Dynamics Of Oceanic Motions

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LONG-TERM GOALS

This research is concerned with accurate and efficient four-dimensional field estimation and fundamental dynamical process studies for the mid-latitude ocean. The research is multiscale, interdisciplinary and generic. The methods are applicable to an arbitrary region of the coastal and/or deep ocean and across the shelf-break. Results contribute to: knowledge of realistic regional processes and general physical and physical/acoustical processes; and the formulation and initiation of studies on physical-biological-chemical interactions essential to the understanding of biogeochemical-cycles and ecosystem dynamics.

OBJECTIVES

General objectives are:

(I) To determine for the coastal and/or coupled deep ocean the multiscale processes which occur in:

- i) the physical response to external and boundary forcings and via internal dynamical processes;
- ii) the physical-biological-chemical interactions which control productivity and provide connectivity and isolation mechanisms for (sub) regional ecosystems;
- iii) the physical-acoustical interactions which influence acoustic propagation and tomographic inversions.

(II) To nowcast, forecast and simulate with data assimilation realistic oceanic fields with (sub) mesoscale resolution over large scale domains and to understand the essential dynamics controlling forecasts and regional predictability. Specific objectives include:

- i) Northwest Atlantic shelf seas studies with atmospheric and river flux;
- ii) Mediterranean studies in the Sicily Straits and the eastern basin;
- iii) extension and application of our balance of terms scheme (EVA) to multiscale, interdisciplinary fields with data assimilation;
- iv) extension and application of our hybrid ESSE data assimilation scheme to interdisciplinary fields and parameter estimation; and,
- v) regional predictability studies.

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APPROACH

Field estimates are obtained via the melding of data and dynamics in a modular, flexible forecast and simulation system (Harvard Ocean Prediction System - HOPS). Dynamically adjusted fields are used in detailed physical, acoustical and biogeochemical/ecosystem process analyses based on the balance of terms of the dynamical equations. Data assimilation is carried out for dynamical adjustment, dynamical interpolation and data-driven simulations. Assimilation algorithms include a robust "optimal" interpolation scheme and a hybrid method for evolving forecast errors based on an EOF representation of the dominant error subspace and an ensemble forecast error estimate (Error Subspace Statistical Estimation - ESSE). The pre-treatment of data before assimilation, via structured data models (e.g. feature models), maximizes the data information content. A sequence of two-way nested model domains and nested observational strategies are used to establish accurate representations of multi-scale processes and interactions. Theoretical, GFD, and data driven simulations are utilized with feedbacks.

WORK COMPLETED

Several of the ESSE methodology publications have been completed and have now appeared. They include a theoretical presentation and a validation of the approach and schemes for data assimilation with filtering and smoothing techniques (4, 5 of the publications list), the four-dimensional estimation of physical fields and their dominant covariances in the Strait of Sicily (3), and the utilization of the ESSE methodologies for real-time adaptive sampling during the Massachusetts Bay Sea Trial 98 (MBST-98) (13). The forecast of the dominant future variability and events, i.e. the continuously evolving EOFs, has been carried out and evaluated, in particular via comparions with simulated Lagrangian drifters: the corresponding work was presented (2) and is being submitted (17).

Important evaluations of the use of forecast systems in interdisciplinary ocean science (12) and the role of adaptive sampling in ocean forecasting (13) have been prepared and are in press. The use of the Harvard Ocean Prediction System (HOPS) in coastal ocean forecasting is presented in (7).

The dynamical and theoretical basis for the advanced study of the Massachusetts Bay/Gulf of Maine multidisciplinary dynamics was completed within Harvard's LOOPS/AFMIS programs. Results of this work have been presented at a Gordon Conference in June '99 and at the IUGG in July '99, as well as at a US/UK Navy Modeling meeting. Physical and multi-disciplinary OSSE's are being carried out prior to the March/April 2000 AFMIS Real-Time Demonstration of Concept exercise.

The second phase of a new general theory of advective effects on biological dynamics in the sea, investigating localization, light limitation and nutrient saturation, has been completed (6). The third phase of this study is underway. A theory on the statistical field description of phytoplankton micropatches has been developed and applies to size-binned particle data from the Baltic Sea (9).

Studies of the structure of the circulation (8) and water masses (10) of the Strait of Sicily and the adjacent Ionian and Tyrrhenian Seas have been published. An important set of studies which describe coupled physical and biological modeling, data assimilation methodology and significant coupled physical and biological processes in the Gulf Stream Region will appear shortly in *Deep Sea Research* (14, 15).

