The Pacific Ocean Boundary Ecosystem and Climate Study (POBEX)

by Emanuele Di Lorenzo, Julie E. Keister, Vincent Combes and Harold Batchelder

The POBEX project (www.pobex.org) is an international effort that brings researchers from North America, Japan and South America together to investigate the mechanisms of climate-related variability in three Pacific boundary ecosystems: Gulf of Alaska (GOA) and California Current System (CCS) referred to as the Northeast Pacific (NEP), the Humboldt or Peru-Chile Current System (PCCS), and the Kuroshio-Oyashio Extension (KOE) region.

The POBEX team includes Principle Investigators from U.S. institutions, sponsored by the NSF-GLOBEC program (E. Di Lorenzo, A. Bracco, J.E. Keister, P.T. Strub, A. Thomas, P.J.S. Franks, S. Bograd, W. Peterson, R. Mendelssohn, F. Schwing) and collaborators from Japan (S. Chiba, Y. Sasai, H. Sasaki, M. Nonaka, B. Taguchi, A. Ishida) and South America (O. Pizarro, R. Escribano, S. Hormazabal, J. Rutllant, V. Montecino).

The main objectives of POBEX are to: (1) understand and quantify how large-scale climate variability has affected boundary ecosystems in the Pacific, and (2) explore the range of uncertainties in responses of these ecosystems to climate change. Specifically, POBEX attempts to quantify how changes in regional ocean processes (*e.g*., upwelling, transport dynamics, mixing and mesoscale structure) at each boundary control phytoplankton and zooplankton dynamics, and the extent to which these regional ocean dynamics are driven by large-scale climate modes such as the Pacific Decadal Oscillation (PDO), North Pacific Gyre Oscillation (NPGO), El Niño Southern Oscillation (ENSO), and potentially others. In doing so, POBEX tests the degree to which changes in each study region reflect a bottom-up control of the ecosystems that is synchronized by large-scale Pacific climate.

To explore how low-frequency variations of upwelling and horizontal transport affect the lower trophic levels of the Pacific boundary marine ecosystems, POBEX is following a two-phase approach. In the first phase, now almost complete, the project has generated a series of high-resolution (10 km) regional ocean model hindcasts in the GOA, CCS, PCCS and KOE. These model hindcasts, available at http://data.eas.gatech.edu, are used in combination with model passive tracer releases to develop indices that quantify the low-frequency changes in upwelling and transport statistics. For each of the boundary regions, we generate an ensemble of historical hindcasts covering the period 1950–present to separate the deterministic and intrinsic (mesoscale eddies) component of ocean variability. In the second phase—still ongoing—the transport indices developed during Phase 1 are used to test the degree to which lower-trophic level ecosystem variability can be explained by changes in physical variability. Specifically, we test the extent to which observed changes in phytoplankton are connected to modeled changes in the strength, structure and timing of upwelling, and explore specific hypotheses of how changes in zooplankton abundance and species diversity are linked to changes in modeled horizontal transport.

Phase 1: Upwelling and transport statistics along the Pacific boundaries *(V. Combes)*

The upwelling and cross-shelf transport dynamics along the Pacific eastern boundary (GOA, CCS and PCCS) are explored using high-resolution (10 km) hindcasts of the Regional Ocean Modeling System (ROMS) for the last 60 years. We report results from three model domains illustrated in Figure 1. As described above, in each regional model domain a set of passive tracers is injected along the coast, both in the surface and subsurface, to quantify the transport dynamics. Below, we present a short summary of the primary findings on low-frequency transport variability along the eastern Pacific boundary.

