Collaborative Research:

GLOBEC Pan-regional Synthesis:

Pacific Ocean Boundary Ecosystems: response to natural and anthropogenic climate forcing

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Ecosystem Modeling:	*Franks, Bracco and Di Lorenzo*
Physical Observations:	*Bograd, Thomas and Strub*
Biological Observations:	*Keister, Peterson, Franks, Bograd and Thomas*
Statistical Modeling:	*Mendelssohn, Peterson, Schwing and Di Lorenzo*
IPCC climate coupled model:	*Chhak and Schwing*

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Canadian Collaborators*: D. Mackas*

Intellectual Merits: Large-scale decadal Pacific climate indices such as the Pacific Decadal Oscillation (PDO) have been linked to changes across multiple trophic levels of marine ecosystems along the eastern and western boundaries. Recent studies of the Northeast Pacific by the PIs show that other independent climate modes are equally important in explaining changes in coastal ocean upwelling and transport dynamics – the fundamental processes controlling regional nutrient fluxes and planktonic ecosystem dynamics. This suggests that the interplay of forcing functions associated with multiple large-scale climate modes must be considered to adequately diagnose the dynamics and mechanics underlying variations in regional ecosystems. With this framework, our study combines extensive national and international in situ and satellite observations with numerical and statistical physical-biological models to diagnose the response of four Pacific boundary ecosystems to large-scale natural and anthropogenic climate forcing. The focus regions are: *the Gulf of Alaska (GOA), the California Current System (CCS), the Peru-Chile Current System (PCCS), and the Kuroshio-Oyashio Extension (KOE) region*. We approach this goal through four core research objectives. **(1)** Assess to what extent, and by what mechanisms, large-scale climate modes (e.g. PDO, NPGO, ENSO, and others) drove coherent changes across Pacific boundary ecosystems over the period 1960-2007. **(2)** Quantify and explain how changes in regional ocean processes (e.g. upwelling, transport dynamics, mixing and mesoscale structure) at each boundary control phytoplankton and zooplankton dynamics. Then, use those results to test the degree to which changes in each study region reflect bottom-up control of their respective ecosystems. **(3)** Quantify the extent to which changes in the statistics of shorter-period events (e.g. intraseasonal oscillation, timing of spring transitions) during different phases of the longer-period climate modes (e.g. PDO, NPGO and others) determine the climate state of boundary-current ecosystems. Finally, **(4)** explore the range of uncertainties in the response of regional ocean dynamics and their ecosystems to climate change using forcing scenarios from selected climate model integrations that are part of the IPCC 2007 report. This last objective begins an assessment of the potential impacts of climate change on regional ocean ecosystems, a topic poorly addressed in the latest IPCC report, but the chief instrument for most fisheries and coastal management.

The success of these analyses relies on the diverse expertise of the PI's, which include physical-biological observations (*Keister, Peterson, Strub, Bograd and Thomas*), numerical regional ocean-ecosystem modeling (*Di Lorenzo, Franks, Bracco and Chhak*), statistical physical-biological modeling (*Mendelssohn, Peterson, Schwing and Di Lorenzo*) and IPCC coupled climate model projections (*Chhak*). These PIs are supported by a collaborative team from Chile, Japan and Canada.

Broader Impacts: This study will provide an improved and unified understanding of low-frequency ecosystem dynamics in the economically vital eastern and western boundaries of the Pacific Ocean. It will also deliver new methodologies for assessing the uncertainties associated with regional climate change in marine ecosystems with direct implication for fisheries management and future assessment of the IPCC. The project team represents a close collaboration of academic and government scientists, and the research will be conducted with the support of international collaborators from South America, Japan and Canada. These collaborations will provide training for both international and US students through scientific exchanges, expanding the international network for both the PIs and foreign collaborators. Four young PIs will be supported (*E. Di Lorenzo, J. Keister, K. Chhak and A. Bracco*), including three female scientists, two of which have no previous NSF support or other sources of funding. Activities and results from this project will also extend to the undergraduate students through REU programs, and underserved high-school students through the SMILE (Science and Math Investigative Learning Experiences) Program.

Results from prior NSF support

Emanuele Di Lorenzo: OCE-0550266**.** **$**199,323 03/01/2006-02/28/2009 Collaborative Research: Eddy-Dynamics and Impacts of Low-Frequency Variations in the California Current System

Summary of Results: Using high-resolution ocean model hindcasts with the Regional Ocean Modeling System (ROMS) we show that low frequency variations of salinity, nutrients and chlorophyll-a observed in the Northeast Pacific between 1950-2004 are controlled by a previously unrecognized large-scale mode of variability that we term the North Pacific Gyre Oscillation (NPGO). Inverse calculations with the ocean model showed how the coastal upwelling cell along the CCS exhibits spatially non-uniform decadal variations along the coast tracking the PDO north of 38°N and the NPGO south of 38°N. The ocean model hindcasts were also used to separate the deterministic and intrinsic variability associated with the eddy field over the entire Northeast Pacific. In the Gulf of Alaska the large-scale eddies in the eastern basin, which drive important ecosystem variability, are directly forced by the atmospheric winds. In contrast eddies in the western basin are generated by intrinsic ocean variability.

Development of Human Resources: One student and one postdoc (not funded through this grant) contributed to the articles published through this grant.

Publications: 6 papers published or submitted related to this grant.

Data sets and Public Service: All the model hindcast and reanalysis products are accessible to the broader community through an OpenDAP server http://dods.o3d.org:8080. The models developed have been made available to the NSF-LTER California Current Ecosystem at Scripps-UCSD.

P. Ted Strub: OCE-0000900. $1,129,210. Period: 2-1-00 to 1-31-06. GLOBEC NEP: Satellite-Observed Ocean Variability.

Summary of Results: Analyses of satellite and other data described and quantified variability in the CCS and Alaska Current System on intraseasonal (mesoscale), seasonal and interannual (El Niño and other) time scales. Physical and biological (CHL-a) aspects of the CCS were compared to other Eastern Boundary Currents in the Pacific and Atlantic Oceans. The evolution of the 1997-98 El Niño was traced from the equator into the NE and SE Pacific Ocean. International collaborations resulted in several papers describing the physical-biological interactions of the coastal ocean off Chile and comparing the EBC's of the world ocean, as well as details of seasonal climatology and El Niño variability along the Chilean coast. Two papers were also written summarizing the GLOBEC NEP Program.

Development of Human Resources: One post-doc, five graduate students and two research associates participated in the work reported above.

Publications: Twenty-three peer-reviewed papers or book chapters were partially or completely funded by this grant.

Data Sets, Public Service: Satellite SST data over the CCS for the period 1992-present were acquired, archived and made available over the web at OSU, along with satellite surface pigment data provided by Andrew Thomas (http://coho.coas.oregonstate.edu). Some of these data were also used in curricular material developed for the OSU Science and Math Interactive Learning Experiences program (http://smile.oregonstate.edu/).

Andrew Thomas: OCE-0531289. $289,486. Period: 5-1-05 to 4-30-08. Large-scale Influences on Mesoscale Structure in the California Current System: A Synthesis of Climate-forced Variability in Coastal Ecosystems.

Summary of Results: **In a Collaborative GLOBEC proposal with Franklin Schwing, Steven Bograd, Roy Mendelssohn** (NOAA) we focused on characterizing basin-scale ocean-atmosphere variability, linkages between large-scale forcing and mesoscale response in the CCS and coastal Gulf of Alaska and especially the variability of CHL-a in the CCS and its relationship to both local and non-local forcing and circulation. We separate components of seasonal, interannual and sub-seasonal CHL-a temporal variability over the entire CCS, comparing these to SST variability and showing links to the PDO. Comparisons of the timing of spring CHL-a development with the onset of upwelling reveal a latitudinal shift in dominant forcing. Negative CHL-a anomalies in the northern CCS in spring 2005 were related to wind anomalies and components of the higher trophic level ecosystem. CHL-a variability in the GOA was dominated by eddies: a satellite altimeter based objective technique provided a 15-year census of GOA eddies. We also quantified the relative contributions of freshwater, heat flux, wind and tidal mixing to spring CHL-a timing. International collaborations with South American colleagues produced two chapters in *The Sea* and a paper in OMBAR, reviewing recent views of eastern boundary current processes, patterns and socio-economic impacts.

Development of Human Resources: At U.Maine: One Masters student, 2 research associates, 2 post doctoral fellows and 1 high school summer student receive(d) support from this grant. At NOAA: Two post-docs and three research associates participated in the work reported above.

Publications: 15 publications from U.Maine and 11 from NOAA PIs were wholly or partially supported by this grant.

Data sets and Public Service: Data products developed as part of this proposal, along with other GLOBEC NEP data sets, are currently being served to the community through a Live Access Server located at NOAA ERD. Others are served through the GLOBEC NEP data server at OSU.

Peter Franks: OCE02-20111. $360,919 06/01/2002-05/31/2006 GLOBEC-01: Zooplankton Population Dynamics on Georges Bank: Model and Data Synthesis

Summary of Results: We have developed an unstructured grid coastal ocean model system for the Gulf of Maine (GoM)/Georges Bank (GB) region. This system includes a) a modified fifth-generation community mesoscale atmospheric model (MM5), b) an unstructured grid Finite-Volume Coastal Ocean Circulation Model (FVCOM), c) a generalized lower trophic level food web model, and d) multi-stage zooplankton models. 4D nudging data assimilation was implemented in FVCOM to incorporate NASA satellite altimeter data, satellite-derived insolation (data source: ISCCP), satellite-derived SST, remote sensing reflectance (RSR) as well as broad-scale hydrographic survey and moored current data.

We have coupled a 9-component lower trophic food web model with FVCOM. This model was tested using 1D, 2D and 3D experiments with the vertical diffusion parameterized by a modified Mellor and Yamada level 2.5 turbulent closure scheme and light intensity computed from the mesoscale meteorological model (MM5) output.

Development of Human Resources: In Franks' lab one postdoc and two graduate students were supported on this project. The larger award supported 3 additional graduate students, and 2 additional postdocs.

Publications: Over 20 papers published or submitted related to this grant.

Data sets and Public Service: FVCOM is now available to the community, and is being used by several groups for research and applied problems. The model was used by other GLOBEC researchers to assimilate data to aid in their analyses.

