Forage Fish

Exploring Links between Ichthyoplankton Dynamics and the Pelagic Environment in the Northwest Gulf of Alaska

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This particular contribution to the Ecosystem Considerations document represents the culmination of this study and the analyses and results have evolved since last year's contribution to the 2005 document.

The impact of climate on marine fisheries is highly variable, and year-to-year recruitment is subject to a complex interplay of influences. Potentially, much of this complexity stems from the impact of environmental conditions during the early life history of marine fish species. The present study focuses on a 21-year time-series of larval fish abundance in late-spring surveys from 1981 through 2003 (no data for 1984 and 1986) in the northwest Gulf of Alaska. In combination with basin and local-scale measures of the state of the atmosphere and ocean in the Gulf of Alaska during these years, links between fish early life history dynamics and the physical environment are explored.

Ichthyoplankton data were selected from an area and time (May 16-June 6) that had the highest sampling density and the most consistent sampling over the years. Numerically dominant species were used in the analysis (Table 8). The environmental data time-series includes climate indices, and atmospheric and oceanographic variables representative of both the broader basin of the Gulf of Alaska and northeast Pacific Ocean, and the local study area (Table 9). The influence of environmental conditions on the abundance and survival of various species of fish larvae is likely to be significant from the initial production of the eggs (predominantly winter to early spring in the Gulf of Alaska) through the period of late larval development, weeks to months later. Consequently, both time-lagged and survey time values of the environmental time-series were included in the analysis (Table 9). Relationships between larval fish abundance and environmental factors were examined using Generalized Additive Modeling (GAM). GAM is a form of non-parametric multiple regression that models a response variable as a function of several predictor variables. For each group of environmental variables (basin and local-scale), GAMs were run for individual species with every possible combination and subset of variables. Best-fit models were selected using generalized cross validation methods (Green and Silverman, 1994).

Interannual patterns in abundance of the larval fish species are presented in Figure 57 and a summary of the GAM analyses by species, variables and months is given in Table 10. The emergent associations between larval species and physical variables indicate that larval abundance in late spring is linked to species-specific combinations of environmental variables, with seasonal variation in linkages apparent (Table 10), and that the nature of the connections between larval abundance and physical variables reflects details of individual species early life history strategies. For instance, in the case of Pacific sandlance the strongest model to emerge from the analysis was the connection between late May larval abundance and local conditions in March (all local scale variables contributing to the model), the period of peak emergence of larvae from eggs incubated in coastal sediments over winter months. The implication in terms of recruitment success, or at least survival to the early juvenile stage, is that the primary period of vulnerability for this species during its early life history is the period of hatching and early exposure of yolk-sac larvae to the pelagic environment. Conversely, the overall connections between starry flounder larvae and the environmental variables were very weak reflecting the limited planktonic stage of this species (transformation to the juvenile stage and settlement occurs at 8-10.5 mm length). The latter observation suggests an early life history strategy of resilience to the pelagic environment, with limited environmental control of recruitment occurring during the larval phase. In Figure 58, species are ranked according to the total significant contributions of the two groups of physical variables to all monthly best-fit GAM models. We would like to propose this ordering of species as a gradient of early life history vulnerability to the physical environment with Pacific cod as the species displaying the strongest links, and therefore vulnerability, to the physical environment and starry flounder showing the weakest connections, implying the greatest resilience.

Summarizing the results across species, the relative influence of the different environmental variables on larval fish abundance in late spring is implied (Tables 11 and 12). For both the basin-scale and the local-scale variables, the combined contributions of the variables to the 12 best-fit species models is strongest for the April values relative to the other months. Seasonal variation in influence of the variables seems most pronounced for the EP-NP Index and the Alongshore Wind Index both with strong connections between spring values and species abundance, and for the Freshwater Index that is primarily connected by the winter values. Ranking the variables according to their overall level of contributions to the species best-fit models (Table 11), it seems that basin-scale atmospheric circulation during spring (EP-NP Index) and the related local-scale spring wind conditions (Alongshore Wind Index) impart the strongest influence on the prevalence of various larval fish species in the favorable productive coastal waters of Shelikof Strait in late May. Influence of larval transport by atmospheric forcing of Alaska Coastal Current dynamics during April and May seems the most likely mechanism of environmental control of spring larval abundance in this instance. River discharge (Freshwater Index) during winter months and Sea Surface Temperature for winter and spring months also rank highly in terms of their potential influence on larval abundance in late May. The former is most likely to affect larval abundance and survival by flushing eggs and larvae from coastal waters during winter and also by influencing Alaska Coastal Current dynamics and subsequent larval transport. The persistent seasonal link with Sea Surface Temperature reflects a negative association with winter water temperature for certain species (walleye pollock, Pacific cod and northern rock sole), a link with spring water temperature for some (northern lampfish and negative link for Pacific halibut), and a positive association with spring water temperature for others (rockfish and southern rock sole) (Table 10). In this instance, likely mechanisms of control on larval abundance in late spring are the potential influence of temperature on the timing of egg and larval production and the physiology of egg and larval development.

