oceanic mixed layer gives us the option of replacing the slab-type Kraus-Turner mixed layer of MICOM by a more sophisticated closure scheme in HYCOM, such as K-Profile Parameterization (KPP) (see Large et al., 1997). Both mixed layer parameterizations are available in HYCOM 1.0.

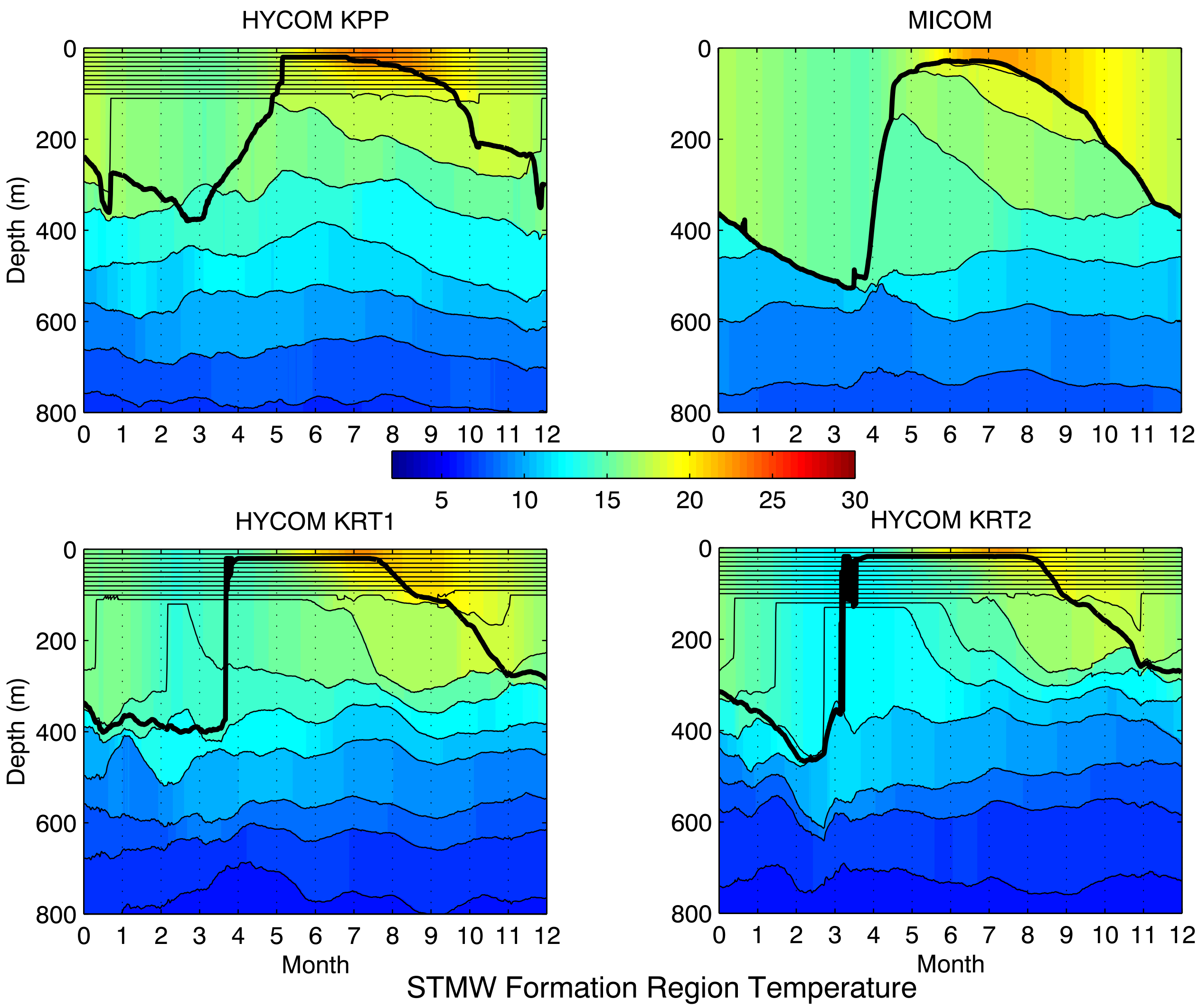

Figure 2: One-year time series of interface depths, temperature and mixed layer depths in the Subtropical Mode Water region for HYCOM 1.0 KPP (upper left panel), MICOM (upper right panel), HYCOM 1.0 KT1 (lower left panel), and HYCOM 1.0 KT2 (lower right panel).

