Development of a Regional Coastal and Open Ocean Forecast System

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LONG-TERM GOALS

The long-term goal is to develop, validate, and demonstrate an advanced relocatable regional ocean prediction system for the real-time forecasting and simulation of interdisciplinary multiscale oceanic fields and their associated errors and uncertainties, which incorporates both autonomous adaptive modeling and autonomous adaptive optimal sampling.

OBJECTIVES

The objectives of this research are:

1. To extend the HOPS-ESSE assimilation, real-time forecast and simulation capabilities to a single interdisciplinary state vector composed of ocean physical-acoustical-biological fields.
2. To continue to develop and to demonstrate the capability of multiscale simulations and forecasts for shorter space and time scales via multiple space-time nests, and for longer scales as appropriate via the nesting of HOPS into other basin scale models.
3. To quantitatively evaluate fields and parameterizations and to model errors adequately for adaptive sampling, adaptive modeling and multi-model ensemble combinations.
4. To extend the conceptual, algorithmic and software structure of HOPS-ESSE to facilitate the exchange and sharing of components with other models and systems and importantly to evolve HOPS into a multi-model ensemble system with web-based infrastructure.

APPROACH

In order to achieve as realistic and valid as possible regional field estimates, an effort is made to acquire and assimilate both remotely sensed and *in situ* synoptic multiscale data from a variety of sensors and platforms in real time or for the simulation period, and a combination of historical synoptic data and feature models are used for system initialization. Real time exercises and predictive skill experiments in various regions are carried out to provide fields for operational and scientific purposes and to test methodology in collaboration with other institutions and scientists including, importantly, the NATO Undersea Research Centre (NURC, formerly SACLANTCEN) and ONR multi-institutional projects. To contribute successfully to the complex system objectives above a careful step-by-step approach to the research is maintained.

Work is ongoing in the areas of:
1. Forecasting and dynamics of Monterey Bay and California Current System
2. Real-time regional forecasting exercises and regional dynamics
3. Methodology, system and software development

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

Forecasting and regional dynamics are intimately linked and several scientists are supported both under our 6.1 (fundamental dynamics) and 6.2 (operational system development) projects, including the PI, Dr. Pierre F.J. Lermusiaux, Dr. Patrick J. Haley, Jr., Mr. Wayne G. Leslie, post-doctoral fellow Dr. X. San Liang and graduate student Oleg Logoutov. A number of important collaborators are identified in the **Related Projects** section.

WORK COMPLETED

1. FORECASTING AND DYNAMICS OF MONTEREY BAY AND CALIFORNIA CURRENT SYSTEM

Re-analysis of physical fields forecast in real-time. A re-analysis of real-time physical field estimates was completed. This included re-calibrated and additional ocean data, improved atmospheric forcing through an improved surface boundary layer representation (formulation and parameterization) for atmosphere-ocean exchanges, and new, improved open boundary conditions, e.g. a weighted combination of Orlanski radiation and buoyancy inflows/outflows.
The 4-dimensional re-analysis fields were distributed to: the AOSN-II website for all scientists; Lagrangian Coherent Structure (LCS) CalTech scientists; Harvard researchers for dynamical studies.
Descriptive oceanography of the re-analysis fields. An analysis of the descriptive oceanography and of the real-time error fields during the AOSN-II experiment was initiated at the mesoscale. This description includes: upwelling and relaxation stages, cyclonic circulation in Monterey Bay, diurnal scales, topography-induced small scales, etc.
Multi-Scale Energy and Vorticity Analysis (MS-EVA)**.** MS-EVA has been performed on the re-analysis fields. The MS-EVA involves: multi-scale spectral analysis on the physical fields; determination of parameters and field decomposition; and, an examination of energy transfer processes from large scale to mesoscale analyzed for the upwelling and relaxation phases. A study of sub-mesoscale interactions has been initiated.
Multi-model estimates and combined HOPS/ROMS results. An Adaptive Bayesian Framework for Multi-Model Forecasting developed in Harvard 6.1 research ("Dynamics of Oceanic Motions") has been applied to HOPS/ROMS AOSN-II temperature re-analysis fields. Forecast error parameters of HOPS and ROMS have been inferred from the AOSN-II data.
Coupled biological-physical simulations. Based on a literature survey, a biological model for Monterey Bay was selected. Using the HOPS generalized biological modeling system, this *a priori* model and two other configuations, which used different equations and parameterizations, were set up for Monterey Bay. Sea Surface Color (SSC) and *in situ* data have been used to tune the three configurations. The resulting simulations have been compared and a preliminary analysis performed.
Sensitivity studies for hierarchy of tidal representations**.** To evaluate impacts of tidal processes, simulations with different parameterizations of tidal effects were carried out. The tidal constituents were estimated based on a regional OTIS inversion, local tidal gauges and global TPX05 fields.
Skill metrics at data points**.** Quantitative skill metrics (bias, RMS Error and Pattern Correlation Coefficient) for physical fields were computed and biological fields were qualitatively compared to SSC and *in situ* biological data.

