Connecting the "Dots" Among Coastal Ocean Metrics and Pacific Salmon Production in Southeast Alaska, 1997-2012

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Complex ocean ecosystem dynamics could be better understood in the context of climate change if relationships among coastal ocean metrics and Pacific salmon (*Oncorhynchus* spp.) production could be identified. We examined annual time series of ecosystem metrics during critical periods of salmon ocean life history to establish these connections and to help foster sustainable fisheries management. One critical period is the early ocean migration of juvenile salmon, which has been recognized as a strong determinant of year class strength for many salmon species (Parker 1968; Heard 1991; Pearcy 1992; Karpenko 1998; Quinn 2005). During this early period, important coastal ocean metrics for consideration include physical factors such as stream flow, coastal temperatures, ocean-basin indices, and biological indicators of juvenile salmon prey, growth, condition, and abundance during their seaward migration. In this study, prior year class strength was purposely excluded in order to isolate the predictive power of coastal ecosystem metrics on salmon production.

The selection of salmon production response variables associated with coastal ocean metrics must capture the appropriate spatial and temporal scales. These variables commonly include commercial harvest and marine survival. Because marine survival of salmon operates on spatial scales within 500 km (Mueter et al. 2002a; Pyper et al. 2005; Malick et al. 2009; Sharma et al. 2013), salmon production response variables should be region-specific as opposed to broad-scale in geographic distribution. These variables should also be time-specific because long term production trends of salmon can alternate between southern and northern domains along the west coast of North America, a pattern attributed to long term climate signals such as the Pacific Decadal Oscillation (PDO; Hare and Francis 1995; Mantua et al. 1997; Mueter et al. 2002b). Therefore, disentangling relationships between coastal ocean metrics and salmon production is most tenable by focusing on spatially-explicit regional production response variables over an intermediate temporal scale.

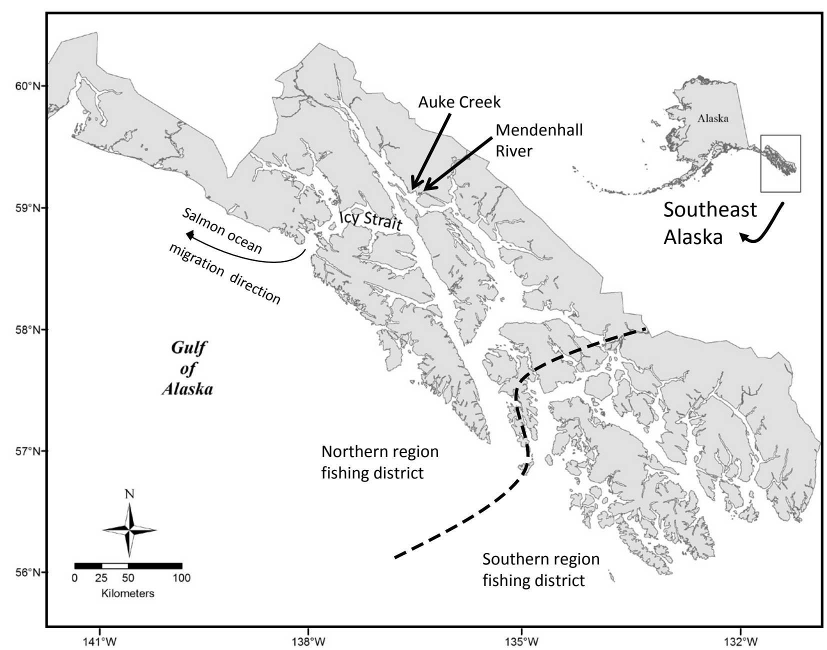

Fig. 1. Localities for sampling regional coastal ocean metrics (from Icy Strait), the estuarine entry point of wild pink and coho salmon (Auke Creek), the freshwater discharge measurement site from the Mendenhall River, and northern and southern commercial salmon harvest regions in Southeast Alaska.

