Implementing FORMS for the Monterey Bay Forecasting System Using HOPS and ROMS

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ABSTRACT

Our long-term goal is to implement the feature-oriented regional modeling methodology for the Monterey Bay (MB) forecasting system in retrospective and real-time operations using (i) the Regional Ocean Modeling System (ROMS) and (ii) the Harvard Ocean prediction System (HOPS). Three specific objectives were pursued to achieve our long-term goal: (i) to develop a synoptic high-resolution regional climatology for Monterey Bay and the California Current System (CCS), (ii) to implement the feature-oriented regional modeling system (FORMS) capabilities in the West Coast ROMS and HOPS modeling efforts for synoptic nowcast, forecast and 3D-VARS and ESSE-based assimilation in the Monterey Bay region, and (iii) to apply this methodology in real time within the nested ROMS and HOPS modeling efforts.

Significant progress has been made in three aspects. The elements of the circulation template for both the upwelling and relaxed phases of the Monterey Bay regional circulation have been identified. A major difficulty in this region has been quantifying the variability of water masses and their inter-relationship with the CCS. The effort to develop the regional climatology clearly pointed out the lack of data in many regions of the coastal as well as offshore regions. We have started a major effort in gathering data sets for the whole region: 20-50N, 140-110W. This regional climatology will be made available to the community at large. The feature models for the upwelling fronts and coastal eddies in the MBay region will be implemented in the background of this regional climatology for the HOPS and ROMS modeling groups for usage in the 2006 AOSN-II real-time experiment.

This grant (N00014-03-1-0206) has been requested to be consolidated with another grant (N00014-03-1-0411: FORMS-MODAS) for its continuation to the next phase from FY06. The title of the forthcoming proposal is: 'Developing a feature based analysis system for shallow water applications.' This proposal will address the issues raised to purse the long-term goals and objectives stated above.

APPROACH

The western coast of the U.S. includes both an offshore region and a very dynamic coastal region. The offshore region is primarily dominated by the large-scale California Current, the California Undercurrent, the inshore countercurrent and parts of subtropical and sub-polar gyre circulations in eastern Pacific. The coastal region includes features such as upwelling fronts, cold pools inshore of these fronts, filaments, squirts, mushroom-head vortices, mesoscale and sub-mesoscale eddies, and meanders.

In the FORMS approach (Gangopadhyay and Robinson, 2002; Gangopadhyay *et al.*, 2003), such structures and their parameterized forms can be implemented to characterize the relevant circulation entities. Such implementation requires careful and detailed scientific analyses to identify the spatial and temporal scales and variability that define and distinguish these features from one another while preserving their individual characteristics. After the major features are identified and their representations chosen, the latter are used in the initialization of a basic dynamical model (e.g., HOPS or ROMS). Dynamical adjustment accomplishes two important tasks: i) a consistent dynamical interaction of the features, and, ii) the generation of smaller scales, such as squirts and sub-mesoscale eddies. We will carry out a series of numerical experiments to implement the feature models in the CCS within the nowcast-forecast-assimilation framework of both ROMS and HOPS.

Figure 1 shows the different components of our overall approach in a conceptual flow-chart. Note that this approach is sufficiently generic for application to other numerical models.