2. Real-time regional forecasting exercises and regional dynamics

Maritime Rapid Environmental Assessment (MREA03) – Ligurian Sea – May/June 2003. A re-analysis of the MREA03 real-time forecasts was completed. This led to dramatically improved detailed agreement of model results with observed profiles. The re-analysis was comprised of sensitivity studies on vertical resolution, initialization procedures, and model parameters (especially vertical mixing) and included revised atmospheric forcing. The re-analysis results provided critical guidance for MREA04.

MREA04 – Portuguese Atlantic Coast – March/April 2004. HOPS was applied in real-time to the NURC operational exercise MREA04. HOPS performed real-time forecasting and ocean and model data transfers were carried out between the NRV Alliance and Harvard University. The Mini-HOPS concept was utilized in real-time to locally solve the problem of accurate representation of sub-mesoscale synopticity. This concept involves rapid real-time assimilation of high-resolution data in a high-resolution locally nested model domain around observational platforms. HOPS provided 2-way nested output in regional and sub-regional domains. These outputs provided initial and boundary data for shipboard Mini-HOPS simulations. Real-time forecasts included an evaluation of model bias and RMS error every day, in routine fashion and were also used for onboard acoustic calculations

3. Methodology, System and Software Development

Adaptive sampling schemes and OSSEs. The adaptive sampling carried out in real-time during AOSN-II (e.g. with the R/V Pt. Lobos) was evaluated. Different adaptive sampling schemes were tested and developed based on OSSEs. The first scheme is full ESSE adaptive sampling with non-linear errors and a dynamic objective field. The values of the objective field and cost function are predicted with nonlinear dynamics and stochastic uncertainties, and evolve as a function of the predicted sampling. The second scheme assumes that the objective field is fixed (e.g. predicted forecast error field) and adaptive sampling generates the optimal path for sampling this objective (e.g. regions of largest forecast errors). Algorithms to generate optimal paths are based on a mixed-integer-programming approach for multiple underwater vehicles and use commercial software to solve the optimization problem. The objective field does not need to be uncertainty related. It can be replaced and/or combined with weighted amplitudes of key MS-EVA terms.

ESSE software and error model development. 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.

Improvements to HOPS software. Concurrent with the applications of HOPS, software development continued with an emphasis outside of the core dynamical modules. A set of scripts was designed to compute and display bias and RMS skill metrics at the data profile level as well as comparing individual profiles to model output. Related scripts were written to read *in situ* data files and instruct the PE model to generate data profiles at the corresponding locations and times. A third set of software was created to best fit the parameters of the HOPS PE mixed layer models with available *in situ* data and atmospheric fields. Resulting parameter sets provided an efficient starting point for sensitivity studies.

