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THE DEVELOPMENT AND DEMONSTRATION OF AN ADVANCED FISHERIES MANAGEMENT INFORMATION SYSTEM

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1. INTRODUCTION

Fishery management regulates size and species-specific fishing mortality to optimize biological production from the fish populations and economic production from the fishery. Fishery management is similar to management in industries and in natural resources where the goals of management are intended to optimize outputs relative to inputs. However, the management of fish populations is among the most difficult. The difficulties arise because (a) the dynamics of the natural production system are extremely complicated; involving an infinitude of variables and interacting natural systems and (b) the size-and species-specific fishing mortality (i.e. system control) is difficult to measure, calibrate, and deploy. Despite the difficulties, it is believed that significant advances can be made by employing a fishery management system that involves knowing the short-term (daily to weekly) variability in the structures of environmental and fish fields.

We need new information systems that bring together existing critical technologies and thereby place fishery management in a total-systems feedback-control context. Such a system would monitor the state of the structure of all stocks simultaneously in near real-time, be adaptive to the evolving fishery and consider the effects of the environment and economics. To do this the system would need to (a) employ new *in situ* and remote sensors in innovative ways, (b) develop new data streams to support the development of new information, (c) employ modern modeling, information and knowledge-base technology to process the diverse information and (d) generate management advice and fishing strategies that would optimize the production of fish.

The Advanced Fisheries Management Information System (AFMIS), built through a collaboration of Harvard University and the Center for Marine Science and Technology at the University of Massachusetts at Dartmouth, is intended to apply state-of-the-art multidisciplinary and computational capabilities to operational fisheries management. The system development concept is aimed toward: 1) utilizing information on the "state" of ocean physics, biology, and chemistry; the assessment of spatially-resolved fish-stock population dynamics and the temporal-spatial deployment of fishing effort to be used in fishing and in the operational management of fish stocks; and, 2) forecasting and understanding physical and biological conditions leading to recruitment variability. Systems components are being developed in the context of using the Harvard Ocean Prediction System to support or otherwise interact with the: 1) synthesis and analysis of very large data sets; 2) building of a multidisciplinary multiscale model (coupled ocean physics/N-P-Z/fish dynamics/management models) appropriate for the northwest Atlantic shelf, particularly Georges Bank and Massachusetts Bay; 3) the application and development of data assimilation techniques; and, 4) with an emphasis on the incorporation of remotely sensed data into the data stream.

AFMIS is designed to model a large region of the northwest Atlantic (NWA) as the deep ocean influences the slope and shelves. Several smaller domains, including the Gulf of Maine (GOM) and Georges Bank (GB) are nested within this larger domain (Figure 1). This provides a capability to zoom into these domains with higher resolution while maintaining the essential physics which are coupled to the larger domain. AFMIS will be maintained by the assimilation of a variety of real time data. Specifically this includes sea surface temperature (SST), color (SSC), and height (SSH) obtained from several space-based remote sensors (AVHRR, SeaWiFS and Topex/Poseidon). The assimilation of the variety of real-time remotely sensed data supported by *in situ* data will allow nowcasting and forecasting over significant periods of time.

A real-time demonstration of concept (RTDOC) nowcasting and forecasting exercise to demonstrate important aspects of the AFMIS concept by producing real time coupled forecasts of physical fields, biological and chemical fields, and fish abundance fields took place in March-May 2000. The RTDOC was designed to verify the physics, to validate the biology and chemistry but only to demonstrate the concept of forecasting the fish fields, since the fish dynamical models are at a very early stage of development. In

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addition, it demonstrated the integrated system concept and the implication for future coupling of a management model. This note reports on the RTDOC.

