Oceanographic and Ecological Indicators for Salmon Returns in the Northern California Current

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Estimates of the number of salmonids returning to spawn in the Columbia River basin are needed by managers to set harvest quotas, to determine the efficacy of improvements to fish passage through the hydropower system, and to determine if there are measurable improvements in returns due to freshwater habitat restoration efforts. These efforts are focused primarily on four species: *Oncorhynchus tshawytscha* (Chinook, both stream-type and ocean-type), *O. kisutch* (coho), *O. nerka* (sockeye) and *O. mykiss* (steelhead). Estimates of the number of adult salmonids returning to spawn are derived from sibling regression (jack) models and age-structured cohort models. The same types of models are used for harvest management for salmonids from coastal rivers and streams.

Missing from the harvest models is any consideration of environmental variability during the time that fish reside in the ocean. Three notable attempts have been made and each has proven capable of providing hindcasts of either the number of adults returning to spawn or recruits-per-spawner, but when used in forecast mode, each has failed soon after results were published. Nickelson (1986) showed a significant relationship between coho returns and interannual variations in coastal upwelling. Logerwell et al. (2003) expanded upon these results and showed that three variables could explain coho salmon returns: ocean temperatures the winter before juveniles entered the sea, the timing of the spring transition (the date when upwelling was initiated each year), and the strength of upwelling in April-May when juveniles first enter the sea. Rupp et al. (2012) continued the work on coho salmon and showed that including the Pacific Decadal Oscillation (PDO) into a statistical model provided a reasonable estimate of adult returns (in hindcast mode) but failed in forecast mode. We suggest here that these models failed in forecast mode because the prediction problem is inherently multivariate, that is, no single factor controls growth or sets survival and also because correlation is not causation: we do not understand the mechanisms that link physical forcing (upwelling and the PDO) with a biological response (salmon returns).

Here we report on two issues: first, our attempts to describe a mechanistic link between the PDO and the food chain upon which salmon feed and second, our attempts to use multiple indicators to provide forecasts of the number of adult salmon returning to spawn. The idea for looking at links between the PDO and salmon came from Francis and Hare (1994) who showed that salmon landings were correlated with the North Pacific Index and from Mantua et al. (1997) who showed that salmon landing around the northeast Pacific were correlated with the PDO. Recently, Peterson and Schwing (2003) showed that Columbia River Chinook were correlated with the PDO and that the survival of coho salmon was correlated with the biomass of “cold water copepods” (we expand on this idea later).

At first glance, one could conclude that it would be difficult to study the effects of the PDO on food chain structure using data from an in situ observational program because historically, the PDO only changes phase every 20-30 years. However, since 1998, the PDO has been changing phase every five years, thus these high frequency changes have provided a natural experiment, which has allowed study of the mechanisms by which PDO signals are transmitted to food chains. We have learned that changes in the sign of the PDO are followed closely by changes in copepod community structure: during the negative (“cool”) phase of the PDO, a “cold water community” dominates, whereas during the positive (“warm”) phase a “warm water community” dominates (Fig. 1). The copepods which are key players during the cool phase are *Calanus marshallae* and *Pseudocalanus mimus*, both of which are large lipid-rich species, whereas key players during the warm phase are small lipid-poor species such as *Paracalanus parvus, Ctenocalanus vanus, Clausocalanus spp. and Calanus pacificus.* None of these species store large quantities of lipids as compared to *C. marshallae* and *Pseudocalanus* sp. (Lee et al. 2006) with the possible exception of *Calanus pacificus,* which does store some wax esters but in lesser quantities per unit body mass than their more northern congeners (Håkanson 1987; Lee et al. 2006). Thus, we suggest that the mechanism that links the PDO with salmon growth and survival is as follows: when the PDO is persistently negative, waters which upwell are cold, salty, and have higher nutrient content (Chhak and Di Lorenzo 2007), and the source waters which feed the northern California Current (NCC) are sub-arctic in character. When the PDO is positive, a subtropical water type dominates coastal waters in the Pacific Northwest (Fig. 1). Source waters from the north bring the “cold water community” to the NCC, which

