

**NORTH PACIFIC RESEARCH BOARD PROJECT FINAL REPORT**

**Four decades of climate-biology covariation in the  
Northeast Pacific: 98 updated ecosystem indicators, 1965-2006**

**NPRB Agreement F1102-10 Final Report**

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**July 2009**

### ***Abstract***

We updated 98 ecosystem indicator time series (31 climate, 67 biology) published by Hare and Mantua (Hare, S.R., and Mantua, N.J. 2000. Empirical support for North Pacific regime shifts in 1977 and 1989. Progress in Oceanography 47:103-145) to assess recent trends in climate-biology covariation in the Northeast Pacific. STARS tests of principal components analysis (PCA) time series from the updated data (1965-2006) supported the 1976-1977 and 1988-1989 shifts in climate and biology systems documented in the original paper. We found evidence of a further shift in the early 1990s that was not reported in the original paper, and which represented an intensification of post-1976-1977 conditions. We also detected a previously unreported shift during 2001-2002 in PC2 of Alaskan biology time series. No similar shift in West Coast (British Columbia, Washington, Oregon and California) PC2 scores was observed. A strong shift in several climate and biology time series was also observed in 1998-1999, but lasted only 2-5 years, suggesting a situation where ecological resilience was adequate to prevent a shift to an alternate stable state. Exploratory analysis of climate-biology correlations suggested that basin-wide warming of the North Pacific may in some instances be the dominant climate variable forcing Alaskan and West Coast ecosystems, and also suggested that biological systems in the two regions may respond to forcing by different climate mechanisms. This analysis may be useful for framing hypotheses for more rigorous investigation into climate change effects on Northeast Pacific ecosystems.

### ***Key Words***

climate change, ecosystem indicators, fisheries management, global warming, Northeast Pacific, Pacific Decadal Oscillation, regime shift

### ***Citation***

Litzow, M.A., and Mueter, F.J. 2009. Four decades of climate-biology covariation in the Northeast Pacific: 98 updated ecosystem indicators, 1965-2006. North Pacific Research Board Final Report, 46 pp.

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## ***Study Chronology***

This study, titled “Hare and Mantua reanalysis”, NPRB agreement number F1102-10, was initiated on Dec. 18, 2008, and completed on June 30, 2009. A progress report was submitted to NPRB on April 1, 2009, and the final report was submitted on July 30, 2009.

## ***Introduction***

During most of the 20<sup>th</sup> century, North Pacific climate and biological systems exhibited decadal-scale quasi-stable states separated by periods of abrupt transition (Mantua et al. 1997, Minobe 1997). The leading mode of decadal-scale North Pacific climate variability during this time was the Pacific Decadal Oscillation (PDO), which is indexed by the first principal component of spatial variability in detrended North Pacific sea surface temperature data (Mantua and Hare 2002). While the mechanisms responsible for the PDO pattern are not fully understood, the PDO index showed strong “regime” behavior during most of the 20<sup>th</sup> century, with decadal-scale periods of persistently positive or negative values that were separated by regime shifts in 1924-1925, 1946-1947, and 1976-1977 (Mantua and Hare 2002). These regime shifts resulted in temporally coherent, population-level changes for fishes and other marine life across the North Pacific (Hare et al. 1999, Anderson and Piatt 1998, Chavez et al. 2003). Proxy data sources also indicate that North Pacific climate has followed a PDO-type pattern since at least 1661 (Biondi et al. 2001). While our understanding of PDO-biology interactions is largely based on correlations, these historical patterns are strong enough to have created a widespread appreciation of decadal-scale climate-biology covariation in the North Pacific marine science community. In particular, the biological reorganization that has historically followed PDO regime shifts implies that management of commercially exploited populations can be improved by including the effects of the PDO and other climate indices in assessment models (Hare and Mantua 2000), and tracking of relevant climate indices may provide early warning of incipient change in managed populations (Bond et al. 2003, Chavez et al. 2003). Recognition of strong climate-biology covariation has also opened an array of important research questions, as both basic marine ecology and fisheries management could be rapidly advanced by the elucidation of mechanisms underlying these observed patterns of climate-biology covariation.

It is therefore a strange twist in the recent history of marine ecology that by the time regime behavior in the PDO was recognized as a leading factor explaining variability in North Pacific biological communities, that regime behavior had disappeared, or at least had been modified considerably. While interdecadal oscillations in North Pacific climate were first recognized in the 1930s (Biondi et al. 2001), the two seminal papers describing the PDO appeared in 1997 (Mantua et al. 1997, Minobe 1997). But regime behavior in the PDO (i.e., strong interannual autocorrelation and occasional shifts to a new "state") had disappeared by 1988-1989, and the PDO index since then has switched between positive and

negative values every 1-3 years (Bond et al. 2003). Recently, attempts to understand continued climate-biology covariation in the North Pacific have pointed to a variety of other climate signals that may be important, including the second principal component in spatial organization of detrended North Pacific sea surface temperature (the “Victoria Pattern”, Bond et al. 2003), the North Pacific Gyre Oscillation (Di Lorenzo et al. 2008, Chhak et al. 2009), spatial reorganization in Arctic atmospheric pressure (Overland and Wang 2005), and global warming (Mackas et al. 2007, Mueter and Litzow 2008). All of these patterns have had some measurable association with regional-scale patterns in biological productivity, and dramatic physical events, such as the retreat of seasonal ice cover from the Bering Sea and seasonal hypoxia in the California Current system, may have overwhelming effects on local biological communities (Grantham et al. 2004, Grebmeier et al. 2006, Mueter and Litzow 2008). However, the demise of autocorrelation in the PDO has meant that marine ecologists no longer have a recognized basin-scale pattern for understanding ongoing climate-biology covariation. Given the rapid current pace of climate change (IPCC 2007), better understanding of basin-scale organization in climate-biology patterns would be an important step towards improving our ability for effective management of marine resources in the North Pacific.

Recognition of sudden reorganization events in climate and biology in the North Pacific has historically been delayed by both the lag in compiling various long-term data sets, and by the pace of conceptual appreciation for the nature of climate forcing on North Pacific ecosystems (Hare and Mantua 2000). A logical first step towards better understanding of recent climate-biology variability in the North Pacific would therefore be to update the long-term data sets that were important in describing historical patterns in climate-biology variability, and to examine these updated data for recent trends. Here we report on an update to the ecosystem indicator time series from a study (Hare and Mantua 2000) that was one of the most thorough descriptions of recent decadal-scale change in climate-biology systems across the Northeast Pacific. Hare and Mantua (2000) identified 100 ecosystem indicator time series (31 climatic and 69 biological) that provided fairly even geographic coverage from Baja California to the southeastern Bering Sea during the period 1965-1997. Climate data in this study included both a group of large-scale climate indices and a variety of local measures of climate. Biological data were dominated by catches of salmon (lagged to reflect the year of ocean entry) and recruitment estimates for other commercially important fish species (lagged to reflect year class strength). We examined these updated time series for recent changes that may suggest hypotheses for future work on understanding climate-biology variation in the Northeast Pacific absent of dominance by a strong PDO signal.

## ***Objectives***

The main goal of our study was to repeat the analysis of Hare and Mantua (2000) with updated data. Specifically, four primary objectives were identified by the statement of work for this study: 1) update as many of the 100 time series from Hare and Mantua (2000) as possible; 2) summarize the updated time series using principal components analysis (PCA) for climate and biology data combined, biology data only, and climate data only; 3) use the updated time series to repeat the “composite analysis” of Hare and Mantua (2000) to evaluate support for the 1976-1977 and 1988-1989 regime shifts reported by that paper; and 4) use the same technique to test for a possible ecological response to sudden climate change occurring in 2000-2001 in the Bering Sea and Gulf of Alaska (Grebmeier et al. 2006, Litzow 2006).

The statement of work for this study also noted that updating the time series from Hare and Mantua (2000) presents opportunities for research into climate-biology covariation using conceptual and analytical advances that have occurred since the publication of the original paper. Specifically, the composite analysis of Hare and Mantua (2000), may produce spurious rejection of the null hypothesis (Rudnick and Davis 2003), and more sophisticated techniques for detecting shifts in time series are now available (e.g., Rodionov 2004). And while Hare and Mantua (2000) made an important contribution towards understanding covariation in Northeast Pacific climate and biology systems, the updates to these time series present an opportunity to conduct explicit tests for correlation between climate and biology time series, which were not included in the original paper. Finally, the updated time series allow for analysis of regional-scale variability in biological systems within the Northeast Pacific that may have become important since the demise of the PDO as an overarching forcing mechanism. In light of these considerations, we identified the following secondary objectives for our study, which we were able to achieve in addition to our primary objectives: 1) use sequential t-test analysis of regime shifts (STARS, Rodionov 2004) to identify statistically significant shifts in the mean state of PCA-summarized time series; 2) conduct regional PCA and STARS analysis to test for regional differences in biological time series following the demise of autocorrelation in the PDO; and 3) test for correlation between regional biological and climate time series to identify falsifiable hypotheses that may lead to better understanding of causative relationships between climate and ecosystem status in the Northeast Pacific.

## ***Methods***

### *Updating time series*

We were able to obtain updated data for 98 of the 100 original ecosystem indicator time series from Hare and Mantua (2000) (see Appendix 1 for sources). We excluded two other time series from our

**Table 1.** Updated time series used in analysis. Time series with abbreviations in bold are replacements for time series from Hare and Mantua (2000) that are no longer maintained, those in italics have not been updated since publication of the original analysis. "No." column refers to numbers used for time series in Hare and Mantua (2000). Data type is either climate (C) or biology (B). Region codes are Basin, basin-wide; BC, British Columbia; EBS, Eastern Bering Sea; GOA, Gulf of Alaska (excluding Southeast Alaska); SEAK, Southeast Alaska; and WC, U.S. West Coast. Correlations between updated time series and data from Hare and Mantua (2000) were calculated for 1965-1997.

No.	Abbreviation	Full name	Type	Region	Correlation with original data ( <i>r</i> )
1	NPATMOS	North Pacific atmospheric pressure index	C	Basin	0.99
2	PDOWIN	Pacific Decadal Oscillation - winter index	C	Basin	1.00
3	PDOSUM	Pacific Decadal Oscillation – summer index	C	Basin	1.00
4	SOI	Southern Oscillation index	C	Basin	0.98
5	ENSOWIN	ENSO 3.4 - winter index	C	Basin	1.00
6	ENSOSUM	ENSO 3.4 - summer index	C	Basin	1.00
7	AO	Arctic Oscillation index	C	Basin	0.99
8	KSAT	King Salmon air temperature	C	EBS	1.00
9	CBAT	Cold Bay air temperature	C	GOA	0.74 <sup>a</sup>
10	KUSSTR	Kuskokwim stream flow	C	EBS	0.95
11	PISST	St. Paul Island sea surface temperature	C	EBS	0.37 <sup>b</sup>
12	BSICE	Bering Sea ice cover index	C	EBS	-0.88
13	<i>EBZOO</i>	Eastern Bering Sea zooplankton biomass	B	EBS	1.00
14	BSJELLY	Eastern Bering Sea jellyfish biomass	B	EBS	1.00
15	EBSPOLL	Eastern Bering Sea pollock recruitment	B	EBS	0.92
16	EBSCOD	Eastern Bering Sea Pacific cod recruitment	B	EBS	0.91
17	EBSYFS	Eastern Bering Sea yellowfin sole recruitment	B	EBS	0.70
18	EBSTRBT	Eastern Bering Sea Greenland turbot recruitment	B	EBS	0.93
19	EBSATF	Eastern Bering Sea arrowtooth flounder recruitment	B	EBS	0.61
20	EBSRSOLE	Eastern Bering Sea rock sole recruitment	B	EBS	0.95
21	EBSFSOLE	Eastern Bering Sea flathead sole recruitment	B	EBS	0.74
22	EBSAKPLA	Eastern Bering Sea Alaska plaice recruitment	B	EBS	0.38
24	EBSHERR	Eastern Bering Sea herring recruitment	B	EBS	0.73
25	AIATKA	Aleutian Islands Atka mackerel recruitment	B	EBS	0.80
26	AIPOP	Aleutian Islands Pacific ocean perch recruitment	B	EBS	0.59
27	WAK_CH	Western Alaska chinook salmon catch	B	EBS	0.89
28	WAK_CM	Western Alaska chum salmon catch	B	EBS	0.92
29	WAK_CO	Western Alaska coho salmon catch	B	EBS	1.00
30	WAK_PI	Western Alaska pink salmon catch	B	EBS	0.54 <sup>c</sup>
31	WAK_SO	Western Alaska sockeye salmon catch	B	EBS	1.00
32	<b>EP/NP</b>	East Pacific / North Pacific teleconnection index	C	Basin	0.64 <sup>d</sup>

<sup>a</sup>Source of discrepancy unknown. Replacing DJF mean in update with DJFM does not improve correlation.

<sup>b</sup>Updated time series correlates with independently compiled Reynolds SST Jan-April values for entire Eastern Bering Shelf ( $r = 0.88$ ) and BSICE ( $r = -0.72$ ). Data from Hare and Mantua (2000) correlate poorly with both (EBS SST,  $r = 0.25$ , BSICE,  $r = -0.22$ ). <sup>c</sup>Source of discrepancy unknown. Data in Hare and Mantua (2000) correlate poorly ( $r = 0.60$ ) with updated data (through 2000) provided by Steven Hare (pers. comm.), which in turn correlate poorly ( $r = 0.48$ ) with Alaska Department of Fish and Game data used in our analysis. <sup>d</sup>Correlation with East Pacific teleconnection index from Hare and Mantua (2000).