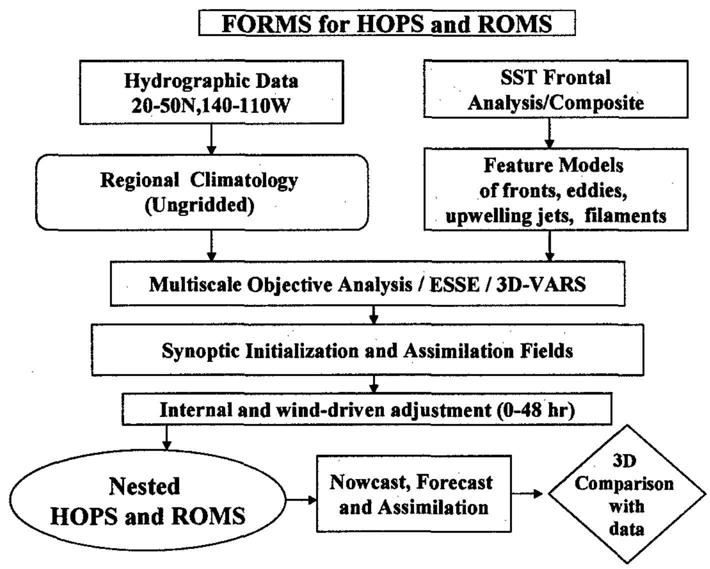

Figure 1: Our approach to FORMS implementation for HOPS and ROMS.

This is a collaborative project led by the University of Massachusetts and closely coordinated with Harvard (HOPS) and JPL (ROMS). Dr. Hyun-Sook Kim, an expert in numerical modeling and data synthesis joined the group as a Research Associate in September 2003 and has led the development of the regional climatology. Dr. Leslie Rosenfeld form NPS and Dr. Frank Bub from NAVOCEANO have been particularly helpful to provide data and expert support for this project.

RESULTS

During the first year of this project, it was realized that the circulation in the Monterey Bay region is highly variable on weekly time-scales and that the synoptic features in this region during both upwelling and relaxed periods are transient with 10-50 km characteristic scales. In order to resolve such synopticity, we decided to develop a high-resolution regional climatology for this region which will provide the background for such transient features of circulation. During the past year, most of our efforts were spent on acquiring data and developing a robust methodology for creating this high-resolution climatology for the month of August.

(1) High-resolution Regional Climatology Development

We developed a procedure for generating a high-resolution regional climatology estimate (*RClimo*) for the temperature and salinity fields off the coast of central California for the month of August. Such climatology might provide an alternative way for model initialization in a numerical nowcast/forecast exercise. The methodology includes two primary steps. These are: (1) averaging available data on a high-resolution grid and (2) objective interpolation to a regular grid. The uniqueness of this method lies in the elements of these two steps. The first step includes computation of averages over density layers in the vertical and allowing for data gaps in the horizontal due to unavailability of data at high-resolution. The objective analysis in the second step uses the correlation length scales derived from the data itself and an averaging radius to preserve the scales and variability of the synoptic fields.

The dataset used to develop this climatology includes the archived CalCOFI dataset, the recently concluded AOSN (I and II) experiments near Monterey Bay, and many other previously undocumented profiles from various sources. As part of the climatology product associated uncertainty is also generated, this would be useful for assessing errors in the forecast and assimilation exercises. Results of the error estimate suggest that uncertainty increases with larger grid-size and less data density. The relative percent error associated with *RClimo* estimate for the 50-km grid is less than 11% for temperature and 0.8% for salinity, whereas those for the 20-km grid are 9% and 0.7% respectively.

Figure 2 shows an example of the sparse-grid temperature climatology (left) and the resulting *RClimo* (middle) in contrast to the available 1/4th degree Levitus climatology for the month of August.