Efficient, distributed, web-based HOPS. The initial coupling of HOPS/ESSE with Web-based front-ends and distributed-Grid computing software to improve efficiency of calculations has been completed.
Adaptive modeling for physical and biological estimates. A generalized biological model suitable for adaptation has been constructed and examples in Massachusetts Bay and Monterey Bay carried out.
MS-EVA. The MS-EVA methodology has been completed and applied to basic instability processes and a realistic study of the Iceland-Faeroe Front.
Multi-model estimates studied via both neural networks and Bayesian approaches. Practical aspects and efficient implementation of an Adaptive Bayesian Framework for Multi-Model Forecasting have been addressed. The method that determines spatially inhomogeneous relative model skill from forecast error parameters has been identified. Bias correction of model vertical structure via neural nets from the observed vertical profiles has been implemented.

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

RESULTS

1. FORECASTING AND DYNAMICS OF MONTEREY BAY AND CALIFORNIA CURRENT SYSTEM

Re-analysis of physical fields forecast in real-time. 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. The simulation was forced with the hourly 3km COAMPS analyses. Tuning the model first proceeded to improve stability. Especially important here were the open boundary conditions, which required the addition of a relaxation mechanism to the radiation conditions. With a stable simulation available, the tuning continued to best match the data. The simulation was repeated, with additional tuning, with the reprocessed glider data. Further details and simulation results are available at http://people.deas.harvard.edu/~leslie/AOSNII/REANALYSIS/.
The 4-dimensional re-analysis fields**:** the fields are available at the web site in the previous paragraph and from the web site http://aosn.mbari.org/.
Descriptive oceanography of the re-analysis fields. The descriptive oceanography of the ESSE error fields and of the OI re-analysis fields has been initiated, including the different stages of the upwelling and relaxation states, the establishment of the cyclonic circulation in Monterey Bay in upwelling conditions, the diurnal scales and the topography-induced small scales.
Multi-Scale Energy and Vorticity Analysis. The multi-scale dynamics of the Aug. 2003 AOSN-II circulation have been investigated. Processes are reconstructed on three mutually exclusive time subspaces: a large-scale window, a mesoscale window, and a sub-mesoscale window. The ocean is most energetic in the upper layers, and the mesoscale structures are primarily trapped above 200m. The dynamics underlying the surface circulation is characterized by a bimodal instability structure: a Bay mode and a Point Sur mode. Both modes are of mixed type, but are distinctly different in dynamics. The former is established when the wind relaxes; the latter is directly driven by the wind. Energy is stored in the large-scale window and then released to fuel mesoscale processes. Upon wind relaxation, the generated mesoscale structures propagate northward along the coastline, in the form of a free thermocline-trapped mode of coastally trapped waves.

Multi-model estimates and combined HOPS/ROMS results. The Adaptive Bayesian Framework for Multi-Model Forecasting was found to be well suited for a modeling environment with limited validation data, scattered observational network, and adaptive nature of the involved forecasting systems. An overall nowcasting/forecasting skill has been shown to improve when HOPS/ROMS products were combined (although not in real-time). It has been shown essential to treat the multi-model forecasting as a non-stationary problem that requires an adaptive version of a methodology, such as Bayesian model fusion via error parameter estimation. Neural net bias correction methodology has been successfully applied to HOPS vertical temperature profiles to dramatically improve detailed agreement with the observed profiles. Bayesian Multi-Model Fusion represents a computationally intensive task that has $O(n^3)$ computational complexity and $O(n^2)$ storage requirement (where n is the dimensionality of the state-space vector), which has been shown impractical for real-size forecasting systems. We have successfully worked around this difficulty by employing a randomized algorithm that cuts the computational complexity and storage to practical limits at a controlled expense of optimality. Our method is based on constructing and maintaining the “randomized sketches” of the full Bayesian Model Averaging matrices and updating the “randomized sketches” instead of their full high dimensional $O(n^2)$ counterparts.

Coupled biological-physical simulations. Our new, generalized, flexible biological model [4] was applied to the AOSN-II region. 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.