Note: **Julie Keister is a full PI** in this proposal and will be faculty at UW when this research takes place. For logistical reasons during submission, Russ McDuff's name (UW) appears in her place until her position there begins.

1. Introduction

Large-scale fluctuations in Pacific Ocean ecosystems on interannual to decadal timescales have been directly observed during the last 50-100 years *[Lluch-Belda et al., 1989; Loeb and Rojas, 1988; Kawasaki and Omori, 1988; Mantua et al., 1997; Mantua and Hare, 2002; Wada and Oozeki, 1999; McFarlane and Beamish, 2001; Chavez et al., 2002; Nakata and Hidaka, 2003; Peterson and Schwing, 2003; Alheit and Niquen, 2004]* and inferred from proxy data over the past 1000-2000 years *[van Geen et al., 1992, Baumgartner et al., 1992; Sandweis et al. 2004]*. These fluctuations include dramatic changes in the reproductive success, population sizes and distributions of commercially and culturally important species (*Schwartzlose et al. [1999]*, *Bakun [2005]*, *Chavez [2005], Theil et al. [2007]*). Management issues often focus on annual and interannual time scales, where changes in the large-scale circulation are at work *[Freeland et al., 2003; Thomas et al., 2003; Strub and James, 2003; Grantham et al., 2004]*. However, the underlying causes and mechanisms through which these fluctuations impact ecosystems often involve changes on shorter time scales. These include the timing of physical and biological seasonal transitions ("phenology", *Chiba et al. [2006]; Kosro et al., [2006]; Hickey et al., [2006]; Schwing et al. [2006]; Thomas and Brickley, [2006]; Henson and Thomas, [2007a]*), and the timing and intensity of intra-seasonal signals (equatorially originating long-period internal waves, synoptic storms, etc. *[Barth et al., 2007; Legaard and Thomas, 2007]*). Thus, insight into the causes of longer-period fluctuations and their potential impact on ecosystems requires understanding of shorter-term changes in local forcing as well as the longer-period changes in large-scale ocean processes, including circulation, stratification, and mixing.

Using U.S. and international GLOBEC (and other) data sets, and both modeling and observational expertise spanning physical and biological processes, **we propose to investigate the mechanisms of climate-related variability in four Pacific boundary ecosystems: the *Gulf of Alaska (GOA),* the *California Current System (CCS),* the *Humboldt or Peru-Chile Current System (PCCS),* and the *Kuroshio-Oyashio Extension (KOE)* region.** We have assembled a multi-disciplinary team of PIs, supported by NOAA scientists and an international team of Japanese, South American and Canadian collaborators. The addition of international collaborations and comparative studies strongly leverages the scope of the U.S. GLOBEC program and its potential to understand basin scale processes and their importance at local scales.

1.1 Brief overview of the circulation patterns

The physical processes we examine in relation to biological responses include horizontal transport, stratification, vertical mixing and upwelling. Similarities and differences between our four boundary regions provide a natural laboratory within which to contrast the impacts of climate scale forcing on ecosystem function *[Hill et al., 1998; Mackas et al., 2006; Kishi et al. 2006; Sugimoto and Kishi, 2006].*

Along the eastern boundaries between 35°-50°, West Wind Drift currents bring Transition Zone and Central Gyre water masses into each region, bifurcating into equatorward flow in the CCS and PCCS and poleward flow in the Alaska and Cape Horn Currents *[Strub and James, 2002a; Montecino et al., 2006; Huyer et al., 2007]*. Poleward undercurrents flow along the shelf break, under the mid-latitude equatorward surface flow, carrying relatively warmer and saltier tropical water masses *[Pizarro et al., 2002; Neshyba et al., 1989]*, while the surface currents bring cooler and fresher water from higher latitudes. From low to mid-latitudes, both regions are characterized by coastal wind-driven upwelling. This wind forcing is persistent throughout the year at lower latitudes, but switches between summer upwelling and increasingly long and strong winter downwelling at higher latitudes. Upwelling fronts and equatorward jets develop that enhance mesoscale variability *[Strub and James, 2000; Mesias et al., 2001, 2003; Keister and Strub, 2007]*, which spreads the regions of upwelling-induced productivity and their associated ecosystems several hundred kilometers into the deep ocean *[Hill et al., 1998,* Figure 2.4*; Thomas and Strub 2001; Thomas et al., 2001a, 2004; Halpin et al., 2004; Venegas et al., 2008]*. At the highest latitudes (GOA and southern Chile), extended periods of downwelling and large coastal freshwater inputs create wind- and buoyancy-forced poleward boundary currents *[Royer, 1998; Stabeno et al., 2004; Strub and James, 2002a]*. Both the PCCS and the CCS are directly affected by signals of equatorial as well as extratropical origin on time scales ranging from intra-seasonal (Madden-Julian) to interannual (ENSO) or longer *[Thomas et al., 2001b; Strub and James, 2002b; Carr et al., 2002; Blanco et al., 2002; Mendelssohn and Schwing, 2002; Espinosa et al., 2004]*. The equatorial signals propagate poleward into our study regions along the coastal wave guides *[Pizarro et al., 2001; Hormazabal et al., 2002]*, more strongly and directly into the PCCS than the CCS, due to (1) the shorter path; (2) the complex coastal geometry off Central America and Mexico; and (3) the presence of the Intertropical Convergence Zone (ITCZ) and "gap winds" *[Chelton et al., 2000]* north of the equator *[Strub and James, 2002b]*. Equatorial sea surface height (SSH) signals reaching mid-latitudes on annual and interannual time scales arrive in opposite seasons in the two hemispheres, leading to different interactions with the seasonal SSH, upwelling and alongshore flows induced by local winds, with potentially differing ramifications for their respective ecosystems *[Strub and James, 2002c]*.

In the NW Pacific ecosystem (KOE), the southward-flowing Oyashio Current (OC) carries cold, fresher water, while the northward Kuroshio Current (KC) carries warm and saltier water, its inner branch modified by mixing with water from the East China Sea *[Lohrenze and Castro, 2006]*. The two currents collide in the Kuroshio-Oyashio Transition region. Wind forcing is seasonal, consisting of westerly winds from synoptic storms and winds associated with the East Asia monsoon north of 25°-30°N. Changes in the wind stress, wind stress curl, precipitation, insolation and currents (their position and strength) are observed on ENSO and decadal scales [*Sugimoto et al*., *2001*; *Qiu, 2002a*, *2002b*]. Variability in both coastal and offshore ecosystem productivity is caused by regional and large-scale changes in the advection patterns of the upstream currents (the OC, KC and Tsugaru Warm Currents), the position of the KOE itself *[Kishi et al., 2006; Sugimoto and Kishi, 2006]* and mesoscale activity (e.g. eddies and filaments) *[Sugimoto and Tameishi, 1992]*.

In each of our study areas, the dominant forcings vary on subseasonal, seasonal, interannual and decadal time scales, all with strong latitudinal gradients. These forcings strongly modulate the stratification, upwelling, mixing and horizontal transport – the fundamental determinants of the ecosystem characteristics and dynamics in the region. Here we propose to investigate the mechanisms by which subseasonal to decadal fluctuations in forcing cause fluctuations in the lower trophic levels of marine ecosystems around the Pacific basin.

1.2 Climate-scale physical-biological signals

Previous studies have explored correlations in the abundance of marine organisms with environmental indices representing El Niño-Southern Oscillation (ENSO) conditions (the SOI, MEI, Niño 3-4 SST, etc.) or large-scale sea surface temperature (SST) variability in the North Pacific (the Pacific Decadal Oscillation – PDO). The GLOBEC program was designed to move beyond correlative relationships, to identify processes and mechanisms responsible for ecosystem fluctuations *[Strub et al., 2002*; *Batchelder et al., 2002, 2005]*. Several of the PIs and their colleagues have recently identified a mode of physical-biological variability in the North Pacific, known as the North Pacific Gyre Oscillation (NPGO) *[Di Lorenzo et al., submitted ms.]*, which is similar to the "Victoria Mode" *[Bond et al., 2003]*. The NPGO is the dominant mode of variability for nutrients, salinity and CHL-a in the Northeast Pacific (Fig. 1). However, unlike indices that rely primarily on SST, Di Lorenzo et al. *[submitted ms.]* identified the NPGO using a more dynamic variable – the second Empirical Orthogonal Function (EOF) of sea surface height (SSH) anomalies over the northeast Pacific. The NPGO reflects the simultaneous spin-up and spin-down of the NE Pacific subpolar and subtropical gyres *[see also Cummins and Freeland, 2007]*. Using inverse modeling and adjoint techniques *[described in Chhak and Di Lorenzo, 2007]* within a high-resolution regional model – including a simple Nitrogen-Phytoplankton-Zooplankton-Detritus (NPZD) ecosystem model *[Powell et al. 2006]* – they found that the atmospheric forcing associated with the NPGO drives changes in coastal ocean upwelling and transport that directly control changes in nutrients, CHL-a and salinity. Furthermore, preliminary use of the model with forcing by Intergovernmental Panel on Climate Change (IPCC) atmospheric projections indicate a growing importance of the NPGO, compared to the PDO, under global warming climate