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Making solid connections between annual coastal ocean metrics and salmon production is challenging because some species have long brood-year cycles that extend across multiple ocean years, thus confounding annual ocean signals. This is certainly true with species that spend two to five winters in the ocean before returning to spawn, such as sockeye (*O. nerka*), chum (*O. keta*), and Chinook (*O. tshawytscha*) salmon (Groot and Margolis 1991). However, pink (*O. gorbuscha*) and coho (*O. kisutch*) salmon exclusively spend one winter at sea, and thus are more suitable candidates for exploring connections among annual coastal ocean metrics and regional salmon productivity. These species, notwithstanding returns of precocious male coho salmon ("jacks"), also lack important leading indicator year class information from younger siblings for use as a forecasting tool. Consequently, stock assessments prior to pink and coho salmon fisheries is problematic because valuable input parameters for pre-season forecasting models are largely lacking (Haeseker et al. 2005; Wertheimer et al. 2011).

In this study, coastal ocean ecosystem metrics were examined in the context of pink and coho salmon production in Southeast Alaska (SEAK). Over two thousand anadromous salmon streams are located throughout the SEAK Archipelago, with pink and coho salmon occurring in most streams. Ongoing ocean research through the Southeast Coastal Monitoring (SECM) project has accrued a 15-yr time series of biophysical metrics associated with seaward-migrating juvenile salmon (Orsi et al. 2012). The study locality is centered in the vicinity of Icy Strait (58°N, 135W) in the northern region of SEAK, where both species are harvested commercially. Regional salmon harvest data are available annually from the Alaska Department of Fish and Game (ADFG), and wild stock marine survival data are available from the Auke Creek research station (Fig. 1).

Table 1. Chronology of annual, physical, and biological coastal ocean metrics related to salmon production response variables in Southeast Alaska, 1997-2012. The temporal context of each metric is shown in relation to months from ocean entry times of pink salmon fry and coho salmon smolts.

Metric	Category	Ocean entry time	Period	Narrative	Abbreviation
Coastal ocean					
Multivariate El Niño / Southern Oscillation (MEI) index	Physical	-6	Nov-Mar	Southern Pacific: temperature, wind, pressure, teleconnection with Icy Strait temperatures (Wolter and Timlin 1993)	MEI-W(Nov-Mar)
Pacific Decadal Oscillation (PDO) index	Physical	-6	Nov-Mar	North Pacific sea surface temperature anomaly (Mantua et al. 1997)	PDO-W(Nov-Mar)
Auke Creek stream temperature	Physical	-3	Sep-May	In stream water temperature, warmer temperatures faster hatching and outmigration	Temp AC Sep-May
Mendenhall River discharge	Physical	-1	Mar-May	Freshwater influx to estuaries, faster juvenile transport offshore of littoral zone (USGS 2011)	MRD-Mar-May
Fry/smolt timing	Biological	0	Apr-May	Julian day of peak outmigration: pink fry in April and coho smolts in May	P-pk outmigr day C-pk outmigr day
Auke Bay dock sea surface temp	Physical	0	Apr-May	Littoral zone sea surface temperatures that fry and smolts are exposed to	SST AB Apr-May
Preferred salmon prey fields	Biological	+1	June	Biomass of integrated zooplankton when juveniles are most abundant	Jun-pref bio
Juvenile salmon peak catches	Biological	+1.5	Jun/Jul	Catch per trawl haul of juveniles in peak month	P-CPUE-pk C-CPUE-pk
Icy Strait temperature	Physical	+2	May-Aug	Integrated 1-20 water temp throughout seaward migration period for juveniles	ISTI-Avg20mMJJA
NP Index	Physical	+2	Jun-Aug	Inverse of Aleutian Low, relaxes coastal downwelling, broadens Alaska Coastal Current (Trenberth and Hurrell 1994)	NPI-jja
PDO	Physical	+2	Jun-Aug	North Pacific sea surface temperature anomaly	PDO(sumJJA)
Preferred salmon prey fields	Biological	+2	May-Aug	Numerical abundance of preferred prey items	MJJA-pref bio

Table 1. Continued.