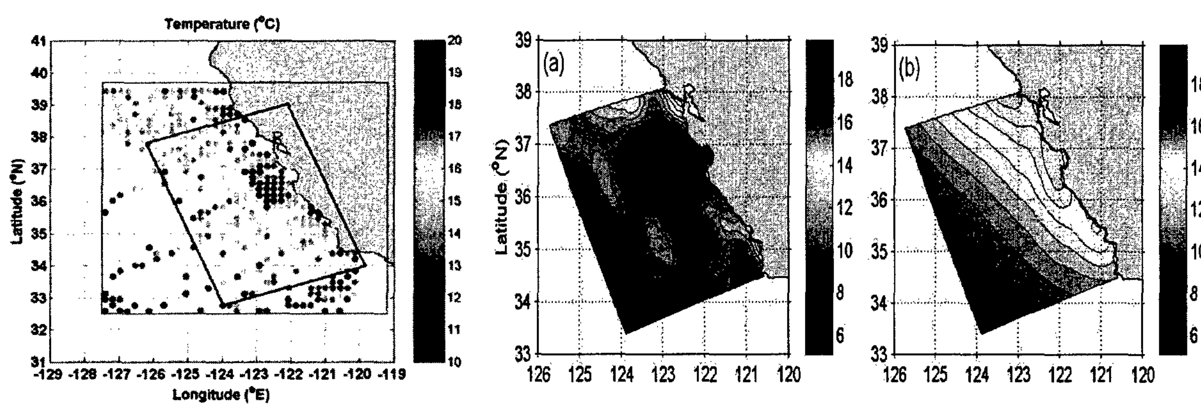

Figure 2: Sparse-grid regional climatology (20-km) temperature field at surface. Boxes represent the climatology region (thin line) and objective analysis domain (thick line).

We have performed benchmark simulations initialized with *RClimo* and the ¼-degree Levitus climatology initial fields, with and without wind-forcing. The 20-km RClimo simulations produced reasonably realistic features like filaments, fronts, meanders, eddies, alongshore currents (< 50 cm/s) and inshore undercurrents (~15 cm/s) under typical upwelling favorable winds. In contrast, the Levitus simulations showed insignificant evolution for most of the domain with or without winds. In these latter simulations, the currents over the simulation period are highly uniform with and without forcing applied. In the future, one could apply this methodology for other months/seasons in the Monterey Bay and implement this methodology for other regions of the world's coastal oceans.

During the AOSN-II experiment in August 2003, Gangopadhyay participated in analyzing the HOPS simulations in a research mode. It was clear from the beginning that this region is highly variable and inhibited by a number of different water masses due to various offshore-onshore interactions. A recent water mass EOF analysis using the MUSE 2000 data, carried out by Warn-Varnas *et al.* (2005), was used to identify the density layers associated with prevalent water masses in the Monterey Bay region (Fig. 3). The elements of the circulation template for both the upwelling and relaxed phases of the Monterey Bay regional circulation have also been identified. On the basis of our analysis prior to and during the AOSN-II experiment, we are now in a position to develop a circulation template for the Monterey Bay region. In summertime, the Bay circulation shows two distinct hydrographic states: upwelling (1-3 weeks) and relaxed (3-10 days). These two periods are related to the prevailing wind patterns and scales forcing such states. During the upwelling periods, the typical circulation in and around Monterey Bay consists of an upwelling front originating from Pt. Ano Nuevo, a cyclonic circulation inshore of the front in the Bay, an anticyclonic eddy-like circulation on the offshore of the upwelling front and another upwelling region off Pt. Sur. As the wind relaxes, the upwelling weakens, and the offshore eddy-like circulation (presumably part of the California Current meandering flow system) flows into the Bay and interacts with the flow over the shelf.

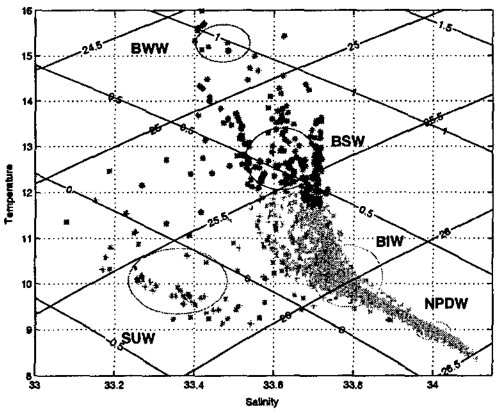

Figure 3. *T-S diagram for the five water masses (Bay Warm Water, Bay Surface Water, Bay Intermediate Water, Subarctic Upper Water and North Pacific Deep Water). Each of them occupies a distinct density-spiciness space.*

Figure 4 shows high resolution regional climatology temperature and salinity fields for August. The climatology is estimated at 2-km grid using the same method (Kim et al., 2005) from historical CTD samplings taken during the month of August. The final product shown in Figure 4 is the climatology field that was objectively analyzed in order to interpolate to a model grid size as well as to fill gaps in the climatology estimate. The climatology in Figure 4 exhibits a cold and saline tongue emanating from Santa Cruz and separating from warm and fresh bay water, which appears to be upwelling water. This is an example that can be utilized to build initial fields and boundary conditions also.