Although individual species display unique patterns of periodicity and amplitude of variation in the time-series of late spring larval abundance, there are also common patterns that emerge (Figure 57) and it is interesting to investigate these similar patterns with respect to shared variable connections and early life history strategies among species (Tables 10 and 13). The degree of within group similarities in variable connections and early life history traits among the four species groups identified (Figure 57 and Table 13) suggest common mechanisms of environmental control on prevalence of larvae in late May for the constituent species. A more detailed discussion of these observations will be included in the manuscript that is presently being prepared for publication.

This type of ichthyoplankton time-series study is valuable in two major respects. It has good potential for assessing the degree of vulnerability or resilience of individual species early life history patterns to fluctuating climate and oceanographic conditions. It also provides crucial information to help identify "environmental indicators" that may have a broad-spectrum effect on multiple species early life history stages as well as those that may be more species-specific in exerting control on early life history survival.

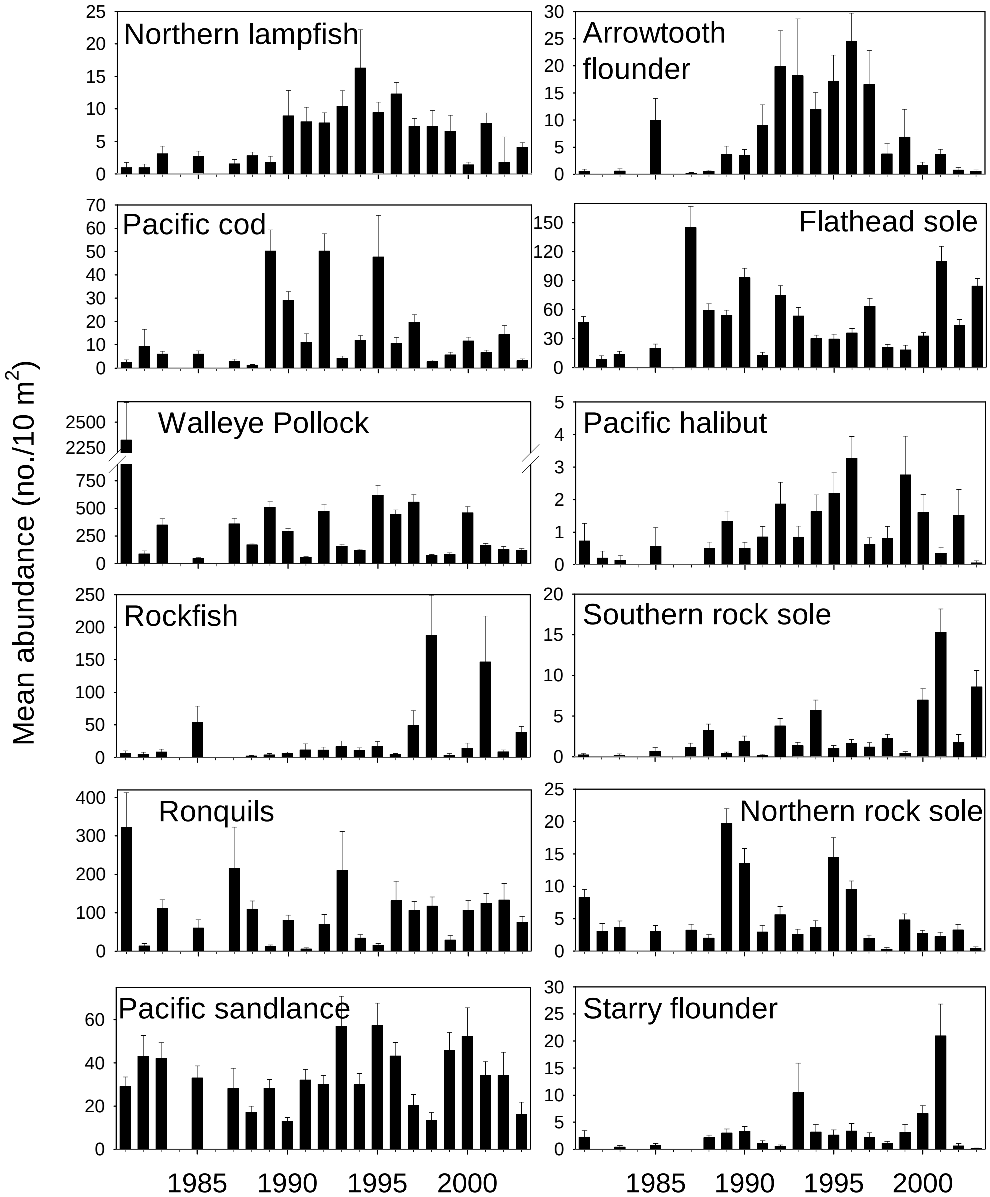

Figure 57. Interannual time-series of larval abundance based on ichthyoplankton collections in the vicinity of Shelikof Strait, Gulf of Alaska, May 16-June 6. No data for 1984 and 1986.

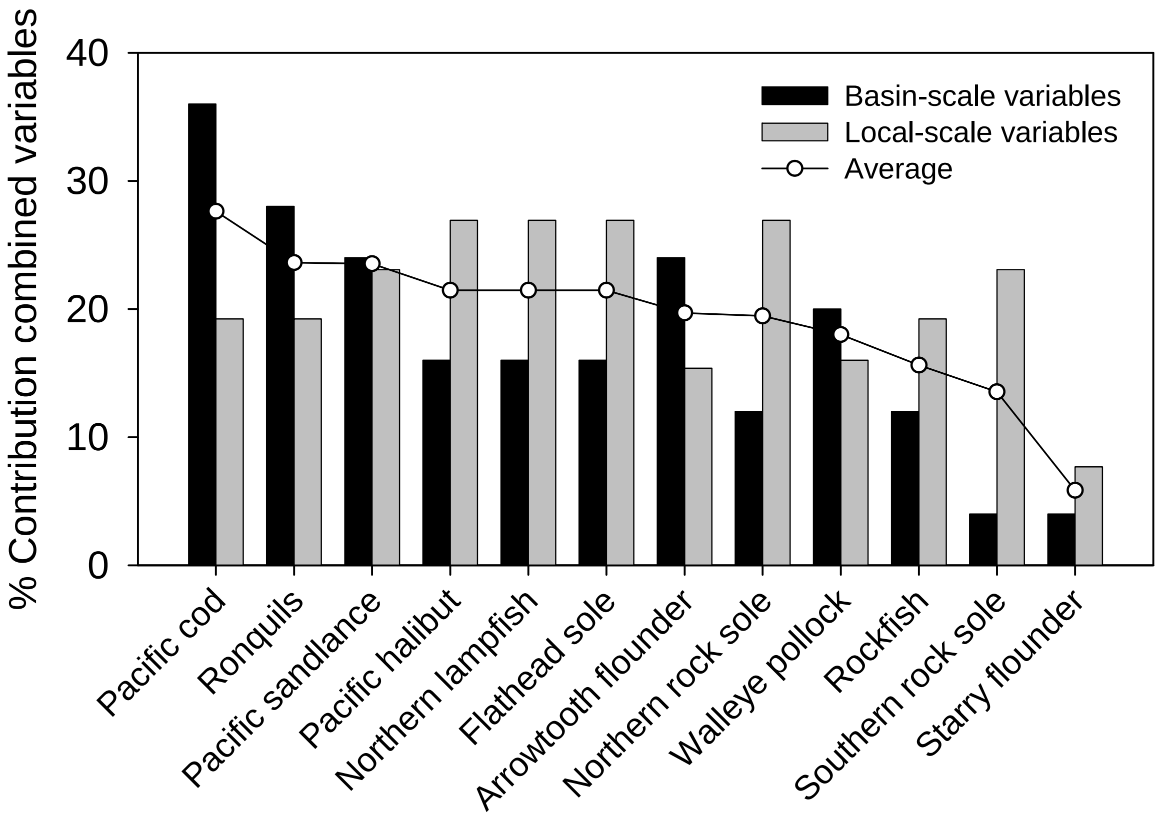

Figure 58. Gradient of vulnerability of species early life history patterns to the Gulf of Alaska physical environment based on the Generalized Additive Modeling results.

