Project Title: Interannual variability in the Northern California Current: the influence of ten El Niño events on salmon populations and pelagic ecosystem structure over the past 50 years.

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Project Summary. The California Current is a highly productive eastern boundary current due in part to wind-driven coastal upwelling. During the late spring and summer seasons, the northern portion of the California Current (NCC) typically supports a food web of lipid-rich copepods, krill, and small pelagic fishes. This nutritious prey community attracts several economically-valuable migratory fish stocks from the southern portion of the California Current (hake, sardine, and mackerel), anadromous salmonids from rivers of the Pacific Northwest, and highly migratory species from the south Pacific such as humpback whales, shearwaters, and albatross. These species migrate to the NCC for one purpose -- to feed on the lipid-rich food chain to store fat for their return to rivers (salmon) or over-wintering grounds (all others).

The lipid characteristics of the prey community are known to vary at seasonal, interannual, and decadal time scales. Seasonal and decadal changes in ecosystem structure are related to processes associated with upwelling and the Pacific Decadal Oscillation (PDO) -- when the PDO is negative (cold phase), lipid-rich copepod species (*Calanus marshallae* and *Pseudocalanus mimus*) are transported southward from the Gulf of Alaska and dominate the lower trophic levels in the coastal NCC. When the PDO is positive (warm phase), lipid-poor copepod species typical of subtropical waters dominate the biomass (Keister et al. 2011; Bi et al. 2011). However, changes at the interannual scale are less well understood. In particular, the influence of the El Niño/Southern Oscillation on the region appears to be inconsistent. Some strong El Niño events have had clear negative impacts on the local ecosystem (1983, 1998) while other extreme events have had no apparent biological impact (1972). In contrast, two weak El Niño events (2005, 2009-10) were coincident with severe impacts on the NCC ecosystem.

We propose to examine relationships between El Niño events and resulting variability in SST, sea level, hydrography, and the abundance and species composition of copepods, krill eggs, larvae and adults, ichthyoplankton and small pelagic fishes along with salmon returns, in waters of the NCC. We will examine statistical relationship between El Niño events and physical and biological anomalies in order to develop a better understanding of the factors which may moderate or exacerbate the influence of El Niño (e.g., the timing of the arrival of physical El Niño signals, duration, and the magnitude of oceanic and/or atmospheric anomalies) on the *biological* components of the ecosystem. The time period for which we have relatively complete and comprehensive data (1970s through 2011) spans ten El Niño events of various magnitudes.

We currently provide forecasts/outlooks of salmon returns in the US Pacific Northwest based on environmental conditions acting during their first summer the salmon spend at sea, one year (for coho salmon) or two years (for Chinook salmon) in advance of their return to their natal streams to spawn. Forecasts are based on a set of physical and ecological indicators including large-scale ocean and atmospheric indicators (PDO and the Oceanic Niño Index), local-to-regional scale physical indicators (SST, coastal upwelling, the date of the spring transition, and temperature and salinity anomalies) and biological indicators (copepod community structure, northern copepod biomass anomalies, the date of the biological spring transition, and ichthyoplankton species composition). These forecasts are posted to our website; they are also

sent directly to managers and other interested parties through our growing list-serve. By determining how past ENSO activity affects the shelf/slope ecosystems of the northern California Current, we should be able to take advantage of El Niño forecasts produced by the NOAA Climate Prediction Center (CPC). That is, when an El Niño is forecast, we should be able to determine the impact of the type of event being forecast (weak or strong), and provide an outlook on the type of response expected within the ecosystem of the NCC.

Background. The response of the NCC ecosystem to changes in upwelling and advection on seasonal and decadal scales associated with the PDO has been studied extensively by us (Peterson and Keister 2003; Hooff and Peterson, 2006; Bi *et al*., 2011; Keister *et al*., 2011). However, the influence of variability at interannual time scales remains poorly understood; this needs attention because it is extreme events at this time scale that have the potential to impact fisheries resources severely. ENSO is the dominant mode of variability at interannual time scales in the tropical and subtropical ocean ecosystems, but the influence of El Niño on ecosystem structure at temperate latitudes is inconsistent and apparently dependent on the pre-existing “background” state of the ecosystem and the "type" of El Niño that is occurring more than the magnitude of the event in the tropics. For example, the 1972-73 El Niño event was one of the most extreme in the tropical Pacific (off Peru and Chile) yet appears to have had no impact in the NE Pacific; in contrast the 1982-83 and 1997-98 events produced extremely warm ocean conditions and well-documented negative impacts on local ecosystems, including salmon (Wooster and Fluharty 1985, Peterson et al. 2002). Additionally, the relatively weak, but chronic El Niño events from 1990-95 (Trenberth and Hoar,1996) were devastating to local salmon fisheries, resulting in the listing of tens of salmon stocks as ‘endangered’ or ‘threatened’. Finally, interannual variability had a surprising and significant impact on multiple tropic levels in the NCC during the summer of 2005 (see special issue of *Geophysical Research Letters* vol. 33, 2006). As a result of the “2005 warm event” the salmon fishery along the West Coast of the US was closed for two years (Lindley et al. 2010) to allow rebuilding of the Sacramento River fall Chinook stocks. $100 million was appropriated by Congress for disaster relief to fishermen.