Metric	Category	Ocean entry time	Period	Narrative	Abbreviation
Juvenile salmon energy density	Biological	+2	Jul	Whole body energy content of fish	P-Energy C-Energy
Prey wt/ body wt	Biological	+2	Jul	Percentage of prey wt divided by whole body weight.	P-prey%bw C-prey%bw
Juvenile salmon condition	Biological	+2	Jun-Aug	Length weight conditional residuals	P-CondR C-CondR
Juvenile size at time	Biological	+2	Jul	Size on the 24th of July (growth proxy) in Icy Strait	P-SzAtT C-SzAtT
Juvenile timing	Biological	+2	Jun-Aug	Peak month of migration along the Icy Strait seaward migration corridor	P-Season C-Season
Predator index	Biological	+3	Jul-Aug	Adult coho abundance and predation rate in Icy Strait (Adult CPUE * predation intensity)	PredIndex
Production response					
Marine survival of Auke Creek jacks	Production response	+4	Sep	Coho salmon (age -0) precocious male jacks that return after a brief coastal residence	COHOjk%ms
Commercial harvest in Southeast AK	Production response	+14	Aug	Pink salmon from purse seine fishery and coho salmon from commercial troll fishery: Both from the northern and entire region of SEAK	PINKharNSE COHOharNSE PINKharSEAK COHOharSEAK
Marine survival of Auke Creek adults	Production response	+16	Oct	Adult pink salmon age -.1 arrive during August and Adult coho salmon arrive in Sep	PINK%ms COHOadult%ms

Ecosystem metrics were chosen to reflect biophysical conditions in the early marine life history phase of pink and coho salmon (Table 1). We examined annual region-specific coastal ocean metrics including overwinter freshwater stream temperatures, spring freshwater discharge, and spring and summer metrics associated with seaward-migrating juvenile salmon (marine water temperature, zooplankton standing stock, salmon migration phenology, abundance, growth-condition-energy, and an associated predation index). Additional annual metrics representing larger basin-scale physical oceanographic conditions included the overwinter Multivariate El Niño/Southern Oscillation Index (MEI), the summer Pacific Index (NPI), and the overwinter and summer Pacific Decadal Oscillation Index (PDO).

The production response variables chosen for pink and coho salmon were the annual commercial harvests of these species in SEAK (northern region and throughout) and stock-specific marine survival from Auke Creek. Salmon harvest data have been used as a historical index of regional productivity (Jaenicke 1995; Jaenicke et al. 1998) and were obtained from ADFG (ADFG 2012). Harvest data from the northern region were examined separately because it encompasses Icy Strait, the locality where most of the coastal ocean metrics were collected (Fig. 1). Fishery harvest data were the number (millions) of fish caught, representing predominantly wild unmarked stocks that fluctuate widely over the time series (Fig. 2). Wild salmon stock survival data were obtained from pink salmon (unmarked) and coho salmon (coded wire tagged, CWT) returning to Auke Creek, where both species are monitored via counting weirs installed for spring downstream migrants and fall upstream returning adults (Fig. 3). The Auke Creek facility is cooperatively managed by NOAA, ADFG, and the University of Alaska to study out migrants and returns of four species of wild salmon fry, smolt, precocious males (jacks), and adults (Taylor 1980; Mortensen et al. 2000; Briscoe et al. 2005; Taylor 2008; Kovach et al. 2013). Coho salmon CWTs allow monitoring of both jacks that return in the same year and adults that are either intercepted in commercial fisheries or return the following year to the system. Thus, marine percent survival data included adults returning after one year at sea (pink salmon age 0.1, coho salmon age -.1), and coho salmon jacks that returned to spawn after 3-4 months at sea (age -.0; Table 1). Coho salmon adult marine survival includes contributions of Auke Creek fish in SEAK commercial fisheries, whereas pink salmon marine survival does not include fishery harvest information.

