# 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: the 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 internal dynamical forcings;
- ii) the physical-biogeochemical interactions which control productivity and provide connectivity and isolation mechanisms for (sub) regional ecosystems;
- iii) the physical-acoustical interactions that influence acoustic propagation, tomographic inversions, and multi-variate coupled physical-acoustical data assimilation.

(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) studies of Monterey Bay and its interaction with the California Current System;
- ii) Northwest Atlantic shelf seas studies with atmospheric and river fluxes;
- iii) regional Mediterranean studies;
- iv) extension and application of our balance of terms scheme (MS-EVA) to multiscale, interdisciplinary fields with data assimilation;
- v) extension and application of our ESSE data assimilation scheme to interdisciplinary fields and parameter estimation; and,
- vi) theoretical bases for objective adaptive sampling, adaptive modeling and automated verification.

## APPROACH

Our approach is to construct realistic (sub) mesoscale resolution physical/interdisciplinary 4-dimensional fields via the assimilation of high-resolution (intermittent) data in nested (coupled) regional dynamical models (HOPS and Mini-HOPS). Optimal (ESSE) and sub-optimal (OI) data assimilation schemes are used. Dominant regional processes are inferred via generally multiscale balance of terms studies of space-time fields, which rigorously conserve energy and enstrophy among scale windows. Companion studies of basic processes are carried out via both idealized GFD simulations and analytical theoretical studies. Generic littoral processes are investigated by comparative regional studies and by (pan) regional syntheses. A substantial effort is directed towards feedbacks between modeling results and data acquisition and utilization on multiple time scales, and data and model error-models are important elements of our research.

Work is ongoing in the areas of:
1. Multi-scale Coupled Physical/Interdisciplinary Dynamical Processes
2. Regional Dynamics, Forecasts and Syntheses
3. Theory and Structure of Prediction Systems

and the **Work Completed** and **Results** sections of this report are organized thusly.

Regional dynamics and forecasting and are intimately linked and several scientists are supported both under our 6.1 (fundamental dynamics) and 6.2 (operational system development) projects, including during FY04, the period of this report, the PI, Dr. Patrick J. Haley, Jr., Mr. Wayne G. Leslie, Dr. Rucheng Tian (now at Univ. Mass.-Dartmouth), post-doctoral fellow Dr. X. San Liang (now at Courant Institute of Applied Mathematics, NYU) and graduate students Oleg Logoutov and Patricia Moreno (partially). A number of important collaborators are identified in the **Related Projects** section.

## WORK COMPLETED

### 1. Multi-scale Coupled Physical/Interdisciplinary Dynamical Processes

1.1 Multi-Scale Energy and Vorticity Analysis (MS-EVA)

- The MS-EVA and multiscale window transform developed previously were applied to the development of a localized hydrodynamic instability analysis for geophysical fluid dynamics. The resulting localized instability theory is now directly applicable to atmospheric and oceanic datasets on a generic basis. The formalism has been applied to the study of the shedding of vortices behind bluff bodies, the variability of the Iceland-Faeroe Front (IFF), and the dynamics of the complex Monterey circulation system.

1.2 Coupled physical-biogeochemical-ecosystem modeling

- A generalized biological model suitable for adaptation has been constructed and examples in Monterey Bay carried out.
- The theory of advective effects on biological dynamics in the sea (A.R. Robinson, *Proc. Roy. Soc*, A, 1999, **455**, 1813-1828) has been applied to study causes of sub-surface phytoplankton maxima in upwelling events.
- The efficacy of using commercial landings data to identify potential environmental correlates with fish distributions has been examined for Atlantic cod and haddock. Historical landings data were used along with historical hydrographic data to infer monthly

mean spatial distributions of catch per unit effort (CPUE), temperature, salinity, density, and stratification over Georges Bank.

1.3 Generic interdisciplinary processes for the global coastal ocean

- Three books (two volumes) have been edited by the principal investigator and K. H. Brink for THE SEA. The volumes comprise 60 chapters, 2550 pages, and are authored by 170 international scientists. They are being produced with the combined support of IOC/UNESCO and ONR. The volumes will be published in the Spring (Vol. 13) and Summer (Vol. 14 Part A, Vol. 14 Part B) of 2005. See also section 2.3 below.

