ABSTRACT

Successful ecological forecasting of fishery yields in the face of climate variability has eluded resource managers for decades. However, recent advances in observing systems, computational power and understanding of ecosystem function offer credible evidence that the variability of the ocean ecosystem and its impact on fishery yield can be forecast accurately enough and with enough lead time to be useful to society. The tools are now in place to provide ocean managers the capability to both protect and wisely use living marine resources. Advances in space-based real time sensors, high performance computing, very high-resolution physical models, and robust ecosystem theory make possible operational forecasts of both fish availability and ecosystem health. Accurate and timely forecasts can provide the information needed to maintain the long-term sustainability of fish stocks and protect the ecosystem of which the fish are an integral part, while maximizing social and economic benefits and preventing wasteful overinvestment of economic resources. We propose to enhance the current decision support system for the small pelagic fishery and upwelling ecosystem in the coastal ocean off Peru with remote sensing information and state-of-the-art coupled physical-biogeochemical three dimensional ocean models to provide operational forecasting and improve ecosystem management. This region is the best in the world for this implementation because it has the world's largest single-species fishery, the Peruvian anchovy, which is supported by the world's most variable ocean ecosystem. This variability is forced mainly by well understood climate variability. Because of the global importance of both the climate variability and the anchovy fishery, there are in place in this region well developed monitoring and decision support systems. No other ocean region has this combination of environmental observations, fish resources, fisheries monitoring and well validated climate forecast models for forcing high-resolution operational ecosystem models. Once implemented for the Peruvian anchovy fishery, these tools will be ported to decision support systems for fisheries along the US West Coast and made available to others working in similar environments of the world ocean.

1. Introduction and Background Information

For at least three decades physical and biological oceanographers have embarked on interdisciplinary observing and modeling programs based on the premise that prediction of the response of coastal ocean ecosystems to natural climate variability, man-made perturbations or different fish harvesting strategies is possible from the knowledge of a few biological, physical and meteorological variables. An important goal of these national and international programs (e.g., TOGA: Tropical Ocean Global Atmosphere, WOCE: World Ocean Circulation Experiment, JGOFS: Joint Global Ocean Flux Study, GLOBEC: Global Ocean Ecosystem Dynamics, CLIVAR: Climate Variability) was to understand these ecosystems and their living resources well enough to make predictions with adequate lead time to be useful to resource managers, but that goal has eluded us. In hindsight, it is clear that we lacked the ability to observe the appropriate variables with the necessary space and time resolution. Furthermore, computational limitations prevented modeling with adequate resolution to capture coastal ocean variability and, finally, the early models simply did not reflect the real physical and biological complexity of coastal ocean ecosystems.

1.1 Operational Forecasting of Marine Ecosystem and Fishery

Now, for the first time, the tools are in place to provide ocean managers the capability to both protect and wisely use the living marine resources of the ocean. Advances in space-based real time sensors, high performance computing, very high-resolution physical models, and robust ecosystem theory make possible operational forecasts of both fish availability and ecosystem health. All of these advances are recent, and now is the time to bring them together to form a powerful decision support system. Accurate and timely forecasts can provide the information needed to maintain long-term sustainability of fish stocks and protect the ecosystem of which the fish are an integral part, while maximizing social and economic benefits and preventing wasteful overinvestment of economic resources. This new power has been won by hard earned advances in technology and science. Previously, forecasting of how environmental variability and fishing pressure affected fish stocks and their ecosystem was impossible because we lacked efficient, high-resolution ocean observing systems to provide the data for assimilation into operational physical-biological models. Furthermore, until very recently computational performance was inadequate to run complex models at the space scales (kilometers) and time scales (hours) required for coastal ocean ecosystems forecasts. For the first time we can envision a clear path, free of crippling observational and computational constraints, to the goal of accurate, timely and efficient forecasts of fish availability and ecosystem health for use in the decision support processes of resource managers and policy makers.

Is this goal really attainable? The answer, almost certainly, is yes because of spectacular improvements in the necessary tools. Our confidence in the attainability of this goal is shared by others. The UK, for example, has recently created a nationwide project to implement operational ecosystem forecasts focused on the ecosystem health of the North Sea.

1.2 Peru Anchovy Fishery and Upwelling Ecosystem as a Model System

We propose to enhance the current decision support system for the small pelagic fishery and upwelling ecosystem in the coastal ocean off Peru with remote sensing information and state-of-the-art coupled physical-biogeochemical three dimensional ocean models to provide operational forecasting and improve ecosystem management. This region is the best in the world for this implementation because it has the world’s largest single-species fishery, the Peruvian anchovy, which is supported by the world’s most variable ocean ecosystem. The variability of the Peruvian anchovy and upwelling ecosystem is forced mainly by well understood climate variability in the form of the El Niño Southern Oscillation (ENSO) phenomenon (Neelin et al., 1998). The longer time scale (decadal to interdecadal) climate variability in the Pacific Ocean, namely the Pacific Decadal Oscillation (PDO), is also shown to have a major impact on the coastal upwelling ecosystem and fishery (Polovina et al., 1995; Mantua et al., 1997; Chavez et al., 2003). The regime transition around 1976-77 is particularly prominent and well documented (Zhang et al., 1997). Figure 1 shows that from 1976 to 1985 there was an anomalously warm period in that there was a virtual absence of cool nutrient-rich water along the Peru coast. The decadal association of the absence/presence of cool water with low/high anchovy catch implicates interacting ENSO and PDO variability in both boom years (1963 to 1971) and collapse (1973 to 1991).