**Table 1** (*continued*)

No.	Abbreviation	Full name	Type	Region	Correlation ( <i>r</i> )
33	KODAT	Kodiak air temperature	C	GOA	0.87
34	KENSTR	Kenai River stream flow	C	GOA	1.00
35	PAPA	Ocean Station Papa trajectory index	C	Basin	1.00
36	GAK1SST	GAK1 sea surface temperature	C	GOA	0.19 <sup>e</sup>
37	U60N149W	Upwelling intensity at 60N, 149W	C	GOA	1.00
38	U57N137W	Upwelling intensity at 57N, 137W	C	SEAK	1.00
39	CPZOO	Central Pacific zooplankton biomass	B	Basin	1.00
40	<b>PAPAZOO</b>	Ocean Station Papa zooplankton phenology	B	Basin	0.29 <sup>f</sup>
41	GOASHR	Gulf of Alaska shrimp catch	B	GOA	0.98
42	GOASAB	Gulf of Alaska sablefish recruitment	B	GOA	0.48
43	GOAHAL	Gulf of Alaska halibut recruitment	B	GOA	0.96
44	GOAPOP	Gulf of Alaska Pacific Ocean perch recruitment	B	GOA	0.68
45	GOATHORN	Gulf of Alaska shortspine thornyhead recruitment	B	GOA	1.00
46	GOAPOLL	Gulf of Alaska pollock recruitment	B	GOA	0.95
47	GOACOD	Gulf of Alaska Pacific cod recruitment	B	GOA	0.61
48	GOAATF	Gulf of Alaska arrowtooth flounder recruitment	B	GOA	0.58
49	PWSHERR	Prince William Sound herring recruitment	B	GOA	0.97
50	SITHERR	Sitka herring recruitment	B	SEAK	1.00
51	CAK_CH	Central Alaska chinook salmon catch	B	GOA	0.97
52	CAK_CM	Central Alaska chum salmon catch	B	GOA	0.94
53	CAK_CO	Central Alaska coho salmon catch	B	GOA	0.99
54	CAK_PI	Central Alaska pink salmon catch	B	GOA	1.00
55	CAK_SO	Central Alaska sockeye salmon catch	B	GOA	0.98
56	SAK_CH	Southeast Alaska chinook salmon catch	B	SEAK	0.94
57	SAK_CM	Southeast Alaska chum salmon catch	B	SEAK	1.00
58	SAK_CO	Southeast Alaska coho salmon catch	B	SEAK	1.00
59	SAK_PI	Southeast Alaska pink salmon catch	B	SEAK	1.00
60	SAK_SO	Southeast Alaska sockeye salmon catch	B	SEAK	1.00
61	SKEESTR	Skeena River stream flow	C	BC	1.00
62	KISST	Kains Island sea surface temperature	C	BC	0.99
63	U51N131W	Upwelling intensity at 51N, 131W	C	BC	1.00
64	NDR	Northern diversion rate	B	BC	1.00
65	BC_CH	British Columbia chinook salmon catch	B	BC	0.96
66	BC_CM	British Columbia chum salmon catch	B	BC	0.99
67	BC_CO	British Columbia coho salmon catch	B	BC	0.96
68	BC_PI	British Columbia pink salmon catch	B	BC	0.92
69	BC_SO	British Columbia sockeye salmon catch	B	BC	0.98
70	FORAT	Forks, Washington air temperature	C	WC	1.00
71	NEWAT	Newport, Oregon air temperature	C	WC	0.99
72	EURAT	Eureka, California air temperature	C	WC	1.00
73	COLSTR	Columbia River stream flow	C	WC	0.96
74	8RIVSTR	Eight Rivers runoff index	C	WC	0.97
75	SCRSST	Scripps pier sea surface temperature	C	WC	1.00

<sup>e</sup>Source of discrepancy unknown. Replacing DJF mean in update with DJFM does not improve correlation.

<sup>f</sup>Correlation with East Pacific zooplankton biomass time series from Hare and Mantua (2000).

**Table 1** (continued)

No.	Abbreviation	Full name	Type	Region	Correlation ( <i>r</i> )
76	U48N125W	Upwelling intensity at 48N, 125W	C	WC	1.00
77	U42N125W	Upwelling intensity at 42N, 125W	C	WC	1.00
78	U36N122W	Upwelling intensity at 36N, 122W	C	WC	1.00
79	CCZOO	CalCOFI zooplankton biomass	B	WC	0.01 <sup>g</sup>
80	OCI	Oyster condition index	B	WC	1.00
81	WCMACK	West coast Pacific mackerel recruitment	B	WC	0.73
82	WCSAB	West coast sablefish recruitment	B	WC	0.67
83	WCDSOLE	West coast Dover sole recruitment	B	WC	0.34
84	WCWIDOW	West coast widow rockfish recruitment	B	WC	0.87
85	WCCHILI	West coast chilipepper rockfish recruitment	B	WC	0.85
86	WCBOCACC	West coast bocaccio recruitment	B	WC	0.75
87	WCCANARY	West coast canary rockfish recruitment	B	WC	0.01 <sup>h</sup>
88	WCYTROCK	West coast yellowtail rockfish recruitment	B	WC	0.75
89	WCHAKE	West coast Pacific hake recruitment	B	WC	0.87
90	<b>WCSARD</b>	West coast sardine catch	B	WC	-0.56 <sup>i</sup>
91	WCPOP	West coast Pacific Ocean perch recruitment	B	WC	0.73
92	WA_CH	Washington chinook salmon catch	B	WC	0.97
93	WA_CM	Washington chum salmon catch	B	WC	0.98
94	WA_CO	Washington coho salmon catch	B	WC	0.97
95	WA_PI	Washington pink salmon catch	B	WC	0.18 <sup>j</sup>
96	WA_SO	Washington sockeye salmon catch	B	WC	0.99
97	OR_CH	Oregon chinook salmon catch	B	WC	0.93
98	OR_CO	Oregon coho salmon catch	B	WC	0.97
99	CA_CH	California chinook salmon catch	B	WC	0.95

<sup>g</sup>Source of discrepancy unknown. Hare and Mantua (2000) CCZOO shows very high interannual variability.

<sup>h</sup>Source of discrepancy unknown. <sup>i</sup>Correlation with West Coast anchovy recruitment time series from Hare and Mantua (2000). <sup>j</sup>Source of discrepancy unknown. Data updated through 2000 (S. Hare, pers. comm.) are well correlated with time series used in present analysis ( $r = 0.99$ ). Time series from Hare and Mantua (2000) is poorly correlated with both updates.

analysis either because the stock in question has been combined with another, larger stock in a single age-structured assessment model (eastern Bering Sea Pacific Ocean perch recruitment) or because of collapse and non-recovery in a fishery (California coho salmon catch). An additional time series, the East Pacific teleconnection index, is now calculated as the East Pacific/North Pacific teleconnection index (Appendix 1). This new index is reasonably well correlated with the original time series ( $r = 0.64$ ), and was used in our analysis. We used the original data (S. Hare, pers. comm.) for three other time series (Table 1) that had not been updated beyond the data included in Hare and Mantua (2000). In two other instances we were able to replace discontinued time series with data that provided geographically and ecologically similar information over a longer time span than the original data (details below). Of the 98 updated time series, 67 were biological data (18 from the eastern Bering Sea, 14 from the Gulf of Alaska, six from Southeast Alaska, six from British Columbia, 21 from the U.S. West Coast, and two from the Northeast Pacific basin), and 31 were climatic data (four from the eastern Bering Sea, five from the Gulf of Alaska

one from Southeast Alaska, three from British Columbia, nine from the U.S. West Coast, and nine basin-scale indices, Table 1).

The two discontinued time series that were replaced with other data sources were Eastern Pacific zooplankton biomass and West Coast northern anchovy recruitment. We used a 1965-2006 time series of northeast Pacific *Neocalanus plumchrus* phenology (Mackas et al. 2007, D. Mackas, pers. comm.) to replace the Eastern Pacific zooplankton biomass time series. Most of these new data were the estimated Julian date of Ocean Station Papa abundance maxima from biomass measurements ( $n = 16$  years) or from the ratios of different development stages in the population ( $n = 12$  years). Following Mackas et al. (2007), date estimates from these two methods were treated as interchangeable. We filled in missing years with information from two complementary time series (D. Mackas, pers. comm.). For eight missing years we used the linear regression of Ocean Station Papa date of biomass maximum (log-transformed) on the leading principal component of the abundance of three zooplankton groups (boreal shelf, southern, and subarctic oceanic) off of southern Vancouver Island ( $R^2 = 0.87$ ). Values for five other missing years were estimated using the relationship between *N. plumchrus* phenology at Ocean Station Papa and the Vancouver Island continental shelf margin ( $R^2 = 0.92$ ). The complete phenology time series was correlated with the eastern Pacific zooplankton abundance time series of Hare and Mantua (2000) at  $r = 0.29$ .

We were also able to replace the discontinued West Coast northern anchovy recruitment time series with West Coast commercial Pacific sardine landings, taking advantage of recognized decadal-scale inverse population trends in sardines and anchovies (Chavez et al. 2003). Sardine landings were lagged four years to correspond with the four year old age class that dominates commercial landings (Hill et al. 2007). Sardine landings at this lag were reasonably well correlated ( $r = -0.56$ ) with 1965-1994 northern anchovy recruitment estimates from Hare and Mantua (2000). Other lags of 0-5 years produced weaker correlations. Catch data were only available to 2007 (corresponding to the 2003 year class). We estimated values for the 2004-2007 year classes with sardine recruitment estimates (Hill et al. 2007), which show a strong quadratic relationship with catch data ( $R^2 = 0.91$ , Appendix 1).

The salmon catch data used in Hare and Mantua (2000) were combined estimates of commercial domestic, high-seas foreign, recreational and subsistence catches. However, these combined catch time series have not been maintained beyond the ocean entry year of 2000 (S. Hare, pers. comm.), so we used only commercial catch time series, for which more recent data were available. This choice is justified by the observation that adding recreational and subsistence catches has little influence on results obtained from commercial catches alone (Hare et al. 1999), and by the generally high correlations between our updated salmon catch time series and the original time series (Table 1).

At times, updated time series did not extend as far back as the original time series in Hare and Mantua (2000). In six instances, we were able to use linear regressions between the original and updated time series to estimate missing values for early years of the updated versions (mean  $R^2 = 0.92$ , range 0.78 – 1, Appendix 1). Thirty time series are recruitment estimates from age-structured assessment models of commercially exploited fish stocks (Table 1). The most recent estimates from these time series are often poorly supported by empirical data, and may represent either median values or estimates from poorly resolved stock-recruit relationships. Such estimates tend to assume a continuation of recent environmental conditions, and result in dampened sensitivity of these time series to recent ecological change. We therefore excluded such estimates from our analysis, identifying them either from personal communication with assessment authors, caveats within assessment reports, or the appearance of inflated variance estimates around recruitment in the final years of a time series. We error-checked all updated time series by calculating Pearson correlations with the original time series (Table 1). The individual data sets are described in Appendix 1, and more detailed descriptions may be found in Hare and Mantua (2000).

Finally, while the PDO has received extensive attention as a climate forcing mechanism for North Pacific ecosystems, and was the focus of many of the conclusions of Hare and Mantua (2000), the PDO index is calculated from detrended sea surface (SST) data that explicitly exclude consideration of monotonic climate change (i.e., global warming). In order to consider the possible role of Pacific-wide warming on Northeast Pacific ecosystems, we included a basin-wide measure of SST (for the North Pacific poleward of 20°N) in our regional-scale analysis of climate-biology covariation. These data were area-weighted mean annual temperatures calculated from the HadCRUT2 combined land and sea surface temperature anomaly data set, expressed as the difference from the 1951-1980 mean (Rayner et al. 2003).

### *Analysis*

We used the composite analysis of Ebbesmeyer (1991) and Hare and Mantua (2000) to assess support for the 1976-1977 and 1988-1999 regime shifts in the updated data set. We also used this method to test for a possible 2000-2001 regime shift in Alaska. These analyses used both climate and biology data, according to the following procedure:

1. We normalized the data in the two proposed regimes by subtracting the mean across both proposed regimes but then dividing the data for each regime by the standard deviation for that regime.
2. We then reversed the sign of some series so that all changed in the same direction across the proposed shift.

3. We computed the average of time series values for each year, using only those time series for which at least five observations were available in each proposed regime. We computed regime averages as the grand mean of annual means within each proposed regime, and calculated standard errors for each year as  $s/\sqrt{n}$ , where  $s$  is the standard deviation across all variables within a year, and  $n$  is the number of observed variables in that year.
4. If annual means and standard errors for each proposed regime were exclusively positive or negative (i.e., none crossed zero), a statistically significant shift was assumed.

We also tested for statistically significant shifts in time series using STARS (Rodionov 2004), a technique that has become available since the publication of Hare and Mantua (2000). STARS uses a t-test to determine whether sequential observations in a time series represent statistically significant departures from mean values observed during the preceding period of a pre-determined duration. STARS is appropriate for analysis towards the end of time-series, and allows for timely detection of shifts. STARS results are determined by the cut-off length for proposed regimes ( $L$ ), and the Huber weight parameter ( $H$ ), which defines the range of departure from the observed mean (in standard deviations) beyond which observations are considered as outliers. For all STARS analyses we set  $L = 10$  years, since we were interested in detecting decadal-scale steady states, and we set  $H = 1$  SD. Although a version of STARS is available that pre-whitens data in order to account for temporal autocorrelation in time series, pre-whitening may also remove real trends from data, and so may inflate the chance of a type-II error (Pyper and Peterman 1998). We therefore used the original version of STARS, without pre-whitening, but set  $\alpha = 0.01$  for all STARS analysis, which makes our conclusions from STARS somewhat conservative, and guards to some extent against the increased chance of a type-I error due to temporal autocorrelation.