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results in a food chain anchored by large sub-arctic cold water lipid-rich copepods, whereas source water from the south or offshore bring sub-tropical lipid-depleted copepods to the NCC (Fig. 2). Thus a negative PDO equates to a food chain with a high bioenergetic content favored by salmon, which need to accumulate vast amounts of body fat both to survive their first winter at sea (Beamish and Mahnken 2001) and fuel their metabolic demands while migrating back to, and up, their natal streams to spawn.

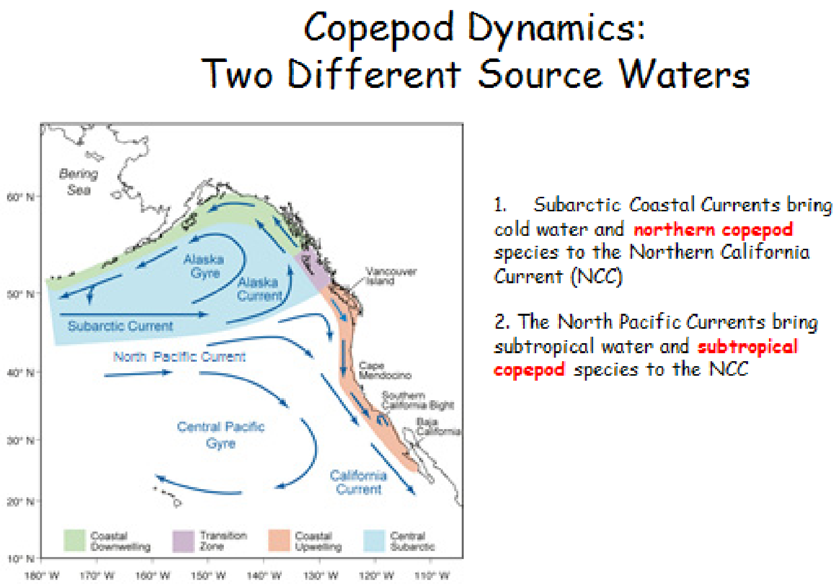

Fig. 1. Chart showing circulation patterns in the eastern North Pacific. The coastal currents transport northern copepods southward from southern British Columbia coastal waters; the North Pacific Current transports subtropical species to the northern California Current. The strength of these currents varies as a function of the sign of the PDO: a negative PDO results in strong southward coastal flows, whereas a positive PDO results in very weak coastal flows and onshore transport of offshore waters from the North Pacific Current to the Oregon coast.

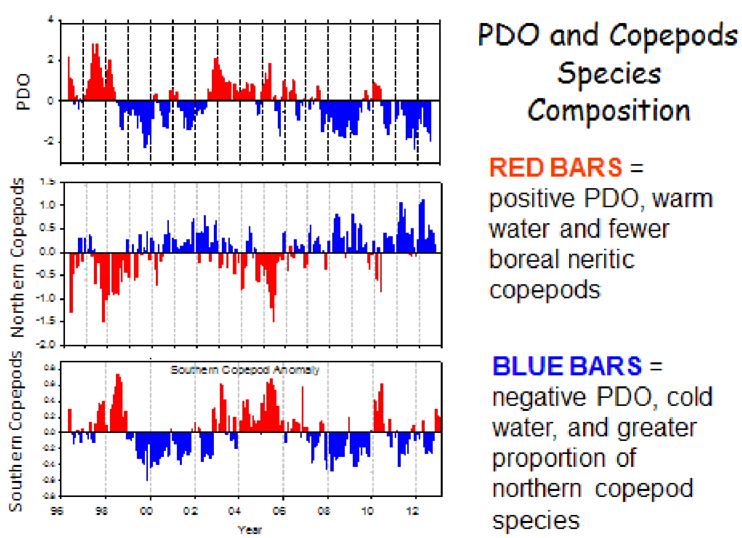

Fig. 2. Time series of the PDO, northern copepods, and southern copepods showing that when the PDO is positive, fewer "northern copepods" are found off Oregon, and vice versa.