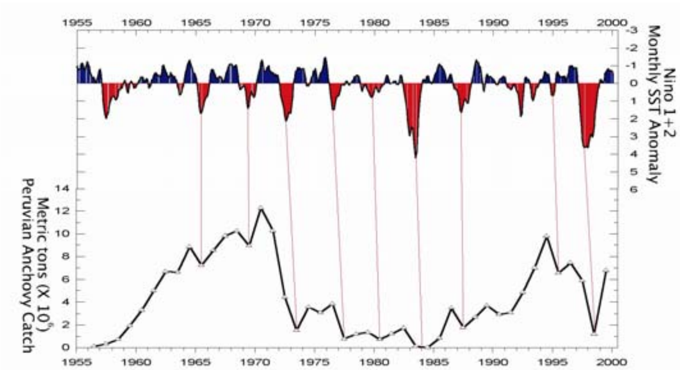


Figure 1. SST anomaly along the coast of Peru with the annual catch of Peruvian anchovy showing that each catch minimum is associated with a period of anomalously warm water. A warm SST anomaly means that warm water has been entrained into the upwelling cell due to ENSO-associated increases in surface layer heat content that deepen the thermocline. The nutricline also deepens so that the warmer water is also lower in nutrient concentration. SST anomaly is a proxy for nutrient concentration.

Because of the global importance of both ENSO and the anchovy fishery, there are in place in this region well developed monitoring systems (Figure 2). No other ocean region has this combination of environmental observations, fish resources, fisheries monitoring and well validated climate forecast models for forcing high-resolution operational ecosystem models. The Peruvian anchovy fishery and upwelling ecosystem is therefore an ideal model system for the proposed integration effort to implement an end-to-end decision support system. Once implemented for the Peru coastal region, the experiences and lessons learned can be directly applied to the U.S. West coast and similar ecosystems throughout the world ocean. To that end we propose an oversight board that includes U.S. end users to ensure that what is implemented off Peru is of immediate use to the U.S.

1.3 The Existing Decision Support Tools for Peruvian Fishery and Ecosystem Management

There are two separate anchovy stocks along the coast of Peru, the north-central stock that ranges from 3°30' to 16° S and the southern stock that ranges from 16° to 24° S (Chile). The proposed project will focus on forecasting the north-central anchovy stock and its changes in response to ENSO and PDO climate variability.

There are about 783 purse-seine fishing vessels with a total carrying capacity of about 150 thousand metric tons. Current regulations state that no new fishing vessels are allowed to enter the fleet unless they are built to replace an equally large existing ship. The Institute del Mar del Peru (IMARPE) determines the annual anchovy fishing quota based upon the following four independent methods to estimate anchovy biomass (Niquen et al., 2000a, b):

- hydro-acoustic research cruises take place during summer every year, and a second survey may occur in winter while assessing egg and larvae production;
- virtual population analysis uses anchovy length and body size information collected by IMARPE from fishery catches and independent data collected during cruises;

- population growth models estimate anchovy biomass assuming different natural mortality rates;
- egg production models estimate the abundance and distribution of eggs and larvae along the coast based upon cruise surveys.

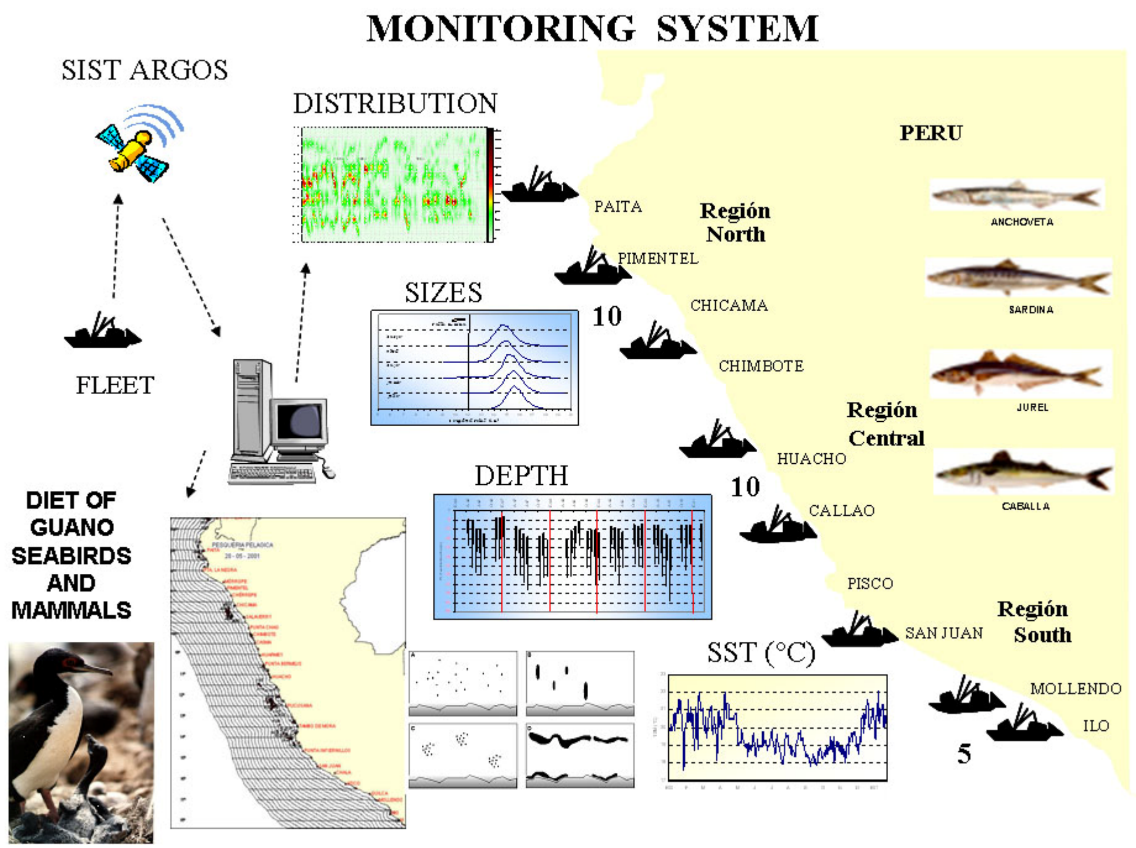


Figure 2. A graphical description of the monitoring system available for Peruvian fisheries. This effort is carried out entirely by our partners at the Instituto del Mar del Peru (IMARPE). Regular monitoring cruises for stock abundance and oceanographic conditions are supplemented by coastal laboratory efforts along the entire coast. The location of the fishing fleet is monitored by onboard ARGOS systems. Data on the diet of seabirds and marine mammals are also used. The data are integrated on a daily basis for the Production Minister (Figure 3).