Important algorithms for HOPS have been formulated and implemented. These include: coastal PE modeling algorithms, surface pressure formulations (rigid lid and free surface), tides, 2-way nesting for n-level multiple nests and riverine input. Feature models for the circulation of the Gulf of Maine have been developed. Simulations have been completed and dynamical analyses are underway for additional regions: Northeast Atlantic (Plankton Patchiness Studies by Ship and Satellite), Georges Bank, New England Bight (PRIMER/CMO).

A major workshop on the "Assimilation of Biological Data in Coupled Physical/Ecosystem Models: Scientific and Technical Topics and Issues" in Bologna, Italy was chaired by the Principal Investigator in June 1999 for International GLOBEC.

RESULTS

The application of Error Subspace Statistical Estimation (ESSE) has resulted in new dynamical insights. In (4), comparisons with existing procedures are made and the usefulness of the subspace ideas are discussed for nonlinear field and error forecasting, predictability and stability studies, objective analyses, data-driven simulations, model improvements, adaptive sampling and parameter estimation. In (5), the data assimilation scheme is exemplified and validated, using nonlinear, primitive equation based, idealized Mid-Atlantic Bight shelfbreak front simulations. The procedures for initializing dominant error or variability subspaces and the resulting new scheme for the mapping of three-dimensional multivariate and multiscale geophysical fields and their dominant errors are in press (11) and their evaluation has been submitted (18). In both (11) and (18), they are applied to the Middle Atlantic Bight and eastern Mediterranean, and the error and variability subspaces obtained confirm or reveal features of dominant nonlinear variability, such as the Ierapetra Eddy in the Levantine basin.

The four-dimensional estimation of physical fields and their dominant covariances in the Strait of Sicily, during a period of ten days and in real-time, has been published (3). With this Sicily experiment, five coupled features associated with the dominant variability in the Strait during August-September 1996 have been confirmed or revealed: the Adventure Bank Vortex, Maltese Channel Crest, Ionian Shelf Break Vortex, Strait of Messina Vortex, and subbasin-scale temperature and salinity fronts of the Ionian slope (3, 8, 19).

MBST-98 has resulted in a unique composite and compatible physical, biological, and chemical multiscale data set applicable to ongoing interactive process studies and interdisciplinary data assimilation, adaptive sampling, and predictive skill OSSEs. Results to date include identification of new patterns of patchiness from microscale to mesoscale, new patterns of circulation, dynamics of interactions of wind flow and buoyancy flow events, energetic fall biological blooms due to wind forcing, tidal mixing and external advection. The error subspace statistical estimation scheme, in conjunction with the optimal interpolation technique, was utilized in real-time for forecasting variability and error covariances, which allowed quantitative adaptive sampling on multiple scales with varied sensors and platforms and the three-dimensional multivariate assimilation of the multiple data streams. Research is in progress on the interpretation of the eigendecomposition of the evolving dominant physical variability, in order to elucidate the main dynamical processes occurring in Massachusetts Bay, and characterize the main external and internal forcings and their dynamical responses.

A general analytical theoretical approach to the study of advective effects on biological oceanographic dynamics has been formulated, developed and applied to the study of some idealized processes of real ocean interest. The intent is to complement related process research based upon experimentation and numerical simulation. A general biological dynamical model consisting of growth, self-interaction and bilinear interactions among n-state variables is coupled to a kinematically specified velocity field suitable for representing phenomenological flow fields over a broad range of time and space scales. The mathematical theory of characteristics provides a model which rigorously combines aspects of local biological dynamics with consideration of fluid particle flow along Lagrangian trajectories, and a symbolic general solution has been obtained. A local stretching deformation flow which can represent, e.g. horizontal fronts and vertical upwelling, has been used to study the competition between biological and advective processes on simple equilibrium states and instabilities. Exemplary results have been obtained for the effect of light, nutrient and grazing limitations on primary productivity in an NPZ model with nutrients from the aphotic zone advected into the euphotic zone by simple kinematic models of eddy injection events or coastal or equatorial upwelling. New results describing the effects of predator mortality, mixing and the sensitivities to the governing non-dimensional parameters have been achieved.