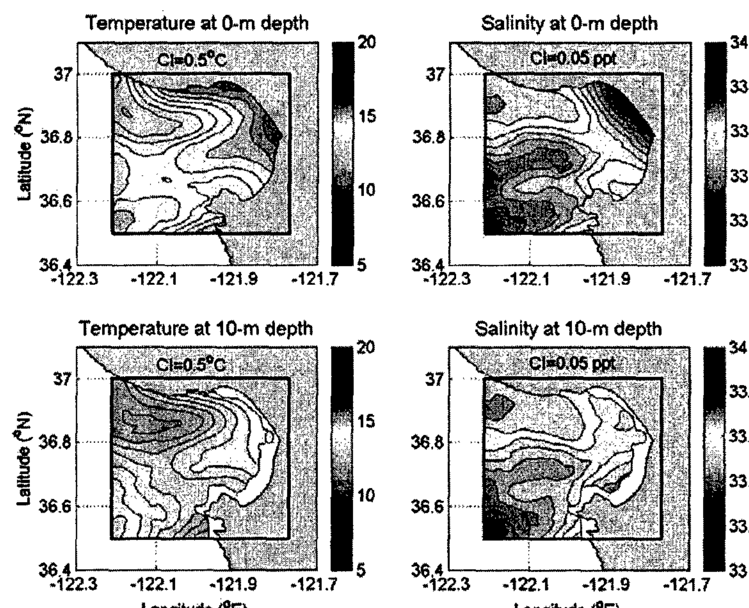

Figure 4. *Objectively analyzed high resolution regional climatology for August in Monterey Bay: temperature and salinity fields at the surface layer (top) and at 10-m depth (bottom).*

(2) Numerical Simulations

The climatological fields are being used for initialization of both ROMS and HOPS set of models with and without data and feature models. Those results will be published in manuscripts under preparation (Gangopadhyay *et al.*, 2005; Kim *et al.*, 2005). Here we present an example of a 15-day simulation with winds using *RClimo* and Levitus as initial conditions to ROMS (Figure 5).

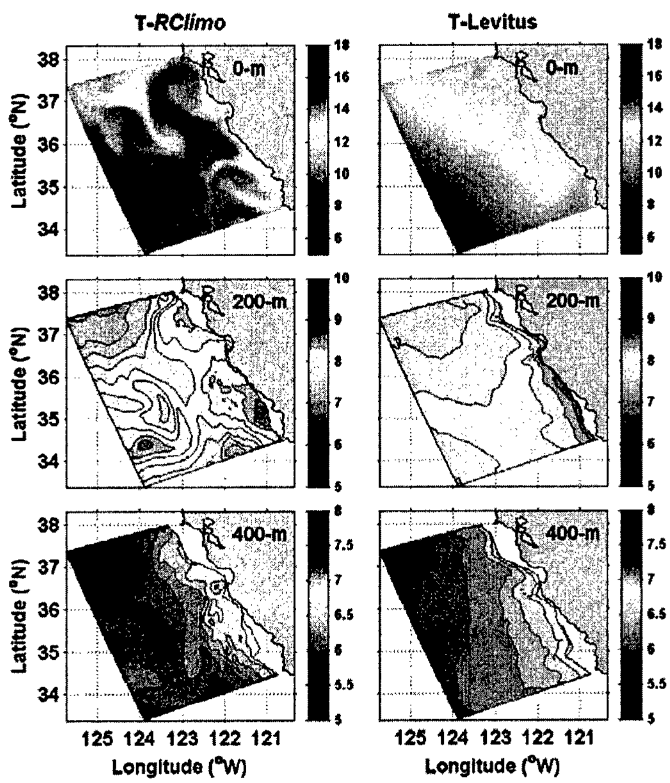

Figure 5. *Comparison of simulation day-15 temperature fields (contour interval = 0.2°C) with forcing for the RClimo (left) and Levitus climatology initial fields (right): (top) sea-surface, (middle) 200-m, and (bottom) 400-m depths.*