All these estimates on anchovy biomass have been incorporated into the anchovy management measures for the coast of Peru. These, together with the data collected by the monitoring system described in Figure 2, serve as the basis for management (Figure 3). However, none of these four independent stock estimates incorporates NASA Earth science data and assimilation model forecasts of the Pacific climatic variability associated with ENSO and PDO as well as their impacts on the Peru coastal upwelling and the ecosystem response.

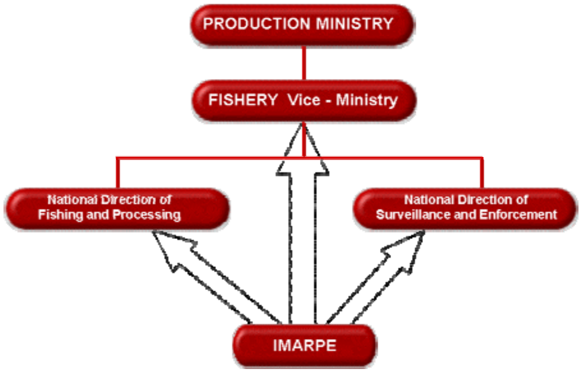


Figure 3. Flow of information from IMARPE to enforcement branches of the Peruvian government.

The proposed project will bring these NASA Earth science data and assimilation model forecasts into the existing stock estimate methods (or decision support tools) and make predictions of anchovy population at different life stages a few months in advance. The forecasted information will be useful for the ecosystem-based management. For example, the spatial distribution of large larvae and juvenile anchovy can be used to protect their survey rates by enforcing short fishing bans on a few specific regions based upon the model produced “hot spots.” Also, the longer fishing bans could be modified based upon the modeled adult spawning populations distribution; specifically it could make the bans more regionally dependent. Providing fisheries managers with a new independent forecasting approach will result in longer term management plans as well as much needed validation for decisions made on the basis of day to day observations. Success of the ecological forecasting developed as part of this proposal hinges on the direct involvement of our partners at IMARPE. The goal is to use scientifically sound information to maintain the long-term sustainability of living marine resources and protect the ecosystem while maximizing social and economic benefits and preventing wasteful overinvestment of economic resources.

2. Objectives and Significance

Our goal is to provide resource managers and leaders of the fishing industry in Peru with accurate, timely and efficient forecasts of fish availability and ecosystem health for use in their decision support processes. Once we demonstrate this capability, we will develop a plan to transfer the developed infrastructure and knowledge to resource managers and leaders of the fishing industry in Peru to enhance their existing decision support tools.

To accomplish this goal, this project brings together a collaborative team of meteorologists, physical and biological oceanographers, fishery scientists, resource managers, decision makers, and business leaders in an end-to-end system with the following objectives:

- Establish a benchmark (or baseline) of the current decision support tools used by decision makers managing the Peruvian upwelling ecosystem and anchovy fishery.
- Implement and refine a multi-scale (or nested) ocean general circulation model (OGCM) that is coupled with a biogeochemical process model and an anchovy population dynamical model for the coast of Peru.
- Assimilate both in situ and satellite observations into this multi-scale coupled physical-ecosystem-fishery model and demonstrate a real-time operational forecasting capability.
- Using the routinely issued El Niño climate forecasts with 3, 6, 9, and 12 months of lead time, issue forecasts of circulation, biological productivity and anchovy abundance and distribution along the coast of Peru with the same lead times; Given the variety among El Niño climate forecasts, provide a range of ecological and fishery forecasts based on the ensemble of different El Niño forecasts.
- Improve the ecosystem management process in the Peruvian coastal region by providing formal uncertainty estimates of the forecasts of anchovy availability and ecosystem function; quantify this improvement enabled by NASA Earth science data and assimilation model forecasts.
- Establish a communication system between the research team and the resource managers, decision makers, and business leaders so that the forecasts and forecast delivery system can be periodically reviewed and critiqued; experiences and lessons learned will be use to develop an implementation plan for the development of an operational ecosystem forecast around the U.S. coastal oceans and transition from research demonstration to real-time operations.

Applying ecological forecasting and ecosystem management for the Peru coastal upwelling system will protect and maintain sustainability of living marine resources. In the near term, successful forecasting of the key biological, physical and meteorological properties will both maximize return from the anchovy fishery and protect and maintain its sustainability; in addition, it will minimize societal expenditures during periods of unfavorable conditions. In the long term, successful ecological forecasting in the Peru coastal upwelling ecosystem will show the global community that ecosystem-based management can be accomplished using a synthesis of the powerful tools now being used in contemporary Earth science. Once implemented for the Peruvian anchovy fishery, the knowledge and lessons learned can easily be applied to other coastal regions around the U.S. and throughout the world ocean.

3. An End-To-End Integrated System for the Peruvian Upwelling Ecosystem and Anchovy Fishery

The proposed "end-to-end" integrated system for the Peruvian upwelling ecosystem and anchovy fishery will build upon several major NASA funded data analysis and modeling efforts. Funded by NASA as part of the National Oceanographic Partnership Program (NOPP) during 2000-2004, several investigators of this proposal (Chavez, Barber, Chai, Chao) have developed a multi-scale modeling capability for the coastal ocean with a coupled physical-ecosystem model. An ongoing effort funded by the NASA Interdisciplinary Science (IDS) team (Barber, Alexander, Chai, Chao, Chavez) has extended the coastal coupled modeling effort into the whole Pacific Ocean and is developing a data assimilation system with forecasting capabilities. This proposal will capitalize on these NASA funded research efforts and deliver an end-to-end integrated system for managing the Peruvian upwelling ecosystem and anchovy fishery.