Although mid-latitude physical responses to El Niño have been examined in depth for the major 1982-83 and 1997-98 events, other events have not been similarly studied. We have the data and tools required to investigate retrospectively how different types of El Niño events affect ecosystem structure using hydrographic, atmospheric, plankton, and fisheries data collected over the past 50 years in the NCC. We propose to investigate past interannual variability in the ecological structure of the NCC using historical physical and plankton data and combine this knowledge with NOAA-Climate Prediction Center's El Niño outlooks to enhance and extend our popular salmon forecasting efforts. We pose two main hypotheses concerning the variable influence of El Niño events on the biological components of the NCC ecosystem:

1. Hypothesis One. The time of year when El Niño signals arrive in the NCC and the duration of the event shapes the ecological consequences of atmospheric and oceanic anomalies; the variability in the timing and duration are important factors in understanding the differences between individual El Niño events. Because the migrations of predators (hake, sardines, salmon, seabirds, and marine mammals) have evolved to take advantage of the lipid-rich prey field of the NCC, modification in the timing of productive periods may impact these migratory predators. El Niño events disrupt the regular seasonality of production and prey availability to predators so the timing and/or duration of an individual El Niño event may be more influential than the magnitude of the physical anomaly.

2. *Hypothesis Two. The ecological impacts of El Niños are moderated by conditions associated with negative PDO; and conversely, impacts are exacerbated during positive PDO conditions.* Widespread ecological changes are related to large-scale ocean and atmospheric processes associated with the PDO (Mantua et al. 1997). For the NCC ecosystem, the production and abundance of salmon, small pelagic fishes, and zooplankton increase during negative (cool) phases of the PDO, and vice versa. It has been shown that when the PDO is negative, boreal, lipid-rich copepod species such as *Calanus marshallae* and *Pseudocalanus mimus* are transported southward out of the Gulf of Alaska and dominate the lower trophic levels in the coastal branch of the NCC (Peterson and Keister, 2003; Peterson and Schwing, 2003; Hooff and Peterson, 2006; Keister et al., 2011; and Bi et al., 2011). When the PDO is positive, lipid-poor copepod species typical of subtropical and offshore waters become dominant. While the PDO displayed multidecadal oscillations for much of the past century (with switches in sign occurring in 1925, 1947, 1977, and 1998), the pattern has recently increased in frequency, with changes in sign occurring in 2003 and 2008. These recent high-frequency changes in "background" ecosystem conditions offer a natural experiment in which to explore the influence of ENSO on the NCC during both positive and negative phases of the PDO.

Approach: We have five extensive data sets available for study**:**

1. The Newport, OR hydrographic line at 44°39'N has been sampled biweekly from the nearshore zone to just beyond the shelf break since 1996. Sampling includes CTD profiles (with fluorescence and oxygen), Secchi depth, nutrients, chlorophyll-*a*, and plankton tows targeting copepods, krill and ichthyoplankton. This 16+year data set will allow us to investigate the five recent El Niño events in great detail.

2. Oceanographers at Oregon State University sampled the Newport line for hydrography during the 1960s on a monthly basis using Nansen bottles and reversing thermometers; in 1972 and 1973, hydrographic data were collected with CTDs during the Coastal Upwelling Experiments (Huyer 1977, 1983; Smith et al. 2001; Huyer et al. 2007). Krill were sampled along the NH line monthly from 1963-67 (Smiles and Pearcy 1971) and zooplankton and ichthyoplankton species were sampled from 1969-73 (Peterson and Miller 1975, 1977; Auth et al. 2010), 1982, 1983, and zooplankton from 1990-92.

3. We will utilize hydrographic and zooplankton species enumeration data from the GLOBEC-Long Term Observations Program (from 1998-2003) which included sampling of shelf and slope waters from Newport south to Crescent City CA in April, July, and September (Huyer et al. 2007; Peterson et al. 2002; Keister et al. 2009a, b). The shelf and slope waters can be compared over a six-year period in spring and summer during a major El Niño (1998) and a moderate El Niño event (2002-2003). Since 2003, we have continued the LTOP sampling at least twice per year (usually May and July). The Newport Line has been sampled 55 times out to 85 miles (140 km) since 1998, allowing comparison of impacts of El Niño events on the dynamics of hydrography and plankton in shelf, slope and oceanic waters.