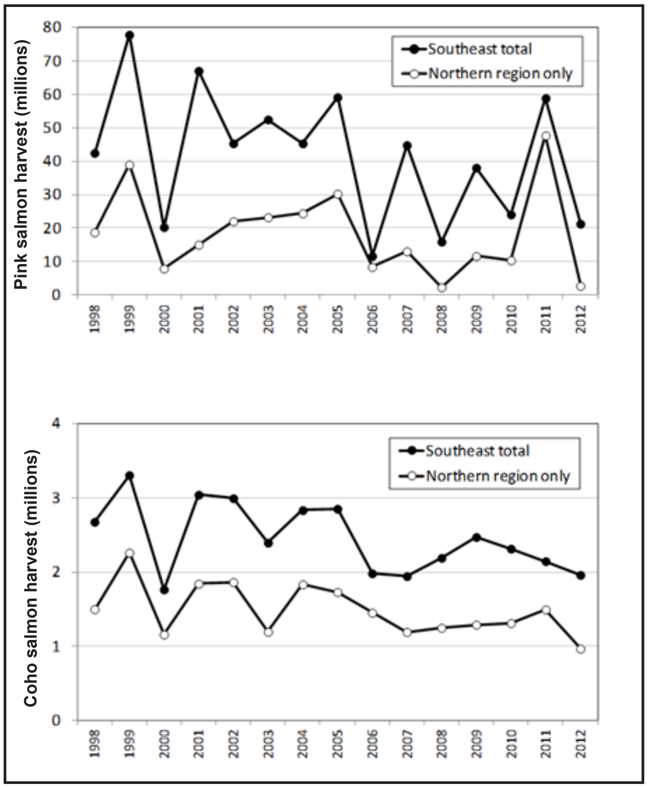

Fig. 2. Commercial harvest patterns of pink and coho salmon in the northern and entire region of Southeast Alaska, 1998-2012.

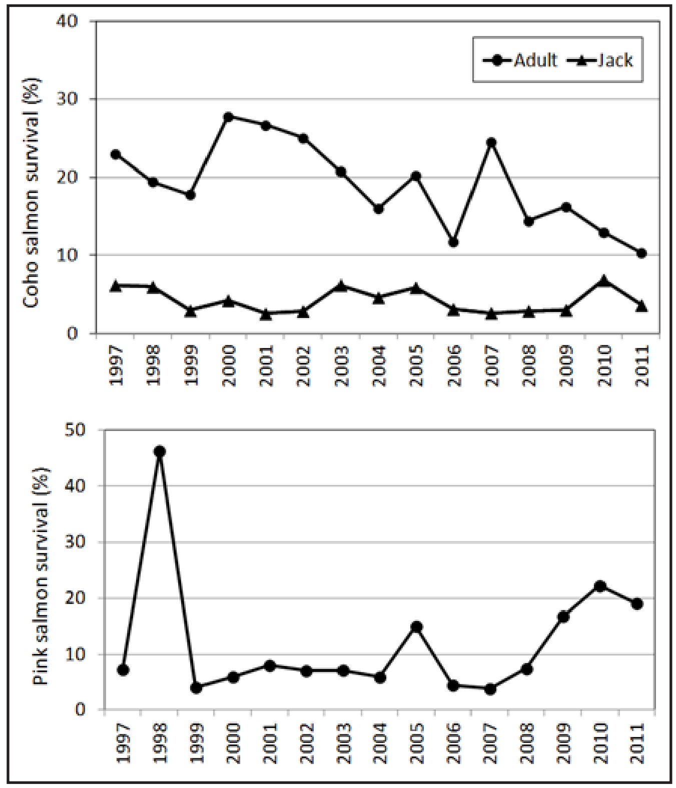

Fig. 3. Wild stock survival of pink and coho salmon from Auke Creek in the northern region of Southeast Alaska, over the 1997-2011 ocean entry years. Pink salmon survival is estimated from unmarked wild fry counted from the downstream trap and subsequent weir counts of returning adults the following year. Coho salmon survival is based on near 100% wild smolt marking and subsequent returns. Coho salmon survival includes jacks returning to Auke Creek the same ocean year as outmigration and of adults returning the following year in addition to fishery harvest estimates.

Our study objective was to examine connections among coastal ocean metrics associated with seaward-migrating juvenile salmon (1997-2011) and adult salmon production response variables for pink and coho salmon (1998-2012). One potential outcome of this study is improved insight into mechanisms operating through ecosystem dynamics or climate change that could influence salmon production in SEAK. Consequently, connecting the dots among coastal ocean metrics and production of pink and coho salmon would provide an opportunity to improve understanding of coastal ecosystem functions and to foster sustainable fisheries through the development of forecast models to benefit resource stakeholders.

A multivariate approach was used to identify and define the relationships among coastal ocean metrics and salmon production response variables for the 15-year time series. First, we used dendrograms from cluster analysis (Fig. 4) based on Spearman rank correlation coefficient resemblances of the normalized data matrix per the average linkage method to define relationship distances (Primer v6 software; Clarke and Gorley 2006). Of the production response metrics, clusters were evident for (a) marine survival of adult pink salmon and coho salmon jacks, and (b) regional harvests of pink and coho salmon (Fig. 4). The clustering of these survival metrics suggests the importance of early marine conditions for both species, as coho salmon jacks return after only four months at sea (Table 1; Fig. 4). In contrast, lack of clustering for adult coho salmon marine survival suggests lack of association with any single coastal ocean metric, which implies that a different factor(s) influences survival of Auke Creek coho salmon beyond their seaward migration phase.