Figure 4 shows the architecture for the proposed end-to-end integrated system using the Earth science data and models to produce forecasts of circulation, ecosystem function and anchovy abundance and distribution to support the decision support processes of the Peruvian

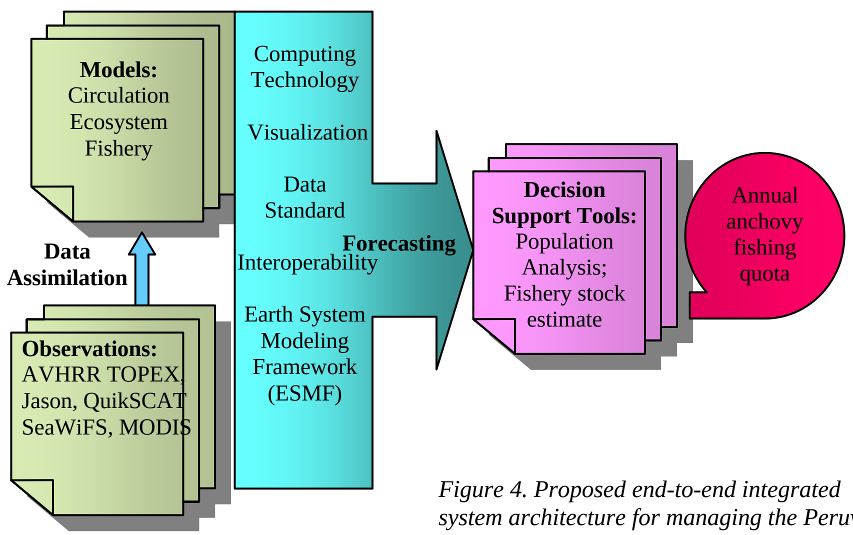


Figure 4. Proposed end-to-end integrated system architecture for managing the Peruvian upwelling ecosystem and anchovy fishery.

upwelling ecosystem and anchovy fishery. Figure 4 summarizes the system architecture and the individual system components are described in detail in the following sections.

3.1 NASA Satellite Observations

NASA satellite observations play a critical role in the proposed work, particularly in providing near real-time data for assimilation. Most of the physical oceanographic data sets can be obtained from the JPL Physical Oceanography DAAC (http://podaac.jpl.nasa.gov), including sea surface temperature, sea surface height and ocean vector winds. High-resolution, near real-time ocean color data sets are essential in validating our ecosystem modeling component and estimating variations in nitrate and potential new production. We plan to utilize the chlorophyll data from MODIS, Terra and Aqua satellites, which can be obtained from the GSFC DAAC.

In addition to satellite observations, we will also utilize a variety of *in situ* observational data sets including historical and ongoing field observations conducted by the Institute del Mar del Peru (IMARPE). The IMARPE data include: (1) historical and ongoing seasonal survey data of temperature, salinity, nutrients and chlorophyll, and (2) information on anchovy eggs, biomass, and fish length along the coast. For the equatorial region near the Peru coast, we will use data from the existing TAO array. In addition to satellite and *in situ* oceanographic observations, we will utilize a variety of other fishery related information, particularly those data sets going back to the 1960s, such as anchovy and sardine catch records and biomass estimates.

A value-added surface wind product has been developed with a particular focus on coastal applications (Chao et al., 2003). Atmospheric wind forcing plays an important role in driving ocean circulation and variability, and atmospheric circulation over the ocean is modified close to continents by coastal topography, creating small-scale variability in the wind field. Alongshore upwelling-favorable wind off the Peru coast drives Ekman transport that moves surface water offshore, and the transport divergence at the coastline draws deeper water towards the surface. But coastal winds are difficult to measure from space due to land contamination, and the complex spatial and temporal sampling of the scatterometer further introduces noise to the gridded wind maps. To deal with these complexities, we have developed a blended wind product from atmospheric models and satellite scatterometers. The initial demonstration for this blended wind was carried out successfully off the central California coast (Chao et al., 2003). This proposal will apply the same technique off the Peru coast.

3.2 Modeling the Pacific Ocean Circulation and its Response to ENSO and PDO

To complement the NASA satellite surface observations, we plan to use a 3-dimensional ocean circulation model with data assimilation. The goal is to reproduce the real-time conditions (also known as nowcasts) of the Pacific Ocean circulation and variability associated with ENSO. The proposed modeling component is based on the Regional Ocean Modeling System (ROMS). ROMS solves the primitive equations in an Earth-centered rotated Cartesian system of coordinates. The Boussinesq approximation (i.e. where density variations are neglected everywhere except in the gravitational force) is used. ROMS is discretized in coastline- and terrain-following curvilinear coordinates.

Funded by the NASA Interdisciplinary Science investigation program, a 3D Pacific basin-scale ocean circulation model has been developed with a spatial resolution of 50 km. With the recent installation of the Columbia supercomputer at the NASA Advanced Supercomputing Division (ranked as the #2 supercomputer in the world), the spatial resolution of this Pacific ROMS has been refined from 50-km to 12.5-km, approaching eddy-resolving resolutions. At this eddy-resolving resolution, we expect that simulation of key oceanographic processes will be significantly improved. For example, Tropical Instability Waves (TIWs) are realistically reproduced (Figure 5). Similarly, energetic mesoscale eddies associated with both the western and eastern boundary currents are clearly evident in the simulated sea surface temperature.

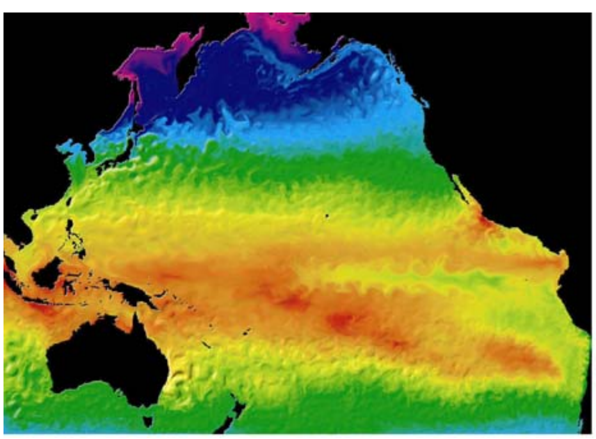


Figure 5. Snapshot of a simulation by the 12.5-km Pacific basin-scale ROMS 3D ocean circulation model; shown are sea surface temperatures (in color) and sea level slope (shaded relief). The model is capable of reproducing Tropical Instability Waves (TIWs) as well as mesoscale eddies near the western and eastern boundary currents.