The surface layer simulations for both temperature and salinity with the *RClimo* initial conditions (Figure 5, left-top) show that highly organized filaments and fronts are developed over the domain, particularly off of Pt. Ano Nuevo, off of Pt. Sur and off of Pt. Conception. In contrast, no similar degree of variability is observed for the Levitus simulations (Figure 5, right column). With increasing depth, the meso-scale variability is persistent for the *RClimo* simulations (Figure 5, left middle and bottom), whereas the Levitus climatology simulations (Figure 5, right middle and bottom). Note that the offshore undercurrent in the RClimo simulation at depths of 200m and 400m is distinctly different from the inshore countercurrent; while the latter is the only poleward flow at depth in the Levitus simulations.

(3) Developing a SST climatology for the west coast of US

Additionally, we have developed a monthly SST climatology for the northeast Pacific (NEPAC) region (130-100W, 20-50N). This work was a collaborative effort with Dr. Ted Strub of Oregon State University. Eleven years (1992-2002) of AVHRR data was made available from the URI archive. Dr. Jorge Mesias was leading this research after a similar effort for western North Atlantic. Subsequently this work was completed by a graduate student, and the monthly fields are available from the Ocean Modeling and Analysis Laboratory at SMAST.

IMPACT/APPLICATIONS

Regional climatology on both sparse and regular grids will be made available to the community at large. Climatology on the basis of water masses would be useful to incorporate EOFs. The SST climatology will be useful for initialization and assimilation for hindcast studies. In the near future, we intend to extend the idea of high-resolution climatology for nutrients and chlorophyll data sets as well in collaboration with Dr. Francisco Chavez of MBARI.

RELATED PROJECTS

This research is part of the larger AOSN-II effort by Bellingham's group (Autonomous Ocean Sampling Network II (AOSN II): System Engineering and Project Coordination - N00014-02-1-0856). Closely related research on ROMS is that by Chao (Development of a Monterey Bay Forecasting System Using the Regional Ocean Modeling System (ROMS) - N00014-03-1-0208), and on HOPS is that by Robinson (Development of a Regional Coastal and Open Ocean Forecast System: Harvard Ocean Prediction System (HOPS) - N00014-97-1-0239). This project is also very closely related to another project to Gangopadhyay, which is entitled: "Integrating Feature-Oriented High-Resolution Synoptic Observations for MODAS" - N00014-03-1-0411. The work on regional climatology development is a collaborative effort with the UCSC group (McManus and Chavez -- Autonomous Ocean Sampling Network II: Assessing the Large Scale Hydrography of the Central California Coast - N00014-03-1-0267), and with the NPS group (Rosenfeld and Paduan) with Shulman (NRL), McGillicuddy (WHOI) and Haddock (MBARI) (Use of a Circulation Model to Enhance Predictability of Bioluminescence in the Coastal Ocean - N00014-03-WR-20009).

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14. ABSTRACT
Three specific objectives were pursued in this project: (i) to develop a synoptic high-resolution regional climatology for Monterey Bay and the California Current System (CCS), (ii) to implement the feature-oriented regional modeling system (FORMS) capabilities in the ROMS and HOPS modeling efforts for synoptic nowcast, forecast and 3D-VARS and ESSE-based assimilation in the Monterey Bay region, and (iii) to apply this methodology in real time within the nested ROMS and HOPS modeling efforts. Significant progress has been made in three aspects. The elements of the circulation template for both upwelling and relaxed phases of the Monterey Bay regional circulation have been identified. The regional climatology (20-50N, 140-110W) will be made available to the community at large. The feature models for the upwelling fronts and coastal eddies in the MBay region will be implemented in the background of this regional climatology for the HOPS and ROMS modeling groups for usage in the 2006 AOSN-II real-time experiment. This grant (N00014-03-1-0206) has been requested to be consolidated with another grant (N00014-03-1-0411; FORMS-MODAS) for its continuation to the next phase from FY06 under a new forthcoming proposal.

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