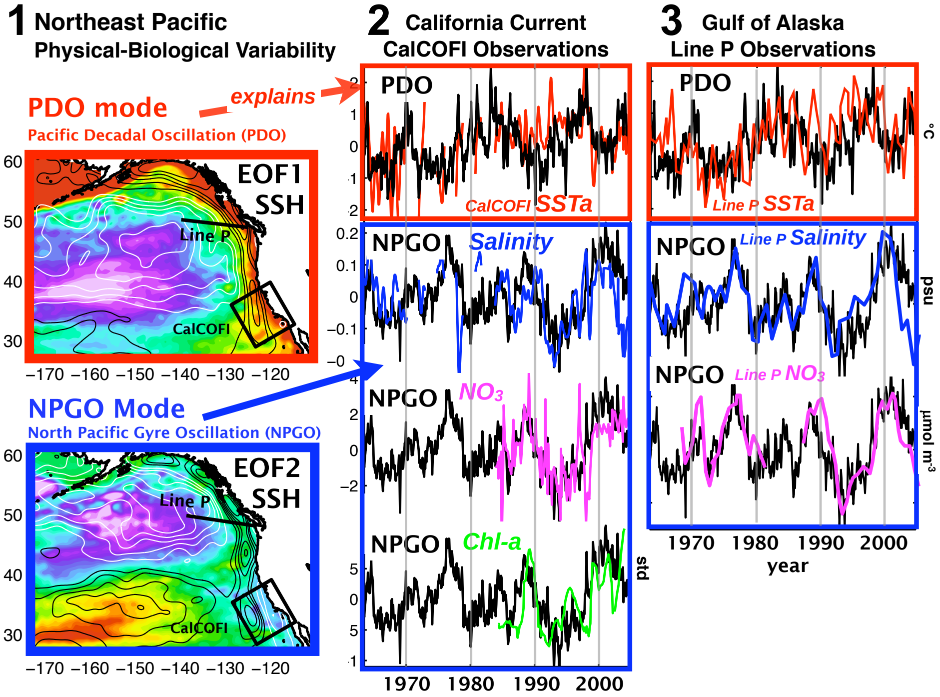


Figure 1: **Dominant modes of physical-biological variability in the Northeast Pacific.** (**1**) Spatial patterns of SSHa EOF1 (equivalent to the PDO mode) and EOF2 (NPGO mode) in the NE Pacific from a high-resolution model hindcast from 1950-2000 *[Di Lorenzo et al., submitted ms.]*. The black and white contour lines on the EOFs represent regions of negative and positive Ekman pumping associated with the mode. Comparison of the SSHa PC1 (equivalent to PDO index) and PC2 (the NPGO index) with timeseries of SSTa, salinity, nitrate and Chl-a in the (**2**) CCS and (**3**) GOA reveals that the NPGO – not the PDO – is the dominant mode of variability for nutrients, salinity and Chl-a.

change scenarios *[Di Lorenzo et al., in prep]*.

These results show clearly that it is necessary to invoke multiple large-scale climate modes to explain the dynamics that underlie interannual and decadal variations of regional marine ecosystems along Pacific Ocean boundaries. They also suggest that regional models of physical-biological processes are necessary and adequate to explore the range of response of coastal ocean dynamics and ecosystems to different scenarios of climate change – a topic central to the IPCC assessments.

2. Objectives and Four Core Research Initiatives

The proposed research combines existing observations with statistical and physical-biological models to explore ecosystem dynamics along the Pacific Ocean boundaries. Our overarching goal is to understand and compare the mechanisms by which coastal ecosystems respond to both past and future climate forcing. We focus on four regions: *the Gulf of Alaska, the California Current, the Peru-Chile Current, and the Kuroshio-Oyashio Extension region* (Fig. 2). We approach this goal through four core research objectives. **(1)** Assess to what extent, and by what mechanisms, large-scale climate modes (e.g. PDO, NPGO, ENSO, and potentially others) drove coherent changes across Pacific boundary ecosystems over the period 1960-2007. **(2)** Quantify and explain how changes in regional ocean processes (e.g. upwelling, transport dynamics, mixing and mesoscale structure) at each boundary control phytoplankton and zooplankton dynamics. Then, use those results to test the degree to which changes in each study region reflect bottom-up control of their respective ecosystems. **(3)** Quantify the extent to which changes in the statistics of shorter-period events (e.g. intraseasonal oscillation, timing of spring transitions) during different phases of the longer-period climate modes (e.g. PDO, NPGO and others) determine the climate state of boundary-current ecosystems. Finally, we will **(4)** explore the range of uncertainties in the response of regional ocean dynamics and their ecosystems to climate change using forcing scenarios from selected climate model integrations that are part of the IPCC 2007 report. This last objective begins an assessment of the potential impacts of climate change on regional ocean ecosystems, a topic poorly addressed in the latest IPCC report, but the chief instrument for most fisheries and coastal management.

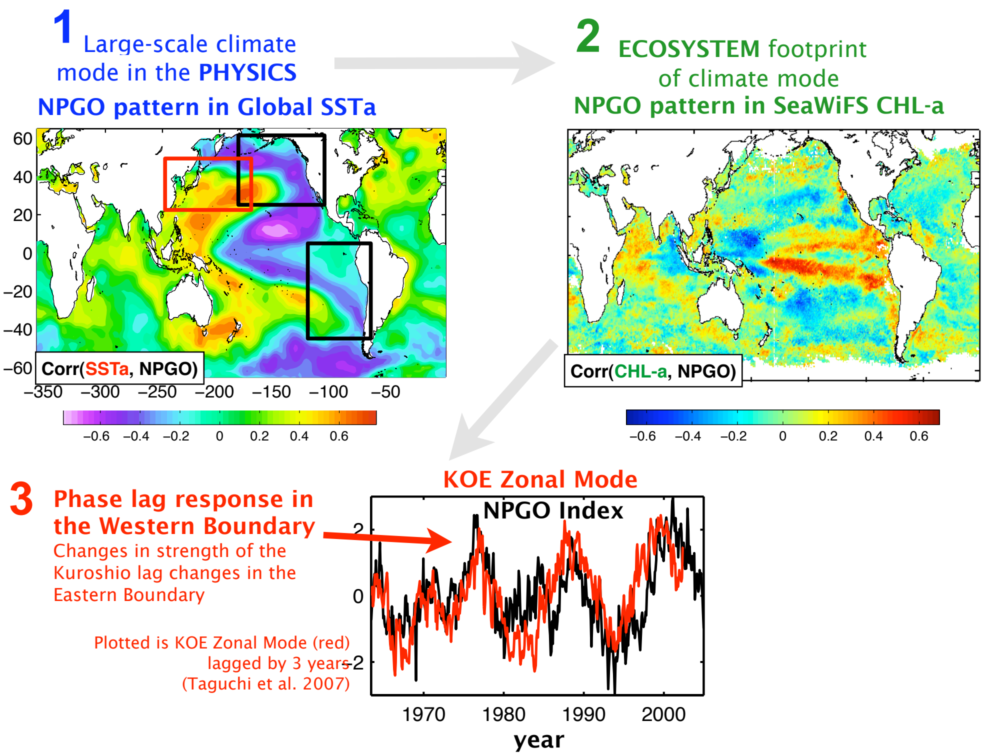


Figure 2: **Large-scale spatial and temporal structure of the North Pacific Gyre Oscillation.** (**1**) Spatial patterns of NPGO in SSTa show an equatorially symmetric structure. The black and red boxes indicate the study regions of this project. (**2**) Spatial pattern of NPGO in CHL-a from the SeaWiFS satellite suggests that coherent patterns in the physics are reflected in ecosystem variability. (**3**) Changes in the strength of the Kuroshio current (the western boundary) are linked to variability in the eastern boundary through the NPGO with a 3-year phase lag.

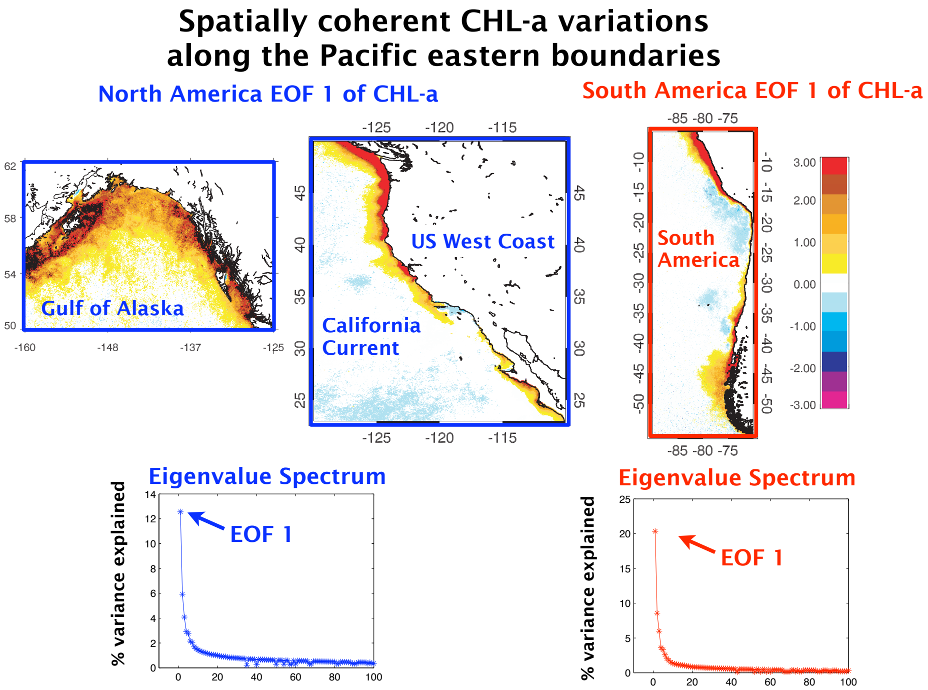
2.1 Regional ecosystem response to multiple modes of large-scale climate forcing

Recent work by

the PIs and colleagues has shown that much of the low-frequency physical-biological variability in the Northeast Pacific can be explained with two dominant modes of climate variability: the Pacific Decadal Oscillation (PDO) *[Mantua et al., 1997]* and the North Pacific Gyre Oscillation (NPGO) *[Di Lorenzo et al., submitted ms.]*. While the PDO is the leading mode of SST variability, the NPGO explains variations in salinity, nutrients and CHL-a (Fig. 1). The spatial and temporal footprints of modes like the NPGO extend beyond the Northeast Pacific involving the entire Pacific and the tropics (see SSTa Fig. 2). Cross-correlation analysis of the 10-year CHL-a SeaWiFS satellite data with the NPGO index suggests that ecosystem variations associated with this mode also exhibit coherent basin-scale fluctuations (Fig. 2). The NPGO also shows a strong 3-year lagged correlation (R=0.7) with the strength of the Kuroshio-Oyashio current (referred to as the KOE Zonal Mode) (Fig. 2), which is implicated in ecosystem variations in the North Pacific western boundary *[Kishi et al., 2006; Sugimoto and Kishi, 2006]*. This cross-basin phase lag is shorter than the time it takes for free baroclinic Rossby waves to propagate across the basin, and reflects the large-scale nature of the atmospheric forcing associated with the NPGO. This forcing extends beyond the eastern boundary into the central and western N Pacific, providing direct forcing closer to the western boundary. These dynamics will be explored in the proposed work.