Simulations of a unique forecast validation/calibration data set from the Iceland-Faeroe Front region are being utilized to develop an exemplary nowcast/forecast system. The dynamical results, including an in-depth sensitivity analysis, are providing insights into the baroclinic instability problem and will form the basis of a multi-scale Energy and Vorticity Analysis (EVA) methodology, useful for the analysis of episodic events in real-world situations.

Our research has indicated the necessity of assimilating both physical and biological compatible fields, as the assimilation of either alone resulted in the misalignment of the physical and biological fronts, causing spurious cross-frontal fluxes of biological quantities. A technique has been presented for deriving the necessary, dynamically-consistent 3-D physical and biological field estimates from data for initialization and assimilation into time-evolving model simulations. Ring-stream interactions have been found to be of significant importance in the net vertical and meridional transports of nutrients and plankton, as compared to jet meandering or wind effects.

An inverse method to estimate the vertical distribution of temperature, salinity and internal pressure and associated errors from altimeter sea surface height observations singly or combined with other sensors has been validated using Rapid Response 1997 altimeter, CTD and AXBT datasets. The algorithm is robust, and the Bayesian *a posteriori* estimates of the errors are consistent with error estimates derived from the observations.

IMPACT/APPLICATIONS

The important ESSE concept is that the evolution of 3D multivariate forecast variability and error can be efficiently described by a small number of adequate functions (e.g. error EOFs). The most energetic variability and error fields are expected to evolve in limited subspaces. In general, ESSE is useful for a wide range of applications, including nonlinear field and error forecasting, finding numerical instabilities, performing predictability studies, objective analyses, data-driven simulations, adaptive sampling and parameter estimation.

We now have a feasible methodology for biological field estimation and data. An important implication is that the assimilation of ocean color data into physical-biological models should be concurrent with the assimilation of SST data. This is not only because the SST data can be used to fill in the gaps of the color data, but especially because the biological features need corresponding physical features to support them. Our methodology, in conjunction with the bio-optical modeling research being carried out in a related project, is also useful for assimilating ship-derived physical and biological data, and thus in ground-truthing satellite-based measurements.

Our improved understanding of the biological response to physical processes in fronts and mesoscale patches will provide useful to the basic research and applied research scientific communities.

Real-time regional forecasting research results are directly applicable to the design of ocean prediction and monitoring systems for: naval operations; research operations; the efficient environmental management of, and commercial operations within, a multi-use Exclusive Economic Zone; interdisciplinary global change research.

TRANSITIONS

Definitive results are passed to Harvard 6.2 research "Development of a Regional Coastal and Open Ocean Forecast System: Harvard Ocean Prediction System (HOPS)". These include, but are not limited to, the ESSE data assimilation methodology, improvements to the dynamical model upper ocean, algorithms for coastal PE modeling, free surface, tides, nesting, etc.

RELATED PROJECTS

This project is closely related to other Harvard projects, including: National Ocean Partnership Program in the development of the scientific and technical conceptual basis of a generally applicable Littoral Ocean Observing and Predictive System (LOOPS) with Johns Hopkins University (APL), MIT - AUV Lab., MIT - Sea Grant, MIT - Ocean Engineering, Naval Underwater Warfare Center, National Marine Fisheries Service, Raytheon, Tracor Applied Science, Univ. of California - Santa Barbara, Univ. of Massachusetts - Dartmouth; research towards the construction of an Advanced Fisheries Management and Information System (AFMIS) with UMass-Dartmouth (Prof. B. Rothschild); BIO-OPTICS research (Dr. Jeffrey Dusenberry); the Shelfbreak PRIMER and Harvard 6.2 research mentioned previously. In addition, important collaborations are ongoing with NRL Stennis (Dr. A. Warn-Varnas and Dr. R. Rhodes); U. Colorado (Dr. A. Moore); SIO (Dr. A. Miller); IMGA, Modena, Italy (Dr. N. Pinardi); Penn State Univ. Applied Research Lab. (Dr. S. Phoha) and the Naval Postgraduate School (Dr. Ching Sang Chiu).

PUBLICATIONS

<u>Published</u>

[1] Kroujiline, D. and H.A. Stone. Chaotic Streamlines in a Steady Bounded Three-Dimensional Stokes Flows. *Physica D*, 130, 105-132, 1999.

[2] Lermusiaux, P.F.J. The evolving sub-space of the three-dimensional ocean variability, *Three-dimensional ocean circulation: Lagrangian measurements and diagnostic analyses*, 31st International Liege Colloquium on Ocean Hydrodynamics, 1999, p57.