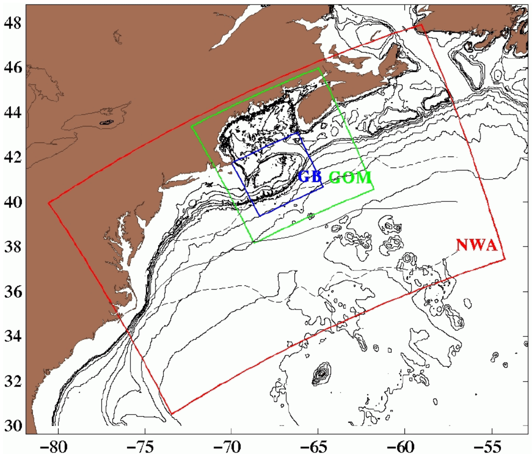

Figure 1. Modeling domains utilized in AFMIS

2. DEMONSTRATION AFMIS OPERATIONAL SYSTEM AND MODELS

The central dynamical models for the AFMIS RTDOC are contained with the Harvard Ocean Prediction System (HOPS). HOPS (see Figure 2a) is a flexible, portable and generic system for inter-disciplinary nowcasting, forecasting and simulations. The present system is applicable from 10m to several thousand meters and the heart of the system for most applications is a primitive equation physical dynamical model. The modularity of HOPS facilitates the selection of a subset of modules to form an efficient configuration for specific applications and also facilitates the addition of new or substitute modules. Data assimilation methods used by HOPS include a robust (suboptimal) optimal interpolation (OI) scheme and a quasi-optimal scheme, Error Subspace Statistical Estimation (ESSE). The ESSE method determines the nonlinear evolution of the oceanic state and its uncertainties by minimizing the most energetic errors under the constraints of the dynamical and measurement models and their errors.

The biogeochemical/ecosystem model used is a simple six-compartment (nitrate, ammonium, phytoplankton biomass, phytoplankton chlorophyll, zooplankton and detritus) ecosystem model. Trophic interactions are described schematically in Figure 2b. Phytoplankton productivity is modeled using a simple two-parameter photosynthesis-irradiance model. The irradiance field is modeled using a simple exponential attenuation model, with a chlorophyll dependent attenuation coefficient. With the exception of chlorophyll, all ecosystem compartments are nitrogen-based. Chlorophyll concentration and the nitrogen-based phytoplankton biomass are treated here as separate state variables; this allows incorporation of photoacclimation kinetics into the model framework. Several "optional" model configurations are available, including a spectral irradiance model coupled with a pigment-specific absorption based productivity model. In addition, detrital effects on light attenuation can be modeled explicitly (in the scalar irradiance model) using a detritus-specific attenuation coefficient.

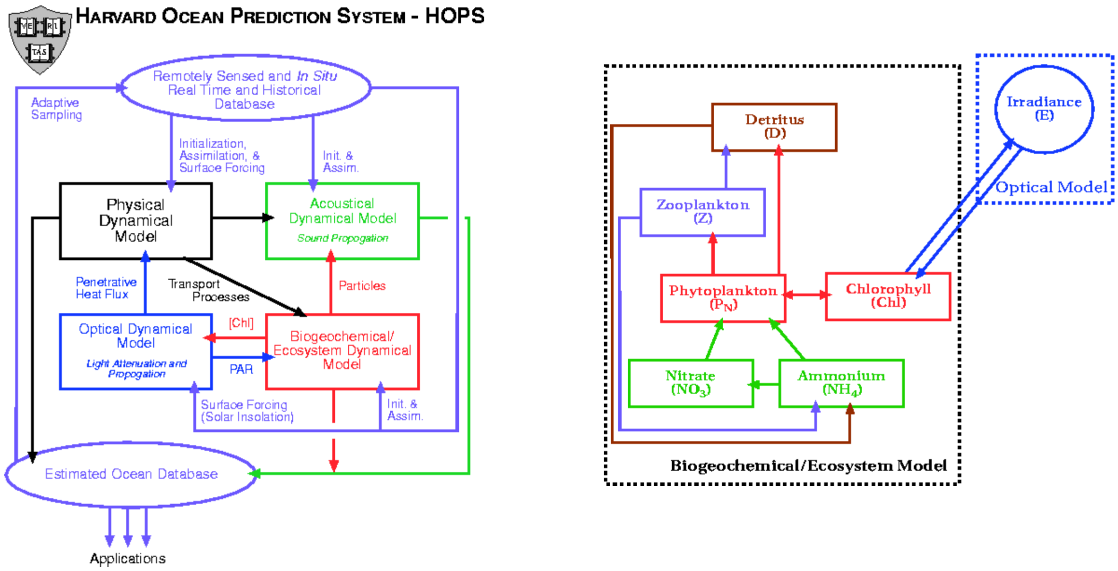

Figure 2 - HOPS system schematics. a) overall HOPS system, b) biogeochemical/ecosystem model

The initial focus in the formulation of the fish dynamics model component of the coupled model system is on two fish populations: cod and herring.