While a large fraction of ecosystem variability can be explained by the dynamics underlying large-scale climate modes, regional forcings are also important. In the E Pacific, regional coastal orography affects local winds. Equatorial signals that propagate along eastern ocean boundaries are absent along western boundaries. These equatorial signals are weak in the NE Pacific (except during strong El Niños), but dominant in the SE Pacific. In addition, EOF analyses of SeaWiFS CHL-a data (Fig. 3) show that while the leading mode of CHL-a variability is coherent and in phase over the entire boundary (as evident from the uniformly positive sign of the EOF), it only explains a relatively small fraction of the total variance (as evident from the eigenvalues spectra of the CHL-a EOFs, Fig. 3). Higher modes (not shown) reveal complex spatial structures along the coast with out-of-phase relationships. These “local” modes are important to understanding ecosystem variations and their coupling to forcing dynamics.

Ecosystem variations inferred from SeaWiFS (Fig. 3) cover only the last 10 years, with no information on higher trophic levels. To extend these analyses in time and to multiple trophic levels we will combine models (both statistical and numerical) with observations collected by the GLOBEC program and other programs in Japan and along the west coasts of N and S America (see Table 1 in section 3.2). Physical-biological modeling experiments (TASK I in the *Proposed Research* section 3.3) will allow identification and quantification of the dynamics underlying ecosystem variations.


Spatially coherent CHL-a variations along the Pacific eastern boundaries

North America EOF 1 of CHL-a

South America EOF 1 of CHL-a

Eigenvalue Spectrum

Eigenvalue Spectrum

Figure 3: CHL-a EOF1 along the NE and SE Pacific boundaries. Top panels show EOF1 for both regions. Bottom panels show the eigenvalue spectrum for each EOF. The first 3 EOFs explain the largest fraction of the variance. EOF1 is in phase along the entire E Pacific boundary, while higher-mode EOFs show regional and local structure.

Preliminary

findings suggest that both large-scale climate modes and regional physical-biological processes contribute to ecosystem variability in our Pacific boundary study areas. When/where basin-scale forcing dominates, coherent ecosystem responses may be expected. In general, regional dynamics will modify (e.g. augment or mitigate) the large-scale signals, leading to highly varied ecosystem responses. The following hypotheses focus our analyses on uncertainties in the relative contribution of remote versus local forcing on ecosystem variability:

H1) Coherent patterns of ecosystem change along the Pacific Ocean boundaries between 1960-2007 were driven by large-scale forcing associated with dominant modes of climate variability (e.g. PDO, NPGO, ENSO and others).

H2) A significant fraction of ecosystem variability in each boundary system is explained by regionally dependent dynamics.

H3) Marine ecosystem variations are coherent over multiple trophic levels and controlled by bottom-up forcing in the ecosystem.

2.2 Isolating the processes controlling regional ecosystem dynamics

Isolating the spatial and temporal patterns of physical-biological variability through modeling and observational analyses (see *Proposed Research* section 3.3 TASK 1) provides only a partial view of Pacific boundary ecosystem dynamics and their relationship to physics. An important goal of this research is to diagnose the processes and mechanisms that link changes in regional and large-scale physical forcing to variations in (1) nutrient fluxes, (2) phytoplankton and (3) zooplankton. Observational and modeling studies of the Pacific eastern boundaries and the KOE suggest that changes in CHL-a biomass are primarily driven by changes in nutrient fluxes controlled by upwelling and transport dynamics *[Thomas et al., 2003; Ware and Thomson, 2005; Chiba et al., 2006; Thomas and Brickley, 2006; Crawford et al., 2005, 2007; Di Lorenzo et al. submitted ms.]*. These findings suggest that bottom-up forcing controls lower trophic level ecosystem variations. However, the physical drivers of changes in upwelling and transport are often difficult to isolate. Retrospective analyses *[Schwing and Mendelssohn, 1997]* and inverse modeling *[Chhak and Di Lorenzo, 2007; 2008]* shows that decadal changes in upwelling along the CCS are not uniform in space and reflect forcing associated with different large-scale climate modes (Fig. 4). While the upwelling cells north of 38°N reflect PDO variability, the cells south of 38°N are controlled by changes in wind stresses

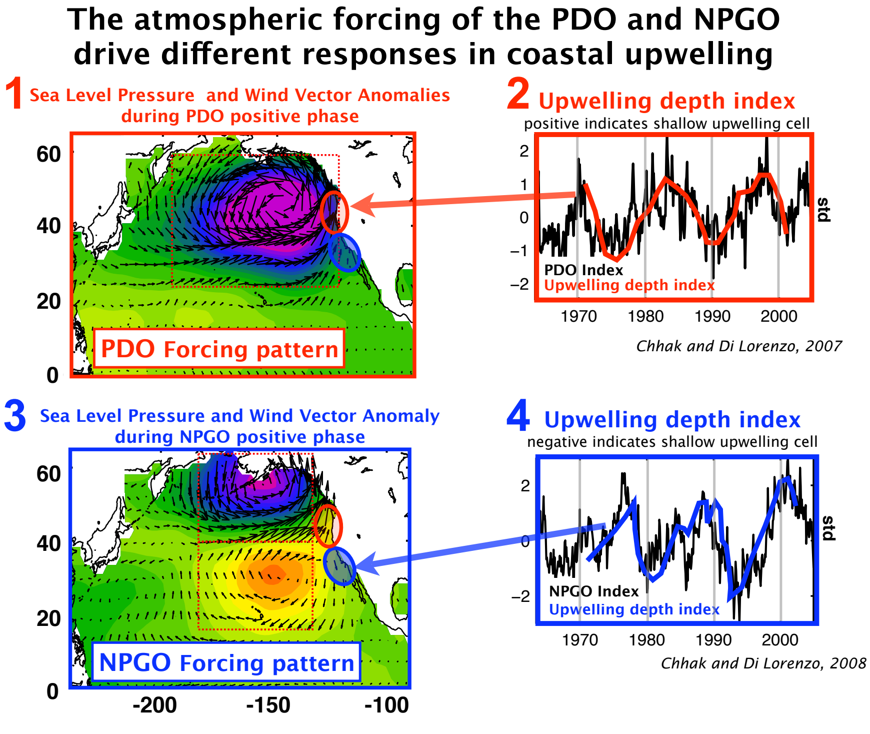


Figure 4: Spatial patterns of atmospheric forcing associated with (**1**) the PDO and (**3**) the NPGO in the N Pacific. The PDO pattern of atmospheric forcing drives the dominant changes in the depth of upwelling north of 38°N (**2**), while the NPGO dominates south of 38°N (**4**). The changes in upwelling are inferred using an upwelling depth index, which tracks changes in the depth of the coastal upwelling cell using an inverse calculation as described in Chhak and Di Lorenzo *[2007]*.

associated with the NPGO. The method used to isolate these upwelling changes relies on injecting a passive tracer during the spring upwelling in a high-resolution ocean model hindcast of the CCS and integrating the model "backward" in time (the adjoint model) to track the depth and horizontal location from which the upwelled water masses originate. This method defines an index of upwelling depth, which correlates well with the PDO and NPGO indices in different regions (Fig. 4). Changes were seen in both the vertical and horizontal transport dynamics. During the negative phase of the PDO, upwelled waters came from deep in the water column and from the south; during the positive phase there is more horizontal entrainment of surface waters from the north into the upwelling boundary layer *[*figure 2 of *Chhak and Di Lorenzo, 2007]*. Performing and comparing these types of analyses across the Pacific boundaries will improve our understanding of the role that atmospheric forcing and ocean circulation play in driving the nutrient fluxes, CHL-a distributions and zooplankton community dynamics. We combine this approach (described further in *Proposed Research* section 3.3 TASK III) with NPZD models, to test the following hypotheses:

H4) Large-scale climate modes (e.g. PDO, NPGO, ENSO and others) reflect coherent changes in the 3-D structure of ocean upwelling, horizontal transport, and nutrient fluxes along the Pacific boundary current systems.

H5) Changes in nutrient fluxes imposed by these modes exert the dominant control on time/space patterns of phytoplankton in each boundary current system (bottom-up control).

The role of vertical and horizontal transport in controlling zooplankton abundance and distribution will be investigated using zooplankton time series (Table 1) and transport modeling. Zooplankton dynamics reflect bottom-up control through changes in food supply (e.g. phytoplankton time/space patterns) that is reflected in total biomass, but physical controls also play a more direct role that is reflected in distributions of individual species. It has been hypothesized that in both the NE Pacific and KOE, broad-scale changes in horizontal transport of subarctic and tropical water masses during the different phases of the large-scale climate modes control the relative abundances of warm-water versus cold-water-associated zooplankton species (Fig. 5) *[e.g., Chiba et al. 2006; Hooff and Peterson 2006]*. Species-level information is critical to understanding ecosystem processes since these community level changes may explain variability in higher trophic levels. In the NE Pacific, piscivorous fatty coho and Chinook salmon may prefer food chains dominated by cold water zooplankton species which are rich in lipids/fats. The high bioenergetic content is passed up the food chain through the small planktivorous fish upon which these salmon feed. Similarly, changes in strength of the KOE may control alternations in the dominance of sardines and anchovies *[Yasuda et al. 1999; Yatsu et al. 2005]* through basin-scale, transport-driven changes in food chain structure *[Takasuka et al.2007]*.

The inverse approach of Chhak and Di Lorenzo [2007], coupled with physical-biological and statistical models and time-series of zooplankton species observations (Table 1) will be used to extend our analyses to zooplankton and higher trophic levels. Specifically, we will test the following hypotheses:

H6) Variations in zooplankton abundance and species distribution can be explained by changes in phytoplankton distribution and in transport pathways of sub-arctic and tropical waters.

H7) Changes in zooplankton biomass and species distribution correlate with variations observed

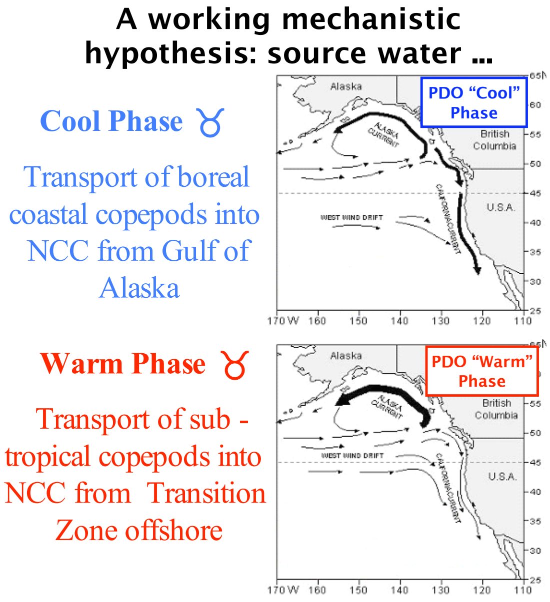


Figure 5: Hypothesis: changes in transport during different phases of the PDO control the relative abundance of zooplankton species (e.g. cold vs. warm water).

at higher trophic levels (i.e., small pelagic fish species common to all boundary current systems).