3.3 Modeling the Peru Upwelling System

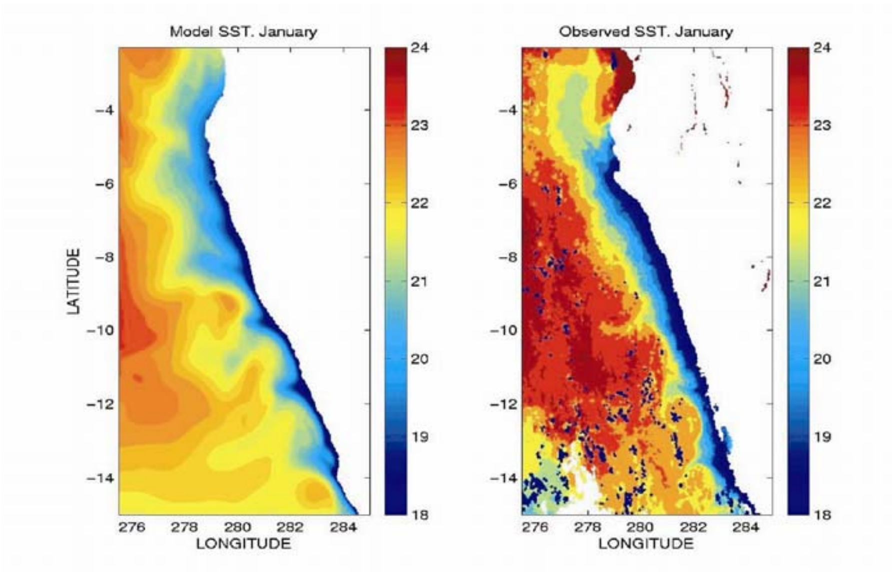


Figure 6. Comparison of a simulation of sea surface temperature (SST) by the 3D ROMS ocean circulation model at 4-km resolution (left panel) with observed AVHRR satellite SST (right panel) for the Peru coastal upwelling system during January.

Using the above described Pacific basin-scale model solution as the boundary condition, we plan to develop a higher resolution regional model centered around the Peru coast. Using the same ROMS code for both basin-scale and regional modeling makes it easier to maintain a smooth transition between the two model solutions at apparently different spatial resolutions. As a first test, we have developed a regional ROMS off the Peru coast at 4-km resolutions. Preliminary results simulating the Peru upwelling conditions during the climatological annual cycle have been successful (Figure 6).

Discrepancies between the satellite observations and the 4-km ROMS simulation are also apparent. For example, there are obvious differences in the northern part of the model domain, suggesting potential problems near the model northern boundary. The 4-km coastline and bottom topography appear much smoother than reality. It is also possible that the Peru upwelling and the associated mesoscale eddies require a much finer spatial resolution. During the course of this project, we will conduct several sensitivity experiments in order to find the best agreement between the available observations and ROMS simulations. Possible model improvements include 1) using a more realistic coastline and bottom topography, 2) placing the northern boundary of the model away from the region of interest, and 3) further refining the spatial resolution approaching 1-km. The goal is to provide the best description of the Peru upwelling system and its response to ENSO, which are required to build predictive capability for the physical circulation and ecosystem response.

3.4 Coupled Physical-Ecosystem Modeling

The ecosystem model was developed to investigate biogeochemical cycling (Chai et al., 1996), systematically tested against observations (Barber et al., 1996) and reproduces well the Low-Silicate, High-Nitrate, Low-Chlorophyll (LSHNLC) conditions in the equatorial Pacific. The current biogeochemical model consists of 12 compartments describing two size classes of phytoplankton (P1, P2) and zooplankton (Z1, Z2), detrital nitrogen (DN) and detrital silicon (DSi), silicate ($Si(OH)_4$), total CO_2 and two forms of dissolved inorganic nitrogen: nitrate (NO_3) and ammonium (NH_4), which are treated separately, thus enabling division of primary production into new production and regenerated production, oxygen (O_2), and phosphate (PO_4).

Below the euphotic zone, sinking particulate organic matter is converted to inorganic nutrients by a regeneration process similar to the one used by Chai et al. (1996), in which organic matter decays to ammonium and then is nitrified to NO_3. The flux of particulate material is