We normalized all time series to have mean zero and unit variance prior to PCA because absolute values are not comparable across time series with different units of measurement. We conducted the PCA for 1965-2006 because the large number of missing observations in 2007 (54) and 2008 (71) precluded meaningful analysis for those years. When these years were excluded, a total of 251 annual values were missing from the data set, or 6% of the total possible values (Table 2). Visual inspection of scatterplots and univariate histograms suggested that the data set approximately followed a multivariate normal distribution, the preferred case for PCA. Because the number of variables ( $p = 98$ ) was larger than the number of annual observations ( $n = 42$ ), the data matrix was not of full rank, which implies that a technically valid covariance or correlation matrix cannot be estimated because there are only  $n-1$  independent comparisons that can be made. This rank-deficiency results in negative eigenvalues in the PCA, which are difficult to interpret. In practice, the first few eigenvectors (the loadings on individual

variables used to compute leading principal component [PC] scores) are little effected if the data matrix is not of full rank (Legendre and Legendre 1998).

Missing values complicated our PCA. While eigenvectors (loadings) and eigenvalues can be obtained from the correlation matrix of the incomplete data, PCA scores for years with missing data cannot readily be estimated. If values had been missing at random, we could have estimated unbiased principal component scores as weighted averages of all non-missing variables (using the eigenvectors, or loadings, as weights). However, missing values were strongly clustered at the beginning and end of certain time series (e.g., recruitment series), so principal component scores calculated with only non-missing values would very likely be biased. In order to obtain unbiased results and to obtain a measure of the uncertainty associated with missing values, we estimated missing values prior to conducting the PCA.

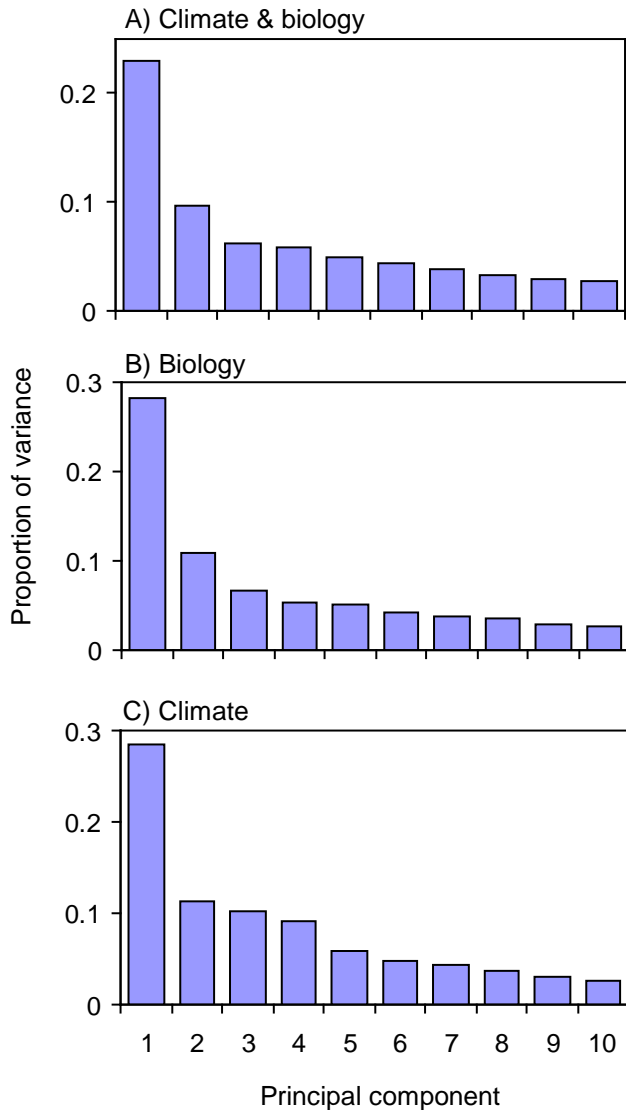
Missing observations were filled in using multiple imputation, a method that allows missing values in multivariate data sets to be estimated without biasing subsequent analysis on the data set (Schafer 1997). We used Bayesian linear regression as implemented in the MICE package in R (Van Buuren and Oudshoorn 1999) to predict missing values in each incomplete time series. In this approach, each of the incomplete series is used as the dependent variable in a multiple regression on a selected set of predictor variables. The regression approach implicitly assumes that linear relationships between each incomplete time series and its set of predictor variables did not change between years with missing values and years without missing values. We had to limit the set of predictor variables in each regression because the number of observations in a multiple regression must be larger than the number of variables (columns). Therefore we first identified reasonable subsets of variables to use in predicting missing values for each target variable, selecting the 20 variables that had the highest absolute correlation coefficient with the target variable. Thus each incomplete time series had its own specific set of predictors. For predictors that were themselves incomplete, the most recently generated imputations were used to complete the predictors prior to imputing the target variable. Due to generally high correlations among sets of variables, analyses selecting 10 or 15 variables for prediction yielded very similar results. To estimate uncertainty in the predicted missing values we generated 100 imputations by taking random draws from the full posterior distribution of the predicted values using Gibbs sampling (Gelfand and Smith 1990). Each imputed, complete data matrix was then used to compute a time series of PCA scores using the loadings from an initial PCA of the incomplete data (i.e., without estimates for

**Table 2.** Pattern of missing annual observations for 98 ecosystem indicator time series.

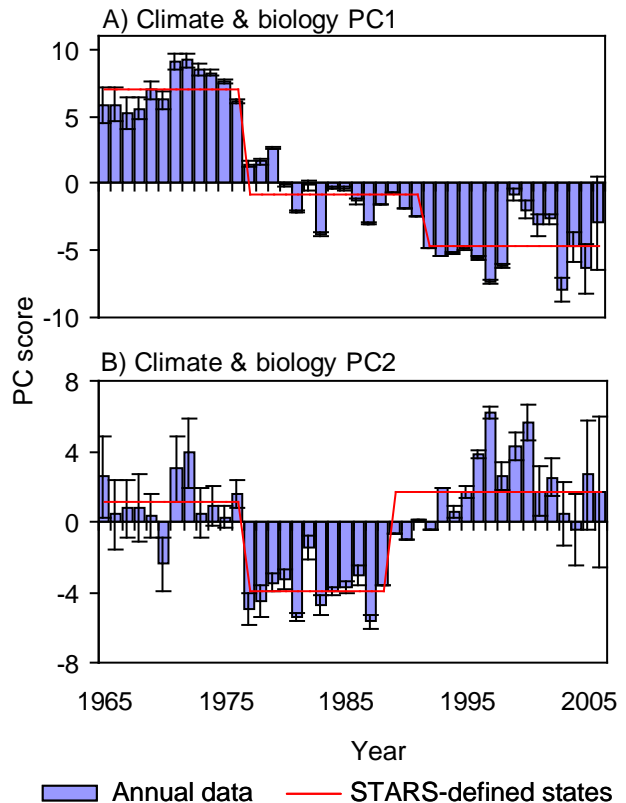
Number of missing years	Number of time series
0	49
1	15
2	5
3	4
4	5
5	2
6	3
7	2
8	1
9	2
10	2
12	2
13	4
15	2

missing values). This initial PCA was computed via a singular value decomposition of the correlation matrix of the (incomplete) data series. A singular value decomposition was used because it results in all positive eigenvalues, even with a rank-deficient correlation matrix based on incomplete data, and avoids other numerical problems. We applied the loadings from this initial PCA to the 100 imputed data sets to obtain 100 sets of PCA scores for each leading principal component. We then calculated the mean and variance for each leading principal component score in each year, which allowed us to account for uncertainty due to the estimation of missing values. The variance of the PCA scores across imputed data sets was plotted as  $\pm 2$  SD from the mean for every year with missing values.

In order to illustrate the variability summarized by our PCA, we plotted the leading individual variables (i.e., those with the highest loadings) for each PC. For biology data, we plotted all variables with  $|\text{loading}| \geq 0.15$ . Loadings for climate variables were typically stronger, so we plotted all climate variables with  $|\text{loading}| \geq 0.2$ . We decided on appropriate groupings for regional-scale analysis of biology time series by plotting mean PC1 and PC2 scores for the eastern Bering Sea, Gulf of Alaska, Southeast Alaska, British Columbia, and U.S. West Coast. We tested regional biology time series with STARS to look for similarities and differences in the occurrence of significant shifts in different regions. In order to frame hypotheses concerning causative relationships between climate and biology time series, we summarized regional climate time series with PCA. These regional climate data included basin-scale indices, since these large-scale indices are often better at describing ecologically important climate patterns than are local measures of climate (Hallet et al. 2004). Before testing for climate-biology covariation, we smoothed all climate data with a 3-year running mean centered on the labeled year (i.e., 1966 value = 1965-1967 mean), reasoning that biological systems respond to mean climate state more strongly than to interannual climate variability (Mueter and Litzow 2008). We tested for intercorrelation between climate variables (i.e., leading climate PCs vs. NP SST) that might have complicated the interpretation of results using Pearson's correlation, and we then calculated correlations between leading biology PCs and climate variables at lags of 0-5 years. Because the high proportion of missing values for regional biology time series in 2006 resulted in increased variance from multiple imputation of missing values in that year, regional climate-biology correlations were calculated for the period from 1972 (the first year that biology data could be compared with smoothed climate data at a 5-year lag) to 2005.



**Figure 1.** Scree plots for PCA of A) combined climate and biology data, B) biology data only and C) climate data only.



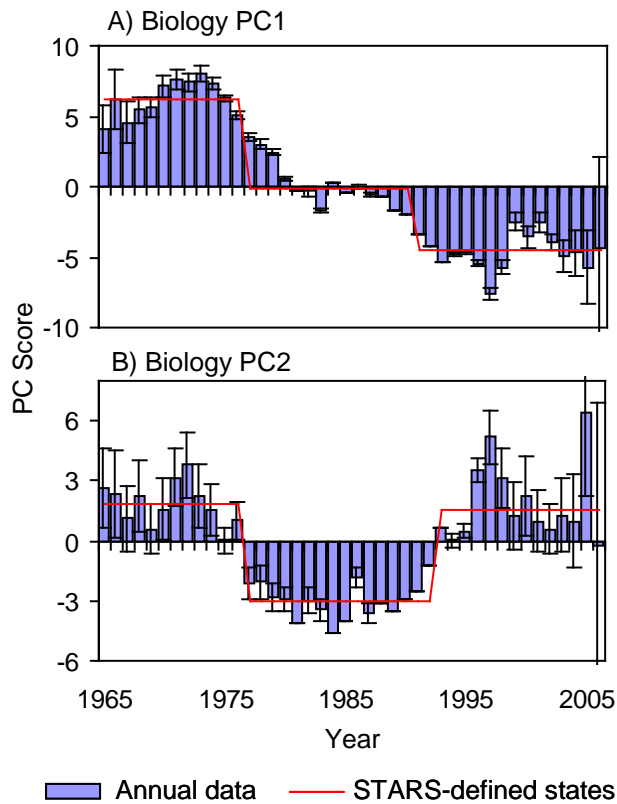
**Figure 2.** PCA time series for combined climate and biology data. Error bars  $\pm 2$  SD.

**Results**

*Principal components analysis*

For all variables combined (climate and biology), the first two eigenvalues explained 23.0% and 9.6% of the total variance, respectively. A scree plot of the eigenvalues shows a sharp drop in the proportion of variance explained after the first eigenvalue and another sharp drop after the second eigenvalue (Figure 1). This result is consistent with the findings of Hare and Mantua (2000), and suggests that at least the first two PCs hold interpretable information. PC1 in the combined climate-biology analysis showed strong temporal autocorrelation throughout the time series, with a STARS-defined shift in 1976-1977 (pre-shift mean score = 7.04, post-shift mean score = -0.84,  $p < 0.0001$ ) and a further shift in 1991-1992, representing a strengthening in post-1976-1977 conditions (post-shift mean = -4.70,  $p < 0.0001$ , Fig. 2). PC2 also showed a STARS-defined shift in 1976-1977 (pre-shift mean score =





**Figure 3.** Biology-only PCA time series. Error bars  $\pm 2$  SD.

mean score = 6.27, post-shift mean score = -0.10,  $p < 0.0001$ ), and another shift in 1990-1991, in the same direction (post-shift mean score = -4.54,  $p < 0.0001$ , Fig. 3). PC2 also showed a significant shift in 1976-1977 (pre-shift mean score = 1.84, post-shift mean score = -3.00,  $p < 0.0001$ ), and a shift in the opposite direction in 1992-1993 (post-shift mean score = 1.55,  $p < 0.0001$ , Fig. 3). Positive values of PC1 were most strongly associated with high salmon catches in British Columbia and the U.S. West Coast, high catches of West Coast sardines, and high values of the Northern Diversion Rate. Negative values of PC1 were most strongly associated with high salmon catches in Alaska, low Gulf of Alaska shrimp catches, and an earlier seasonal peak in zooplankton abundance at Ocean Station Papa (Fig. 4). Increased recruitment in various Alaska groundfish stocks was associated with both positive (Eastern Bering Sea turbot) and negative (Gulf of Alaska halibut, Eastern Bering Sea arrowtooth flounder) PC1 scores. Although we illustrate results only for variables with absolute loading values  $\geq 0.15$ , the loadings for PC1 showed a smooth gradient across different variables, with no one group dominating the loadings. Positive values of PC2 were associated with higher catches of jellyfish in the Eastern Bering Sea, increased oyster condition in Washington and reduced catches or recruitment for a variety of salmon