2.3 Ecosystem sensitivity to seasonal and shorter-period events (e.g. intraseasonal oscillation, timing of spring transitions)

Many marine organisms have life histories adapted to seasonal and shorter-period events in the environment, thus changes in the amplitude or phase of seasonal events (upwelling, stratification, transport, nutrient fluxes) can significantly affect the productivity and community structure of marine ecosystems *[Cushing, 1990; Beare and McKenzie, 1999; Bograd et al., 2002; Logerwell et al., 2003]*. Such phenological effects are potentially more disruptive than those associated with interannual climate events and decadal climate shifts. The impact of an anomalous seasonal cycle was particularly evident in 2005, when the onset of coastal upwelling was delayed by several weeks in the northern CCS *[Schwing et al., 2006]*, resulting in anomalously warm SST *[Kosro et al., 2006; Pierce et al., 2006]*, and pan-trophic ecosystem changes *[Thomas and Brickley, 2006; Mackas et al., 2006; Brodeur et al., 2006; Sydeman et al., 2006; Weise et al., 2006]*. This disruption of the regional ecosystem was driven mainly by large-scale intraseasonal oscillations of the Jet Stream *[Barth et al., 2007]*, which may have affected other boundary systems similarly. Phenological changes have been observed in the subarctic Pacific, where peak biomass of the dominant copepod, *Neocalanus*, occurs about one month earlier now than during the 1960s and 1970s *[Mackas et al., 2007]*. In the Kuroshio, Chiba et al. *[2006]* showed that the timing of the spring peak in zooplankton has been delayed by one month since the 1977 PDO phase shift, whereas the summer peak has shifted one month earlier. Our analyses of such changes in ecosystem function are focused by testing the following hypotheses:

H8) Large-scale climate modes reflect coherent phenological changes in Pacific boundary ecosystems.
H9) Low-frequency changes in the timing of the spring transition have occurred in each Pacific boundary system, leading to discernable changes in primary production and zooplankton community structure.

2.4 Regional ecosystem response to climate change scenarios

The response of Pacific regional boundary ecosystems to climate change is uncertain. The IPCC Fourth Assessment Report provides almost no assessments of regional ecosystems of the Pacific. Evaluations of 22 IPCC coupled atmosphere-ocean general circulation models (GCMs) have shown that not all are able to reproduce the observed 20th century ocean variability in the N Pacific *[Overland and Wang, 2007]*. For example, only half replicate the dominant mode of N Pacific SST variability (the PDO), suggesting that only selected IPCC models should be used to explore 21st century ocean climate change in the N Pacific. The PIs have extended this screening process to verify which of these models reproduce the NPGO. Only one-quarter of the IPCC models adequately capture the features of both the PDO and NPGO. Further analyses conducted on one of these IPCC models (the GFDL 2.0) indicate that the relative amplitude of these natural modes may change significantly during global warming, perhaps reflecting a re-adjustment of the global atmospheric teleconnection patterns. Other natural modes may also become more dominant. These preliminary findings lead to the following hypotheses that we will test using the selected/screened IPCC models:

H10) The relative amplitude of low-frequency natural climate fluctuations (e.g. PDO, NPGO and others) will change during global warming and is reflected in regional ecosystem variations.
H11) Other large-scale natural climate modes of the Pacific Ocean intensify.

In addition to changes in the natural climate modes, IPCC projections show a general warming over the entire Pacific Ocean. The amplitude of upper-ocean warming is expected to surpass the PDO by 2040 *[Overland and Wang, 2007]*, suggesting that changes in ocean stratification may become a dominant control on nutrient fluxes. A persistent anomalously deep, strong thermocline can result in long-term reductions in significant ecosystem changes *[McGowan et al., 2003; Palacios et al., 2004]*. Indeed, long-term fluctuations in biological production within the southern CCS have been associated with interannual to decadal scale variability in stratification *[Chelton et al., 1982; Roemmich and McGowan, 1995;*

McGowan et al., 2003; Di Lorenzo et al., 2005]. Changes in the strength, depth, or timing of maximum stratification could be key processes regulating coastal marine ecosystems under expected climate change scenarios *[Snyder et al., 2003; Diffenbaugh et al., 2004; Diffenbaugh, 2005]*. The relative control that wind stress and stratification exert on upwelling has not been fully investigated, but both are likely to play increasingly important roles as global warming progresses. Using the selected/screened IPCC model augmented with regional projections with higher resolution ocean models (see *Proposed Research* section 3.3 TASK VII) we propose to test the following hypothesis:

H12) With increasing global warming, upper ocean stratification rather than wind induced upwelling, exerts a dominant control on vertical nutrient fluxes.

Other important aspects of global warming are the projected changes in the distribution and intensity of short-period events (e.g. heat waves, storms, spring transitions, etc.) [IPCC-AR4]. These may have dramatic impacts on marine organisms. For this reason this project will test the following hypothesis:

H13) Changes in phenology associated with global warming drive dramatic responses in regional marine ecosystems.

3. Proposed research

This section is organized as follows: first we introduce the physical-biological models (3.1) and observational datasets (3.2) that will be used in this project, including the ones provided by our international collaborators in Japan and South America. We then outline seven research tasks (3.3) designed to test hypotheses 1-13 posed above. Within each task we include a brief description of "*Synergistic activities*" showing how the research work is divided among the PIs and how we plan to interact with our international collaborators.

3.1 Physical-biological ocean model datasets

The analyses proposed in this project rely on the output of state of the art physical-biological models. Specifically we will use the existing output from the Japanese Earth Simulator eddy-resolving (10-km resolution) OFES-NPZD model (see below) augmented by nested integrations in the focus study regions using the ROMS-NPZD (see below). We will also make use of the recently developed inverse ocean modeling platform based on the ROMS-Adjoint *[Moore et al., 2004; Di Lorenzo et al., 2007; Chhak and Di Lorenzo, 2007]* to diagnose the transport dynamics (as described in research TASK III). Below is a brief description of each model:

OFES-NPZD: The physical model is the eddy-resolving Ocean Model for the Earth Simulator (OFES) *[Masumoto et al., 2004]*. This global model covers 75°S to 75°N with an average horizontal resolution of 10 km with 54 vertical levels. A 50-year integration using climatological mean forcing (NCEP/NCAR reanalysis data *[Kalnay et al., 1996]*) and restoring conditions to observed temperature and salinity fields from the World Ocean Atlas (WOA98) has been used to spin-up the model. After the spin-up, the model has been integrated from 1950 to 2007 driven by the daily mean forcing of NCEP/NCAR reanalysis.

The marine ecosystem model component of OFES is a simple nitrogen-based Nitrogen-Phytoplankton-Zooplanton-Detritus (NPZD) pelagic model *[Oschlies, 2001]*. The evolution of any biological tracer concentration is governed by an advective-diffusive equation *[Sasai et al., 2006]*. The initial nitrate field is taken from the WOA98. The initial phytoplankton and zooplankton concentrations are set to 0.14 mmol N m^{-3} and 0.014 mmol N m^{-3} at the surface, respectively, decreasing exponentially with a scale depth of 100 m *[Sarmiento et al., 1993]*. Detritus is initialized to 104 mmol N m^{-3} everywhere. To establish a stable biological system, the coupled physical-biological model is integrated over a 5-year period under climatological mean forcing. The biological fields at the end of the 5 years are used as the initial condition. So far the coupled model has been integrated over the period 1999 to 2004 driven by the daily mean surface wind stress data (QuikSCAT) and atmospheric daily mean heat and salinity fluxes from the NCEP/NCAR reanalysis *[Kalnay et al., 1996]*. The model captures the seasonal variability observed in SeaWiFS [*Sasai et al., 2007a; 2007b*]. Our Japanese collaborators from JAMSTEC are completing the entire 50-year OFES-NPZD hindcast, which will be used for the ecosystem comparison analyses between ROMS-NPZD and available data. Output from the OFES-NPZD will be used to provide open ocean boundary conditions for the ROMS-NPZD model simulations.

ROMS-NPZD: The ocean forward model that we will use for the nested regional integration is the Regional Ocean Modeling System (ROMS) *[Shchepetkin and McWilliams, 2005; Haidvogel et al. 2007]*. This model solves the incompressible, hydrostatic primitive equations on a C-grid. It has a free surface with time splitting for barotropic and baroclinic modes, a terrain-following vertical coordinate (s-coordinate), and boundary layer parameterization. The s-coordinate better captures the interactions between bottom topography and ocean dynamics in coastal regions when compared to the traditional height coordinate. A more complete report of the model numerics is given by Shchepetkin and McWilliams *[2005]*.

For this project we will configure three nested regional integrations in the (a) NE Pacific, (b) Kuroshio-Oyashio and (3) SE Pacific domains (see Fig. 2, panel 1). The horizontal resolution will be the same as the OFES model (10 km average) with 42 vertical layers for the regional domains (Fig 2). Higher resolution (2-5 km) nested grids will be imbedded within ROMS to resolve coastal processes in selected coastal regions to allow a better model-data comparison. The integrations will cover the period 1950-2007. At the open boundary we will use nudging to the solutions from the OFES model combined with a modified radiation condition *[Marchesiello et al. 2001]*, which allows for stable, long-term integration of the model. The nudging is stronger (timescale of one day) if the direction of the flow is inward and weaker (timescale of one year) if the flow is outward. Daily surface fluxes will be derived from both the NCAR-NCEP and the ECMWF reanalyses, which will lead to two model realizations of the 1950-2007 hindcast (preliminary conversation with the South American collaborators have indicated that ECMWF may be better suited for the PCCS). The surface heat flux will be corrected using a nudging to the monthly NOAA SSTa *[Smith and Reynolds, 2004]*. The initial condition will be derived from the end state of a 50-year integration using climatological boundary conditions and forcing. Using a similar model setup for the NE Pacific domain, the PI *[Di Lorenzo et al., submitted ms.]* was able to capture the variability in temperature, salinity, nutrients and CHL-a observed in the California Current (CalCOFI dataset) (Fig. 6) and Gulf of Alaska (Line P dataset).