**2. Regional Dynamics, Forecasts and Syntheses**

2.1 Monterey Bay

- A re-analysis of real-time physical field estimates was completed, distributed to the AOSN-II community and utilized at Harvard for dynamical studies via term balances, MS-EVA (see Results section 1.1) and for application of the multi-model estimation methodology.
- New software to compute the balance of dynamical tracer fluxes was written. Instantaneous fluxes (e.g. for heat and salt) are computed in the primitive-equation model. Using new Matlab scripts, one can then define any box in the full HOPS domain and evaluate horizontal/vertical fluxes on all sides and surface. Temporal and spatial means are then computed as desired. Software for computing and storing term-by-term balances in the dynamical tracer equations of HOPS were also written and utilized. Using Matlab scripts, each stored term in these equations can be evaluated on any surface or box, and averaged in time or space as desired.

2.2 Massachusetts Bay

- During June 2001, Harvard, NURC and the Univ. of Mass. carried out a coupled physical-biological-acoustical experiment (ASCOT-01) in Massachusetts Bay and the western Gulf of Maine from the NRV Alliance and the UMass. coastal ocean vessels Lucky Lady (Dartmouth) and Neritic (Boston). To study and understand the effects of upwelling events on a marine ecosystem (with focus on plankton and nutrients) in Massachusetts Bay during early summer a coupled physical-biological simulation has been set up with these data and hourly atmospheric forcing and assimilation of temperature and salinity. This work has included determining the non-observed biological variables from the observed one to initialize the biological variables as well as adjusting the physical and biological variables prior to the start of the simulation.

2.3 Interdisciplinary regional studies and syntheses for the global coastal ocean

- Volume 14 of THE SEA has been completed in two parts: Part A – Pan-regional Syntheses and the Coasts of North America and South America and Asia; and, Part B – The Coasts of Africa, Europe, Middle East, Oceania and Polar Regions.

**3. Theory and Structure of Prediction Systems**

3.1 Multi-models

- A robust and practical methodology for multi-model ocean forecasting has been developed. It is suited for an adaptive forecasting system that evolves in response to modeled processes and model-data misfits through changes in parameterization, resolution, boundary conditions, etc. Two general approaches have been identified, implemented, and explored: adaptive neural nets and Bayesian fusion based on error parameter estimation. We have extended the methodology of Maximum Likelihood (ML) Error Parameter Estimation from the atmospheric sciences to multi-model ocean predictive systems. These approaches have been tested on AOSN-II HOPS/ROMS re-analysis products to improve the quality of the hindcasts.

3.2 Improve existing and research new efficient models of errors and uncertainties

- The model of model errors can now be specified on either *z* or sigma coordinates. A Schur product multiplication with a specified error covariance was implemented in the computation of the dominant ESSE error covariance, so as to eliminate possibly spurious covariances at long distances when the size of the ESSE ensemble is too small. The spectra of the HOPS model and buoy data at M1/M2 were compared in the near-inertial scale range. The use of Principal Orthogonal Decomposition (POD) for faster field uncertainty calculations and predictions was investigated.

Additional information on the work accomplished for this project is available via the principal investigator's web site: http://www.deas.harvard.edu/~robinson.

## RESULTS

### 1. Multi-scale Coupled Physical/Interdisciplinary Dynamical Processes

1.1. Multi-Scale Energy and Vorticity Analysis (MS-EVA)

- The MS-EVA-based instability theory has been used to derive a physically robust measure for mean-eddy interactions in terms of space-time fields [11, 12, 13]. Globally it reduces to the classical Reynolds formalism. The theory has also helped to identify several important ocean dynamical processes, which would be otherwise difficult to identify. We have found that the intrusion along the IFF [1] is essentially a convective instability followed by an absolute instability; the wind-driven upwelling along the Monterey Bay coast is due to the large-scale energy from the wind, which is then transferred into the mesoscale window both directly under the wind and also by processes occurring during relaxation and leads to localized mesoscale upwelling structures. These processes, though identified from specific ocean datasets, are expected to have generic consequences.

1.2. Coupled physical-biogeochemical-ecosystem modeling

- Three versions of our new, generalized, flexible biological model [4] have been applied to the AOSN-II region and a regional model for August 2003 identified. Physical data is assimilated as in the physical re-analysis and biological data is currently used for model testing and dynamical evaluation. The biological response to upwelling is well reproduced by the current model and several biological features observed in the data occur in the simulation. Further improvements include higher biological grid resolution, lower biological production and higher mortality offshore.
- Analytic theory – Sub-surface phytoplankton maxima occur because of: i) zooplankton grazing; ii) a well-mixed near-surface layer in the upper euphotic zone; and, iii) the existence of a nutricline in which nutrients increase with depth below the euphotic zone. A non-dimensional parametric representation of these causes has been completed and a manuscript is in preparation.
- Using historical landings data for two commercially important species, relationships between CPUE and these environmental variables plus bottom sediment type and bottom depth were examined on seasonal, annual, and interannual time scales [5]. Empirical analysis suggests that both cod and haddock are found preferentially in water temperatures of approximately 5$^{o}$C in winter/spring, and as high as 10–11$^{o}$C during late fall. Both species are also found preferentially over coarse sand and gravel as opposed to fine sand, and in water depths between 60 and 70 m. These preferences appear to vary seasonally. The above results are consistent with findings of previous investigators using semi-annual research