[3] Lermusiaux, P.F.J. Estimation and Study of Mesoscale Variability in the Strait of Sicily. *Dynamics of Atmospheres and Oceans, Special Issue in honor of Prof. A.R. Robinson,* 29, 255-303, 1999.

[4] Lermusiaux, P.F.J. and A.R. Robinson. Data Assimilation via Error Subspace Statistical Estimation, Part I: Theory and Schemes. *Monthly Weather Review*, Vol. 127(8), 1385-1407, 1999.

[5] Lermusiaux, P.F.J. Data Assimilation via Error Subspace Statistical Estimation, Part II: Mid-Atlantic Bight Shelfbreak Front Simulations, and ESSE Validation. *Monthly Weather Review*, Vol. 127(8), 1408-1432, 1999.

[6] Robinson, A.R. On the Theory of Advective Effects on Biological Dynamics in the Sea II: Localization, Light Limitation, and Nutrient Saturation. *Proceedings of the Royal Society A*, 455, 1813-1828, 1999.

[7] Robinson, A.R. Forecasting and Simulating Coastal Ocean Processes and Variabilities with the Harvard Ocean Prediction System in ***Coastal Ocean Prediction***, (C.N.K. Mooers, editor), AGU Coastal and Estuarine Studies Series, 77-100, American Geophysical Union, 1999.

[8] Robinson, A.R., J. Sellschopp, A. Warn-Varnas, W.G. Leslie, C.J. Lozano, P.J. Haley, Jr., L.A. Anderson and P.F.J. Lermusiaux. The Atlantic Ionian Stream, — Special Issue — in Memory of Dr. Antonio Michelato. *Journal of Marine Systems*, 20, 129-156, 1999.

[9] Rothschild, B.J., P.J. Haley, Jr. and D. Cai. Influence of Physical Forcing on Microclouds of Dissolved Organic Matter and Nutrients in the Ocean. *Journal of Plankton Research*, 21(7), 1217-1230, 1999.

[10] Warn-Varnas, A., J. Sellschopp, P.J. Haley, Jr., W.G. Leslie and C.J. Lozano. Strait of Sicily Water Masses. *Dynamics of Atmospheres and Oceans, Special Issue in honor of Prof. A.R. Robinson,* 29, 437-469, 1999.

In Press

[11] Lermusiaux, P.F.J., D.G. Anderson and C.J. Lozano. On the Mapping of Multivariate Geophysical Fields: Error and Variability Subspace Estimates. *Q.J.R. Meteorol. Soc*., 1999

[12] Robinson, A.R., J.J. McCarthy, and B.J. Rothschild. Interdisciplinary Ocean Science is Evolving and a Systems Approach is Essential. *Journal of Marine Systems*, 1999.

[13] Robinson, A. R. and S.M. Glenn. Adaptive Sampling for Ocean Forecasting. *Naval Research Reviews*, 1999.

[14] Anderson, L.A., A.R. Robinson and C.J. Lozano. Physical and Biological Modeling in the Gulf Stream Region: I. Data Assimilation Methodology. *Deep-Sea Research*, 1999.

[15] Anderson, L.A. and A.R. Robinson. Physical and Biological Modeling in the Gulf Stream Region, II: Physical and Biological Processes. *Deep-Sea Research*, 1999.

Submitted

[16] Kroujiline, D. and Kuang, K. The Effect of a Finite Shearing Layer in Kinematic Ponomarenk O-Type Dynamos. *Geophysical and Astrophysical Fluid Dynamics*, 1999.

[17] Lermusiaux, P.F.J. Evolving the sub-space of the three-dimensional ocean variability, *Journal of Marine Systems*, 1999.

[18] Lermusiaux, P.F.J., C.J. Lozano and D.G. Anderson. On the Mapping of Multivariate Geophysical Fields: Studies of the Sensitivity to Error Subspace Parameters. *Journal of Atmos. Oceanic Tech*, 1999.

[19] Lermusiaux, P.F.J. and A.R. Robinson. Forecasting and Analyzing the Dominant Mesoscale Summer Variability in the Strait of Sicily. *Deep-Sea Research*, 1999.

[20] Robinson, A.R. and J. Sellschopp. Rapid Environmental Assessment. In: *Ocean Forecasting - Conceptual Basis and Applications*, N. Pinardi, J.D. Woods, and S. Vallerga (eds.), MAST Advanced Study Course, International Marine Center, Torregrande, Sardenia, Italy, 1999.