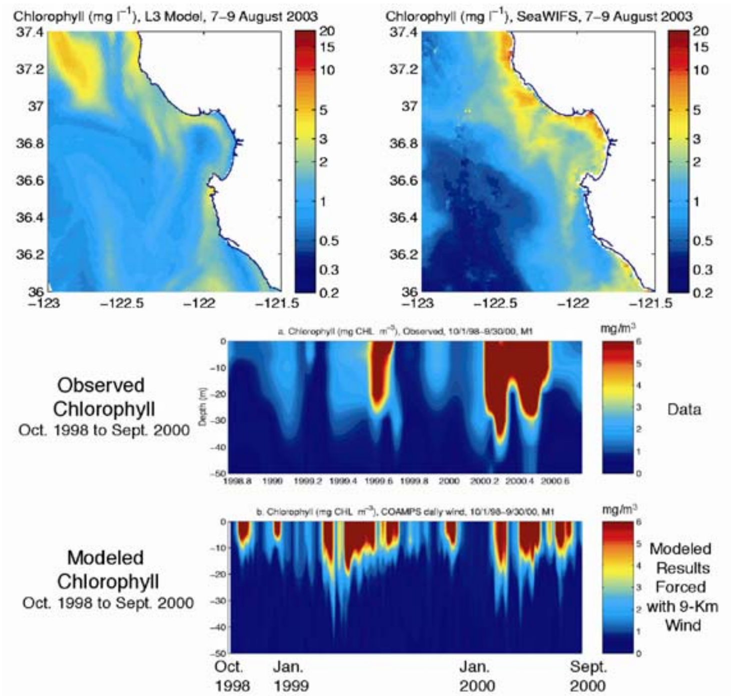


Figure 7. The top two panels show a comparison of a simulation of sea surface chlorophyll by the 3D ROMS physical-biogeochemical coupled ocean circulation model at 1-km resolution (left panel) with observed SeaWiFS satellite chlorophyll (right panel) for the California upwelling system during August 7-9, 2003. The bottom two panels show the observed (top) and modeled (bottom) chlorophyll comparison at the M1 mooring in Monterey Bay from late 1998 to late 2000. The model was forced with the 9-km operational daily wind (COAMPS).

specified using an empirical function from Karl et al. (1996). Incorporating oxygen into the biogeochemical model adds extra constraints on the treatment of regeneration processes in the model, and there are many dissolved oxygen measurements along the coast of Peru. Silicate regeneration is modeled through a similar approach but with a deeper regeneration depth profile, which reflects the tendency of biogenic silica to have higher preservation efficiency compared to other particulate organic matter (Ragueneau et al., 2000). The detailed equations and parameters used for the biological model were described in a paper by Chai et al. (2002). The ecosystem governing equations have been coupled both to Pacific basin-wide OGCM (Li et al., 2001; Chai et al., 2003a) and the regional OGCM off the California coast, see Figure 7.

3.5 Anchovy Population Modeling

One of the most dramatic ecological effects during ENSO is the significant reduction in the catch of Peruvian anchovy (Figure 1). The anchovy feeds mainly on diatoms and lives less than 3 years. The anchovy stock is very sensitive to environmental conditions. Using the 1982-83 El Niño as an example, the dramatic decrease in phytoplankton primary production decreased growth, survival, and reproductive success of anchovy. Growth and survival were affected because adult anchovy feed directly on phytoplankton so that larval survival and reproduction depend upon its abundance. Consequently, reproductive success was reduced during the 1982-83 El Niño (Barber and Chavez, 1986). These combined larval and adult processes reduced the anchovy catch to record low levels in 1983.

In order to link phytoplankton biomass with growth, survival, and reproduction of anchovy,

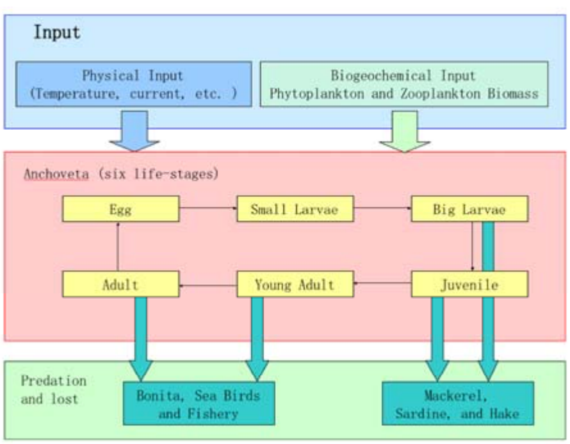


Figure 8: A schematic diagram of an anchovy population model with six life stages, and its linkages with the output from the 3-D physical-biogeochemical model.

an anchovy population model with six life stages will be developed in collaboration with the Peruvian scientists and managers, who currently use mainly statistical models for estimating anchovy stocks. The anchovy population model we will use (Figure 8) includes the egg, yolk-sac larvae, late larvae, early and late juveniles and adults, and simulates the biomass and the transition of the anchovy population from each phase. The environmental conditions (temperature and currents) and food availability (phytoplankton and zooplankton biomass) are directly linked with growth and fecundity rate in the model. The natural mortality rates will be estimated and linked with the guano-producing seabird populations (Jahncke et al., 2004) and historical data of other fish populations, such as mackerel, sardine, and hake (Pauly and Tsukayama, 1987; Pauly et al., 1989). Fishing mortality will be constrained with anchovy catch data, which are available on a monthly basis.

The anchovy population model simulations are driven from the physical-biogeochemical model output for the period from 1950 to the present. The simulated results will be evaluated and constrained with anchovy population survey data collected by scientists at the Institute del Mar del Peru (IMARPE), one of the partners on this project. By coupling the population model with a realistic three-dimensional physical-ecosystem model for the coast of Peru, we can model the spatial distribution of each life stage of the anchovy population, and their changes in abundance in response to El Nino and La Nina variability. The anchovy population forecast will be used as a new and independent anchovy biomass assessment for use as a decision support tool.

3.6 Forecasting the Peru Upwelling Ecosystem and Anchovy Fishery

Recognizing the complexity of forecasting Pacific climate variability and its impact on marine ecosystems and fishery, we will apply two different but independent approaches for forecasting the Peruvian ecosystem to provide a decision support tool for fisheries management.

Dynamical Forecasting

Great progress has been made regarding different aspects of El Nino and Southern Oscillation (ENSO) in the past several decades. A hierarchical modeling strategy has been developed to understand and predict ENSO. This includes simplified conceptual models, intermediate coupled models, hybrid coupled models (OGCM coupled to a simple atmospheric model) and coupled OGCMs to AGCMs. Several institutions have developed operational ENSO forecasts, which produce monthly and seasonal forecasts out to 12 months on a daily basis. Since last August, the National Centers for Environmental Prediction (NCEP) has implemented such a forecasting system, which produces daily air-sea surface fluxes, such as wind stress, heat and freshwater fluxes, etc. These forecasted fluxes, with up to 12 months lead time, will be used to drive our physical-biogeochemical-anchovy model for the coast of Peru. The physical-biogeochemical model will be integrated forward from the present conditions to forecast temperature, circulation and phytoplankton and zooplankton biomass, which are used to drive the anchovy population model for the coast of Peru. In turn, the anchovy population model will produce both adult and egg anchovy population distributions along the coast, 12 months out from the present conditions. The forecasts will be delivered to fishery managers, who will incorporate them into their decision support system for improving anchovy management.