Second, a BEST analysis (Clarke and Gorley 2006) was used to identify a subset of coastal ocean ecosystem metrics having the highest correlation with salmon production response variables. A matrix of production response variables was constructed using Euclidean distances, and then an iterative process was used to choose a subset of coastal ocean variables that it best matched based on Spearman rank correlation coefficients between the two matrices. Results from the BEST analysis indicated that the MEI_{winter} and PeakPinkCPUE variables were closely related ($r = 0.67$) to subsequent salmon production, suggesting that both a lagged, long-distance climate signal and localized, early marine conditions may influence pink and coho salmon production in SEAK.

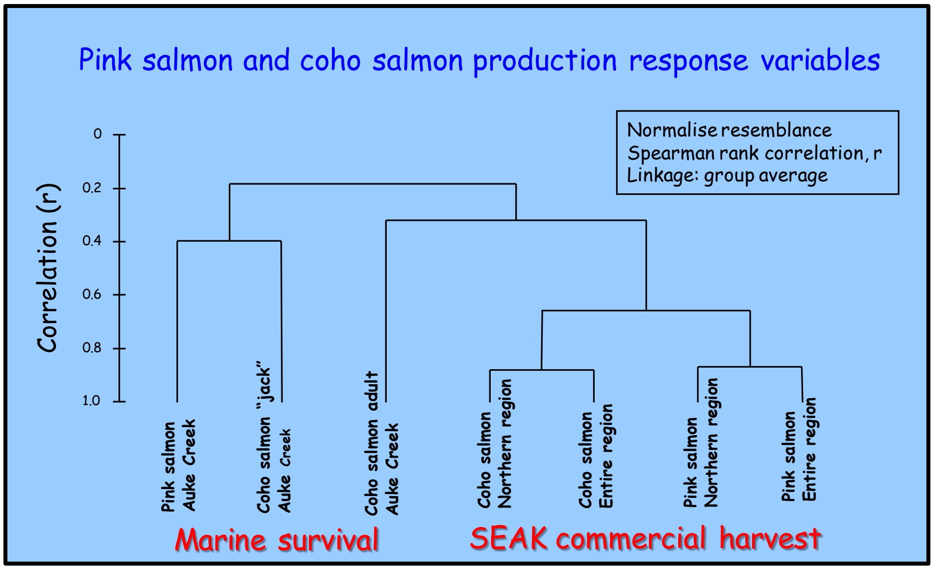

Fig. 4. Spearman rank correlation dendrogram of production response metrics of pink salmon and coho salmon. These represent survival of pink and coho salmon (adult and jack) from Auke Creek in the northern region of Southeast Alaska, as well as commercial fishery harvest in the northern and entire Southeast Alaska region over the 1997-2011 ocean entry years.