***Sensitivity studies for hierarchy of tidal representations*.** Impacts of tidal processes were evaluated. The principal barotropic tidal constituents were estimated in the region by a nested regional OTIS inversion, using the local tidal gauges as synoptic data and the global TPX05 fields as background and open boundary field. The sensitivity of mesoscale features to these tidal forcings was then studied. Numerical simulations using a hierarchy of simple to more complex parameterizations (e.g. bottom, vertical and/or horizontal-momentum Reynolds tidal stresses) were carried out. Tidal effects introduce smaller scales but also alter the shapes and positions of mesoscale features through tidal advections and mixing. The inclusion of (even simple) tidal parameterizations thus appears especially important for uncertainty estimates and adaptive sampling.

Skill metrics at data points. Quantitative skill metrics for physical fields (bias, RMSE and PCC) were computed and the physical fields found to beat persistence from 50 to 90 percent of the time.

2. Real-time regional forecasting exercises and regional dynamics

Maritime Rapid Environmental Assessment (MREA03) – Ligurian Sea – May/June 2003. Prior to the MREA04 exercise, a re-analysis of the HOPS forecasts of the May-June 2003 MREA03 exercise was performed. This re-analysis was motivated by observations of recurring mismatches between HOPS near surface structure and that observed in the CTD profiles. The general stability of the simulations was first improved with parameter tuning and slight modifications to the filtering and open boundary algorithms. Sensitivity studies on the model parameters (especially vertical mixing) produced a moderate improvement in the bias and RMS error between the simulation fields and a set of generally troublesome profiles. A much larger improvement was obtained by redistributing the vertical model levels to better resolve the near surface fields. Moderate improvement came by correcting the pre-processing of atmospheric fields to construct the net heat flux. A final, smaller, improvement came by revising the initialization procedures. Lessons learned were immediately applied when setting up for the MREA04 exercise. Comparisons are in http://oceans.deas.harvard.edu/haley/MREA03/Reanalysis/.

MREA04 – Portuguese Atlantic Coast – March/April 2004. HOPS provided real-time forecasts during the period 6-10 April 2004. A regional survey during 31 March - 6 April 2004 provided the initial state. Subsequent restarts were used to assimilate additional data gathered in the period 7-10 April 2004. Data gathered by the Alliance was transmitted to Harvard and used to support a pair of 2-way nested domains. The larger regional domain was defined based on the regional survey and maintained the external forcing for the smaller "super-mini" domain. The "super-mini" domain encompassed the primary focus area of the subsequent sampling and was extended to the coast (to resolve any coastal currents) and ~5km offshore (to provide a buffer to the coarser regional domain dynamics). System parameters were tuned during the course of the experiment to improve the near surface modelling, the spin-up of coastal currents and general model stability. The standard HOPS products for this experiment were horizontal maps and cross sections of temperature, salinity and velocity; regional domain PE output for use in acoustic simulations; temperature and salinity bias and RMS error estimates of the previous day's forecast against new data; and initial conditions and hourly boundary conditions extracted from the "super-mini" domain for a 24 hour period starting from 1000Z on day 1 for the "mini-HOPS" domains. Standard products are at http://people.deas.harvard.edu/~leslie/BP04/.

The “mini-HOPS” concept and its use in NATO Tactical Modeling are presented in [7].

Real-time regional forecasting and regional dynamics. Advanced operational forecasting systems in general are presented in [6] and the use of HOPS in operational and potential fisheries applications is discussed in [9]. HOPS has been utilized to forecast and investigate the synoptic circulation and transports in the Eastern Ligurian Sea [8, 10].

3. Methodology, System and Software Development

Adaptive sampling and OSSEs. The evaluation of the adaptive sampling carried out in real-time during AOSN-II shows that the large meander developing in the prediction prior to adaptive sampling and reduced by the assimilation of the R/V Pt Lobos data can be substantially reduced when re-calibrated data is utilized or some of the real-time data is not assimilated. The use of the full ESSE approach for adaptive sampling allows the quantitative 2-3 day prediction of the glider/ship path that reduces predicted uncertainties the most. The ensemble of candidate paths needs to be of $O(10)$ at most for the adaptive sampling computations to be carried out in real-time. If one assumes that the objective field is fixed (does not change while a rapid sampling of a few hours duration is carried out), the optimal path(s) can be computed exactly very rapidly, using modified integer programming. These algorithms and software continue to be developed.