The state variables to be modeled and predicted are the abundances (mass densities) of life stages (or size classes) of selected species as functions of three dimensional space and time, hereafter referred to as fish fields. The space-time resolution of the fish fields is, of course, dependent upon the specific problem under investigation. The field equations for the fish variables conserve the abundances, taking into account sources (birth, metamorphosis, growth) and sinks (predation, death, metamorphosis), advection and behavior (vertical and horizontal swimming). Swimming behavior includes seeking favorable environmental parameters (e.g. temperature preference, location in the water column) and food, spawning and avoidance of predators. Density dependent dispersal of individuals is modeled statistically as a diffusive process acting upon the fish field, i.e. a flux down the gradient of the abundance. Seeking favorable conditions in response to the distribution of another field variable to which the fish are attracted is modeled as a flux up the gradient of the attractor. The term *taxis* applies to such tactic searching behavior.

Distributions and abundances of two commercial fish stocks, cod and haddock, were examined in relation to environmental variables over Georges Bank in the Northeast Atlantic. Historical CTD data and commercial catch report data are used to generate coarse monthly climatologies of catch per unit effort (CPUE), temperature, salinity, density, and stratification (Figure 3a-b). Using these climatologies, correlations between environmental variables and CPUE are used to establish seasonal, annual, and inter-annual relationships between fish stocks and their environment, and to develop predictive models for the distributions of the stocks over Georges Bank.

The empirical data show that both cod and haddock exhibit a tendency toward a preferred water temperature which varies varies seasonally from approximately 5.2 - 5.4 degrees C in winter/spring, rising to 9 degrees C during summer/fall (Figure 3c). Both species also show a slight affinity toward the more stratified regions of the bank during all times of the year. A simple analytical/numerical model demonstrates the predictive capability of such relationships, and indicates that bottom temperature alone accounts for 35% - 37% of spatial variance within the smoothed monthly distributions. The same model accounts for a much smaller percent of the observed catch variance in individual years. Correlations between total CPUE over the bank and the same environmental variables further indicate a significant but weak negative correlation (correlation coefficients between -(0.47 - 0.60) between bottom salinity values in fall and haddock abundances in winter/spring.

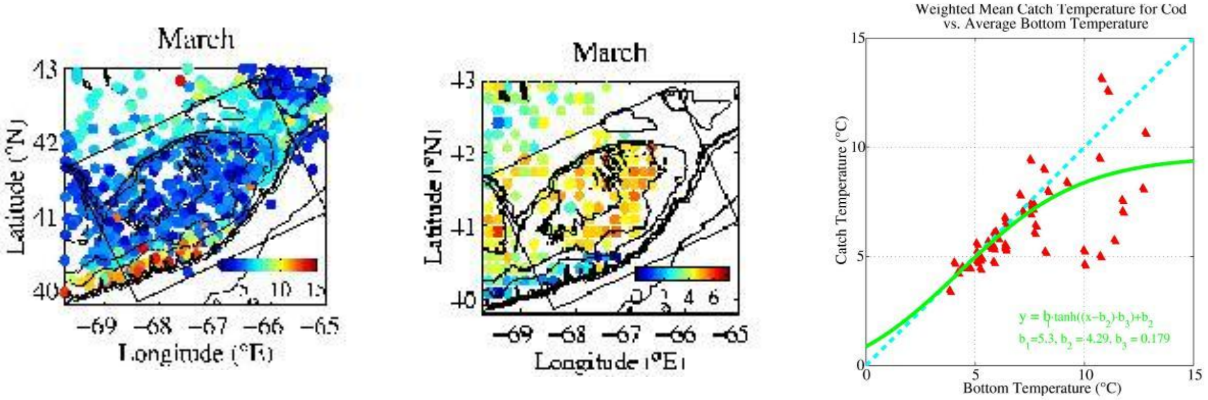

Figure 3: (a) Bottom temperature and (b) cod CPUE data coverage for the month of March over Georges Bank from 1982-1992; and (c) the empirical relationship between mean bottom temperature and CPUE-weighted catch temperature spanning all months of the same eleven-year period.

Initialization of any dynamical model requires the specification of each prognostic variable at each grid point of the three-dimensional model domain. An initialization methodology that requires limited number of observations and uses past synoptic information-based feature models was developed by Gangopadhyay *et al*. (1997) for the Gulf Stream Meander and Ring (GSMR) region. In a similar manner, a synoptic initialization scheme for feature-oriented regional modeling and synthesis (FORMS) of the buoyancy-driven circulation in this coastal-to-deep region has been developed by Gangopadhyay *et al.* (2000). For this coastal region, the circulation structures are characterized and parameterized based on their unique water-mass (T-S) and flow properties. These include the buoyancy-driven Maine Coastal Current (MCC), the Georges Bank anticyclonic frontal circulation system, the basin scale cyclonic gyres (Jordan, Georges and Wilkinson), the deep inflow through Northeast channel (NEC) and the shallow outflow via the Great south channel (GSC) (Brooks, 1985; Pettigrew *et al*., 1994). A schematic representation of their geographic extent is shown in Figure 4a.