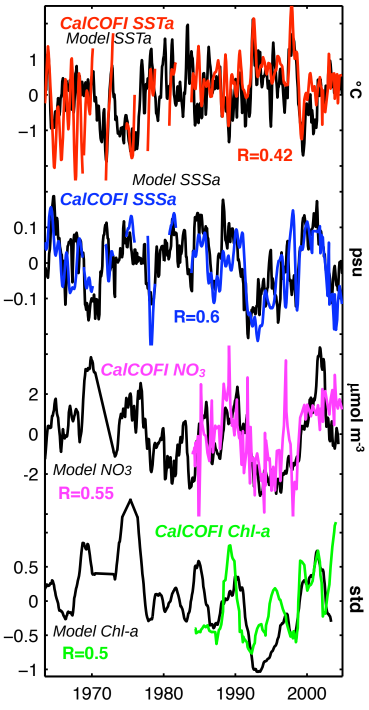


Figure 6: NE Pacific ROMS-NPZD model hindcast from 1950-2004. Comparisons of model time series in the CCS with CalCOFI data show that the model is able to capture the observed low-frequency variations. We then use the model to diagnose the underlying physical and biological dynamics.

The NPZD component of ROMS is similar to the one used in the OFES-NPZD model except that it also includes iron limitation *[Fiechter et al., 2007]*, which is important to adequately capture ecosystem variations in the Gulf of Alaska. Several of the PIs (Franks, Di Lorenzo, Bograd) are PIs in the California Current Ecosystem Long-Term Ecological Research program (CCE-LTER) based at SIO. As part of this modeling effort we are employing the NEMURO marine ecosystem model *[Kishi et al., 2007]* in a ROMS-based physical model. Because of its greater complexity, the NEMURO model is not as efficient to integrate as the NPZD model. However, NEMURO will offer a more detailed view of ecosystem changes than possible with an NPZD model. We will leverage our participation in the CCE-LTER program and use ROMS-NEMURO to explore the effects of climate fluctuations on higher trophic levels in the study regions.

ROMS-Adjoint Model: In a recently completed effort, the ROMS Data Assimilation Tools Development Team *[Moore et al., 2004; Di Lorenzo et al., 2007]* has implemented the Tangent Linear and Adjoint models for ROMS. The tangent linear model and its associated adjoint are powerful tools for analyzing model sensitivity and the dynamics of flow fields. For discrete dynamical systems, the tangent linear model provides the Jacobian of the dynamical operators that are tangent linear to a solution trajectory of the nonlinear system. The adjoint of this Jacobian operator provides information about the sensitivity of the system to variations in the model state vector, boundary conditions and model parameters. If the adjoint model is used to integrate a passive tracer advection equation, the sensitivity information is equivalent to the output of a "backward" in time simulation of the forward model *[Vukicevic and Hess, 2000; Fukumori et al.,2004; Chhak and Di Lorenzo, 2007]*. This is true if the passive tracer equation is linear (no feedback on the advection velocities) and the diffusion is set to zero. This type of calculation will be crucial to perform the analysis of the transport dynamics described in TASK III.

3.2 Physical-biological Observations

A comprehensive suite of physical and biological observational time series is available to support the proposed research. Here we provide additional detail on the biological datasets and the foreign datasets brought to this proposal by our South American and Japanese collaborators (see Letters), as these are crucial to the success of our work. These datasets allow comparisons a) between boundary ecosystems, b) to basin scale forcing and c) to the models to evaluate responses to climate signals.

Global Data Sets: These have at least 20-year time series, often significantly longer. Examples include World Ocean Database 2005, wind and surface flux data from ECMWF and NCEP, upwelling indices, SST data from COADS, NCEP-GTS, hydrography and circulation fields from SODA and OFES (model output), and climate indices such as PDO, NPGO, PNA, AO, NAO and MEI. Satellite data fields and their time spans include CHL-a (and derived productivity) (1997-present), SST (1985-present), SSH (AVISO and NASA data, 1992-present) and surface winds (1999-present).

In Situ Physical Data sets: U.S. GLOBEC LTOP and process cruise data, CalCOFI data (southern California, 1949-present), archived Oregon shelf CTD and current meter data sets from OSU (various time series, some extending back to 1961), IFOP northern Chile hydrographic surveys (1964-present, *[Blanco et al., 2001]*) , U. Concepcion shelf/slope current meters at 21, 30 and 36°S (some extending back to 1991), COPAS central Chile shelf and offshore (2002-present *[Escribano et al., 2007]*).

Table 1: Available ***in situ* biological data sets**

Data Set	Location/Resolution	Time	Properties
CalCOFI	Southern CCS; usually quarterly	1949 – pres. 1984-pres (chl)	Nutrients, chl, pp profiles; zoo biomass+ ichthy species
GLOBEC LTOP	Oregon shelf to 85 miles offshore; quarterly. Gulf of Alaska, along Seward Line.	1997 – 2005, 2007	CTD, nutrient and chl-a profiles, zooplankton species
Newport Line	Newport shelf and slope (quarterly) Newport shelf and slope; ~ monthly	1961-1972 1963-1967	Nansen bottles and reversing thermometers. Krill species
Newport Line	Oregon shelf and shelf break bi-weekly, 7 stations (1 to 25 miles from shore)	1969-1972; 1996– pres.	1969-72 SST only. 1996-present CTD, chl-a, nutrients, zoopl species
Newport Line	Oregon shelf, biweekly, summer	1973,78,83, 90-92	Zoopl only
Washington and Oregon shelf	6-7 stations along 7-8 transects between northern WA and central OR	2x/summer 1998-pres. 1981-1985.	CTD, chl-*a* and nutrients, zoop. species, trawls for pelagic fish & juv. salmon).
Stn PAPA	N. Pacific subarctic gyre, 3x/year	1956-pres.	Zoopl biomass
BC shelf	Vancouver Island southern shelf, quarterly	1985-pres.	CTD, chl, nutes, zoo species
Odate	Western N. Pacific, Kuroshio Oyashio, transition regions, monthly	1951-pres.	CTD, chl, zoopl species
Hokkaido University	Western / central subarctic Pacific, annual	1953-2001	Oshoro-Maru zooplankton Time series
Japan Nat. Fish. Res. Inst.	W. Subtrop. Pac., Kuroshio, 5-8 x per year	1971-pres.	Zoop, fish egg, larvae surveys

Hokkaido Nat. Fish. Res. Inst.	W. Subarctic Pac., Oyashio, 5-8x / year	1987-pres.	Line A monitoring, zoopl.
IMARPE	Peru upwelling region, seasonal	1964-pres.	zooplankton
IFOP	Northern Chile, cross-shelf surveys, seasonal	1985-pres. 1996-pres (chl)	Zooplankton, www.IFOP.cl
Antofagasta research	Northern Chile coastal, at least annually	1991-2003	zooplankton
COPAS	Central Chile, off Concepcion	2002-pres.	CTD, nutrients, chl-a, zoop

3.3 Research Tasks

Each research TASK outlined below is led by a subset of the PIs and Co-PIs. The results from each TASK will be discussed by the entire team through monthly conference calls. Two graduate students will be focused on the observational analyses (obs-graduate student) and modeling (mod-graduate student). Our international collaborators bring a wide range of experience and connections to related projects. From Chile, Dr. Ruben Escribano (U. Concepcion) leads the Chile-GLOBEC efforts and specializes in zooplankton population dynamics. Dr. Oscar Pizarro (U. Concepcion) analyzes data from current meter time series (some extending back to 1991) at three latitudes, combined with tide gauge, satellite and model data. Dr. Vivian Montecino (U. Chile) is a phytoplankton ecologist who combines in situ biological and optical measurements and recently served as Director of the national fisheries institute (IFOP). Dr. Jose Rutllant (U. Chile) is an atmospheric scientist with long-term interests in climate change effects on South America. From Canada, Dr. David Mackas is a zooplankton ecologist who has carried out quarterly cruises hydrography and zooplankton off Vancouver Island since 1985. From Japan, Sanae Chiba is a zooplanktologist who works closely with global climate modelers at the Frontier Research Center in Yokohama, Drs. Taguchi and Nonaka are experts in large-scale low-frequency variability of the Pacific and Drs. Ishida and Sasai are established ecosystem modelers with the OFES-NPZD.

TASK I) Regional ROMS-NPZD hindcast physical-biological simulations 1960-2007

The goal of this task is to assemble all the modeling datasets for the hindcast period 1960-2007 that will be used in subsequent analyses. Specifically we will gather the outputs from the OFES-NPZD and the nested regional integrations of the ROMS-NPZD. While the OFES-NPZD model output already exists, the ROMS-NPZD simulations for each of the four boundary regions will be conducted on the Georgia Tech 264 cpu cluster owned by the PIs Di Lorenzo and Bracco. The ROMS-NPZD model setup is the same for each region and is described above in section 3.1. The PIs have extensive experience using ROMS and have estimated that these calculations will require no more than 6 months of computer wall-clock time with 64 cpus Opteron Cluster. To be conservative, we have allocated 264 cpu for 8 months wall-clock time for this project with possibility of on demand computing if necessary. Part of this allocation is also intended for the regional ocean model climate-change projection simulations discussed in TASK VII.

Synergistic activities: Di Lorenzo and mod-graduate student will lead the physical aspect of the ROMS-NPZD simulation, while Bracco and Franks will be responsible for the NPZD component. Drs. Taguchi and Sasai from JAMSTEC-Japan will help in extracting and configuring the open boundary conditions for the ROMS-NPZD using the OFES-NPZD model data. Bograd, Mendelssohn, Schwing, Strub and Thomas will use statistical tools to compare model fields with satellite data for periods of coincident coverage. These simulations will be made available to both the Japanese and South American collaborators, who will perform independent analyses and comparisons of the model data as indicated in their letters of support. Model output will be accessed through the Georgia Tech OpenDAP server hosted at http://dods.PacificEcosystemsClimate.org.