We also use ENSO forecasts from other institutions, such as the International Research Institute (IRI), the Australian Bureau of Meteorology Research Centre (BMRC), and the European Centre for Medium-Range Weather Forecasts (ECMWF) to force our multi-scale, multi-process model for Peru and compare the forecasts. By doing so, we will have a suite of forecasts representing different initial ocean and atmospheric states, a crucial factor in forecasting climate variability. Using the ensemble climate forecasts, our system produces a range of ecological and fish availability forecasts in response to the range of uncertainties in the climate forecasts. The ensemble approach in ecological modeling and forecasting has been highlighted in a recent review article by de Young et al. (2004).

Statistical Forecasts

We will also use a statistical forecasting approach for the coastal region of Peru. Statistical forecasts can complement the dynamical forecasts, as they are relatively easy and economical to perform and, for some applications, have more skill than the dynamical model. Our primary tool will be a Linear Inverse Model (LIM) in which the dynamical properties of a system can be obtained directly from the observed statistics. LIM assumes that a system can be separated into a linear deterministic portion and a nonlinear portion that can be represented by white noise - random fluctuations that are correlated in space but not over time. The deterministic portion, the part that would be used in forecasts, is essentially given by multiple linear regressions. However, the full LIM allows one to test several aspects of the forecasts, including its error characteristics.

LIM has been used to study and predict many aspects of the climate system (e.g. Farrell and Ioannou, 1995; Zhang and Held, 1999; Winkler et al. 2002), and has been used extensively at the Climate Diagnostics Center (CDC) to make forecasts of SST anomalies in the tropical Pacific associated with ENSO that have skills at lead times of up to 18 months (Penland and Magorain, 1993; Penland and Sardeshmukh, 1995). While these forecasts vary geographically (see http://web1.cdc.noaa.gov/forecasts/for4.html), they are based on coarse resolution (4º lat x 10º lon) data and used only SST observations. We will explore improving LIM by including higher resolution SST data obtained from the 50 km physical model hindcast and by including thermocline depth, a key variable in both physical and ecosystem dynamics (Barber and Chavez, 1983 and 1986). Given that the observed records of most biological fields are relatively short and that including too many predictors can actually degrade forecasts, we will not include ecological variables directly within LIM. Instead, we will develop independent measures of the relationship between SST and/or thermocline depth with ecologically relevant variables such as chlorophyll concentrations or anchovy biomass. These relationships can be estimated using multiple linear regression or non-linear statistical methods and can be derived using satellite measurements or from the physical-ecosystem model hindcast. For example, Chavez et al. (1989) used multiple linear regression to relate thermocline depth anomalies to nitrate concentration and primary productivity in the Peruvian upwelling system.

4. Project Management, Roles and Responsibilities

The PI, Dr. Francisco Chavez, will be responsible for the overall management of the project. He has over twenty years of experience in coastal upwelling ecosystems and has recently managed a multi-disciplinary modeling project funded by NASA through NOPP (http://www.mbari.org/nopp).

The core team (Barber, Chai, Chao, Chavez) has been working on an ongoing NASA IDS effort led by Prof. Barber focusing on linking ocean physics to ecosystem variability. Dr. Yi Chao from JPL is a physical oceanographer/meteorologist with expertise in 3-D ocean circulation modeling. He will be responsible for providing the NASA satellite data and working on the physical modeling and data assimilation. Professors Richard Barber and Fei Chai are biological oceanographers with considerable experience in coastal upwelling systems and have responsibility for the ecosystem model and its linkage to fisheries.

New partners have been added to this interdisciplinary team to provide the needed expertise to connect with the anchovy fishery and decision making processes. Renato Guevara is scientific director and Miguel Ñiquen is head of a small pelagic research group at the Instituto del Mar del

Peru (IMARPE). They have over twenty years experience working on the Peruvian small pelagic fishery. Guevara is responsible for providing the Production Minister with stock and quota estimates. The decision on quotas is ultimately made by the Production Minister but rarely if ever does it not follow IMARPE's advice.

5. Integrating Remote Sensing and Modeling into Operational Fisheries Management

The principal role of IMARPE is to provide the Peruvian government with advice regarding the health of a stock and the maximum level of harvest to maintain a healthy stock. It is extremely important to IMARPE, both nationally and internationally, to demonstrate that their decision support system is solid and supported by the best and most current information. In other words IMARPE will be very eager to adopt the remote sensing and modeling tools. Clearly IMARPE is not in the position to launch satellites or maintain supercomputers so that material will need to be provided routinely. The key to a successful integration will be the early involvement of the users and early demonstration of the utility of the system. We have little doubt that we can transition the tools to IMARPE.

Schedule

The proposed statements of work are summarized in Table 1 in terms of major tasks, task descriptions, evaluation criteria and milestones that can be tracked by the proposed schedule (Table 2).

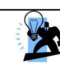
The described tasks will be accomplished over a period of three years. These tasks will be evaluated against the success criteria described in Table 1. The major milestones and their delivery dates are shown in Table 2. Critical dates when the project reports and milestones are submitted are also listed in Table 2.

Table 1. Proposed tasks, descriptions, evaluation criteria and milestones.