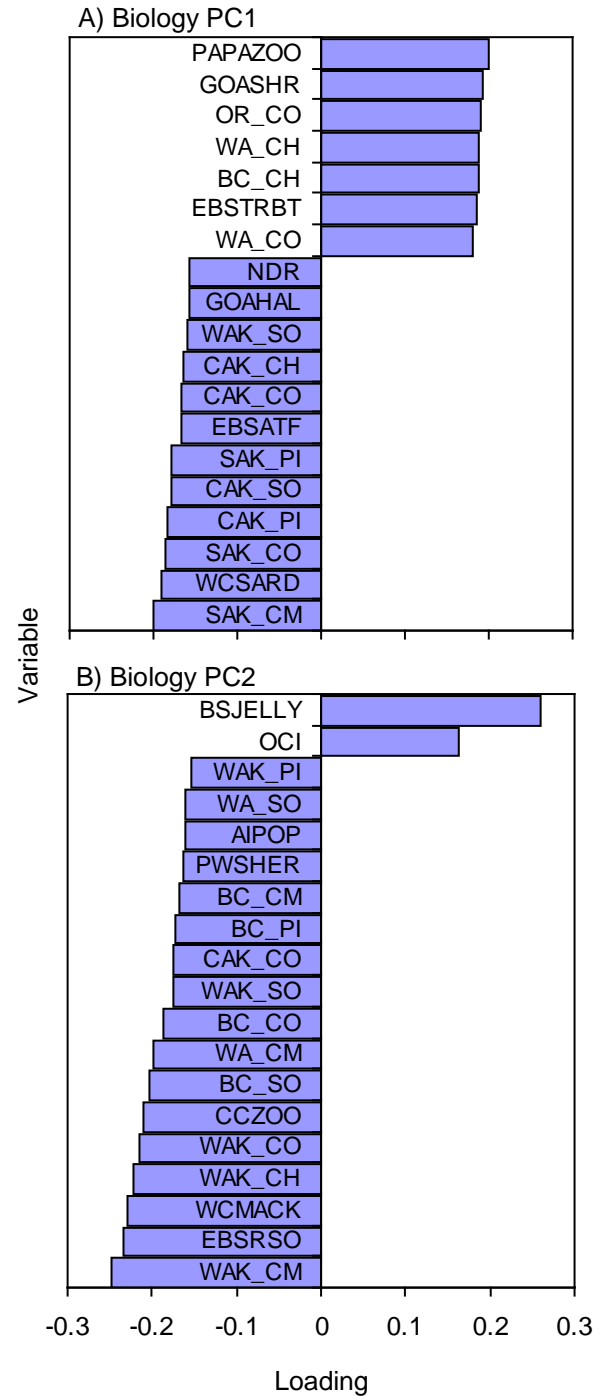
1.11, post-shift mean score = -3.99,  $p < 0.0001$ ), with a subsequent reversal in 1988-1989 (post-shift mean score = 1.64,  $p < 0.0001$ , Fig. 2).

PCA of the biology-only time series generally replicated the patterns shown by the entire data set, although shifts were more gradual in the biology-only time series, and the 1988-1989 shift from the combined climate-biology analysis was delayed several years when only biology data were considered. The first two eigenvalues for the biology-only PCA accounted for 28.2% and 10.9% of the total variance in the biology data, with a clear drop in variance accounted for after the second eigenvalue (Fig. 1), a result that is consistent with Hare and Mantua (2000). STARS detected a significant shift in biology PC1 scores in 1976-1977 (pre-shift

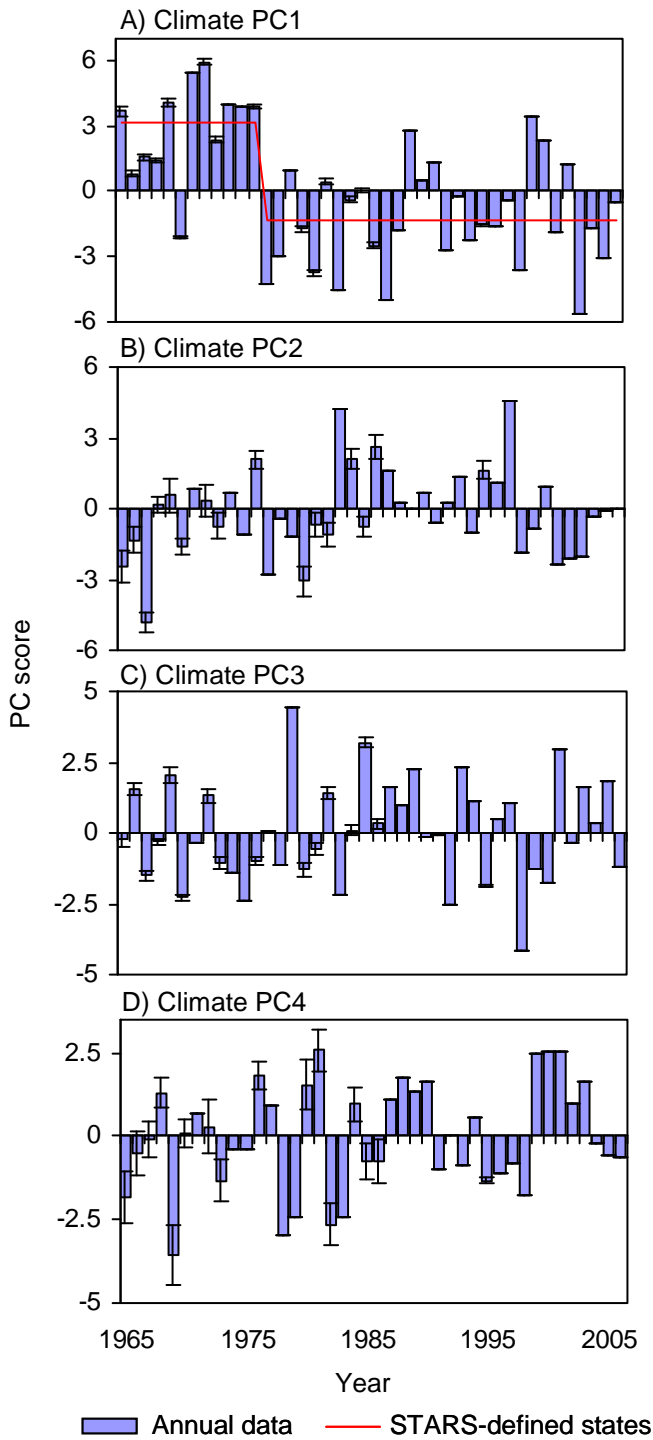
stocks, groundfish and pelagic fish in all geographic areas, as well as lower zooplankton abundance in California (Fig. 4). Complete loadings for biology-only PC1 and PC2 are given in Appendix 2.

Temporal variability in the climate variables was apparently more complex than that in the biology-only data set, as indicated by an increased number of informative leading PCs from the climate-only PCA. The first four PCs accounted for 28.5%, 11.2%, 10.3% and 9.1% of total variance, respectively, with a sharp decline in variance accounted for by subsequent PCs (Fig. 1). Interannual variability in climate PC scores was much larger than for the biology-only PCs. Nevertheless, STARS showed a significant shift in climate PC1 occurring in 1976-1977, with the post-shift state persisting through the remainder of the time series (pre-shift mean score = 3.11, post-shift mean score = -1.34,  $p < 0.0001$ , Fig. 5). STARS did not detect significant shifts in climate PC2, PC3, or PC4 (Fig. 5).

Climate PC1 essentially captured the contrast between warm conditions (negative scores) and cold conditions (positive scores) in the Northeast Pacific. Negative PC1 scores are associated with a high winter PDO index, North Pacific atmospheric pressure index and the winter El Niño-Southern Oscillation (ENSO) 3.4 index. The Southern Oscillation index, which is highly correlated with the winter ENSO 3.4 index, also showed a strong loading with climate PC1. At local scales negative PC1 scores are most strongly associated with high Kodiak, King Salmon and West Coast air temperatures; high Pribilof Islands, Kains Island and Scripps Pier sea surface temperatures; and a large Ocean Station Papa trajectory index (Fig. 6).



**Figure 4.** Strongest loadings from biology-only PCA.



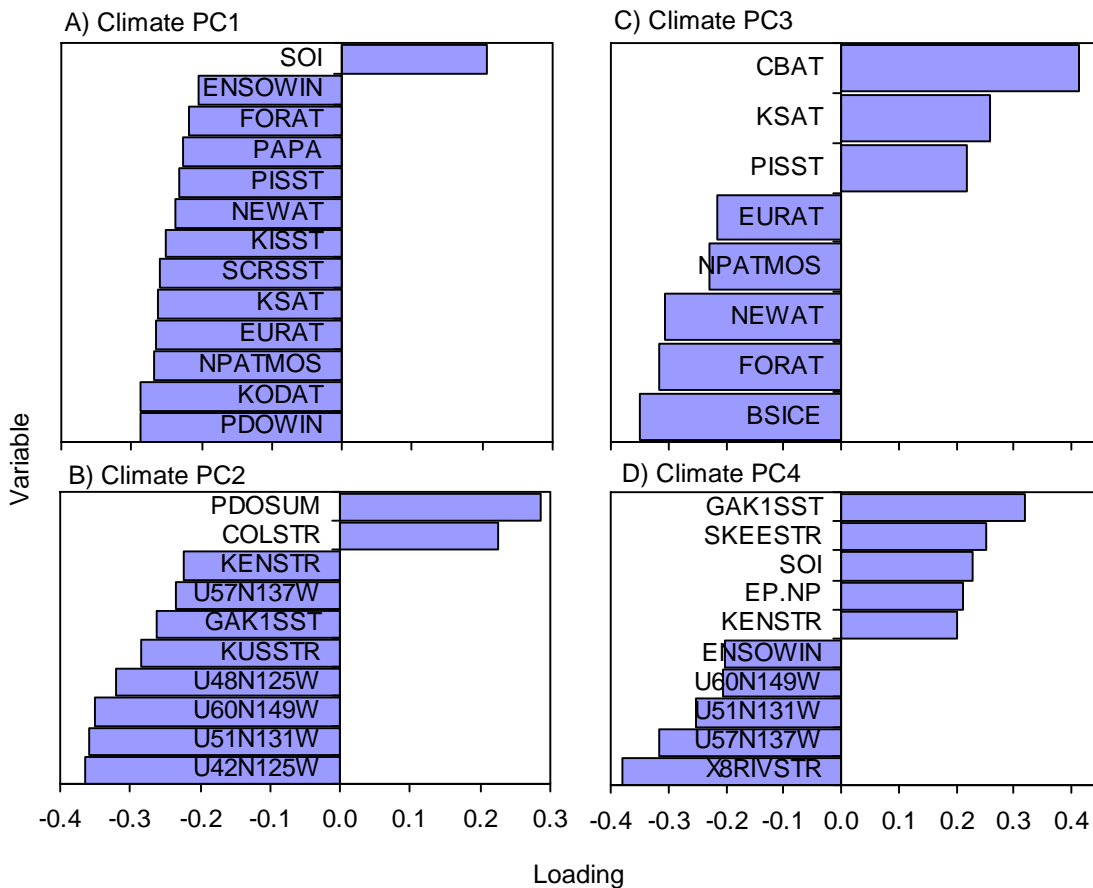
**Figure 5.** PCA time series for climate-only analysis. Error bars  $\pm 2$  SD.

climate-only PCA are presented in Appendix 3.

Climate PC2 reflected the strength of the summer PDO index (positive loading). Local-scale variables showing the strongest association with PC2 were Columbia River stream flow (positive loading), and Kuskokwim River and Kenai River stream flows, GAK1 sea surface temperature and upwelling strength between  $42^{\circ}\text{N}$  and  $60^{\circ}\text{N}$  (all negative loadings, Fig. 6).

Climate PC3 was negatively associated with the strength of the North Pacific atmospheric index. Positive values of PC3 indicated warm conditions in the Bering Sea (reduced Bering Sea ice cover index, increased Pribilof Islands sea surface temperature, increased Cold Bay and King Salmon air temperature). Negative values indicated cold conditions along the U.S. West Coast, as reflected in negative loadings with West Coast air temperature variables (Fig. 6).

Positive values of PC4 for climate-only data, such as those from 1999-2003, reflect weak El Niño conditions, as indicated by negative loading on the winter ENSO 3.4 index and positive loading on the Southern Oscillation index and East Pacific/North Pacific teleconnection index. At the local scale, these conditions tend to be associated with warm GAK1 sea surface temperature and high Kenai River and Skeena River stream flows (positive loadings), and weak upwelling (strong downwelling) between  $51^{\circ}\text{N}$  and  $60^{\circ}\text{N}$  (negative loadings, Fig. 6). Complete eigenvectors for the



**Figure 6.** Strongest loadings from climate-only PCA.

Finally, the basin-scale measurement of North Pacific temperature (NP SST) showed STARS-defined shifts in 1988-1989 (increase of  $0.32^{\circ}\text{C}$ ,  $p < 0.0001$ ) and in 2003-2004 (increase of  $0.25^{\circ}\text{C}$ ,  $p < 0.0001$ , Fig. 7).

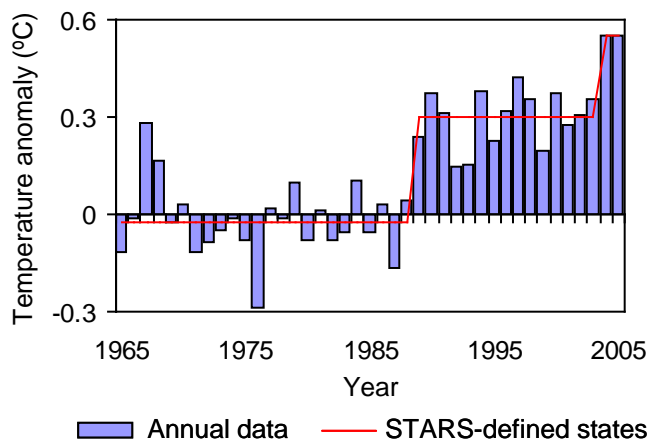
#### *Composite analysis*

Our repeat of the composite analysis of Hare and Mantua (2000) replicated the findings of shifts in 1976-1977 and 1988-1989 that were presented in the original paper. In both cases, the standard error calculated for each year in the hypothesized regime failed to cross zero, thus meeting the test for regimes proposed for composite analysis (Fig. 8). The proposed shift for Alaskan ecosystems in 2000/01 was not supported (i.e., the mean and/or standard error for some data points in the proposed pre-shift regime cross zero, Fig. 8).