Table 8. Numerically dominant species of fish larvae included in the study, ranked according to percentage occurrence in the study area during late spring for all years combined.

Species	Common name	% Occurrence	Mean abundance (no./10m²)
Theragra chalcogramma	Walleye pollock	90.18	362.11
Hippoglossoides elassodon	Flathead sole	76.57	50.01
Ammodytes hexapterus	Pacific sandlance	75.15	33.38
Bathymaster spp.	Ronquils (genus *Bathymaster*)	66.43	99.42
Gadus macrocephalus	Pacific cod	49.78	14.65
Lepidopsetta polyxystra	Northern rock sole	35.05	5.29
Stenobrachius leucopsarus	Northern lampfish	33.03	5.88
Sebastes spp.	Rockfishes	30.99	29.03
Lepidopsetta bilineata	Southern rock sole	20.55	2.77
Atheresthes stomias	Arrowtooth flounder	18.79	7.32
Platichthys stellatus	Starry flounder	18.56	3.24
Hippoglossus stenolepis	Pacific halibut	10.00	1.07

Table 9. Environmental variables included in GAM analysis (abbreviation on left), source of data and associated reference. Monthly mean values for January through May were used in all instances except for FLOWKL8 and RI. SPEM model output is unavailable prior to March so the latter variables are represented by March through May means.

Variable name		Source	Reference
1. Basin Scale Variables			
PDO	Pacific Decadal Oscillation (Leading pattern of North Pacific SST)	Joint Institute for the Study of the Atmosphere and Ocean, University of Washington.	Mantua et al., 1997.
NP	North Pacific Index (Intensity of the mean winter Aleutian Low pressure cell)	NOAA - National Center for Atmospheric Research	Trenberth and Hurrell, 1994.
AO	Arctic Oscillation Index (See-saw pattern of polar-middle latitude atmospheric pressure)	NOAA - Climate Prediction Center	Thompson and Wallace, 1998.
EP-NP	East Pacific - North Pacific Index (Leading mode of North Pacific atmospheric variability in spring)	NOAA - Climate Prediction Center	Barnston and Livezey, 1987.
MEI	Multivariate ENSO Index (See-saw pattern of tropical sea level pressure, East-West Pacific.)	NOAA - Climate Diagnostics Center	Wolter and Timlin, 1998.
2. Local Scale Variables			
FRESH	GOA River Discharge	Tom Royer	Royer et al., 2001
ALONG MIXING	Alongshore Wind Index, 59^{o}N, 150^{o}W Wind Mixing Index (wind speed cubed)	Calculated from coastal wind data at Gore Point	Stabeno et al., 2004.
SST	Sea Surface Temperature (SST) 57.5^{o}N,155.5^{o}W	NOAA - Climate Prediction Center	Reynolds and Smith, 1994.
FLOWKL8 RI	Flow through Line 8, Kodiak side (Proxy for transport up the sea valley) Retention Index (Percent particles released in study area not lost to advection in 15 days)	Computed from the SPEM circulation model	Hermann and Stabeno, 1996.

Table 10. Results of GAM analysis for late spring larval species abundance versus monthly mean basin-scale variables (top half of list), and local-scale variables (bottom half of list). R2 values and levels of variable significance are for best-fit GAM models for each species and month combination. Blank columns indicate weak best-fit models with insignificant level of contribution (at P>0.05) from constituent variables.