trawl survey data, and suggest that commercial landings data, despite their known errors and biases, can be used effectively to infer associations between fish and their environment.

1.3. Generic interdisciplinary processes for the global coastal ocean

- Volumes 13 and 14 of THE SEA deal with fundamental multiscale interdisciplinary processes that occur generally throughout the coastal seas of our planet, and with the specific combination of processes, which govern the dynamics of regions of the coastal seas, which together constitute the whole. These volumes complement and supplement Vol. 10 and 11 of THE SEA, which respectively deal generally and regionally with the physical oceanography of the global coastal oceans. Vol. 13 [6] is comprised of four parts. Part 1 provides general perspective, and Chapter 1 on multiscale interdisciplinary processes [9], which has been prepared as a general introduction, refers throughout to all the other chapters of the volume. Part 2 on sediment, biogeochemical and ecosystem dynamics and Part 3 on episodic and long time scale dynamics together constitute the dynamical core of the volume. Part 4 presents scientific issues for applications.

## 2. Regional Dynamics, Forecasts and Syntheses

2.1. Monterey Bay

- A re-analysis of the Aug.-Sep. 2003 AOSN-II experiment was made in order to produce a tuned continuous 4D representation of the region. The final result was a 35-day simulation of the period 6 Aug. - 10 Sep. 2003, with daily assimilation of CTD, glider and aircraft SST data during 7 Aug. - 6 Sep. 2003.
- We computed volume term-by-term and flux balances in the Pt. Ano Nuevo (AN) region for the upwelling and relaxation periods (time-averaged as well as snapshots). The time-evolution of these snapshot balances shows the complexity of 3D upwelling regimes, with strong in-homogeneities due to strong eddying and meandering of the coastal upwelling current and jets. On average during the upwelling, balances are closer to classic descriptions. For example, the heat flux balance over the AN region involves alongshore, surface equatorward cooling, and, across-shore surface westward cooling and sub-surface eastward warming (e.g. anti-cyclone offshore from Monterey Bay). The term-by-term balance in across-shore sections at AN show that the mean rate of change term is in balance with the cross-shore, alongshore and vertical advections: horizontal eddy diffusions are 10 times smaller and vertical diffusion fluxes (in balance with atmospheric heat/salt fluxes at the surface) are only important right at the thermocline, where vertical gradients are largest.

2.2. Massachusetts Bay

- Massachusetts Bay (including Cape Cod Bay) is subject to a variety of storms, which subject the semi-enclosed embayment to a variety of upwelling winds. Thus the biological response is a variety of upwelling events around the coastline of the bay. Biological parameters and their ranges of variations for early summer conditions in Massachusetts Bay have been determined based on the ASCOT-01 biological data set collected in June 2001 and previously published studies. A sensitivity study of the biological parameters is underway. The physical aspects of the simulation have been studied and analyzed for interesting dynamical events. Two upwelling events, which occur at the end of the simulation, are under analysis. A sensitivity study will be carried out based on the forcing parameters, including the duration and strength of the wind events. This study complements in an interesting way the sustained upwelling study from Monterey Bay.

2.3. Interdisciplinary regional studies and syntheses for the global coastal ocean

- Volume 14 of THE SEA is being published in two parts [7, 8]: Part A - Pan-Regional Syntheses and the Coasts of North and South America and Asia (Chapters 1-19; Coastal Segments 1-14); and, Part B - The Coasts of Africa, Europe, Middle East, Oceania and Polar Regions (Chapters 20-37; Coastal Segments 15-32). The initial four chapters of Part A are pan-regional syntheses for western ocean boundaries (W), eastern ocean boundaries (E), polar ocean boundaries (P), and semi-enclosed seas, islands and Australia (S). These four chapters serve to summarize and introduce the material in the subsequent chapters on regional interdisciplinary oceanography.