### Regional comparisons

A plot of PC1 and PC2 loadings for the biology-only data showed clear regional differences, with negative average PC1 loadings for Eastern Bering Sea, Gulf of Alaska and Southeast Alaska time series and positive average loadings for British Columbia and U.S. West Coast time series (Fig. 9). We therefore grouped Alaskan data and British Columbia / U.S. West Coast (hereafter, “West Coast”) data for our regional biology PCA. Eigenvalues for this regional analysis showed a pattern similar to that from PCA of all biology time series, with high proportions of variance explained by PC1 (33.3% for Alaska, 33.8% for the West Coast) and PC2 (11.1% for Alaska, 11.5% for the West Coast), and a sharp decline in the amount of variance explained by subsequent PC scores.

The regional PCA revealed differences in the timing and number of STARS-defined shifts between Alaska and the West Coast. PC1 scores in Alaska showed a dramatic shift in 1976-1977 (pre-shift mean score = -5.67, post-shift mean score = 2.31,  $p < 0.0001$ , Fig. 10). The West Coast PC1 time



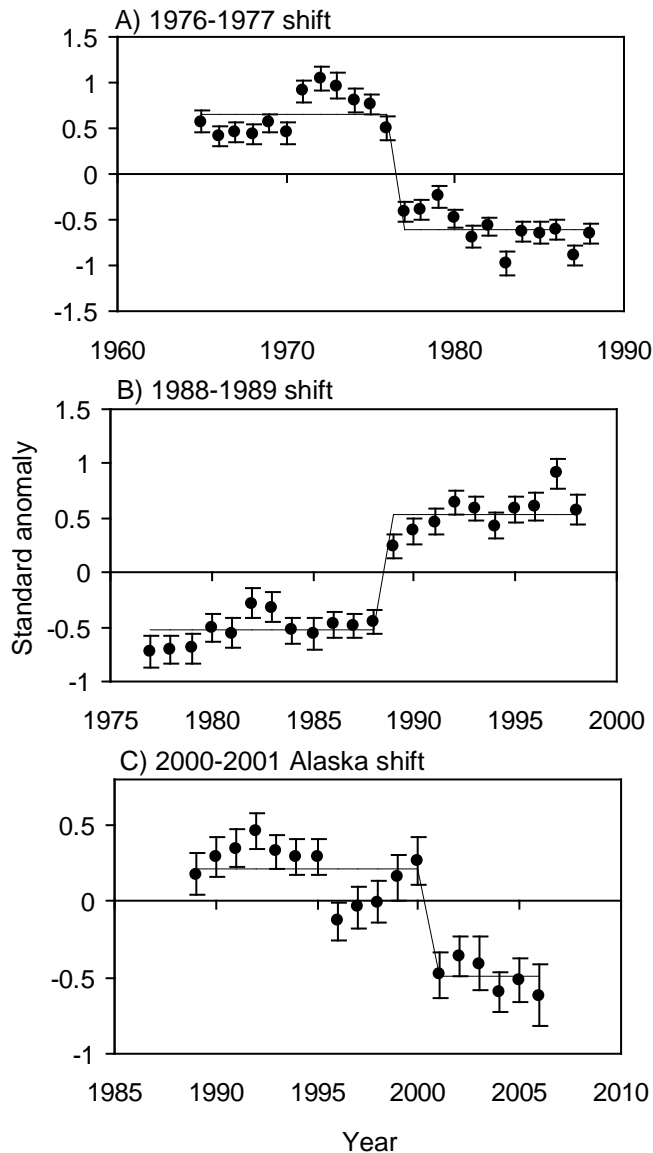
**Figure 7.** Time series of North Pacific sea surface temperature (NP SST). Data are area-weighted means for the North Pacific poleward of 20°N, expressed as difference from 1951-1980 mean.

series showed a trend of change in the opposite direction in the late 1970s (i.e., declining positive scores), but a reversion to strong positive scores in the 1980s meant that STARS did not detect a positive-to-negative PC1 shift for the West Coast until 1990-1991 (pre-shift mean score = 1.97, post-shift mean score = -2.96,  $p < 0.0001$ , Fig. 10).

Alaska biology PC2 scores showed a pattern initially similar to the biology-only analysis for all areas combined: a STARS-defined shift in 1977-1978 (pre-shift mean score = -0.19, post-shift mean score = -1.66,  $p = 0.0001$ ), with a reversal of that shift in 1993-1994 (post-shift mean score = 2.46,  $p < 0.0001$ ). However, STARS also detected a 2001-2002 shift back to a pre-1977 state (post-shift mean score = -0.28,  $p = 0.0003$ , Fig. 10). West Coast PC2 scores, on the other hand, showed no evidence of this 2001-2002 shift, but did show a shift in 1979-1980 (pre-shift mean score = 1.15, post-shift mean score = -1.55,  $p < 0.0001$ ) and a subsequent reversal in 1996-1997 (post-shift mean score = 1.08,  $p < 0.0001$ , Fig. 10).

### Climate-biology covariation

Basin-scale sea surface temperature (NP SST) was poorly correlated with any of the leading regional climate PC scores ( $|r| \leq 0.34$ ), indicating that NP SST reflected climate variability not captured in PCA of the updated climate time series. NP SST showed correlations with biology PC scores that were as strong as, or stronger than, any of the climate PC time series in three out of the four instances we



**Figure 8.** Composite analysis of A) 1976-1977 shift, B) 1988-1989 shift and C) 2000-2001 Alaska shift. A) and B) include data from all areas, and all analyses combine climate and biology data. Timing of Alaska shift was hypothesized *a priori*, before STARS analysis of Alaska-only biology data. Error bars  $\pm$  SE.

examined. NP SST showed strong correlations with Alaska biology PC1 (peak correlation at lag 0 years,  $r = 0.69$ ), Alaska biology PC2 (peak correlation at lag 4 years,  $r = 0.75$ ) and West Coast biology PC1 (peak correlation at lag 2 years,  $r = 0.86$ , Fig. 11). Alaska biology PC1 was also strongly correlated with regional climate PC1 (peak correlation at lag 1 year,  $r = -0.69$ ), while Alaska biology PC2 and West Coast biology PC1 showed correlations with regional climate PC scores that were considerably weaker than those with NP SST. Finally, West Coast biology PC2 scores showed weak correlations with several climate time series (Fig. 11).

### Discussion

#### Primary objectives

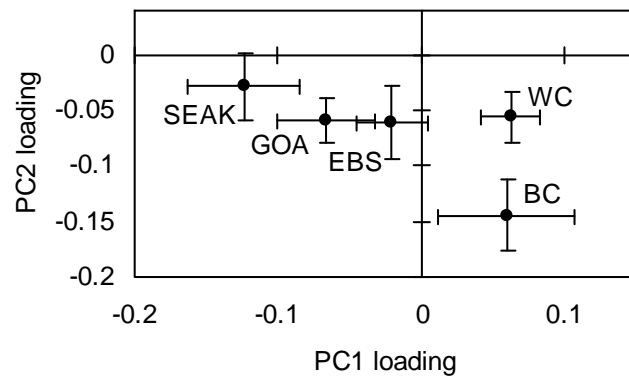
Updating 98 of the ecosystem indicators from Hare and Mantua (2000) for the years 1965-2006 produced a time series 27% longer than the time series from the original paper (1965-1997). Our analysis of the updated time series both supported the core findings of the original paper, and also provided evidence for recent shifts in time series that were not observed in the original data. The updated data show the pervasive

shift in combined climate-biology PC1 and PC2 values during 1976-1977, coincident to a regime shift in the PDO index, and also show a subsequent shift in PC2 values during 1988-1989 (Fig. 2). Similar patterns appear in PC1 and PC2 for the biology-only analysis (Fig. 3). Documentation of the 1976-1977 and 1988-1989 shifts was the central finding of Hare and Mantua (2000), and that result is both supported by STARS (see *Secondary objectives*, below) and robust to the inclusion of recent data. The updated time series also show a shift during the early 1990s in PC1 values of both the combined climate-biology data (Fig. 2) and the biology-only data (Fig. 3), representing an intensification of post-1976-1977 conditions. This shift was not detected in the shorter data set (Hare and Mantua 2000), and the persistence of this negative state in PC1 score through 2006 is inconsistent with the suggestion that a late-1990s shift might have returned the North Pacific to ecological conditions similar to those observed between the 1940s and 1970s (e.g., Chavez et al. 2003, Peterson and Schwing 2003).

Inspection of patterns in PCA time series of biology-only (Fig. 3) and climate-only (Fig. 5) data indicate that the strong interannual correlation and sudden switches in the combined climate-biology data are largely the properties of the biology time series. Both PC1 and PC2 of the biology-only data reproduce the switches detected in the combined time series, while the climate

data show higher interannual variability, with only one significant shift in average conditions (1976-1977 shift in climate PC1) detected by STARS (see *Secondary objectives*, below). This result confirms the observation that biology time series are more dominated by “regime”-type temporal variability than are climate data (Hare and Mantua 2000), and this difference represents a fundamental distinction in the behavior of the two types of data, with biological communities more prone to transitions between alternate stable states, and climate parameters more subject to stochastic variability (Hsieh et al. 2005).

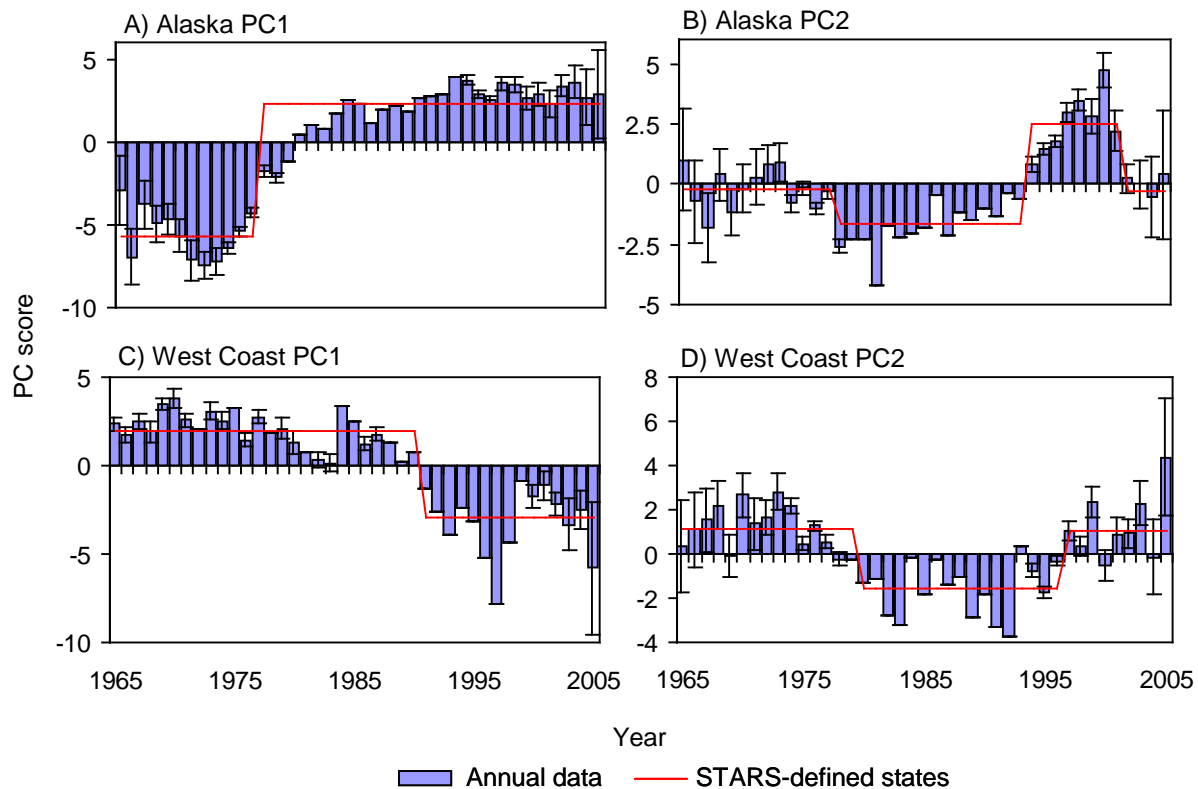
Biology-only PC1 scores were strongly influenced by variability in salmon run strength, as commercial salmon catches comprised 12 of the 19 time series showing loadings with absolute value  $\geq 0.15$  (Fig. 4). PC1 was positively related to West Coast salmon catches, and negatively related to Alaska salmon catches, representing the inverse decadal-scale patterns of salmon production between the two regions (Hare et al. 1999). Strongest loadings for PC2 scores, on the other hand, had the same sign for



**Figure 9.** Averages of biology-only PC1 and PC2 loadings by region. Error bars  $\pm$  SE. SEAK = Southeast Alaska, GOA = Gulf of Alaska, EBS = Eastern Bering Sea, WC = U.S. West Coast, BC = British Columbia.

both Alaska and West Coast time series (Fig. 4), suggesting that PC2 reflects a common forcing mechanism with similar effects on the productivity of salmon and other species in both areas.