TASK II) Analysis of coherent patterns of physical-biological variability

H1) Coherent patterns of ecosystem change along the Pacific Ocean boundaries between 1960-2007 were driven by large-scale forcing associated with dominant modes of climate variability (e.g. PDO, NPGO, ENSO and others).

H2) A significant fraction of ecosystem variability in each boundary system is explained by regionally dependent dynamics.

H3) Marine ecosystem variations are coherent over multiple trophic levels and controlled by bottom-up forcing in the ecosystem.

This research task addresses hypotheses ***H1***, ***H2*** and ***H3*** and is primarily focussed on isolating patterns of physical-biological variability. Subsequent tasks explore the dynamics and mechanisms underlying the observed variations. To test ***H1,*** we will combine the satellite, *in situ* and modeling data to isolate coherent patterns of physical-biological variability with a focus on primary and secondary trophic levels. The long-period climate indices (e.g. the PDO, NPGO and others) will be used as the conceptual framework to interpret patterns. Obervational time series of biomass and individual species (or combinations of species) using data outlined in Table 1 will be compared with time series of the climate modes to look for common periodicities *[e.g. Hooff and Peterson, 2006, Brinton and Townsend, 2003, Beaugrand and Reid, 2003]*. We will use multi-species analysis techniques such as ordination and cluster analysis to describe community structure of phytoplankton, zooplankton, ichthyoplankton, and pelagic fish species and their relationships with physical variables and satellite-observed surface patterns. Following this analysis we will be able to test ***H2*** by quantifying the fraction of physical-biological variability that is *not* coherent across the study regions and by isolating important regional modes of variability. We will then address ***H3*** by quantifying the degree to which lower-trophic variability inferred from the observations and from the OFES-NPZD and ROMS-NPZD correlate with variations in higher trophic levels. This last activity will be continued in more depth through TASK V.

Synergistic activities: Peterson, Keister, Strub, Thomas, Bograd and obs-graduate student will lead the analyses of the observational datasets. Both graduate students will analyze the modeling data under the supervision of Di Lorenzo and Thomas. International collaborators Ishida, Sasaki, and Chiba will supervise the analysis of the OFES-NPZD and Kuroshio-Oyashio region data by interacting with Di Lorenzo. South American collaborators will supervise the analysis of the Chilean System by interacting with Strub, Thomas, Bograd, Mendelssohn and Schwing. Climate patterns and results from these analyses will be posted on a dedicated webpage http://www.PacificEcosystemsClimate.org.

TASK III) Analysis of nutrient fluxes and transport dynamics

H4) Large-scale climate modes (e.g. PDO, NPGO, ENSO and others) reflect coherent changes in the 3-D structure of ocean upwelling, horizontal transport, and nutrient fluxes along the Pacific boundary current systems.

To test hypothesis ***H4,*** we will characterize the changes of nutrient fluxes and the 3-D circulation during different phases of the large-scale climate modes (e.g. PDO, NPGO, ENSO and others). We will combine the NPZD model output (OFES and ROMS) with forward and inverse calculations that track changes in the 3-D ocean transport. The inverse approach (section 2.2 and Chhak and Di Lorenzo *[*2007*]*), uses passive tracer injections in the adjoint ocean model to isolate, for any given geographical region, the source waters that are advected in that region (see example Fig. 7). This approach is complementary to simple water mass transport calculations as it provides a 3-D view of the source waters both in space and time. The locations of passive tracer injections will be

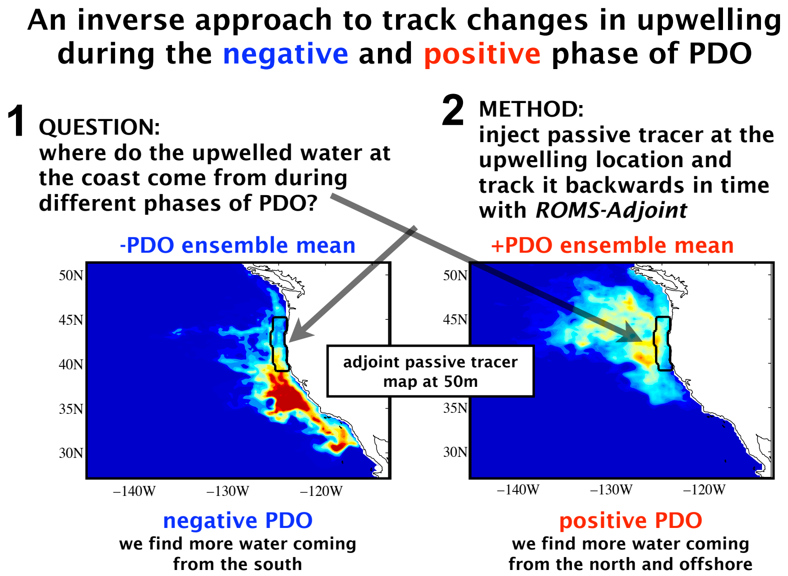


Figure 7: Example of inverse calculation to identify the sources of water upwelled into the domain indicated by the black box at the coast. The color maps of passive tracer indicate the source waters, revealing the strong differences with different phases of the PDO.

selected for each of the study regions guided by results from TASK II and will likely include regions of strong variability in surface nutrients and phytoplankton biomass (e.g. coastal upwelling locations for the CCS and PCCS; meandering region of the KOE). Transport pathways will be compared with those evident in SSH satellite data, which have been successfully used to identify increased transports between the subarctic and subtropical gyres and subsequent changes in surface pigment concentrations (from satellite color) in the NE Pacific *[Thomas et al.*, 2003; *Strub and James*, 2003*]*. Note that to fully characterize the ocean dynamics that drive changes in nutrient fluxes, it is necessary to consider both the NPZD model outputs and the passive tracer calculations together, with additional comparisons to the satellite analyses. The satellite time series now span 10-25 years and allow us to independently identify patterns of annual and interannual variability. This provides the foundation upon which to evaluate the ability of the models to recreate the past and project future states for the boundary circulation and lower ecosystem dynamics. These types of analysis will be instrumental to isolating the important forcing functions that control nutrient fluxes and quantifying their relation to both large-scale and regional modes of variability.

Synergistic activities: Chhak and mod-graduate student will perform the forward and inverse calculations; Keister and obs-graduate student will analyze the NPZD model output and its relationship to changes in 3-D circulation and mescoscale eddy transport; Strub and Thomas will explore relationships between the model diagnoses of transport dynamics and satellite observations, working with South American colleagues Escribano, Pizarro, Montecino and Rutllant in the EBC's and with Chiba in the analysis of data from the KOE.

TASK IV) Linking transport dynamics to phytoplankton and zooplankton

H5) Changes in nutrient fluxes imposed by large-scale climate modes exert the dominant control on time/ space patterns of phytoplankton in each boundary current system (bottom-up control).

H6) Variations in zooplankton abundance and species distribution can be explained by changes in phytoplankton distribution and in transport pathways of sub-arctic and tropical waters.

This task tests hypotheses ***H5*** and ***H6*** by building on results from TASK III**.** To test ***H5,*** in each study region we will combine the output of the NPZD models with available observations of phytoplankton from *in situ* and satellite data to assess the degree to which phytoplankton abundance and patterns are controlled by bottom-up forcing. These analyses focus on isolating temporal and spatial patterns of nutrient-phytoplankton co-variability. To test ***H6,*** we will perform two separate analyses. The first will quantify the relationship between phytoplankton biomass and zooplankton biomass/species abundances (NOTE: We will use only the observational zooplankton dataset to infer connections to phytoplankton and physics. We will ignore the modeled zooplankton, which is used in the NPZD model only to control phytoplankton growth). The second will directly test the hypothesis that changes in transport associated with large-scale and regional forcing explain changes in zooplankton species relative abundances (as described in section 2.2). This second analysis will also involve additional inverse calculations using the passive tracers to track source waters in the ROMS-NPZD which will be compared to shifts in zooplankton distributions.

Synergistic activities: Franks, Thomas, and the obs-graduate student will lead the analyses required to test ***H5***, while Keister and Peterson will address ***H6*** with Chhak, who will conduct the inverse calculations. Chiba will supervise the observational analysis of zooplankton data in the KOE, while Escribano will supervise the analyses of the SE Pacific. Sasai and Ishida will provide support with the OFES-NPZD analyses. Mackas will join these efforts. He chairs SCOR Working Group 125 which is investigating global synchronies in long-term zooplankton data sets (North Sea, North Atlantic, Benguela, California, Humboldt and Kuroshio and Oyashio Currents and the Japan/East Sea). Chiba is also a member of this WG.

TASK V) Connecting lower and higher trophic levels

H7) Changes in zooplankton biomass and species distribution correlate with variations observed at higher trophic levels (i.e., small pelagic fish species common to all boundary current systems).

To test ***H7*** we will use observational time series of zooplankton, ichthyoplankton, and fishes that are highly dependent upon zooplankton resources. Ichthyoplankton species composition data are of great interest: we expect fishes with very different life history and spawning strategies to respond differently to basin and regional-scale transport and local forcing. For example, Hsieh et al. *[2005]* showed a link between the PDO and oceanic taxa (chiefly mesopelagic fishes) but no correlation with coastal taxa. We propose to re-analyze these data using the NPGO index and other recently-identified indices associated with dominant modes of variability isolated in TASK II.

As part of this task, we will also revisit hypotheses behind the alternating cycles of anchovies and sardines around the Pacific Rim (California Current, Japan, Peru-Chile), which have received a great deal of attention from the SCOR Working Group 98, the International GLOBEC Small Pelagics and Climate Change (SPACC) Working Group, and a host of individual investigators from these three regions (e.g., Kawasaki and Omori *[1988]*, Schwartzlose et al. *[1999]* and many others). We will work with our international colleagues on this problem, focusing chiefly on correlative relationships with large-scale climate modes (e.g. NPGO and other modes isolated in TASK II) that have not received previous attention. Yatsu et al. *[2005]* have shown that transport in the Kuroshio, which fluctuates with the NPGO, is a key variable explaining recruitment of sardines and mackerels. Given the link between the NPGO and transport in the CCS, relating the NPGO to sardine cycles might be fruitful. Similarly, in Chile, variations in the transport of jack mackerel larvae are believed to be the dominant source of recruitment variability .
Synergistic activities: Peterson and Keister will lead this task with statistical input from Strub, Thomas, Mendelssohn, Bograd and Schwing. Since the PIs' expertise is not in higher trophic ecosystem levels, this task will leverage the PIs' strong connections with PICES working groups (see Mackas letter of support) and their Japanese counterparts, and with US stock assessment scientists. Strub and Thomas will interact with our South American collaborators.