The KPP mixing algorithm has several advantages: It provides mixing throughout the water column with an abrupt but smooth transition between the vigorous mixing in the surface boundary layer and the relatively weak diapycnal mixing in the ocean interior. It works on a relative coarse and unevenly-space vertical grid. It parameterizes the influence of a larger number of physical processes that other commonly used mixing schemes. In the ocean interior, the contribution of background internal wave breaking, shear instability mixing, and double diffusion (both salt fingering and diffusive instability) are parameterized. In the surface boundary layer, the influences of wind-driven mixing, surface buoyancy fluxes, and convective instability are parameterized. The KPP algorithm also parameterizes the influence of nonlocal mixing of T and S, which permits the development of countergradient fluxes.

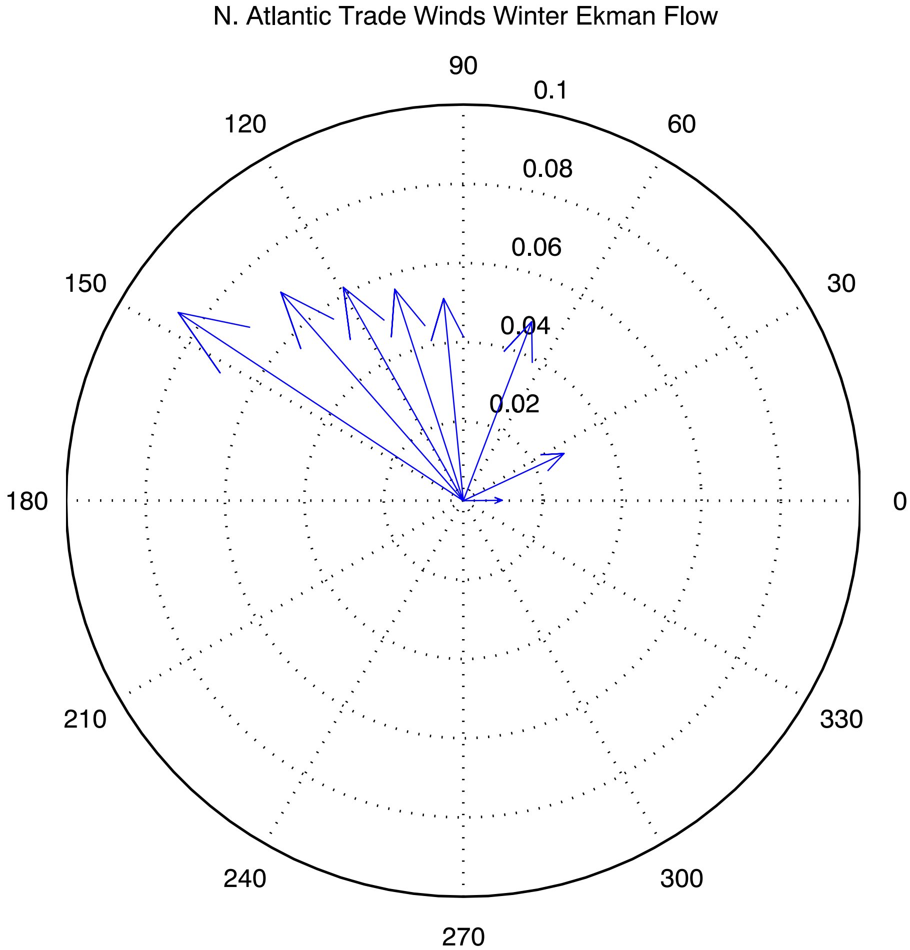

Figure 3: Ekman spiral representation in the North Atlantic trade winds region (HYCOM 1.0 KPP).