While the 1976-1977 shift in climate and biology time series is typically explained in terms of the PDO (Hare and Mantua 2000, Mantua and Hare 2002), climate PC1 showed strong loadings both with indices associated with the PDO (North Pacific atmospheric pressure index and PDO winter index) and with indices associated with ENSO events (Southern Oscillation index and ENSO 3.4 winter index). Thus, the PC1 shift in 1976-1977 indicates change in both PDO and ENSO conditions. The ability of climate PC1 to capture variability in both the ENSO and PDO signals is consistent with the view that decadal-scale patterns in the PDO are actually expressions of direct ENSO forcing, seasonal delay of the ENSO signal, and white-noise variability in atmospheric forcing (Newman et al. 2003). For fisheries managers and other marine ecologists, however, the mechanisms behind variability in climate PC1 are likely less important than expressions of this time series in local climate variables. Negative associations between PC1 and temperature were observed both in Alaska (Pribilof Islands SST, King Salmon and Kodiak air temperature) and along the West Coast (Kains Island and Scripps Pier SST, Forks, Newport and Eureka air temperatures, Fig 6). Inverse patterns of salmon production between Alaska and the West Coast are apparently the result of opposite responses to temperature change by salmon stocks in the two

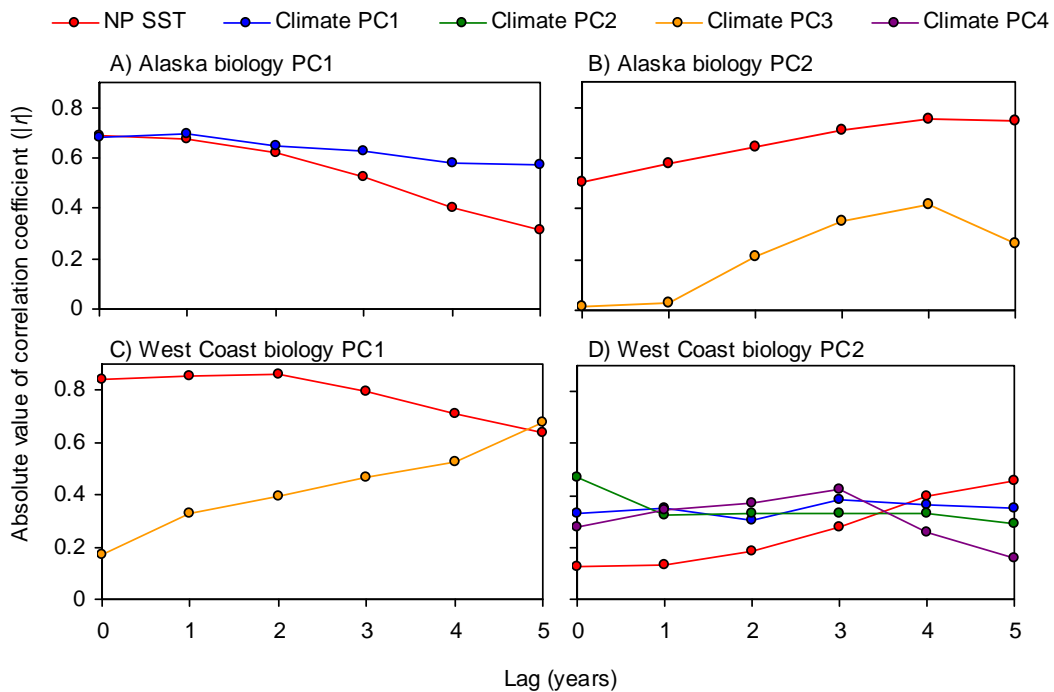


**Figure 10.** Regional time series of biology-only PCA. Error bars  $\pm 2$  SD.



regions (Mueter et al. 2002). Detailed maps of SST change in the Northeast Pacific across the 1976-1977 event are given in Hare and Mantua (2000).

Our updated time series allow some inferences to be made about the ecological implications of a possible 1998-1999 shift in the Victoria Pattern (Bond et al. 2003). To our knowledge, the present report is the first analysis of basin-scale patterns following a possible 1998-1999 shift in climate and biology time series in the Northeast Pacific. Several of the updated PCA time series show strong shifts in 1998-1999 (i.e., climate-biology PC1 [Fig. 2], biology PC1 [Fig. 3] and climate PC1 and PC4 [Fig. 5]). However, this shift proved to be ephemeral, lasting only 2-5 years in various time series, and so was not detected by our STARS analysis at  $L = 10$  years (see *Secondary objectives*, below). While both climate and biology variables showed a brief shift following 1998-1999, differences in temporal variability displayed by climate and biology systems (Hare and Mantua 2000, Hsieh et al. 2005) suggest a different interpretation for the 1998-1999 “proto-shift” for the two data types. A strong shift lasting for only a few years suggests the type of stochastic variability expected for climate data. The same pattern in biological data, on the other hand, suggests a situation where biological systems absorbed a strong perturbation (the concomitant shift in climate data) without transitioning to an alternate stable state (Scheffer et al. 2001).



**Figure 11.** Leading correlations between regional biology PCA time series and climate variables (NP SST and regional climate PCs). All climate variables were smoothed with 3-year running mean before correlations were calculated.

This pattern is consistent with a situation where ecological resilience in the Northeast Pacific (defined as the size of the maximum perturbation that can be accepted by a biological system without undergoing a transition to an alternate state, Scheffer and Carpenter 2003) was sufficient to maintain ecosystems in their current state. This brief change in several time series following 1998-1999 may therefore present an opportunity for better understanding of the factors that regulate resilience in Northeast Pacific ecosystems, which is an important step towards understanding the propensity of managed ecosystems to occasionally undergo sudden ecological reorganizations (Hughes et al. 2005, de Young et al. 2008).

### *Secondary objectives*

At the time of publication of Hare and Mantua (2000), analytical methods for detecting shifts in ecological time series, especially at the ends of time series, were not well developed. While we repeated the composite analysis of Hare and Mantua (2000) in order to assess the degree of support for the findings of that paper with the updated time series, that method may be fundamentally flawed. Reversing individual time series so that they all change in the same direction during a proposed shift may result in spurious results (Rudnick and Davis 2003), the method requires *a priori* specification of the timing of a proposed shift, and the probability of obtaining observed results under the null hypothesis cannot be assessed. The STARS approach of Rodionov (2004) addresses these concerns, and provides a better analytical tool for detecting shifts in ecosystem indicator time series. It is notable, though, that while the composite analysis of Hare and Mantua (2000) may have been flawed, STARS analysis of PCA time series replicated those authors' findings of significant shifts in climate and biology time series occurring in 1976-1977 and 1988-1989 (Figs. 2, 3 and 5). Using STARS also gave us the ability to empirically identify early-1990s shifts in PC1 of combined climate-biology data (Fig. 2) and biology-only data (Fig. 3). These shifts, representing intensification of post-1976-1977 conditions, have not, to our knowledge, been previously identified, and so could not be examined with an *a priori* hypothesis; their detection was the result of the sort of time series monitoring that STARS was developed for (Rodionov 2004).

While an early 2000s climate-biology shift in the northern Bering Sea has previously been reported (Grebmeier et al. 2006), a test for simultaneous biological change in the Gulf of Alaska produced negative results (Litzow 2006). Our observation of a 2001-2002 shift in Alaska-wide biology PC2 scores (Fig. 10) is therefore noteworthy. This result may be useful in framing more detailed analysis, such as an examination of PC2 loadings to identify the populations most strongly associated with this shift, and an examination of climate change events that may have played a causal role in the shift. Alaskan climate has recently been highly variable, and the timing of this shift is suggestive of a link to sudden changes in temperature, ice cover, and atmospheric pressure observed in the early 2000s (Overland and Wang 2005, Grebmeier et al. 2006, Litzow 2006).

Strong correlations between North Pacific SST (NP SST) and regional biology PC scores (Fig. 11) suggest the possibility that basin-scale temperature change may be as important as any of the climate PC scores in regulating Northeast Pacific biological communities. Similarly, observed correlations between regional climate and biology PC scores (Fig. 11) suggest examining regional climate PC loadings on individual time series as a logical step towards understanding the role played by individual climate variables in forcing regional biological systems. And differences in the patterns of climate-biology correlation between the two regions (Fig. 11) suggest that a regional, rather than basin-scale, approach may be more suitable for understanding climate forcing of biological communities in the Northeast Pacific. However, it should be stressed that the climate-biology relationships identified in Fig. 11 are merely the tools for framing falsifiable hypotheses about the nature of climate-biology covariation in the two regions. Testing these hypotheses is an analytically and conceptually difficult proposition, complicated, *inter alia*, by the potential for climate-biology relationships that cannot be expressed by mathematical functions (Scheffer et al. 2001), relationships between variables that change based on the direction of change in the forcing variable (i.e., hysteresis, Scheffer et al. 2001), strong autocorrelation in time series (Pyper and Peterman 1998), and the possibility of intercorrelation between climate variables at various lags (Fig. 11). While the problem of testing these hypotheses is beyond the scope of this report, the longer time series that are provided by our update to the data of Hare and Mantua (2000) may provide a data set with the statistical power that will allow for more rigorous examination of climate change effects on Northeast Pacific ecosystems.

### **Conclusions**

- 1) The findings by Hare and Mantua (2000) of significant shifts in the coupled climate-biology system of the North Pacific in 1976-1977 (for PC1 and PC2) and 1988-1989 (for PC2) were supported. The updated time series also showed a previously undescribed shift in PC1 scores in 1991-1992, representing an intensification of post-1976-1977 conditions. Biology-only PCA showed a pattern similar to that for combined climate and biology data.
- 2) Alaska biology PC2 showed a significant shift during 2001-2002, representing a reversal of the 1988-1989 shift. This shift is consistent with an ecosystem shift reported for the northern Bering Sea in the early 2000s (Grebmeier et al. 2006), but is, to our knowledge, the first report of an Alaska-wide shift at that time. A similar shift was not observed in West Coast biology time series.
- 3) A strong shift was observed in several climate and biology time series in 1998-1999. However, this shift was typically short-lived (2-5 years), and was not detected by STARS at a proposed regime length of  $L = 10$  years. We hypothesize that ecosystem resilience in 1998-

1999 was high enough to accept a strong climate perturbation without undergoing a shift to an alternate ecosystem state.

- 4) Basin-wide temperature (NP SST) appeared to be strongly correlated with three of the four regional biology time series we examined, leading us to hypothesize that basin-scale warming plays an important role in changing the structure of Northeast Pacific biological communities. Correlations between biology PCs and climate PCs appeared to differ between regions, leading us to hypothesize that causal relationships between climate change and biological community structure differ between Alaska and the West Coast. Testing these hypotheses would give insight into the possible biological consequences of further climate change in the North Pacific.

### ***Publications***

The statement of work for this project noted that publication of results would not be possible given the brief duration of the study.

### ***Outreach***

Outreach activities were not included in the statement of work for this project. However, we will disseminate our results with one conference presentation:

Mueter, F.J., and Litzow, M.A. 2009. The spatial footprint of biological re-organization in a demersal community. Invited presentation, PICES Annual Meeting, Jeju, South Korea.

### ***Acknowledgements***

We are extremely grateful to Steven Hare for providing copies of the original time series as well as patiently answering many questions about the original analysis. We also thank the following people for helping us to access various data sets: Jennifer Boldt, Jen Bowen, Greg Buck, Melissa Carter, Paul Crone, Sherri Dressel, Michael Folkes, Dana Hanselman, Amy Hays, Jim Ianelli, Jim Ingraham, Bruce Kauffman, David Mackas, Steve Moffitt, Paul Spencer, Grant Thompson, Dan Urban, John Wallace and Muyin Wang.

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**Appendix 1.** Description and source for 98 time series used in analysis. "H&M" refers to Hare and Mantua (2000). Indices spanning two years were assigned to the year corresponding to January.

No.	Dataset	Description	Source for update	Time span
1	North Pacific atmospheric pressure index	The average of three indices measuring variability in the Aleutian Low during winter: the Pacific/North American teleconnection index (DJF), the North Pacific index (DJF) and the Aleutian low pressure index (DJFM).	<a href="http://www.cgd.ucar.edu/cas/jhurrell/npindex.html">http://www.cgd.ucar.edu/cas/jhurrell/npindex.html</a> , <a href="http://jisao.washington.edu/analyses0302/">http://jisao.washington.edu/analyses0302/</a> , <a href="http://www.pac.dfo-mpo.gc.ca/sci/sa-mfpd/climate/clm_indx_alpi.htm">http://www.pac.dfo-mpo.gc.ca/sci/sa-mfpd/climate/clm_indx_alpi.htm</a>	1965-2008
2	Pacific Decadal Oscillation - winter index	Leading PC of monthly detrended SST anomalies in the North Pacific Ocean, poleward of 20N, DJF mean.	<a href="http://jisao.washington.edu/pdo/PDO.latest">http://jisao.washington.edu/pdo/PDO.latest</a>	1965-2008
3	Pacific Decadal Oscillation - summer index	Leading PC of monthly detrended SST anomalies in the North Pacific Ocean, poleward of 20N, JJA mean.	<a href="http://jisao.washington.edu/pdo/PDO.latest">http://jisao.washington.edu/pdo/PDO.latest</a>	1965-2008
4	Southern Oscillation index	Winter (DJF) averages of normalized pressure difference between Tahiti and Darwin.	<a href="http://www.cgd.ucar.edu/cas/catalog/climind/SOI.signal.ascii">http://www.cgd.ucar.edu/cas/catalog/climind/SOI.signal.ascii</a>	1965-2008
5	ENSO 3.4 - winter index	East Central Tropical Pacific SST (5N-5S)(170-120W), DJF mean.	<a href="http://www.cdc.noaa.gov/data/correlation/nina34.data">http://www.cdc.noaa.gov/data/correlation/nina34.data</a>	1965-2008
6	ENSO 3.4 - summer index	East Central Tropical Pacific SST (5N-5S)(170-120W), JJA mean.	<a href="http://www.cdc.noaa.gov/data/correlation/nina34.data">http://www.cdc.noaa.gov/data/correlation/nina34.data</a>	1965-2008
7	Arctic Oscillation index	Winter (JFM) leading PC of northern hemisphere sea level pressure north of 20N.	<a href="http://www.cpc.noaa.gov/products/precip/CWlink/daily_ao_index/monthly.ao.index.b50.current.ascii">http://www.cpc.noaa.gov/products/precip/CWlink/daily_ao_index/monthly.ao.index.b50.current.ascii</a>	1965-2008
8	King Salmon air temperature	Winter (DJF) average temperature at King Salmon airport.	<a href="http://climate.gi.alaska.edu/Climate/Location/TimeSeries/Data/aknT">http://climate.gi.alaska.edu/Climate/Location/TimeSeries/Data/aknT</a>	1965-2008
9	Cold Bay air temperature	Winter (DJF) average temperature at Cold Bay airport.	<a href="http://climate.gi.alaska.edu/Climate/Location/TimeSeries/Data/cdbT">http://climate.gi.alaska.edu/Climate/Location/TimeSeries/Data/cdbT</a>	1965-2008
10	Kuskokwim stream flow	Sum of Sept.-Oct. monthly mean flow values at USGS Crooked Creek gauge station.	<a href="http://waterdata.usgs.gov/nwis/monthly?referred_module=sw&amp;search_site_no=15304000&amp;format=sites_selection_links">http://waterdata.usgs.gov/nwis/monthly?referred_module=sw&amp;search_site_no=15304000&amp;format=sites_selection_links</a>	1965-2007