The Gulf of Alaska

The marine ecosystem of the GOA is very rich despite an open ocean that is characterized by high nutrient and low chlorophyll-*a* concentration and coastal downwelling. Primary production of the GOA is limited by low iron, perhaps due to low aeolian iron input (Martin and Fitzwater, 1988, *Nature*, Vol. 331, 341–343), and recent observational studies suggest that advection of iron-rich coastal water may be the primary mechanism controlling open ocean productivity. Specifically, there is evidence that mesoscale eddies along the coastal GOA entrain iron-rich coastal waters into the ocean interior. The statistics of coastal waters transport are computed using a model passive tracer, which is continuously released at the coast at the surface (white hatched box on Fig. 1). On average along the Alaska Current, we find that at the surface, while the advection of tracers by the average flow is directed towards the coast, consistent with the dominant downwelling regime of the GOA, it is the mean eddy fluxes that contribute to offshore advection into the gyre interior. South of the Alaskan Peninsula, both the advection of tracers by the average flow and the mean eddy fluxes contribute to the mean offshore advection. On interannual and longer time scales, the offshore transport of the passive tracer in the Alaskan Stream does not correlate with large-scale atmospheric forcing, or with local winds (intrinsic variability). In contrast, in the Alaska Current region, stronger offshore transport of the passive tracer coincides with periods of stronger downwelling (forced variability), in particular during positive phases of the PDO, which trigger the development of stronger eddies, known as "Haida" and "Sitka" eddies (Combes *et al*., 2007, *Prog. Oceanogr.*, Vol. 75 (2), 266–286; Combes *et al*., 2009, *J. Phys. Oceanogr.*, Vol. 39 (4), 1050–1059).

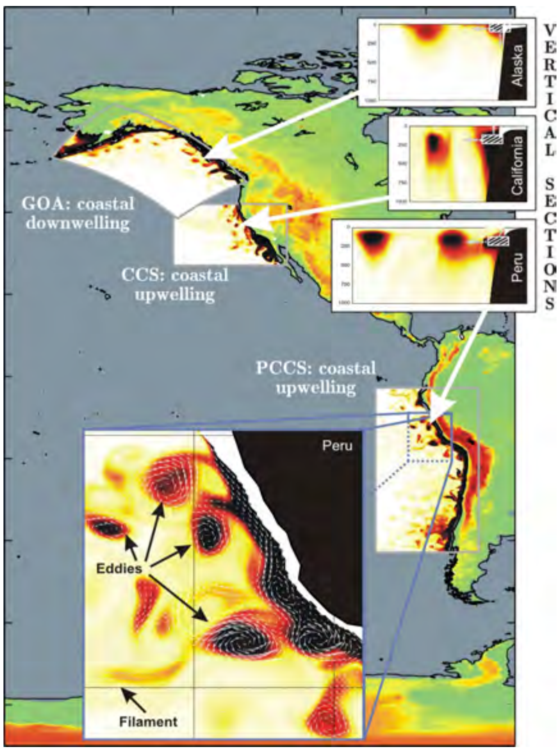

Fig. 1 Snapshot of passive tracer concentrations for the model domains (GOA, CCS, PCCS). A tracer is continuously released (white hatched boxes inset). White arrows correspond to the current velocity (only plotted when tracer concentration is high). Top right panels show vertical sections of tracer across mesoscale eddies.

The California Current System

South of the GOA, the CCS is a typical eastern boundary current coastal upwelling system. To characterize the effects of linear (Ekman upwelling) and non-linear (eddy activity) circulation regimes on the statistics of low-frequency advection of coastal waters, an ensemble of passive tracers is released in the numerical model in the subsurface between 150 and 250-m depth at the coast (white hatched box on Fig. 1). The resultant concentration of the tracer at the surface provides an index of coastal upwelling. We find that the low-frequency upwelling and the surface offshore transport of the upwelled nutrient-rich coastal water are strongly correlated with the alongshore wind stress, and with the NPGO (large-scale climate variability index). Our results also show that the poleward California Undercurrent, at about 200-m depth, affects the alongshore transport and provides nutrient-rich waters to the Central California dominant upwelling cell. However, if we look only at the surface transport dynamics, the offshore transport of the surface coastal water is associated with mesoscale eddy activity; both surface and subsurface waters propagate offshore mainly through cyclonic eddies (top-right panel vertical section in Fig. 1) (Combes *et al.*, 2010a, *J. Phys. Oceanogr.*, submitted).