The idea that transport is what links the PDO with local food chains was first suggested by Peterson and Hooff (2005) and Hooff and Peterson (2006). This idea was examined rigorously and elegantly by Keister et al. (2011) who used a ROMS model to show that during positive phases of the PDO current anomalies were northward and onshore resulting in transport of warmer waters and warm water copepod species to the coastal waters off central Oregon. During negative phase of the PDO, equatorward current anomalies led to a copepod community dominated by cold water species. Further, Bi et al. (2011) used satellite altimeter and coastal sea level (tide gauge) data to calculate geostrophic transport between the coast and the first offshore altimeter grid point (~ 50 km from shore) and found that alongshore currents and biomass of cold neritic copepods (*P. mimus*, *C. marshallae*, and *Acartia longiremis*) exhibited a strong seasonal pattern that fluctuated in opposite phase: positive alongshore currents (from the south) lead to low biomass of these species in winter and negative alongshore currents (from the north) lead to high biomass in summer (Fig. 3).

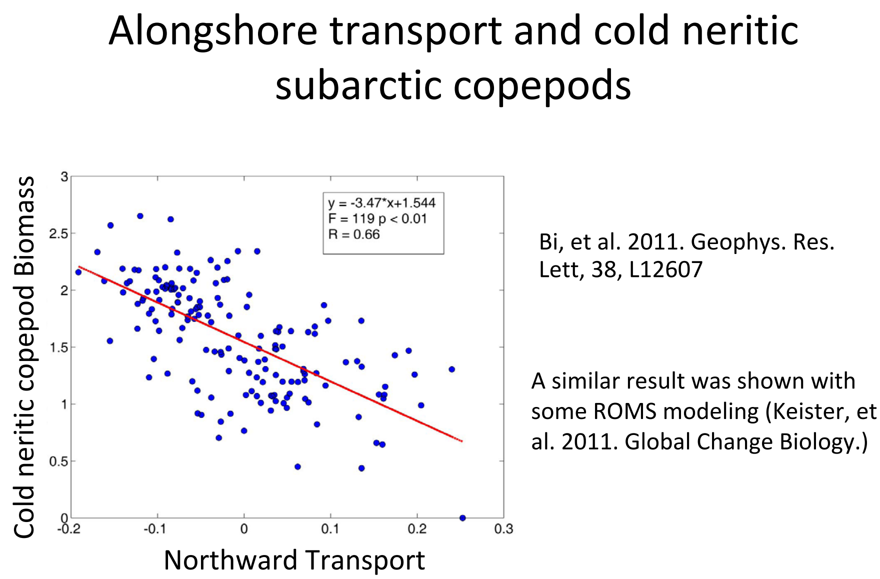

Fig. 3. Scattergram of "cold water" copepod biomass and northward transport. The weaker the northward transport (which is the same thing as strong southward transport), the lower the biomass of cold water lipid-rich copepods.

With these ideas in mind, we have developed a number of physical and ecological indicators, set in the context of an ecosystem approach to management, that have proven useful for providing both management advice as well as forecasts of salmon returns. All data and indicators are publically available on our Center's website: http://www.nwfsc.noaa.gov and by clicking on the "Salmon Forecasts" button. The indicators are of thee types: those that capture basin-scale physical forcing (the PDO and ENSO) and local-scale physical forcing (upwelling), and those that demonstrate the biological response—primarily bottom-up forcing of food chain structure. Some of the indicators are from web-based sources (SST, upwelling, and the PDO) whereas others are from two long-term at-sea monitoring programs. Data on in situ physical and biological oceanographic variables come from the Newport Hydrographic Line, a line that was sampled intensively by oceanographers from Oregon State University in the 1960s and early 1970s. Sampling along this line languished for a quarter century until 1996 when the line was re-opened and thereafter, sampled biweekly, yielding (now) a 17+ year biological oceanographic time series. Variables monitored include temperature, salinity, oxygen and chlorophyll fluorescence profiles, nutrients, chlorophyll-*a*, and abundance and biomass of copepods, krill, and ichthyoplankton. Data also originate from a long-term study of the distribution and abundance of juvenile salmonids resulting from survey cruises in May, June, and September from 1998 to present. Biological data that are used in the forecasting include biomass of northern and southern copepods, abundance of the fish larvae in winter (using only those larvae that salmon will consume as juveniles in spring), and catches of Chinook salmon in June and coho in September.