TASK VI) Analysis of Phenology

H8) Large-scale climate modes reflect coherent phenological changes in Pacific boundary ecosystems.

H9) Low-frequency changes in the timing of the spring transition have occurred in each Pacific boundary system, leading to discernable changes in primary production and zooplankton community structure.

Using both observations and model hindcasts we will determine if changes in the timing of seasonal forcing, both mechanical and radiative, have played a dominant role in characterizing marine ecosystem response to climate forcing. To test ***H8***, we will relate observed changes in various metrics characterizing the seasonal cycle of coastal upwelling, boundary current transport, and phytoplankton time/space distribution to the regional manifestations of the PDO, NPGO and other dominant modes. We will determine the extent to which the large-scale climate modes contribute to a basin-wide coherent signal of phenological changes. We will also compare the amplitude and timing of these processes in the observations and ROMS-NPZD output to better understand how changes in seasonal forcing propagate to higher trophic levels. To test ***H9***, we will compare key diagnostics of phenological changes (e.g., upwelling indices, phytoplankton biomass) among the boundary systems, using both observations and ROMS-NPZD model output. These analyses will also be done using ROMS-NPZD model runs driven by the forcing functions derived from selected IPCC model projections, to evaluate the likely impact of future climate change on the phenology of key processes (see TASK VII). Various statistical techniques will be applied to the observational and model time series, including wavelet and state-space models, which effectively separate nonparametric trends from non-stationary seasonal behavior *[*e.g. *Mendelssohn et al. 2003; Henson and Thomas 2007b,c]*.
Synergistic activities: Bograd, Thomas, Di Lorenzo, Keister, obs-graduate student and mod-graduate student will lead this task. Bograd (*in situ* and retrospective observations) and Thomas and obs-graduate student (satellite data) will describe phenological changes from the observations. Di Lorenzo and mod-graduate student, with Bograd, Thomas, and Keister, will compare observed and modeled phenology of key processes, and investigate pan-Pacific comparisons in collaboration with Chiba, Mackas, and Escribano. Mendelssohn will lead the statistical modelling of long-term seasonal behavior.

TASK VII) Regional Future physical-biological projections from IPCC model focing: 2000-2050

H10) The relative amplitude of low-frequency natural climate fluctuations (e.g. PDO, NPGO and others) will change during global warming and is reflected in regional ecosystem variations.

H11) Other large-scale natural climate modes of the Pacific Ocean intensify.

H12) With increasing global warming, upper ocean stratification rather than wind induced upwelling, exerts a dominant control on vertical nutrient fluxes.

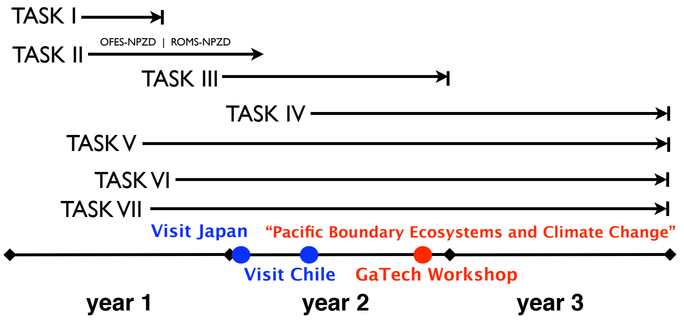
H13) Changes in phenology associated with global warming drive dramatic responses in regional marine ecosystems.

To test hypotheses ***H10, H11*** and ***H12,*** we will use selected/screened IPCC model outputs together with regional simulations of the ROMS-NPZD model. These will be driven by forcing functions derived from these selected IPCC model projections for the A1B scenario, which is characterized by a moderate increase in the concentrations of greenhouse gases**.** The selection of IPCC models will rely on quantifying the ability of the coupled models to simulate multiple dominant modes of variability in the 20th century climate (as metioned in section 2.4). To test ***H10*** and ***H11,*** we will rely on statistical analyses (e.g. EOFs, state-space and common trend analyses). We expect that the simulated regional expressions of Pacific climate modes (e.g. PDO, NPGO, ENSO) will show significant differences from those observed, reflecting the coarse nature of the ocean models. These factors will be taken into account when selecting the forcing functions from the IPCC runs to drive regional simulations of the ROMS-NPZD. For example, in the N Pacific the IPCC models misrepresent features known to be crucial to the marine ecosystem, such as the location of the subarctic fronts and upwelling winds along the coast. Preliminary analysis of GFDL 2.0 show that this model is comparable to the NCEP and ECMWF products, and we anticipate that one realization of the ROMS-NPZD projections for each of the study regions will use forcing from this model. We expect to conduct at least 3 realizations using the output of two other IPCC models. These regional integrations will allow testing of ***H12*** on the role of stratification. Diagnostics of the ROMS-NPZD regional model projections will include inverse passive tracer calculations with and without the upper ocean warming to separate the effects of wind stress and stratification on upwelling. These runs will be accomplished by alternatively setting the surface windstresses and heat fluxes of the ROMS-NPZD regional projection model to climatology. Finally, to test ***H13*** we will apply the same analyses described in TASK VI, in particular the state-space analysis, which separate nonparametric trends from non-stationary seasonal behavior [*Mendelssohn et al. 2003*].

Synergistic activities: Mendelssohn, Chhak and Schwing will conduct the statistical analyses of the IPCC models. Chhak, Di Lorenzo and Bracco will conduct the regional ROMS-NPZD model projections and the inverse calculations. Bograd and Thomas will conduct the phenological analyses.

4. Project Management and Timeline

Di Lorenzo will be responsible for overall project management. A timeline of the research tasks is provided by the diagram on the right. Each task is led by one of the PIs with involvement of other PIs and international collaborators as indicated in the "*Synergistic Activities*" above. Di Lorenzo will coordinate the project through regular conference calls planned every month, a method that has proven quite effective in the preparation of this proposal. International collaborators will join selected conference calls. We have requested funds to travel to a central site for a PI science team meeting each year. We will also meet where possible at national/international conferences to save travel costs. We plan two international visits to JAMSTEC-Japan and Chile in year 2 (end of year 1) to interact more closely with our international collaborators. We also plan to organize a workshop on "*Pacific Boundary Ecosystems and Climate Change*", which will be attended by the international collaborators. The goal of this workshop is to discuss the science relevant to this proposal and also to initiate discussions with scientists involved in IPCC assessments of regional Pacific ecosystem responses to climate change that will be included in future IPCC reports.



5. Broader Impacts

The broader impacts of the proposed research will be realized through activities corresponding to all five criteria defined by the National Science Board and discussed in the July 2007 NSF guidance document on broader impacts (www.nsf.gov/pubs/gpg/broaderimpacts.pdf). Brief descriptions are given below; some activities are more thoroughly described in section 3.3, Research Tasks.

5.1 Advance Discovery and Understanding While Promoting Teaching, Training and Learning

- We will build on an existing relationship (PI Strub's) with the Oregon SMILE (Science and Math Investigative Learning Experiences) Program. SMILE serves more than 700 students and 60 teachers in 35 schools in areas that are poor, largely rural, and educationally under-served. Each spring, SMILE high school participants visit Oregon State University to participate in the annual Challenge Event that features ocean science and remote sensing content. Strub will work with event organizers (see letter of collaboration) to incorporate selected model results and time series data into units that will foster the development of students' analytical skills and nurture their interest in pursuing higher education.
- OSU and SIO have NSF REU programs; PIs at those institutions will mentor students funded by that program as well as request supplementary funding for REU students to work on this project.
- We will incorporate elements of the proposed research into both undergraduate and graduate courses taught by the PIs. Project data, results and methodologies will inform lectures, problem sets, and serve as vehicles for problem-based learning.
- The proposed work will form the core of the thesis work for two graduate students.

5.2 Broaden Participation of Underrepresented Groups

- The proposed work includes substantial mentorship of early-career scientists and will represent the first post-postdoctoral NSF support for three young female scientists: Keister, Chhak and Bracco, who have no previous NSF support.
- Collaboration with the SMILE Program, described above in section 5.1, will enable us to engage traditionally underserved students in educational activities.

5.3 Enhance Infrastructure for Research and Education

- This project represents a close collaboration between academic and government scientists.
- This project synthesizes international GLOBEC results across four large marine ecosystems and with at least four countries including the US.
- Our international partnerships form an integral part of the proposed work. We will work closely with scientists in Japan and Chile in exchanging data, model results, and expertise. We will co-convene workshops in both countries attended by the PIs in year 2 of the project.

5.4 Broad Dissemination to Enhance Scientific and Technical Understanding for Operational Resource Management

- The NOAA scientists involved in this project work closely with stock assessment experts responsible for providing guidance to managers of a number of fishery resources in the NE Pacific known to be sensitive to climate forcing (Schwing and Bograd for rockfish and sardines, Schwing and Peterson for salmon). Our NOAA scientists will pass our project results to the stock assessment scientists and assist them in incorporating them into operational marine ecosystem assessment and prediction.
- We will make our model output accessible online through the Georgia Tech OpenDAP server hosted at http://dods.PacificEcosystemsClimate.org. This output will be used by our international collaborators, and will be available to anyone interested in climate-change science.
- PIs will tap their experience in broad, public communication and existing relationships with journalists as well as institutional and agency public information officers to communicate key findings to non-scientists.
- PIs, through publications, presentations at interdisciplinary conferences and organization of workshops, will communicate effectively with fellow researchers.

5.5 Benefits to Society

- The proposed research will elucidate the mechanisms by which climate change affects marine ecosystems in the Pacific Ocean. Understanding the links between climate indicators and ecosystem fluctuations may allow some predictive capability for the effects of climate change. This capability will inform policy decisions, allowing better management of marine resources in the face of anthropogenic forcing. We entrain GLOBEC collaborators from three other countries to spread this impact internationally. This research will provide an important contribution to the next IPCC Scientific Assessment, which will require a much greater emphasis on the impacts of climate change on marine ecosystems.

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