4. Juvenile salmonids and other pelagic fish are sampled in May, June and September, 1998-present, along eight cross-shelf transects from Newport north to La Push WA with a 20mx30m (mouth size) rope trawl– sampling at stations includes CTD profiles, nutrients, chlorophyll, zooplankton and ichthyoplankton (Peterson et al. 2010). The focus will be on the

juvenile salmonids as well as pelagic fish community structure (using ordinations) and on occurrence of “unusual” warm-water species (e.g., ocean sunfish) during El Niño events.

5. The numbers of coho and Chinook salmon returning to the Columbia River to spawn have been enumerated at the Bonneville Dam (the first dam on the Columbia, a few miles upstream of Portland), since 1938, yielding more than 60 years of data. ENSO-related variability in annual salmon returns will be examined in this time series.

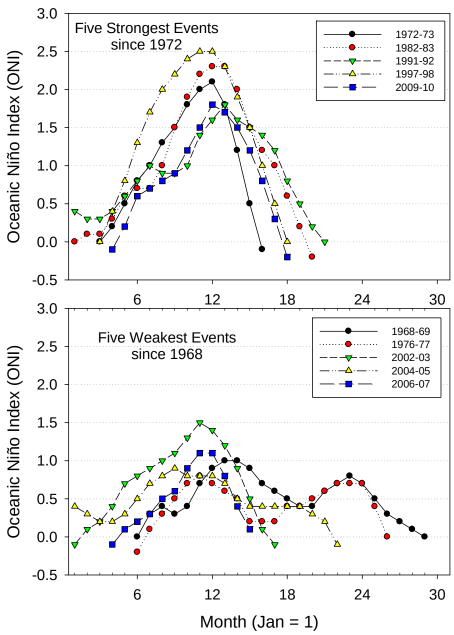

Figure 1. Time series of the Oceanic El Niño index (= SST anomalies in the Niño 3.4 region) for five strong and five weak El Niño events.

Types of El Niño events to be compared. We have sufficient hydrographic, copepod and ichthyo-plankton data to compare the impact of ten past El Niño events on lower trophic levels (1968-69, 1972-73, 1976-77, 1982-83, 1991-92, 1997-98, 2002-03, 2004-05, 2006-07 and 2009-10). Five strong events (max ONI ≥ 1.5) have occurred in equatorial waters since the early 1970s (Figure 1), most of which were initiated in spring, and lasted ~ 12 months. Three of these events have coincided with positive phases of the PDO (1982-83, 1991-92, 1997-98) while two occurred during negative phases of the PDO (1972-73 and 2009-10). There were also five weaker, but prolonged events (identified in Figure 1). There were two other moderate events (1963-64 and 1965-66 – not illustrated) but we only have hydrographic and krill data from this time period.

Limitations of our proposed research. Even though we have zooplankton and ichthyoplankton data from more than 500 sampling dates over nearly 50 years, there are data gaps (Figure 2). This limits somewhat our ability to compare the timing of the onset of El Niño at the equator to the timing when the event expresses itself in the coastal waters of the NCC for events prior to 1996. However, the data collected since 1996 provide unprecedented detail (biweekly sampling) allowing relatively precise evaluation of the relationships between timing of initiation of an El Niño event at the equator and the subsequent appearance of a signal off Oregon in the atmosphere (winds), the physical ocean (SST and T-S properties of deep waters), lower trophic levels (copepods), small pelagic fish including juvenile salmon, and adult salmon returns to Bonneville Dam.