Values for each variable are listed in an excel table, ranked across years from 1998 to present (Table 1), and analyzed using principal component (PC) analysis. PC scores are listed in the table as well. An additional analysis uses values from the table along with a set of fish and food chain attributes (growth, salmon diets, estimated numbers of anchovy [as prey] and hake, as well as zooplankton sampled during salmon surveys) that are analyzed using maximum covariance analysis (Burke et al. 2013).

Table 1. List of physical and ecological indicators which summarize ocean conditions in a given year. Green = good, yellow = average, and red = poor. The value of the "mean rank" and the value of the "first principal component--P1" is used to estimate adult salmon returns (see Fig. 4).

Ecosystem Indicators	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
PDO (December-March)	14	6	3	10	7	15	9	13	11	8	5	1	12	4	2
PDO (May-September)	9	4	6	5	10	14	13	15	11	12	2	8	7	3	1
ONI Jan-June	15	1	1	6	11	12	10	13	7	9	3	8	14	4	5
46050 SST (May-Sept)	13	8	3	4	1	7	15	12	5	14	2	9	6	10	11
NH 05 Upper 20 m T winter prior (Nov-Mar)	15	9	6	8	5	12	13	10	11	4	1	7	14	3	2
NH 05 Upper 20 m T (May-Sept)	13	10	12	4	1	3	15	14	7	8	2	5	11	9	6
NH 05 Deep Temperature	15	4	8	3	1	11	12	13	14	5	2	10	9	6	7
NH 05 Deep Salinity	15	3	6	2	5	13	14	9	7	1	4	11	12	8	10
Copepod Richness Anomaly	15	2	1	6	5	11	10	14	12	9	7	8	13	3	4
N. Copepod Biomass Anomaly	14	10	6	7	4	13	12	15	11	9	3	8	5	1	2
S. Copepod Biomass Anomaly	15	3	5	4	2	10	12	14	11	9	1	7	13	8	6
Biological Transition	14	10	6	5	7	13	9	15	12	2	1	4	11	3	8
Winter Ichthyoplankton	16	8	2	4	6	15	14	10	13	12	1	9	3	11	7
Chinook Juv Catches (June)	14	3	4	12	8	10	13	15	9	7	1	5	6	11	2
Coho Juv Catches (Sept)	11	2	1	4	3	6	12	14	8	9	7	15	13	5	10
Mean of Ranks	13.9	5.5	4.7	5.6	5.1	11.0	12.2	13.1	9.9	7.9	2.8	7.7	9.9	5.9	5.5
RANK of the Mean Rank	15	4	2	6	3	12	13	14	10	9	1	8	10	7	4
Principle Component Scores (PC1)	6.56	-2.22	-2.95	-1.60	-2.12	2.08	3.12	4.21	1.10	-0.30	-4.39	-0.91	1.13	-1.76	-1.96
Principle Component Scores (PC2)	-0.51	0.04	-0.24	-0.76	-1.96	-1.53	2.55	-0.43	-0.66	1.07	-0.50	0.96	-0.74	1.36	1.35
Ecosystem Indicators not included in the mean of ranks or statistical analyses															
Physical Spring Trans (UI Based)	3	6	14	12	4	9	11	15	9	1	5	2	7	8	13
Upwelling Anomaly (Apr-May)	7	1	13	3	6	10	9	15	7	2	4	5	11	13	11
Length of Upwelling Season (UI Based)	6	2	14	9	1	10	8	15	5	3	7	3	11	13	11
NH 05 SST (May-Sept)	10	6	5	4	1	3	15	13	8	12	2	14	9	7	11
Copepod Community Structure	15	3	5	7	2	12	11	14	13	8	1	6	10	9	4