Northern lampfish

Variables	Jan	Feb	Mar	Apr	May
PDO					
NP				Neg	Pos
AO					
EP-NP					
MEI					
R^2(adj)	0.05	0.15	0.41	0.22	0.26
SST					
ALONG				Pos	
MIXING	Neg				
FRESH					
FLOWKL8				Pos	
RI					
R^2(adj)	0.38	0.05	0.09	0.34	0.70

Ronquils

Variables	Jan	Feb	Mar	Apr	May
PDO	Pos			Pos	
NP			Neg		
AO				Pos	
EP-NP					
MEI					
R^2(adj)	0.49	0.17	0.26	0.45	0.17
SST					
ALONG					
MIXING					
FRESH			Pos		
FLOWKL8				Neg	
RI					
R^2(adj)	0.13	0.19	0.81	0.52	0.53

Starry flounder

Variables	Jan	Feb	Mar	Apr	May
PDO					
NP					
AO					
EP-NP					
MEI					
R^2(adj)	0.07	0.04	0.27	-0.01	0.04
SST					
ALONG					
MIXING					
FRESH		Pos			
FLOWKL8					
RI					
R^2(adj)	0.18	0.45	0.03	0.05	0.33

Pacific cod

Variables	Jan	Feb	Mar	Apr	May
PDO		Neg			
NP				Pos	
AO		Pos	Pos	Neg	
EP-NP				Pos	Pos
MEI		Pos			
R^2(adj)	0.16	0.66	0.19	0.70	0.33
SST		Neg			
ALONG					
MIXING					
FRESH					
FLOWKL8					
RI					
R^2(adj)	0.04	0.17	0.50	0.48	0.05

Pacific sandlance

Variables	Jan	Feb	Mar	Apr	May
PDO					Neg
NP					
AO					Neg
EP-NP					
MEI					
R^2(adj)	0.16	0.28	0.35	0.21	0.42
SST					
ALONG					
MIXING					
FRESH	Neg		Neg		
FLOWKL8					
RI			Neg		
R^2(adj)	0.37	0.21	0.65	0.03	0.27

Pacific halibut

Variables	Jan	Feb	Mar	Apr	May
PDO					
NP					
AO				Neg	
EP-NP					Pos
MEI				Neg	
R^2(adj)	0.11	0.21	0.37	0.40	0.17
SST				Neg	
ALONG				Pos	
MIXING					
FRESH		Neg	Neg		
FLOWKL8					
RI					
R^2(adj)	0.15	0.16	0.33	0.82	0.03

Walleye pollock

Variables	Jan	Feb	Mar	Apr	May
PDO					
NP					
AO		Pos		Neg	
EP-NP				Pos	Pos
MEI					
R^2(adj)	0.07	0.50	0.02	0.50	0.40
SST	Neg				
ALONG					
MIXING					
FRESH					
FLOWKL8					
RI					
R^2(adj)	0.31	0.23	0.23	0.42	0.04

Arrowtooth flounder

Variables	Jan	Feb	Mar	Apr	May
PDO				Neg	
NP				Neg	
AO				Neg	
EP-NP					Pos
MEI					
R^2(adj)	0.01	0.31	0.23	0.69	0.34
SST					
ALONG	Pos			Pos	
MIXING	Neg				
FRESH	Neg				
FLOWKL8					
RI					
R^2(adj)	0.58	0.06	0.15	0.66	0.03

Southern rock sole

Variables	Jan	Feb	Mar	Apr	May
PDO					
NP					
AO					
EP-NP					
MEI					
R^2(adj)	0.02	-0.03	0.26	0.02	0.09
SST			Pos	Pos	
ALONG					
MIXING					
FRESH	Pos	Pos			
FLOWKL8				Pos	
RI					
R^2(adj)	0.20	0.60	0.16	0.47	0.45

Rockfish

Variables	Jan	Feb	Mar	Apr	May
PDO					
NP					Pos
AO	Neg				
EP-NP					
MEI					
R^2(adj)	0.22	0.05	0.03	0.00	0.55
SST		Pos	Pos	Pos	
ALONG					
MIXING					
FRESH					
FLOWKL8					
RI					
R^2(adj)	0.44	0.38	0.62	0.37	0.50

Flathead sole

Variables	Jan	Feb	Mar	Apr	May
PDO	Pos				
NP					
AO					
EP-NP	Neg				
MEI					
R^2(adj)	0.79	0.01	0.22	0.19	0.13
SST					
ALONG					
MIXING		Pos			
FRESH		Pos	Pos		
FLOWKL8					
RI					
R^2(adj)	0.22	0.58	0.26	0.45	0.31

Northern rock sole

Variables	Jan	Feb	Mar	Apr	May
PDO					
NP					
AO		Pos			
EP-NP				Pos	
MEI					
R^2(adj)	0.11	0.46	0.15	0.32	0.41
SST		Neg	Neg		Neg
ALONG				Pos	
MIXING					
FRESH					
FLOWKL8					
RI					
R^2(adj)	0.00	0.26	0.66	0.56	0.20

variable contribution to model significant at P<0.05

variable contribution to model insignificanr at P≥0.05

Pos variable effect positive

Neg variable effect negative

variable absent from model

data unavailable

Table 11. Total significant contributions (at P<0.05) of variables by month to 12 best-fit species models.