During each baroclinic time step, the surface fluxes of momentum, heat, and mass are all applied to the uppermost model layer with the exception of the shortwave radiation flux, which penetrates beneath the upper layer with an exponential decay scale dependent on the Jerlov water type (assumed equal to 3). The KPP algorithm then calculates vertical profiles of viscosity along with T and S diffusivity coefficients at each interface. These coefficients are parameterized as functions of boundary layer thickness and a third-order polynomial "shape" function, the latter insuring an abrupt but smooth transition between the small diffusivities of the ocean interior and the large diffusivities in the surface boundary layer. Given the profiles of viscosity and T, S diffusivities, the vertical diffusion equation is solved for each variable using a tri-diagonal matrix algorithm. The solution is semi-implicit and performed in two iterations. For the second iteration, the vertical viscosity and diffusivity profiles are re-calculated from the momentum, T, and S profiles that were calculated during the first iteration. Since HYCOM equations are solved on the C grid, the two iterations are first performed on pressure grid points using velocity components interpolated to these points. The viscosity profiles calculated on the pressure points are then interpolated to the u and v grid points where the vertical diffusion equation is solved once. Mixed layer thickness is diagnosed as the interpolated depth at which the density first exceeds the surface layer density by a specified amount. Mixed layer variables are calculated by integrating them over the depth of the mixed layer.

The Kraus-Turner (KT) mixed layer model was also implemented in HYCOM 1.0 as a benchmark for comparison with MICOM and for comparison with new mixed layer models such as the KPP. The implementation of the KT mixed layer model differs substantially from MICOM since, in HYCOM, the prognostic mixed layer thickness does not coincide with any vertical coordinates and the mixed layer base cuts across layer interfaces. To calculate the evolution of mixed layer thickness in the KT model and entrainment fluxes across the mixed layer base, it is necessary to quantitatively estimate the jumps in momentum and thermodynamical variables that exist at the mixed layer base. This is trivial in MICOM since the interface at the bottom of layer one is the mixed layer base. For HYCOM, an ″unmixing" algorithm was developed to estimate these jumps at each grid point by dividing the layer containing the mixed layer base into two sublayers. The upper sublayer is part of the mixed layer while the lower sublayer is part of the stratified interior. Since the KT algorithm governs mixing only within the mixed layer, a separate diapycnal mixing algorithm must be included for the interior ocean. HYCOM 1.0 has been equipped with two diapycnal mixing algorithm choices: the one traditionally used in MICOM (KT1) and an implicit procedure (KT2) that is essentially the interior diapycnal mixing component of the KPP mixing algorithm.

The performance of HYCOM 1.0 were compared to MICOM 2.8 in a 2° North Atlantic configuration with monthly climatological COADS forcing. Three primary cases were run using HYCOM 1.0: KPP mixing, KT mixing with the explicit diapycnal mixing used in MICOM 2.8 (KT1), and KT mixing with the implicit diapycnal mixing extracted from the KPP mixing algorithm (KT2). The latter diapycnal mixing algorithm parameterizes the influence of background internal wave breaking, double diffusion, and shear instability. The model is first spun up for thirty years using the COADS climatological annual cycle forcing, then run for one year with three-dimensional fields saved monthly for further analysis. Time series of all variables were also saved at high time resolution (five times per day) at locations representing dynamically distinct regimes.

Model performance for the four cases is illustrated by the maps of winter (15 March) mixed layer thickness (Fig. 1) and by 1-year time series of mixed layer thickness, interface depths, and temperature in the upper 800 m at a grid point in the Subtropical Mode Water (STMW) formation region (Fig. 2). The winter mixed layer depth (Fig. 1) shows qualitatively similar patterns for the four cases. The mixed layer over most of the subtropical gyre is less deep in HYCOM 1.0 KPP than in MICOM 2.8 and in the two HYCOM 1.0 cases using the KT mixed layer model. The KPP mixing model tends to produce a thinner winter mixed layer in this region than the KT model. The mixed layer is also shallower in the region west of central Europe in the two HYCOM 1.0 KT cases than in the other two cases. The annual cycle of temperature and mixed layer thickness in the STMW formation region (Fig. 2) also displays qualitatively similar behavior among the four cases with the deepest winter mixed layer found in the MICOM simulation. High vertical resolution in the HYCOM surface mixed layer now allows for a representation of the Ekman dynamics as illustrated in Fig. 3.