Data Analysis. We intend to approach this analysis from two directions: 1) investigation of tropical El Niño signals in our NCC ecological records, and 2) attribution of interannual anomalies in the NCC ecosystem time series to physical processes which may or may not be related to ENSO variability (e.g., PDO, winds, sea level). The first of these approaches will examine time series of copepod, krill and ichthyoplankton species compared to time series of the Oceanic Niño Index, which may be viewed as a "bottom-up" investigation, where the source of anomalies is assumed to originate from physical processes in the tropical Pacific, and the possible consequences on the NCC ecosystem examined. The second approach is different in that it initially identifies anomalies in the NCC ecosystem and then examines them in relation to salinity, SST and SSH anomalies which are indicative of ENSO events. We will place emphasis on monthly anomalies in the seasonal cycle of plankton time series during positive and negative phases of the PDO in order to address the two hypotheses outlined above. Statistical analyses will include characteristics of the monthly time series (of 18 years duration by the end of 2013) of the PDO, ONI, SST, T/S properties of upwelled water, T/S properties of the California Undercurrent and nutrients at a depth of 150 m (at the station 25 miles off shore of Newport); biological data will be examined with ordinations and cluster analysis to determine relationships between community types (warm vs. cold water) and how these relate to El Niño events, and cross-correlation with physical time series with appropriate corrections for auto-correlation (as in Keister et al. 2011). Indicator species analysis will identify those species which are typical of strong vs. weak El Niño events (as in Keister et al. 2005); we already know that the presence of older zoea stages of *Emerita analoga* (mole crabs) are an excellent indicator of strong northward transport of coastal waters which typically occur during stronger El Niño events (Sorte et al. 2001). These were common in 1998 and again, in 2009-10.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	PDO	peak ONI (month)	
1969						x	x	x	x	x	x	x	-0.9	1.0	(1)
1970	x	x		x	x	x	x	x	x	x		x	0.8	0.5	(1)
1971	x	x	x		x	x	x	x	x	x	x	x	-1.8	-0.8	(5)
1972			x	x	x	x	x	x	x				-2.0	2.1	(12)
1973					x	x	x	x	x				-0.5	1.8	(1)
1977							x	x			+	+	1.2	0.7	(11)
1978	+	+	+	+	x+	x+	x	x	x				1.0	0.7	(1)
1982				x+	x+	x+	x+		x+				0.2	2.3	(12)
1983					x	x	x	x	x				1.3	2.3	(1)
1990							x	x	x				-0.5	0.4	(12)
1991		x		x	x	x	x	x					-1.3	1.6	(12)
1992							x	x					0.3	1.8	(1)
1996					x	x	x	x	x	x	x	x	0.8	0.0	(7)
1997	x	x	x	x	x	x	x	x	x	x	x		0.4	2.5	(11)
1998	x	x	x	x	x	x	x	x	x	x	x	x	1.5	2.3	(1)
1999		x	x	x	x	x	x	x	x	x	x	x	-0.4	-0.8	(4)
2000	x	x	x	x	x	x	x	x	x	x	x	x	-0.8	-0.4	(7)
2001	x	x	x	x	x	x	x	x	x	x	x		0.4	0.2	(7)
2002	x	x	x	x	x	x	x	x	x	x	x	x	-0.3	1.5	(11)
2003	x	x	x	x	x	x	x	x	x	x	x		1.8	1.2	(1)
2004	x	x	x	x	x	x	x	x	x	x	x	x	0.5	0.9	(9)
2005	x	x	x	x	x	x	x	x	x	x	x	x	0.9	0.7	(1)
2006		x	x	x	x	x	x	x	x	x	x	x	0.6	1.1	(11)
2007	x	x	x	x	x	x	x	x	x	x	x	x	-0.1	0.8	(1)
2008		x	x	x	x	x	x	x	x	x	x	x	-0.8	0.0	(8)
2009	x	x	x	x	x	x	x	x	x	x	x	x	-1.5	1.8	(12)
2010	x	x	x	x	x	x	x	x	x	x			0.7	1.7	(1)
2011	x	x	x	x	x	x	x	x	x	x			-0.8	-1.3	(1)

Figure 2. Months for which hydrographic and plankton data are available from 1969-present. Data in the right hand columns show values of the PDO and ONI, and the month when the ONI peaked during "strong" El Niño events. '+' indicates plankton samples that need to be enumerated.

Benefits and Deliverables. Results of our proposed research will be directed at four target audiences. **(1) Scientific community:** We will produce scientific manuscripts submitted to peer-reviewed journals which assess the variable influence of ten individual El Niño events on ecosystem structure and salmon during different phases of the PDO. Apart from the large events of 1983 and 1998, there is very little literature on the impacts of the "smaller" El Niño events on northeast Pacific ecosystems. **(2) Resource managers.** Data sets, analyses and outlooks will be sent to our growing list-serve, and posted to our salmon forecasting web-page on our Center's home page: http://www.nwfsc.noaa.gov/research/divisions/fed/oeip/a-ecinhome.cfm; we expect these new analyses will enhance and extend our salmon forecasting efforts especially when combined with NOAA Climate Prediction Center' El Niño forecasts. Results will also be posted to the PaCOOS website with links to the NANOOS webpage. **(3) The FATE Community.** Our ecosystem indicators are being incorporated into the northern California Current IEA activity led by the Northwest and Southwest Fisheries Science Center. The forecasting data are used by Columbia River salmon managers and by Native American tribal fisheries biologists. It should be obvious that a better understanding of past El Niño events will allow us to better evaluate the impacts of future ENSO activity on the NCC; they also may add value to the forecasts provided by the NOAA/CPC of impending El Niño events. **(4) Coastal communities and the general public:** Through our website, frequent lectures to the general public, and enhancements to our NOAA-funded "interactive display" on salmon forecasting in the Public Wing of the Hatfield Marine Science Center, we will increase public awareness of the changing climate system and its impacts on environmental resources. By highlighting the variability among individual El Niño events, we hope to increase public appreciation of the complexities in the climate system and the uncertainties associated with projecting future climate change.

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