To quantify the information needed for a feature-oriented regional modeling system representation, consider setting up a synoptic realization. Once the location of each of these features are identified from various data sources, for example, from broad-scale NMFS surveys, coastal moorings, buoy information, synoptic surveys and satellite imagery including AVHRR, Color and Altimeter (if possible) etc., the feature models can then be located in the model analysis domain. For example, the MCC is represented here by its three major segments with two bifurcation regions (near Bay of Fundy and near Penobscot Bay) and the trifurcating region near the GSC. The Georges Bank frontal system follows the topography very well, which is an advantage in locating these features. The strengths of the three subbasin scale gyres and the identification of anomalous features are the critical unknown in this feature model approach. The gyres' mean location and geographical extents are preset from observational studies as default.

In order to generate the three-dimensional initialization fields for the HOPS based AFMIS system, the temperature and salinity feature model fields are selectively sampled along and across the important features as shown in Figure 4b. The sampled fields are objectively analyzed with appropriate background seasonal climatology in the coastal region. These fields are then melded with synoptic GSMR feature model fields (Gangopadhyay *et al.*, 1997). The temperature and salinity fields from the GSMR feature models are first mapped and interpolated on the coastal regional domain grid points (deep fields). The deep and the shallow fields (T, S) are then blended along and across the shelf slope front. Experimental short-term synoptic forecasts are presented for different domains with different resolution are presented for the AFMIS RTDOC period in Gangopadhyay *et al.* (2000).

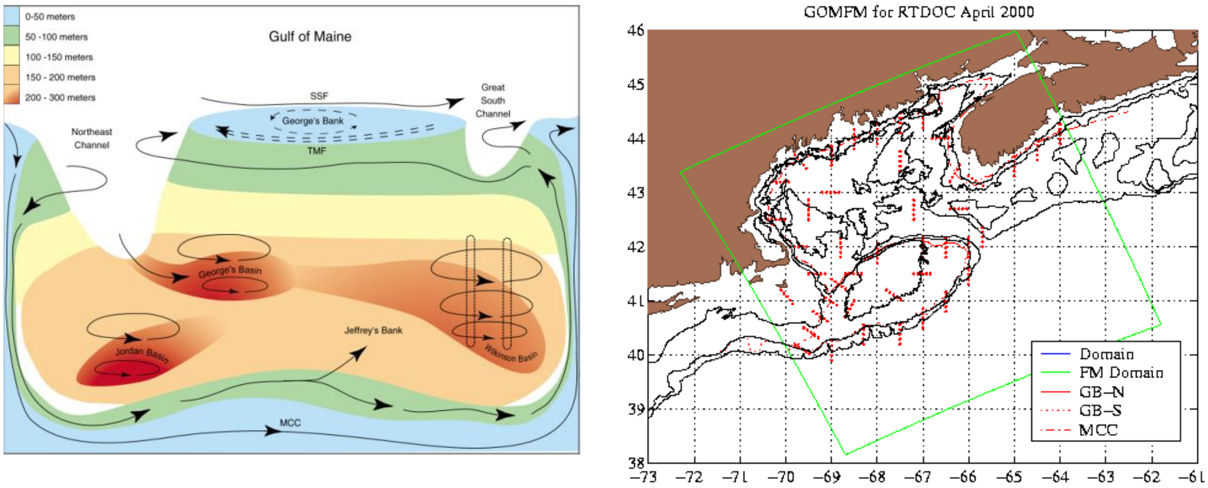

Fig. 4. a) A 3-D perspective of the circulation of the Gulf of Maine/Georges Bank system. The selected features of the coastal circulation system are shown overlaid on preferred topographic regions. The blue band signifies the 0-50m region, the green depicts 50-100m depths, the yellow band covers the 100-150m levels, the orange covers the 150-200m deep interior regions and the red regions are the 200-300m deep basins. MCC = Maine Coastal Current, TMF = Tidal Mixing Front, SSF = Shelf-Slope Front. b) A sampling strategy for the features model initialization scheme. Temperature and salinity profiles are sampled along and across the important features of circulation and then melded in background climatology for generating coastal ocean field. The coastal fields are then melded with the deep (GSMR) fields via the shelf-slope front to yield the initialization for the AFMIS simulations.