**Appendix 1** (continued)

No.	Dataset	Description	Source for update	Time span
11	St. Paul Island sea surface temperature	DJF mean temperature at 56-58N, 176-172W from Extended Reconstructed Sea Surface Temperature data set.	<a href="http://lwf.ncdc.noaa.gov/oa/climate/research/sst/sst.php">http://lwf.ncdc.noaa.gov/oa/climate/research/sst/sst.php</a>	1965-2008
12	Bering Sea ice cover index	Winter ice cover - combined from old (1965-2006) and new (1979-2008) indices.	<a href="http://www.beringclimate.noaa.gov/data/index.php">http://www.beringclimate.noaa.gov/data/index.php</a>	1965-2008
13	Eastern Bering Sea zooplankton biomass	Mean summer (JJA) biomass estimates from Hokkaido University surveys on Bering shelf east of 180° longitude.	S. Hare, IPHC, pers. comm., Hare and Mantua 2000	1965-1997
14	Eastern Bering Sea jellyfish biomass	Biomass of large medusae from NMFS summer trawl survey. Pre-1982 data calculated from H&M data using formula: new data = 0.1784*H&M data + 0.177, R <sup>2</sup> = 1.	<a href="http://access.afsc.noaa.gov/reem/EcoWeb/EcoChartDataMainFrame.htm">http://access.afsc.noaa.gov/reem/EcoWeb/EcoChartDataMainFrame.htm</a>	1982-2008
15	Eastern Bering Sea pollock recruitment	Recruitment of age 1 walleye pollock by year class, log transformed	<a href="http://www.fakr.noaa.gov/npfmc/SAFE/SAFE.htm">http://www.fakr.noaa.gov/npfmc/SAFE/SAFE.htm</a>	1965-2006
16	Eastern Bering Sea Pacific cod recruitment	Recruitment of age 0 Pacific cod by age class, log transformed.	<a href="http://www.fakr.noaa.gov/npfmc/SAFE/SAFE.htm">http://www.fakr.noaa.gov/npfmc/SAFE/SAFE.htm</a> , also G. Thompson, AFSC, pers. comm.	1974-2006
17	Eastern Bering Sea yellowfin sole recruitment	Recruitment of age 5 yellowfin sole by year class, log transformed.	<a href="http://www.fakr.noaa.gov/npfmc/SAFE/SAFE.htm">http://www.fakr.noaa.gov/npfmc/SAFE/SAFE.htm</a>	1965-2002
18	Eastern Bering Sea Greenland turbot recruitment	Recruitment of age 0 Greenland turbot, log transformed. Current model combines AI and EBS populations.	J. Ianelli, AFSC, pers. comm. Also <a href="http://www.fakr.noaa.gov/npfmc/SAFE/SAFE.htm">http://www.fakr.noaa.gov/npfmc/SAFE/SAFE.htm</a>	1968-2005
19	Eastern Bering Sea arrowtooth flounder recruitment	Recruitment of age 2 arrowtooth flounder by age class, log transformed. Current models begin in 1974, H&M used time series beginning in 1968. Years 1968-1973 estimated as (new value) = 0.1582(H&M value) + 2.3402; R <sup>2</sup> = 0.37.	<a href="http://www.fakr.noaa.gov/npfmc/SAFE/SAFE.htm">http://www.fakr.noaa.gov/npfmc/SAFE/SAFE.htm</a>	1974-2003

**Appendix 1** (continued)

No.	Dataset	Description	Source for update	Time span
20	Eastern Bering Sea rock sole recruitment	Recruitment of age-4 rock sole by year class, log transformed.	<a href="http://www.fakr.noaa.gov/npfmc/SAFE/SAFE.htm">http://www.fakr.noaa.gov/npfmc/SAFE/SAFE.htm</a>	1971-2002
21	Eastern Bering Sea flathead sole recruitment	Recruitment of age-3 flathead sole by year class, log transformed.	<a href="http://www.fakr.noaa.gov/npfmc/SAFE/SAFE.htm">http://www.fakr.noaa.gov/npfmc/SAFE/SAFE.htm</a>	1974-2003
22	Eastern Bering Sea Alaska plaice recruitment	Recruitment of age-3 Alaska plaice by year class, log transformed. Current model begins with 1972 year class, H&M used data beginning with 1969 year class. Relationship between the two data sets during overlap (1972-1994) judged too weak ( $R^2 = 0.15$ ) for estimating pre-1972 values in current data set.	<a href="http://www.fakr.noaa.gov/npfmc/SAFE/SAFE.htm">http://www.fakr.noaa.gov/npfmc/SAFE/SAFE.htm</a>	1972-2004
24	Eastern Bering Sea herring recruitment	Recruitment of age-4 herring in Togiak district, by year-class, log transformed. H&M data run 1965-1991, current ADF&G Togiak data run 1973-2005. Linear regression during period of overlap (new data = $0.3461 \times \text{H\&M data} + 2.0575$ , $R^2 = 0.54$ ) used to estimate 1965-1972 values for update.	G. Buck, ADF&G, pers. comm., <a href="http://access.afsc.noaa.gov/reem/ecoweb/">http://access.afsc.noaa.gov/reem/ecoweb/</a>	1973-2005
25	Aleutian Islands Atka mackerel recruitment	Recruitment of age-1 Atka mackerel by age class, log transformed. Current model combines EBS and AI assessment, begins with 1976 year class. H&M used time series beginning in 1975. Relationship during years of overlap (1976-1995: current model = $0.213(\text{H\&M}) + 2.5989$ , $R^2 = 0.64$ ) used to estimate 1975 value for new model.	<a href="http://www.fakr.noaa.gov/npfmc/SAFE/SAFE.htm">http://www.fakr.noaa.gov/npfmc/SAFE/SAFE.htm</a>	1975-2003
26	Aleutian Islands Pacific ocean perch recruitment	Recruitment of age-3 Pacific Ocean perch by year class, log transformed.	P. Spencer, AFSC, pers. comm.; <a href="http://www.fakr.noaa.gov/npfmc/SAFE/SAFE.htm">http://www.fakr.noaa.gov/npfmc/SAFE/SAFE.htm</a>	1965-1998

**Appendix 1** (continued)

<b>No.</b>	<b>Dataset</b>	<b>Description</b>	<b>Source for update</b>	<b>Time span</b>
27	Western Alaska chinook salmon catch	Commercial catch in Bristol Bay, Peninsula and Arctic-Yukon-Kuskokwim management areas, log transformed and lagged 3 years.	D. Eggers, ADF&G, pers. comm., <a href="http://www.cf.adfg.state.ak.us">www.cf.adfg.state.ak.us</a>	1965-2005
28	Western Alaska chum salmon catch	Commercial catch in Bristol Bay, Peninsula and Arctic-Yukon-Kuskokwim management areas, log transformed and lagged 3 years.	D. Eggers, ADF&G, pers. comm., <a href="http://www.cf.adfg.state.ak.us">www.cf.adfg.state.ak.us</a>	1965-2005
29	Western Alaska coho salmon catch	Commercial catch in Bristol Bay, Peninsula and Arctic-Yukon-Kuskokwim management areas, log transformed and lagged 1 year.	D. Eggers, ADF&G, pers. comm., <a href="http://www.cf.adfg.state.ak.us">www.cf.adfg.state.ak.us</a>	1965-2007
30	Western Alaska pink salmon catch	Commercial catch in Bristol Bay, Peninsula and Arctic-Yukon-Kuskokwim management areas, log transformed and lagged 1 year.	D. Eggers, ADF&G, pers. comm., <a href="http://www.cf.adfg.state.ak.us">www.cf.adfg.state.ak.us</a>	1965-2007
31	Western Alaska sockeye salmon catch	Commercial catch in Bristol Bay, Peninsula and Arctic-Yukon-Kuskokwim management areas, log transformed and lagged 2 years.	D. Eggers, ADF&G, pers. comm., <a href="http://www.cf.adfg.state.ak.us">www.cf.adfg.state.ak.us</a>	1965-2006
32	East Pacific / North Pacific teleconnection index	Northern Hemisphere teleconnection indices have been changed as of June 1, 2005. EP has apparently been combined with North Pacific pattern as EP/NP. H&M used DJF means for EP. EP/NP mode does not exist in Dec. We used JF means of EP/NP, which are more highly correlated with standardized 1965-1997 EP data from H&M ( $r = -.64$ ) than JFM means of EP/NP ( $r = -0.52$ ). Data multiplied by -1 to match sign in H&M data.	<a href="http://www.cpc.noaa.gov/data/teledoc/teleindcalc.shtml">http://www.cpc.noaa.gov/data/teledoc/teleindcalc.shtml</a>	1965-2008
33	Kodiak air temperature	Winter (DJF) average temperature at Kodiak airport.	<a href="http://climate.gi.alaska.edu/Climate/Location/TimeSeries/Data/adqT">http://climate.gi.alaska.edu/Climate/Location/TimeSeries/Data/adqT</a>	1965-2008

**Appendix 1** (continued)

No.	Dataset	Description	Source for update	Time span
34	Kenai River stream flow	Mean flow at USGS Soldotna gauge station. Annual index calculated as sum of Sept.-Oct. monthly mean flow values.	<a href="http://waterdata.usgs.gov/nwis/monthly?referred_module=sw&amp;search_site_no=15266300&amp;format=sites_selection_links">http://waterdata.usgs.gov/nwis/monthly?referred_module=sw&amp;search_site_no=15266300&amp;format=sites_selection_links</a>	1966-2007
35	Ocean Station Papa trajectory index	Endpoint latitude for OSCURS (Ocean Surface Current Simulator) model run 90 days beginning at 50°N 145°W on Dec. 1 of the year before labeled year.	J. Ingraham, PMEL, retired, pers. comm.; <a href="http://www.pfeg.noaa.gov/products/las/OSCURS.html">http://www.pfeg.noaa.gov/products/las/OSCURS.html</a>	1965-2009
36	GAK1 sea surface temperature	Mean winter (DJF) GAK1 temperature at 0 m depth.	<a href="http://www.ims.uaf.edu/gak1/">http://www.ims.uaf.edu/gak1/</a>	1971-2007
37	Upwelling intensity at 60N, 149W	Monthly upwelling intensity values averaged over spring-summer (MAMJJA).	<a href="http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/upwelling.html">http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/upwelling.html</a>	1965-2008
38	Upwelling intensity at 57N, 137W	Monthly upwelling intensity values averaged over spring-summer (MAMJJA).	<a href="http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/upwelling.html">http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/upwelling.html</a>	1965-2008
39	Central Pacific zooplankton biomass	Mean summer (JJA) biomass estimates from Hokkaido University surveys from 40°N to Aleutian chain, 170°E to 160°W.	S. Hare, IPHC, pers. comm., Hare and Mantua 2000	1965-1997
40	Ocean Station Papa zooplankton phenology	Julian date of maximum <i>Neocalanus plumchrus</i> biomass at 50°N, 145°W.	D. Mackas, DFO, pers. comm., Mackas et al. 2007	1965-2006
41	Gulf of Alaska shrimp catch	Proportion (by weight) of shrimp in annual small-mesh survey catches. H&M included data for 1970-71, we begin time series in 1972, when methods were standardized and catches became comparable.	D. Urban, AFSC, pers. comm.	1972-2008
42	Gulf of Alaska sablefish recruitment	Recruitment of age-2 sablefish by year class, log transformed. Current model is for all Alaskan waters, but population is predominantly in GOA.	<a href="http://www.fakr.noaa.gov/npfmc/SAFE/SAFE.htm">http://www.fakr.noaa.gov/npfmc/SAFE/SAFE.htm</a>	1965-2005