For assimilation of surface altimetry data, the Reduced Order Information filter (ROIF) has been ported from MICOM to the HYCOM coordinate system. ROIF is a reduced order implementation of Kalman filter that has been shown (Chin et al. 1999; 2000) effective in observation system simulation experiments (twin experiments) for assimilation of sea surface heights sampled sparsely as in the Topex/Poseidon satellite. The assimilation technique has also been proven mathematically to preserve positive definiteness in the approximated covariance matrix (Chin, 2000).

Porting of ROIF assimilation system from MICOM to HYCOM is achieved by converting its vertical axis from one that based on layer-thickness to a pressure-based coordinate. The HYCOM-adapted

ROIF is tested first in a 2 x 2 degree grid model of North Atlantic with the KPP mixing scheme. Preliminary analysis show that the sea surface height field converges exponentially towards the truth (a twin run) through assimilation of the sparsely sampled (Topex/Poseidon track) data. This result is consistent with the previous performance with MICOM. The data were assimilated at every model time step (if available), instead of every 10 days.

Further examination of the HYCOM-adapted ROIF is underway. Our agenda is to perform (i) quality checks of the new ROIF numerics, e.g., matrix conditioning, (ii) an evaluation of the vertical profiling and its sensitivity to the prior/empirical statistics, (iii) an evaluation with finer resolution HYCOM, i.e., 1/3-degree North Atlantic.

A parallel development is an examination of the use of drifter data to reduce geoid uncertainty associated with the Topex/Poseidon altimetry data. Initial runs of ROIF-based assimilation of drifter-based velocity data have recently completed. The next step is co-assimilation of these velocity data and altimetry data.

IMPACT/APPLICATIONS

Generation of optimal estimates of the time-varying ocean state in support of the NAVY's needs on synoptic time scales on the order of weeks to months and on spatial scales typically on the order of 10-1000 km (mesoscale).

TRANSITIONS

None

RELATED PROJECTS

This effort is part of a multi-institutional NOPP project which includes E. Chassignet (Coordinator), T. Chin, G. Halliwell, and A. Mariano (U. of Miami/RSMAS), R. Bleck (LANL), H. Hurlburt, A. Wallcraft, P. Hogan, R. RHodes, C. Barron, and G. Jacobs (NRL-Stennis), O.M. Smedstad and J.F. Cayula (Planning Systems, Inc.), W.C. Thacker (NOAA/AOML), and M. O'Keefe (U. Minnesota).

REFERENCES

Large, W.G., G. Danabasoglu, S.C. Doney, and J.C. McWilliams, 1997: Sensitivity to surface forcing and boundary layer mixing in a global ocean model: Annual-mean climatology. *J. Phys. Oceanogr.*, **27**, 2418-2447.

PUBLICATIONS (1999-2000)

Chin, T.M., A.J. Mariano, and E.P. Chassignet, 1999: Spatial regression with Markov random fields for Kalman filter approximation in least-squares solution of oceanic data assimilation problems. *J. Geophys. Res.*, **104**, 7991-8014.

Halliwell, Jr., G. R., 1999: Simulations of quasi-decadal and interdecadal veriability in the Atlantic Ocean associated with the North Atlantic Oscillation. Invited Paper, IUGG99, Birmingham, UK.

Paiva, A.M., J. T. Hargrove, E.P. Chassignet, and R. Bleck, 1999: Turbulent behavior of a fine mesh (1/12 degree) numerical simulation of the North Atlantic. *J. Mar. Sys.*, **21**, 307-320.

Sun S., R. Bleck, C. G. Rooth, J. Dukowicz, E. P. Chassignet, and P. Killworth, 1999: Inclusion of thermobaricity in isopycnic-coordinate ocean models. *J. Phys. Oceanogr.*, **29**, 2719-2729.

Chassignet, E.P., and P. Malanotte-Rizzoli (Eds.), 2000: *Ocean circulation model evaluation experiments for the North Atlantic basin*. Elsevier Science Ltd., special issue of *Dyn. Atmos. Oceans*, **32,** 155-432.