3. **Theory and Structure of Prediction Systems**

   3.1. Multi-model estimation

   - Bayesian Fusion via multi-model error parameter estimation has been selected as the most practical and well-suited approach. The developed methodology consists of the following three steps: a) parameterization of forecast uncertainties through either a suitable parametric family (offers computational advantage) or through a low-rank approximation (allows for non-homogeneous dynamically motivated dominant error subspaces); b) update of forecast uncertainty parameters via Maximum-Likelihood (details below) once new validation data becomes available; c) combining model forecasts based on current estimates of their relative uncertainties via Maximum-Likelihood. To implement step b), we have extended the standard ML Error Parameter Estimation to multi-model systems through the Expectation-Maximization technique. Synthetic data tests indicate the importance of the EM-based approach as opposed to simple transfer of the existing methodology developed for a single model system to multi-model systems.

   3.2. Improve existing and research new efficient models of errors and uncertainties

   - The use of new error models for the ESSE computations allows the prediction of more accurate uncertainty estimates for the HOPS ocean fields. This is especially important for acoustic computations and predictions with acoustic uncertainties. Preliminary improvements in the distribution of the ESSE ensemble predictions have already increased the ESSE speed by a factor of 1.5 - 2.

   3.3. Published results

   - An invited keynote address illustrating the concept of interdisciplinary ocean prediction systems with coupled data assimilation was presented at the Sixth International Conference on Theoretical and Computational Acoustics [2]. The development of the conceptual basis of adaptive modeling for physical and biological estimates has been completed [3]. Examples in Massachusetts Bay and Monterey Bay were carried out to highlight ongoing progress. Advanced operational forecasting systems in general are presented in [10] and the use of HOPS in operational and fisheries applications is discussed in [16]. HOPS has been utilized to forecast and investigate the synoptic circulation and transports in the Eastern Ligurian Sea [14]. Issues in adaptive modeling for interdisciplinary forecasting are addressed in [15].

## IMPACT/APPLICATIONS

Knowledge of regional littoral dynamical processes is essential input to the development of regional littoral ocean prediction systems, which are at the threshold of enabling powerful new methods for operating in, and the management of, coastal seas and adjacent deep seas. Military applications include submarine warfare, mine warfare, special operations and littoral homeland security. Societal applications include input to the rational management of our multiuse coastal seas, pollution control, response to accidental and aggressive events and the management of fisheries and mineral resources. The generic approach to the study and synthesis of regional coastal dynamics facilitates our ability to deal with less well-known regions of our national coastlines and the global coastal ocean generally. In his foreward to Volumes 13 and 14 of THE SEA on the Interdisciplinary Global Coastal Ocean, Dr. Patricio Bernal, Executive Secretary, IOC, states "The results emerging from the present volumes are expected to lead to the sustainable use of the resources of the coastal oceans, producing a knowledge base for developed and developing nations alike".

## TRANSITIONS

Definitive results are passed to the Harvard 6.2 research "Development of a Regional Coastal and Open Ocean Forecast System: Harvard Ocean Prediction System (HOPS)" with the same principal investigator and from there transitioned to other research groups, including MIT-OE, Princeton, WHOI and UMass.-Dartmouth. ESSE and MS-EVA are being transitioned to the NATO Undersea Research Centre (NURC) and incorporated into the NATO Tactical Ocean Modeling (NTOMS) framework. The Multi-Model Estimation methodology is to be transitioned to NURC as well.

## RELATED PROJECTS

During FY04, the period of this report, this project has been closely related to other current Harvard projects, including: "Development of a Regional Coastal and Open Ocean Forecast System: Harvard Ocean Prediction System (HOPS)", an NSF-OIT project "Rapid Real Time Interdisciplinary Ocean Forecasting Adaptive Sampling and Adaptive Modeling in a Distributed Environment" (Prof. N. Patrikalakis and Prof. H. Schmidt - MIT; Prof. J.J. McCarthy - Harvard); the ONR project "Uncertainties and Interdisciplinary Transfers Through the End-to-End System (UNITES): Capturing Uncertainty in the Common Tactical Environmental Picture". Important collaborations are ongoing with the NATO Undersea Research Centre (NURC) (Dr. E. Coelho and Dr. M. Rixen), University of Massachusetts-Dartmouth (Prof. A. Gangopadhyay), NRL Stennis (Dr. A. Warn-Varnas); University of Bologna, Italy (Dr. N. Pinardi); and the Naval Postgraduate School (Dr. Ching-Sang Chiu).

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