ESSE software and error model development. 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.

Efficient, distributed, web-based HOPS. To improve the efficiency of HOPS, the initial coupling of HOPS/ESSE with Web-based front-ends and distributed-Grid computing software has been completed [11], in collaboration with Ocean Engineering at MIT.

Adaptive modeling for physical and biological estimates. The development of the conceptual basis of adaptive modeling for physical and biological estimates has been completed [2]. Illustrative examples in Massachusetts Bay and Monterey Bay were carried out to highlight ongoing progress. A generalized biological model suitable for rapid adaptation has been constructed [4].

Multi-Scale Energy and Vorticity Analysis. The Multi-Scale Energy and Vorticity Analysis (MS-EVA) methodology [5, 12] has investigated sub-mesoscale, mesoscale, and large-scale dynamical interactions in oceanic free jets. The MS-EVA has been used to diagnose the dynamics of the Iceland-Faeroe Front (IFF) [1]. The calculated energetics, when locally averaged, reveal that the formation of the observed mesoscale meander is a result of both a baroclinic instability and a barotropic instability, with the first dominant in the western region at mid-depths, with the latter more active in surface layers.

Interdisciplinary data assimilation in coupled models. 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 [3].

IMPACT/APPLICATIONS

Ocean Prediction Systems are at an early stage of significantly impacting and accelerating ocean science generally, as well as enhancing and enabling powerful new methods for the support of marine operations and the management of our coastal seas. Data assimilative systems can provide detailed, accurate and sustained multiscale estimates of interdisciplinary fields not feasibly attained by any other means. Important applications include naval submarine warfare, mine warfare and special operations; littoral homeland security of our coasts; response to accidental and aggressive pollution events, and management of living and non-living resources. The ocean itself is a natural complex system and ocean prediction system research can contribute to and benefit from progress generally in complex system science, conceptually, methodologically and computationally.

TRANSITIONS

Recently completed and continuing research transitions and collaborations include: MIT Ocean Engineering; NRL-Stennis; Naval Postgraduate School; NATO Undersea Research Centre; WHOI; SIO; JPL Pasadena; Univ. of Bologna, Italy; OGS-Trieste, Italy; CNR-Ancona, Italy; Cal. Tech.; U.Cal. - Santa Cruz; Monterey Bay Aquarium Research Institute (MBARI); Princeton University; Brown University; Portuguese Hydrographic Office; TNO-FEL, Netherlands; and U. Mass.-Dartmouth.

RELATED PROJECTS

This project enables, on an ongoing basis, our support of real time exercises and experiments (for ONR multi-institutional projects, NURC and others) with novel and state-of-the-art forecasts. During FY04 this project has been related to: the ONR multi-institutional projects AOSN-II (J. Bellingham - MBARI, Y. Chao - JPL, F. Chavez - MBARI, R. Davis - SIO, J. Marsden – CalTech, *et al*.); “Uncertainties and Interdisciplinary Transfers Through the End-to-End System (UNITES)”; “ASAP – Optimal Asset Distribution for Environmental Assessment and Forecasting Based on Observation, Adaptive Sampling, and Numerical Prediction” (N. Leonard – Princeton, J. Marsden – CalTech, R. Davis - SIO); and an NSF-OIT project “Rapid Real Time Interdisciplinary Ocean Forecasting Adaptive Sampling and Adaptive Modeling in a Distributed Environment” (N. Patrikalakis and H. Schmidt - MIT; J.J. McCarthy - Harvard). The ongoing collaboration with the NATO Oceanography Group – NURC (E. Coelho and M. Rixen) is demonstrated by the MREA04 exercise and planned future exercises. This project is intimately linked to the Harvard 6.1 research (“Dynamics of Oceanic Motions”) and several publications are jointly supported.

PUBLICATIONS

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