Variables	Months Jan	Feb	Mar	Apr	May	% Contribution Months combined
Basin-scale						
EP-NP	2	0	4	4	7	28.33
AO	2	3	1	5	1	20.00
NP	1	2	3	3	2	18.33
PDO	2	4	1	2	1	16.67
MEI	1	1	0	1	0	5.00
% Contribution Total variables	13.33	16.67	15.00	25.00	18.34	17.67
Local-scale						
ALONG	1	1	4	6	4	26.67
FRESH	5	4	5	1	1	26.67
SST	1	3	3	5	3	25.00
FLOWKL8	no data	no data	1	5	0	16.67
MIXING	2	1	2	2	1	13.33
RI	no data	no data	1	2	1	11.11
% Contribution Total variables	18.75	18.75	22.22	29.17	13.89	20.83

Table 12. Ranking of variables in terms of overall level of contribution (at P<0.05) to best-fit GAM models, and number of species to which the variable was linked.

Variable	% Contribution	No. of Species
EP-NP	28.33	12
ALONG	26.67	12
FRESH	26.67	10
SST	25.00	8
AO	20.00	9
NP	18.33	7
PDO	16.67	5
FLOWKL8	16.67	6
MIXING	13.33	6
RI	11.11	4
MEI	5.00	3

Table 13. Common linkages with physical variables relative to interannual patterns in species abundance, and exploration of potential mechanisms of environmental forcing on late spring larval abundance in the vicinity of Shelikof Strait, Gulf of Alaska.

Species	Interannual Trend Group	Variable Connections in Common	Shared Early Life History Strategy Traits for GOA Populations	Likely Primary Vulnerability during Early Life History
Northern lampfish Arrowtooth flounder Pacific halibut	Decadal pattern of highest levels of abundance during 1990s.	Primarily positive with spring EP-NP and ALONG. Negative with winter FRESH (A. flounder, P. halibut). Spring SST (N. lampfish and negative for P. halibut.)	Winter-spring spawning deep water. Mesopelagic eggs. Shoreward and along-shelf larval drift.	Shoreward transport variability (A. flounder and P. halibut). Limited food availability winter-early spring.
Pacific cod Walleye pollock Northern rock sole	Occasional anomalous years of high levels of abundance, late 80s to mid 90s.	Positive with spring EP-NP. Mar-Apr ALONG. Negative with winter SSTs. Positive with Feb AO.	Late winter-early spring spawning in shelf waters on or close to bottom. April peak in larval abundance. Larval size range and duration similar. Along-shelf larval drift.	Spring larval transport variability. Anomalous high winter temps. Limited food availability winter-early spring.
Rockfish Southern rock sole Starry flounder	Trend of increasing abundance towards the end of the time-series.	March or May EP-NP, May ALONG. Positive with Mar-Apr SST (Rockfish, S. rock sole). Positive winter FRESH (S. rock sole, Starry flounder).	Late spring-summer spawning (Rockfish, Southern rock sole). Dispersal from shallow water (S. rock sole, S. flounder), shoreward from slope (rockfish). Along-shelf larval drift.	Spring larval transport variability. Diminished winter river discharge (S. rock sole, Starry flounder). Anomalous low early spring temps (Rockfish, Southern rock sole).
Ronquils Flathead sole	Greatest amplitude of variation in abundance 1980 through early 1990s. Moderately abundant mid-90s through 2003.	Strongest connections with Jan basin-scale variables including positive with PDO. Positive with late winter FRESH. April FLOWKL8.	Late winter-summer spawning with peak larval abundance May-June and larvae present in plankton through October. Along-shelf larval drift.	Winter atmospheric variability and negative PDO anomalies prior to spawning. Diminished winter river discharge.