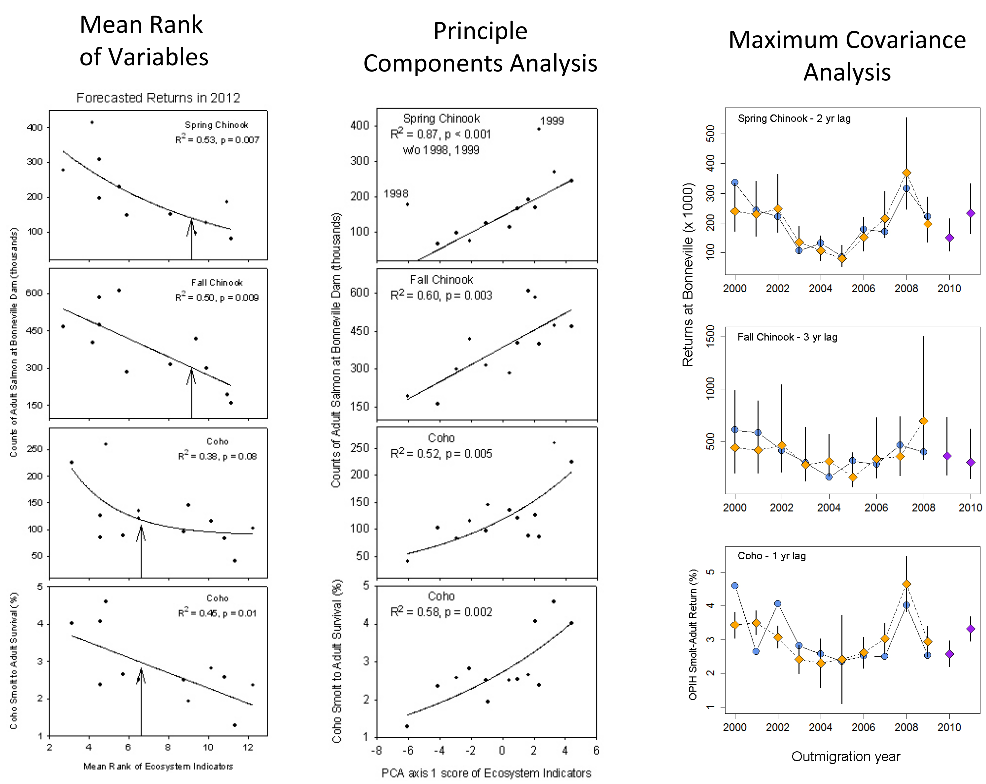

Fig. 4. Examples of the correlations of counts of adult salmon at Bonneville Dam and the mean rank of variables listed in Table 1 (left); correlations with the first principal component of the variables listed in Table 1 (PC1) (center); and the time series of expected versus observed sounds of salmon at Bonneville Dam using maximum covariance analysis (right).

Results of each of these analyses are used to produce three separate “outlooks” using simple correlation analysis (Fig. 4) with each yielding a similar result. To date our efforts have not been adopted by managers, although most are aware of our work. The chief obstacle to the wide-spread use of our indicators is that there is (and always be) uncertainty in our ability to continue to collect oceanographic data during monitoring cruises, due to vagaries associated with funding such work. Regardless, our results are popular because they provide plausible explanations for why salmon runs succeed or fail and clearly show the powerful influence that the ocean has on salmon growth, survival, and returns.

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