The Peru-Chile Current System

In the southern hemisphere, the PCCS is one of the world's most productive regions in fish landings, providing ~20% of the world marine catches despite covering less than 1% of the world's ocean surface. This high productivity results principally from the upwelling of nutrient-rich water into the photic zone. Both changes in surface wind and coastally trapped Kelvin waves control the variability of the coastal upwelling. We assessed the effect of ocean remote forcing by comparing the output of two model simulations that do and do not include the presence of waves at their boundaries. Similar to the analyses performed in the CCS, a passive tracer approach is used to characterize the coastal upwelling variability of the PCCS. The evolution of the passive tracers indicates that, off the coast of Peru, the ENSO strongly modulates the efficiency of coastal upwelling, due principally to the propagation of downwelling equatorial Kelvin waves rather than to changes in the local wind stress. Our results show that the central Chile upwelling region is also very sensitive to the Kelvin waves generated at the equator, and is considerably reduced during strong El Niño events. Different model experiments have also been conducted to explore the sensitivity of the PCCS upwelling to air–sea fluxes of momentum (ECMWF *vs*. NCEP surface wind stress forcings). Similar to the CCS region, we find that mesoscale eddies play an important role in the offshore advection of nutrient-rich coastal waters. Both cyclonic and anticyclonic eddies (bottom-left panel on Fig. 1) are able to transport nutrient-rich coastal waters (Combes *et al*., 2010b, *J. Phys. Oceanogr.*, submitted).

The passive tracer experiments, performed in the GOA, CCS, and PCCS, provide a dynamical framework to understand the dynamics of the upwelling/downwelling and horizontal transport of water masses. Indices derived from the passive tracer can be used as proxies of the vertical and horizontal advection of important biogeochemical quantities, essential in understanding the ecosystem variability along the Pacific eastern boundary.

Phase 2: Linking transport dynamics to lower-trophic ecosystem variability *(J.E. Keister)*

In Phase 2, we investigate the effects of large-scale climate variability on lower trophic levels with passive tracer release data generated during Phase 1. Specifically, long-term time-series of biological observations in the CCS, KOE, and PCCS are used to test hypotheses of how changes in advective transport associated with the large-scale climate modes, drive changes in the lower trophic levels.

Our initial experiments were conducted in the northern CCS where zooplankton have been collected approximately bi-weekly to monthly since 1996 off Newport, Oregon by William Peterson and colleagues. The continental shelf zooplankton community off Oregon cycles between communities that are dominated by species with warm-water associations and those dominated by species with cold-water associations (*e.g*., Peterson and Keister, 2003, *Deep-Sea Res. II*, Vol. 50, 2499–2517; Hooff and Peterson 2006, *Limnol Oceanogr.* Vol. 51, 2607–2620). The non-seasonal, low-frequency variability in species composition strongly correlates with the PDO. Using an index of the zooplankton community developed from ordination of the copepods (called the Copepod Community Index, or "CCI"), we compare the zooplankton community to transport statistics to determine the extent that advection explains observed biological changes. The high-resolution regional ocean model developed in Phase 1 is applied over the Oregon Shelf region with independent passive tracers released in the surface layer at the NORTH, SOUTH, EAST and WEST boundaries. These tracers are used to test the hypothesis that *changes in warm* vs. *cold zooplankton species are associated with the intrusion of warmer (colder) waters from the southern (northern) boundary*. The passive tracer experiment results are consistent with this hypothesis; we find that a reconstruction of the CCI with a weighted average of the modeled transport time-series from all boundaries correlates with R=0.34 to the raw (monthly) time series (Fig. 2A), but when lowpass filtered, the low-frequency component correlates with R=0.95 (Fig. 2B, from Keister *et al*., 2010, *Global Change Biol.*, submitted). This shows that changes in horizontal surface transport can explain nearly all of the multi-year variance in zooplankton communities in this region. We also find that most of the explanatory power is associated with the NORTH/WEST and SOUTH tracers, with the NORTH and WEST tracer time-series being very highly correlated with each other. These high correlations indicate that when the PDO is positive, there is less advection of cold-water species from the north and stronger advection of warm-water species from the west, in addition to those coming from the south. Looking more closely at the relationships among the zooplankton community, transport, and climate variability, we find that a zooplankton community reconstruction calculated over the full 50+ year model time period, correlates strongly with a model reconstruction of the PDO (R=0.55, not shown). The lowpass filtered time series (Fig. 2C) correlates more strongly (R=0.87) and reveals decadal variability superimposed upon multi-year cycles of ~6- to 7-year duration. The observational data (1996–present) falls in a period of fluctuating but primarily positive anomalies, indicating a relative dominance of warm-water zooplankton compared to previous decades.