Chassignet, E.P., H. Arango, D. Dietrich, T. Ezer, M. Ghil, D.B. Haidvogel, C.-C. Ma, A. Mehra, A.M. Paiva, and Z. Sirkes, 2000: DAMÉE-NAB: The base experiments. *Dyn. Atmos. Oceans*, **32**, 155-184.

Halliwell, Jr., G.R., R. Bleck, E.P. Chassignet, and L.T. Smith, 2000: Mixed layer model validation in Atlantic Ocean simulations using the hybrid-coordinate ocean model (HYCOM). *EOS*, 80 (abstract), 304.

Özgökmen, T.M., A. Griffa, A.J. Mariano, and L.I. Piterbarg, 2000: On the predictability of Lagrangian trajectories in the ocean. *J. Atmos. Ocean. Tech.*, **17**, 366-383.

Paiva, A.M., E.P. Chassignet, and A.J. Mariano, 2000: Numerical simulations of the North Atlantic subtropical gyre: Sensitivity to boundary conditions and horizontal resolution. *Dyn. Atmos. Oceans*, **32**, 209-238.

Pratt, L.J., K.R. Helfrich, and E.P. Chassignet, 2000: Hydraulic adjustment to an obstacle in a rotating channel. *J. Fluid Mech.*, **404**, 117-149.

Smith, L.T., E. P. Chassignet, R. Bleck, and G. R. Halliwell, Jr., 2000: A hybrid-coordinate open-boundary condition regional model for the Inter-American Seas. *EOS*, **80** (abstract), 232.

Smith, L.T., E.P. Chassignet, and R. Bleck, 2000: The impact of lateral boundary conditions and horizontal resolution on North Atlantic water mass transformations and pathways in an isopycnic coordinate ocean model. *J. Phys. Oceanogr*., **30**, 137-159.

Stammer, D., and E.P. Chassignet, 2000: Ocean state estimation and prediction in support of oceanographic research. *Oceanography*, **13**, 51-56.

Stern, M.E., and E.P. Chassignet, 2000: Mechanism of eddy separation from coastal currents. *J. Mar. Res.*, **58**, 1-27.

Garraffo, Z.D., A.J. Mariano, A.Griffa, C. Veneziani, and E.P. Chassignet, 1999: Lagrangian data in a high resolution numerical simulation of the North Atlantic. I: Comparison with *in-situ* drifter data. *J. Mar. Sys*., in press.

Garraffo, Z.D., A. Griffa, A.J. Mariano, and E.P. Chassignet, 2000: Lagrangian data in a high resolution numerical simulation of the North Atlantic. II: On the pseudo-Eulerian averaging of Lagrangian data. *J. Mar. Sys*., in press.

Özgökmen, T.M., E.P. Chassignet, and C.G.H. Rooth, 2000: On the connection between the Mediterranean outflow and the Azores Current. *J. Phys. Oceanogr.*, in press.

Adler, R.J., R. Rosu, and A.J. Mariano, 2000: Estimating feature displacements velocities from scalar space-time data: application to sea surface temperatures. *J. Applied Statistics*, submitted.

Chassignet, E.P., Z.D. Garraffo, R.D. Smith, and H.E. Hurlburt, 2000: High resolution Gulf Stream modeling. *Geophys. Res. Let.*, submitted.

Chin, T.M., 2000: On Kalman filter solution of space-time interpolation. I*EEE Trans. Image Processing*, submitted.

Chin, T.M., A.C. Haza, and A.J. Mariano, 2000: A reduced-order information filter for multi-layer shallow water models: profiling and assimilation of sea surface height. *J. Atmos. Ocean. Tech.*, submitted.

Özgökmen, T.M., L.I. Piterbarg, A.J. Mariano and E. Ryan, 2000: Predictability analysis of drifter clusters in the tropical Pacific Ocean using a data- assimilative Lagrangian model. *J. Phys. Oceanogr.*, submitted.

Paiva, A.M., and E.P. Chassignet, 2000: The impact of surface flux parametrizations on the modeling of the North Atlantic Ocean. *J. Phys. Oceanogr.*, submitted.