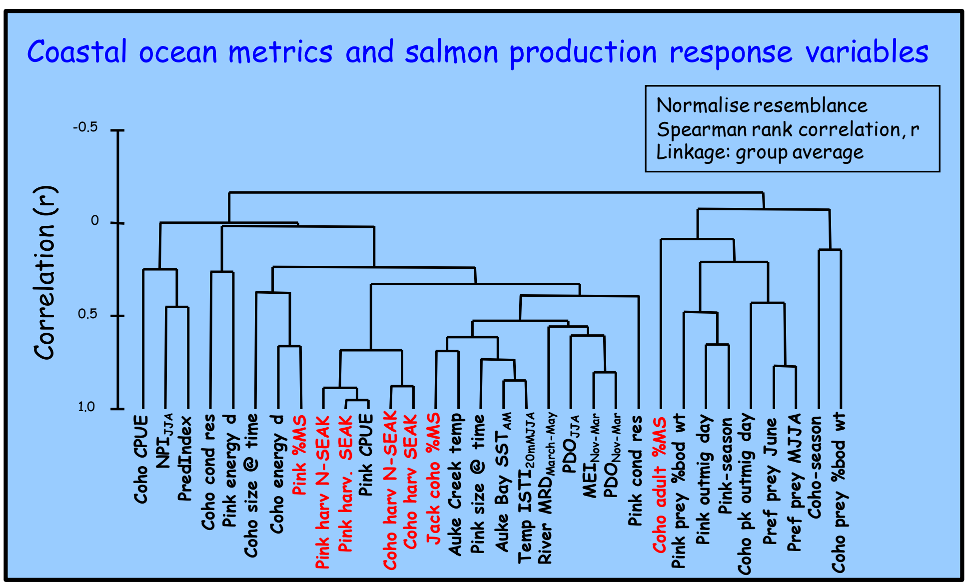

Fig. 5. Spearman rank correlation dendrogram of all normalized coastal ocean metrics associated with seaward migrating pink and coho salmon and response production metrics in Southeast Alaska over the 1997-2011 ocean entry years. Definitions of the metrics are shown in Table 1.

Third, in order to identify similarities among the coastal ocean and salmon production variables in the time series, a second dendrogram was constructed from a matrix of Spearman rank correlation coefficient resemblances for all 32 coastal ocean and salmon production variables (Fig. 5). All of the salmon production response variables except coho salmon adult marine survival grouped into clusters strongly associated ($\rho > 0.6$) with coastal ocean metrics. The strongest associations were for: (1) pink salmon harvest and peakPinkCPUE; (2) coho salmon harvest and peakPinkCPUE; (3) coho salmon jack marine survival and stream temperature in Auke Creek$_{Sept\text{-}Apr}$; and (4) pink salmon marine survival and juvenile coho salmon energy density. No survival response except coho salmon jacks was linked with local stream temperatures. The unusual connection between adult pink salmon survival and juvenile coho salmon energy density could be explained by a common trophic linkage driven by temperature.

Table 2. Forecast models constructed for each of the salmon production response variables, using a forward-backwards stepwise regression and considering all coastal ocean metrics associated with juvenile salmon seaward migration to the Gulf of Alaska, 1997-2011. The metrics shown in the models include: the Multivariate El Niño/Southern Oscillation Index (MEI, November-March), juvenile salmon peak abundance (CPUEpeak, average catch [Ln +1] in June or July), Mendenhall River freshwater discharge (MRD, March-May), Auke Bay sea surface temperature (AB-SST, April-May), Icy Strait monthly 1-20 m temperature index (ISTI, May-August), the Pacific Decadal Oscillation (PDO, November-March prior to ocean entry of juvenile salmon), and an Adult Predator index (API, July-August).

Species	Production response metric	Terms in best model	Probability
Pink salmon	**Marine survival** Auke Creek	MEI_{winter}	$p = 0.014$
Pink salmon	**Harvest** Northern Southeast only	PDO_{winter} + CPUEpeakPink + API	$p < 0.0001$
Pink salmon	**Harvest** Southeast	CPUEpeakPink + MRD	$p < 0.0001$
Coho salmon – Adult	**Marine survival** Auke Creek	%Prey/Coho body wt.	$p = 0.075$
Coho salmon – Jack	**Marine survival** Auke Creek	AB-SST	$p < 0.0001$
Coho salmon	**Harvest** Northern Southeast only	CPUEpeakPink + API + ISTI	$p < 0.0001$
Coho salmon	**Harvest** Southeast	CPUEpeakPink + API	$p = 0.001$

Finally, forecast models were constructed for each of the salmon production response variables, using a forward-backwards stepwise regression approach (General Linear Model, GLM). Of these seven different production response metric models, all models but one (Auke Creek coho survival) were significant ($p < 0.05$; Table 2). Coastal ocean metrics identified as terms in these models included PeakPinkCPUE (four models), API (three models), and MEI_{winter}, PDO_{winter}, MRD, ISTI, and AC stream temperature (one model each). Two of these metrics in the GLM models were also identified in the BEST analysis (PeakPinkCPUE and MEI) and two were identified by Spearman rank correlation coefficient resemblances (PeakPinkCPUE and AC stream temperature).

This study identified coastal ocean metrics associated with juvenile salmon as important leading ecological and performance indicators suitable for forecasting pink and coho salmon production in SEAK, and also links distant ocean basin climate signals such as the MEI_{winter} and PDO_{winter} to subsequent salmon production.

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