In our next investigations, we will compute similar transport statistics for the deep circulation that is important to diapausing copepods and taxa which perform deep vertical migrations, and will compare those statistics to a relevant subset of the zooplankton community. Moving to the western Pacific boundary, we will compare the role of transport in controlling zooplankton variability in the KOE region, in collaboration with Sanae Chiba and colleagues at JAMSTEC. Chiba and her colleagues hypothesize that observed changes in zooplankton biomass and distributions seen in the Oyashio and Transition region are driven by climate-related changes in the strength and position of the Kuroshio and Oyashio Currents (Chiba *et al*., 2009, *Global Change Biol.*, Vol. 15, 1846–1858). The changes are related to the PDO, indicating that some degree of across-basin synchrony in lower trophic level response to climate change may exist. As in the CCS, we will directly explore the effect of transport on zooplankton communities using passive tracer release experiments.

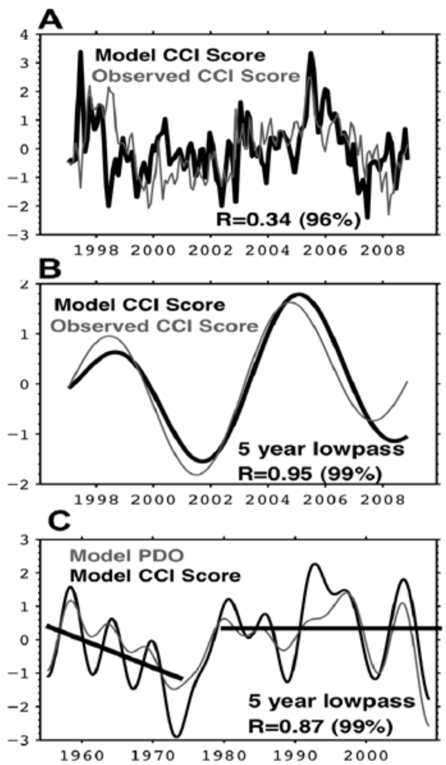

Fig. 2 Model reconstruction of the Copepod Community Index (CCI): (a) compared with the monthly-averaged observations, (b) as above, but 5-year lowpass filtered, and (c) reconstructed over the full >50-year model time period and compared to the 1st Principal Component of the model SST, which represents the PDO. The model CCI is constructed using the four passive tracers: NORTH, SOUTH, EAST, and WEST (modified from Keister et al., 2010).