3. REALTIME DEMONSTRATION OF CONCEPT

The real-time demonstration of concept of forecasting physics, biology and fish stock abundances for fisheries management applications was carried out for Georges Bank from 17 April to 15 May 2000. The Georges bank forecasts and associated preliminary OSSEs in the nested GOM and WNA domains utilized primarily i) satellite data (sea surface: temperature (SST), color (SSC) and height (SSH)), ii) feature models, and iii) historical quasi-synoptic surveys adjusted to 2000 conditions by atmospheric fluxes. SeaWiFS SSC was interpreted as chlorophyll and extended throughout the mixed layer. The highly idealized fish dynamics model represented cod swimming behavior as an attraction to a preferred bottom temperature together with a dispersive tendency. The model was regarded as examplary rather than realistic.

The goals of the RTDOC were: 1) to demonstrate real-time nowcasting and forecasting of coupled physical, biochemical and fish distribution fields on Georges Bank for a period on the order of 1 to 2 weeks and 2) utilize the data obtained to produce information relevant to fisheries management. These goals were based on several hypotheses, including the assumption that a dedicated ocean prediction system (AFMIS) which properly incorporates the interaction processes and feedback between the three dynamics can nowcast and forecast state variables of interest and that fish abundance distributions vary over 1 to 2 week time scales in ways that are important for fisheries management and fishing. The demonstration of concept was structured to directly address these hypotheses by providing results in near real time to a variety of users.

Real-time forecasting for the RTDOC took place from late-March through mid-May 2000. Product packages were issued twice-weekly via the web and electronic mail from 17 April – 15 May. The product packages included daily maps of: sea surface temperature with superimposed vectors of sub-tidal velocity; chlorophyll at 15 meters; bottom temperature with superimposed vectors of sub-tidal velocity; Cod abundance; and, forecast tendency. Each product package included a description of the data utilized in the simulation and a discussion of the evolution of the fields included within the package. Examples of the fields produced are shown in Figure 5. The 15m temperature field (5a) shows cooling on Georges Bank as a result of tidal mixing and recent strong wind events. The chlorophyll field (5b) has evidence of enhancement by local tidal effects and wind-driven mixing of nutrients into the upper layers.

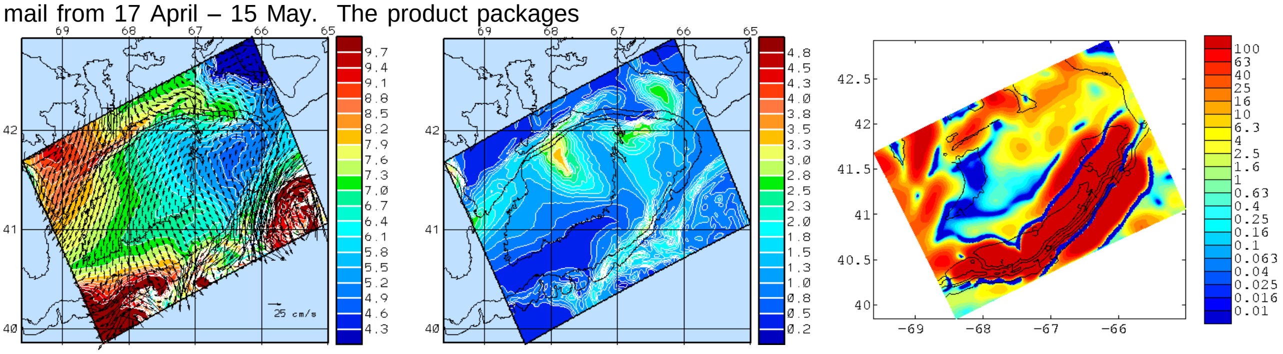

Figure 5 – Example RTDOC products for April 28, 2000. A) 15m temperature, b) 15m chlorophyll-a, c) bottom cod abundance forecast with an exemplary rather than realistic model.

4. CONCLUSION

The April/May 2000 RTDOC was successful in that a operational AFMIS Mark 1.0 for Georges Bank produced a sustained series of weekly nowcasts and forecasts of a selected suite of physical, biological and fish fields. We are presently working on AFMIS Mark 1.1, which will incorporate the depth-dependence of fish movement into the fish model. The evolution in the complexity of the fish model – a high priority for the future- will be guided by comprehensive suite of analyses of the fisheries database that has been developed (and is being continually updated) at CMAST. During the next year, as Harvard/CMAST scientists develop AFMIS Mark 2.0, AFMIS Mark 1.1 will become operational at CMAST. In addition to the revised RTDOC-like information products, we intend to begin regularly web-serving a suite of new data products, starting with satellite imagery.

5. REFERENCES

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