Task	Task Description	Evaluation Criteria	Milestone
Manage data & model	Identify data formats and data sharing protocols for providing observational data and model derived products to decision making partners	Both observational data and model-derived products can be delivered to our decision making partners	IT server
Decision Support Tools (DST) benchmarking	Benchmark decision support tools currently being used by the decision making partners	Establish a quantitative measure of the decision support tools so that its subsequent improvement enabled by NASA data and models can be further quantifies	DST-Benchmark
Pacific climate modeling	Develop a high-resolution Pacific Ocean model that can assimilate both *in situ* and satellite observations	Deliver the nowcast/forecast of the Pacific ocean circulation and climate to our decision making partners	ROMS- Pacific
Peru upwelling modeling	Develop a multi-scale (or nested) model that is able to simulate the Peru upwelling system	Deliver the nowcast/forecast of the Peru upwelling circulation to our decision making partners	ROMS-Peru
Coupled physical-ecosystem modeling	Develop a coupled physical-ecosystem model for both the Pacific basin-scale climate and the Peru upwelling system	Deliver the nowcast/forecast of the Peruvian upwelling ecosystem to our decision making partners	Model-Eco
Peruvian fishery modeling	Develop a population model to simulate the Peruvian fishery	Deliver the nowcast/forecast of the Peruvian anchovy fishery to our decision making partners	Model-Fish
DST-New	Integrate the developed NASA	Deliver all the developed NASA Earth	DST-New

	Earth science data and model forecasts into the DST; Compare the improved DST with the DST-benchmark	science data and model forecasts in a timely manner to our decision making partners	
Transition to operations	Develop a transition to real-time operations	Define the hardware and software; complete training of local scientists and decision makers	Transition-Plan

Table 2. Project schedule, milestones and their delivery dates.

ID	Milestone	Year 1				Year 2				Year 3			
		1	2	3	4	1	2	3	4	1	2	3	4
0	Project start												
1	IT Server												
2	DST-Benchmark												
3	ROMS-Pacific												
4	ROMS-Peru												
5	Model-Eco												
6	Model-Fish												
7	DST-New: test												
8	Training-I												
9	DST-New: demo.												
10	Training-II												
Annual Reports													
Transition plan from research to operations													
Final Project Report													

To ensure the success of the proposed tasks, we propose a test of the individual data and modeling component and system integration in year 2. The goal of this early testing is to make sure that the data format and standard and the modeling infrastructure can meet the proposed success criteria. Problems identified during this early test and lessons learned will be used to refine our proposed data and modeling components as well as the system integration.

An important part of the transition plan from research demonstration to real-time operations is to involve the local scientists and decision makers from Peru as early as possible. In the proposed schedule, we plan to host at least two working sessions with the following objectives:

- to introduce the developed NASA Earth science data and assimilation model forecasts,
- to start the training process of local support staff, and
- to collect application users' input and feedback.

According to the proposed task listed in Table 1, each task manager will provide regular (at monthly project conference calls and annual face-to-face meetings) updates to their individual schedules and milestones. These tasks are evaluated against the evaluation criteria as well as the milestone delivery dates as described in Table 2. If potential slips are identified, the PI in consultation with the project team will develop alternative schedules for the task at risk.

Performance Measures and Management Metrics

The Principal Investigator (PI), Dr. Francisco Chavez from Monterey Bay Aquarium Research Institute (MBARI), is responsible for the scientific integrity of the project and is the final authority on all issues. Our proposal team consists of an experienced physical oceanographer/meteorologist (Chao) and biological oceanographers (Barber, Chai), as well as fishery and population scientists (Guevara, Ñiquen). Such a broad representation of disciplines will ensure the success of our proposed tasks by sound planning, open communication, and reliance on the experience of our team members.

The PIs of this proposal will plan and implement a set of processes and practices that will assure effective accomplishments of the proposed tasks. The PI is responsible for management of the schedule as the primary tools in tracking performance. A master project schedule will be created at the start of this project and maintained during the 3-year project. Each project element schedule will consist of specific tasks with milestones depicting activities matching the Statement of Work in this proposal. Critical paths will be established to ensure the subsequent implementation of future tasks. Our specific tasks include:

Year 1

- Set up a project web site and establish data formats and data sharing protocols for providing observational data (both in situ and satellite) and model derived products to decision making partners
- Develop the ability of assimilating both in situ and satellite observations into the proposed Regional Ocean Modeling System (ROMS)
- Develop a high-resolution ROMS configuration for the Peru coastal ocean linking the physics with ecosystem
- Benchmark the existing Decision Support Tools (DSTs) currently used by decision makers managing the Peruvian upwelling ecosystem and anchovy fishery

Year 2

- Develop a population model for the Peruvian anchovy fishery which includes environmental information
- Develop forecasting capabilities for the Peru coastal ocean including biological, physical and meteorological conditions
- Provide both hindcasts and forecasts to decision makers for use as a decision support tool in managing the Peruvian upwelling ecosystem and Anchovy fishery
- Compare the improved decision support tool with the DST benchmark and quantify the improvement

Year 3

- Refine the multi-scale and multi-process modeling and forecasting system if necessary
- Full integration of NASA remote sensing measurements and assimilation model forecasting products into our partners' DSTs for real-time operations
- Develop a transition plan from research and development to real-time operations
- Submit final project report and submit peer-review manuscripts for publications

Each task manager will provide regular updates to their individual schedules and milestones. If potential slips are identified, the PI will develop alternative schedules for the task at risk. Another performance measure is to evaluate the milestones identified in this proposal. The evaluation of milestones can be achieved through the receivable/deliverable process, based on the project master schedule. We will establish and maintain a baseline of critical and minor deliverables for the various project elements.

One of the biggest challenges of a distributed team is ensuring that communications and information sharing are timely and accurate. We will use common information tools or linkage of member organization tools to transfer needed data products within the project. A web site will be established that serves both internally within the project team and externally to outside users. The project will continue to use voice and data networking. These tools include a DocuShare on-line library and Net Meeting software. In addition, JPL maintains a teleconference facility that can be used at no cost to this proposal to facilitate regular and *ad hoc* interactions.

In addition to monthly teleconference to exchange progress among team members, the project performance will be evaluated every six months using a variety of metrics including schedule, technical performance, and cost. This evaluation can be conducted through either informal or formal review processes. If the performance metrics are violated, the PI will organize all-hand meetings (via phone, internet or face-to-face if necessary) to come up with specific recommendations of alternative solutions or termination to a particular task.

Throughout the course of this project, the PI will keep the NASA HQ program managers well informed of the status of the project. Annual reports and the final project report will be distributed to both the program managers and our DST partners.

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