Synergies between POBEX and PICES *(H. Batchelder)*

The POBEX investigations are aimed at elucidating the mechanistic physical basis for potential bottom-up control of these Pacific boundary ecosystems by large-scale climate forcing. While the detailed mechanisms may differ in the various ecosystems, it is important to understand what the key processes are so that future (and specifically those of FUTURE) investigations, such as those being examined by PICES' Climate, Oceanographic Variability and Ecosystems Advisory Panel (COVE-AP), can integrate the process-based understanding into model-based assessments and forecasts. PICES' new integrative science program named FUTURE (**F**orecasting and **U**nderstanding **T**rends, **U**ncertainty and **R**esponses of North Pacific Marine **E**cosystems) was developed to enhance the PICES nations' scientific capability to understand and forecast the consequences of future climate and anthropogenic change to marine ecosystems. To accomplish this, we need to document past changes in ecosystems and climate forcing, and identify the detailed mechanisms that relate the two. Without the underlying mechanistic basis relating climate variation to ecosystem patterns and changes, it would be difficult, perhaps impossible, to skillfully project the "potential ecosystem consequences" of future climate scenarios of the type developed by the Intergovernmental Panel on Climate Change (IPCC) and by PICES' Working Group on *Evaluation of Climate Change Projections*. Moreover, the POBEX program's emphasis on quantifying the uncertainty in the processes will supply critical information to PICES' Status, Outlooks, Forecasts and Engagement Advisory Panel (SOFE-AP), which is tasked with identifying and communicating the uncertainties (or skill) of ecosystem assessments and forecasts to potential users. Thus, the studies of POBEX will provide great advances on key issues of both COVE and SOFE, and significantly contribute to the goals of FUTURE. It should be noted that POBEX and most GLOBEC studies have assumed that the connection between climate variability (including global warming) and ocean ecosystems occurs through bottom-up processes (see Fig. 1 of Batchelder and Kashiwai, 2007, *Ecol. Model.*, Vol. 202, 7–11). Additional studies are needed to consider whether bottom-up forcing is truly the dominant mechanism, or whether top-down forcing (direct impacts of climate on fish or higher trophic levels) is equally important in marine ecosystems.

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From left to right, Julie Keister, Vincent Combes, Emanuele Di Lorenzo with his one-year-old Isaac getting started on fishing, and Hal Batchelder

Dr. Emanuele (Manu) Di Lorenzo (edl@gatech.edu) is an Associate Professor at the School of Earth and Atmospheric Sciences, Georgia Institute of Technology, U.S.A. His research interests and experience span a wide range of topics from physical oceanography to ocean climate and marine ecosystems. More specific focus is on dynamics of basin and regional ocean circulation, inverse modeling, Pacific low-frequency variability, and impacts of large-scale climate variability on marine ecosystem dynamics. In PICES he is a member of the Working Group on Evaluations of Climate Change Projections and of the Advisory Panel on Climate Ocean Variability and Ecosystems (COVE-AP). He also serves on the U.S. Comparative Analysis of Marine Ecosystem (CAMEO) Science Steering Committee.

Dr. Julie Keister (jkeister@u.washington.edu) is an Assistant Professor in the School of Oceanography, University of Washington, U.S.A. Her research focuses on understanding the physical and biological processes that affect zooplankton communities in coastal ecosystems, especially how variability in advection affects zooplankton distributions on kilometer-to-basin scales, and how climate impacts those relationships. She has been active in PICES for over a decade and is currently the PICES convenor of the 5th International Zooplankton Production Symposium, which will be held in March 2011, in Pucón, Chile.

Dr. Vincent Combes (vincent.combes@eas.gatech.edu) received his PhD degree in June 2010 at the Georgia Institute of Technology, U.S.A. He is currently working as a Post Doctorate at Oregon State University. His background includes hydraulics, fluid mechanics and regional physical oceanography. His research focuses on eastern boundary dynamics, in particular, upwelling and offshore low-frequency variability. Within POBEX, Vincent has played a major role in coordinating the collaborations with South American scientists and spent a year in Chile developing regional ocean model applications for ecosystem studies.

Dr. Harold (Hal) Batchelder (hbatchelder@coas.oregonstate.edu) is a Professor in the College of Oceanic and Atmospheric Sciences at Oregon State University, U.S.A. His present research focuses on individual based modeling the biological-physical coupling of marine environments and marine populations, including studies on Calanus finmarchicus in the North Atlantic, and krill and juvenile salmon in the Northeast Pacific. In PICES, he served as Co-Chairman of the Climate Change and Carrying Capacity (CCCC) Program and as a member on PICES Science Board from 2001–2009, and presently is a member on the Status, Outlooks, Forecasts and Engagement Advisory Panel (SOFE-AP). He is also active in the Marine Ecosystem Model Inter-comparison Project (MEMIP) of PICES. He served as Coordinator of the U.S. GLOBEC National Program for 6 years, and Executive Director of the U.S. GLOBEC Northeast Pacific regional program for 12 years.