**Appendix 1** (continued)

No.	Dataset	Description	Source for update	Time span
43	Gulf of Alaska Pacific halibut recruitment	Recruitment of age-8 halibut by year class for management areas 2B, 2C, 3A, log transformed. Data series is based on new assessment model (1988-2001). Older model did not account for migration, we corrected estimates for 1965-1987 with linear regression: new model = 1.1796*old model - 0.0119, $R^2 = 0.92$ .	S. Hare, IPHC, pers. comm.	1965-2001
44	Pacific Ocean perch recruitment	Recruitment of age-2 POP by year class, log transformed.	<a href="http://www.fakr.noaa.gov/npfmc/SAFE/SAFE.htm">http://www.fakr.noaa.gov/npfmc/SAFE/SAFE.htm</a> , also D. Hanselman, AFSC, pers. comm.	1965-2002
45	Gulf of Alaska shortspine thornyhead recruitment	Recruitment of shortspine thornyheads, log transformed. This population no longer assessed with an age-structured model.	S. Hare, IPHC, pers. comm., Hare and Mantua 2000	1965-1993
46	Gulf of Alaska pollock recruitment	Recruitment of age-2 pollock by year class, log transformed.	<a href="http://www.fakr.noaa.gov/npfmc/SAFE/SAFE.htm">http://www.fakr.noaa.gov/npfmc/SAFE/SAFE.htm</a>	1965-2005
47	Gulf of Alaska Pacific cod recruitment	Recruitment of age-0 Pacific cod by year class, log transformed. "Model B" results used.	G. Thompson, AFSC, pers. comm. <a href="http://www.fakr.noaa.gov/npfmc/SAFE/SAFE.htm">http://www.fakr.noaa.gov/npfmc/SAFE/SAFE.htm</a>	1974-2005
48	Gulf of Alaska arrowtooth flounder recruitment	Recruitment of age-3 arrowtooth flounder by year class, log transformed.	<a href="http://www.fakr.noaa.gov/npfmc/SAFE/SAFE.htm">http://www.fakr.noaa.gov/npfmc/SAFE/SAFE.htm</a>	1965-2003

Appendix 1 (continued)

No.	Dataset	Description	Source for update	Time span
49	Prince William Sound herring recruitment	Recruitment of age-3 Pacific herring by year class, log transformed. Current model results only available for 1977-2005. Relationship between current model estimates and H&M data during overlapping years (1977-1992, current model = $0.3274 * H\&M + 2.281$ , $R^2 = 0.94$ ) used to estimate 1969-1976. No relationship between current model and another source (E. H. Williams. 1999. Ph.D. dissertation, UAF) across years of overlap (1977-1985).	<a href="http://access.afsc.noaa.gov/reem/ecoweb/">http://access.afsc.noaa.gov/reem/ecoweb/</a>	1969-2005
50	Sitka herring recruitment	Recruitment of age-3 Pacific herring by year class, log transformed. Relationship between current model estimates and H&M data during overlapping years (1977-1995, current model = $1.6347 * H\&M - 3.3079$ , $R^2 = 0.999$ ) used to estimate 1968-1976.	<a href="http://access.afsc.noaa.gov/reem/ecoweb/">http://access.afsc.noaa.gov/reem/ecoweb/</a> , S. Dressel, ADF&G, pers. comm.	1968-2005
51	Central Alaska chinook salmon catch	Commercial catch in Chignik, Kodiak, Cook Inlet, Prince William Sound and Copper River management areas, log transformed and lagged 3 years	D. Eggers, ADF&G pers. comm., <a href="http://www.cf.adfg.state.ak.us">www.cf.adfg.state.ak.us</a>	1965-2005
52	Central Alaska chum salmon catch	Commercial catch in Chignik, Kodiak, Cook Inlet, Prince William Sound and Copper River management areas, log transformed and lagged 3 years.	D. Eggers, ADF&G pers. comm., <a href="http://www.cf.adfg.state.ak.us">www.cf.adfg.state.ak.us</a>	1965-2005
53	Central Alaska coho salmon catch	Commercial catch in Chignik, Kodiak, Cook Inlet, Prince William Sound and Copper River management areas, log transformed and lagged 1 year.	D. Eggers, ADF&G pers. comm., <a href="http://www.cf.adfg.state.ak.us">www.cf.adfg.state.ak.us</a>	1965-2007
54	Central Alaska pink salmon catch	Commercial catch in Chignik, Kodiak, Cook Inlet, Prince William Sound and Copper River management areas, log transformed and lagged 1 year.	D. Eggers, ADF&G pers. comm., <a href="http://www.cf.adfg.state.ak.us">www.cf.adfg.state.ak.us</a>	1965-2007

**Appendix 1** (continued)

<b>No.</b>	<b>Dataset</b>	<b>Description</b>	<b>Source for update</b>	<b>Time span</b>
55	Central Alaska sockeye salmon catch	Commercial catch in Chignik, Kodiak, Cook Inlet, Prince William Sound and Copper River management areas, log transformed and lagged 2 years.	D. Eggers, ADF&G pers. comm., <a href="http://www.cf.adfg.state.ak.us">www.cf.adfg.state.ak.us</a>	1965-2006
56	Southeast Alaska chinook salmon catch	Commercial catch in Southeast and Yakutat management areas, log transformed and lagged 3 years	D. Eggers, ADF&G pers. comm., <a href="http://www.cf.adfg.state.ak.us">www.cf.adfg.state.ak.us</a>	1965-2005
57	Southeast Alaska chum salmon catch	Commercial catch in Southeast and Yakutat management areas, log transformed and lagged 3 years	D. Eggers, ADF&G pers. comm., <a href="http://www.cf.adfg.state.ak.us">www.cf.adfg.state.ak.us</a>	1965-2004
58	Southeast Alaska coho salmon catch	Commercial catch in Southeast and Yakutat management areas, log transformed and lagged 1 year	D. Eggers, ADF&G pers. comm., <a href="http://www.cf.adfg.state.ak.us">www.cf.adfg.state.ak.us</a>	1965-2007
59	Southeast Alaska pink salmon catch	Commercial catch in Southeast and Yakutat management areas, log transformed and lagged 1 year	D. Eggers, ADF&G pers. comm., <a href="http://www.cf.adfg.state.ak.us">www.cf.adfg.state.ak.us</a>	1965-2007
60	Southeast Alaska sockeye salmon catch	Commercial catch in Southeast and Yakutat management areas, log transformed and lagged 2 years	D. Eggers, ADF&G pers. comm., <a href="http://www.cf.adfg.state.ak.us">www.cf.adfg.state.ak.us</a>	1965-2006
61	Skeena River stream flow	Mean flow at Environment Canada Usk gauge station. Annual index calculated as sum of Sept.-Oct. monthly mean flow values.	<a href="http://www.wsc.ec.gc.ca/hydat/H2O/index_e.cfm?cname=graph.cfm&amp;RequestTimeout=300">http://www.wsc.ec.gc.ca/hydat/H2O/index_e.cfm?cname=graph.cfm&amp;RequestTimeout=300</a>	1965-2007
62	Kains Island sea surface temperature	Mean winter (DJF) SST at Kains Island lighthouse, BC.	<a href="http://www.pac.dfo-mpo.gc.ca/sci/osap/data/Searchtools/Searchlight_house_e.htm">http://www.pac.dfo-mpo.gc.ca/sci/osap/data/Searchtools/Searchlight_house_e.htm</a>	1965-2008
63	Upwelling intensity at 51N, 131W	Spring-summer (MAMJJA) upwelling intensity values.	<a href="http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/upwelling.html">http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/upwelling.html</a>	1965-2008
64	Northern diversion rate	Proportion of Fraser River sockeye returning via Johnstone Strait.	M. Folkes, DFO, pers. comm.	1965-2006

**Appendix 1** (continued)

No.	Dataset	Description	Source for update	Time span
65	British Columbia chinook salmon catch	Commercial catch, log transformed and lagged 3 years.	<a href="http://www.pac.dfo-mpo.gc.ca/sci/sa/Commercial/default_e.htm">http://www.pac.dfo-mpo.gc.ca/sci/sa/Commercial/default_e.htm</a>	1965-2005
66	British Columbia chum salmon catch	Commercial catch, log transformed and lagged 3 years.	<a href="http://www.pac.dfo-mpo.gc.ca/sci/sa/Commercial/default_e.htm">http://www.pac.dfo-mpo.gc.ca/sci/sa/Commercial/default_e.htm</a>	1965-2005
67	British Columbia coho salmon catch	Commercial catch, log transformed and lagged 1 year.	<a href="http://www.pac.dfo-mpo.gc.ca/sci/sa/Commercial/default_e.htm">http://www.pac.dfo-mpo.gc.ca/sci/sa/Commercial/default_e.htm</a>	1965-2007
68	British Columbia pink salmon catch	Commercial catch, log transformed and lagged 1 year.	<a href="http://www.pac.dfo-mpo.gc.ca/sci/sa/Commercial/default_e.htm">http://www.pac.dfo-mpo.gc.ca/sci/sa/Commercial/default_e.htm</a>	1965-2007
69	British Columbia sockeye salmon catch	Commercial catch, log transformed and lagged 2 years.	<a href="http://www.pac.dfo-mpo.gc.ca/sci/sa/Commercial/default_e.htm">http://www.pac.dfo-mpo.gc.ca/sci/sa/Commercial/default_e.htm</a>	1965-2006
70	Forks, Washington air temperature	Mean winter (DJF) air temperature, corrected for time of observation, changes in station history, missing observations, and urbanization.	<a href="http://cdiac.ornl.gov/epubs/ndp/ushcn/newushcn.html">http://cdiac.ornl.gov/epubs/ndp/ushcn/newushcn.html</a>	1965-2006
71	Newport, Oregon air temperature	Mean winter (DJF) air temperature, corrected for time of observation, changes in station history, missing observations, and urbanization.	<a href="http://cdiac.ornl.gov/epubs/ndp/ushcn/newushcn.html">http://cdiac.ornl.gov/epubs/ndp/ushcn/newushcn.html</a>	1965-2006
72	Eureka, California air temperature	Mean winter (DJF) air temperature, corrected for time of observation, changes in station history, missing observations, and urbanization.	<a href="http://cdiac.ornl.gov/epubs/ndp/ushcn/newushcn.html">http://cdiac.ornl.gov/epubs/ndp/ushcn/newushcn.html</a>	1965-2006
73	Columbia River stream flow	Mean flow at USGS gauge station at the Dalles, OR. Annual index calculated as sum of Sept.-Oct. monthly mean flow values.	<a href="http://waterdata.usgs.gov/nwis/monthly?referred_module=sw&amp;search_site_no=14105700&amp;format=sites_selection_links">http://waterdata.usgs.gov/nwis/monthly?referred_module=sw&amp;search_site_no=14105700&amp;format=sites_selection_links</a>	1965-2007



**Appendix 1** (continued)

<b>No.</b>	<b>Dataset</b>	<b>Description</b>	<b>Source for update</b>	<b>Time span</b>
74	Eight Rivers runoff index	Total runoff of 4 rivers in Sacramento drainage + total runoff of 4 rivers in San Joaquin drainage, calculated for Oct.-July.	<a href="http://cdec.water.ca.gov/cgi-progs/iudir/WSIHIST">http://cdec.water.ca.gov/cgi-progs/iudir/WSIHIST</a>	1965-2008
75	Scripps pier sea surface temperature	Winter (DJF) SST at Scripps Pier, California.	M. Carter, UCSD, pers. comm.	1965-2008
76	Upwelling intensity at 48N, 125W	Spring-summer (MAMJJA) upwelling intensity values.	<a href="http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/upwelling.html">http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/upwelling.html</a>	1965-2008
77	Upwelling intensity at 42N, 125W	Spring-summer (MAMJJA) upwelling intensity values.	<a href="http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/upwelling.html">http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/upwelling.html</a>	1965-2008
78	Upwelling intensity at 36N, 122W	Spring-summer (MAMJJA) upwelling intensity values.	<a href="http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/upwelling.html">http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/upwelling.html</a>	1965-2008
79	CalCOFI zooplankton biomass	Mean summer (JJA) zooplankton biomass from CalCOFI lines 80-93, log transformed.	A. Hays, SWFSC, pers. comm.	1965-2008
80	Oyster condition index	Index of meat:shell ratio for Pacific oysters from four sites (Stackpole, Stony Pt., Parcel A, Oysterville) in Willapa Bay, WA. Monthly values for each site were transformed to standard anomalies, using all observations for that site, available data for each month from all four sites then averaged, and annual means calculated from monthly means.	B. Kauffman, WDFW, pers. comm.	1965-2008

**Appendix 1** (continued)

No.	Dataset	Description	Source for update	Time span
81	West coast Pacific mackerel recruitment	Recruitment of age-0 Pacific mackerel off southern California and Mexico, log transformed. Estimates are by "fishing year" (July-June), these were lagged one year to achieve consistency with other variables (mostly climate) that span years, i.e., to the year corresponding to January.	P. Crone, SWFSC, pers. comm., also <a href="http://www.pcouncil.org/cps/cpsafe.html">http://www.pcouncil.org/cps/cpsafe.html</a>	1965-2008
82	West coast sablefish recruitment	Recruitment of age-0 sablefish by year class, log transformed.	<a href="http://www.pcouncil.org/groundfish/gfsafe.html">http://www.pcouncil.org/groundfish/gfsafe.html</a>	1965-2006
83	West coast Dover sole recruitment	Recruitment of age-0 Dover sole by year class, log transformed.	<a href="http://www.pcouncil.org/groundfish/gfsafe.html">http://www.pcouncil.org/groundfish/gfsafe.html</a>	1965-2003
84	West coast widow rockfish recruitment	Recruitment of age-3 widow rockfish by year class, log transformed.	<a href="http://www.pcouncil.org/groundfish/gfsafe.html">http://www.pcouncil.org/groundfish/gfsafe.html</a>	1965-2000
85	West coast chilipepper rockfish recruitment	Recruitment of age-0 chilipepper rockfish by year class, log transformed.	<a href="http://www.pcouncil.org/groundfish/gfsafe.html">http://www.pcouncil.org/groundfish/gfsafe.html</a>	1965-2004
86	West coast bocaccio recruitment	Recruitment of age-1 bocaccio rockfish recruitment off California by year class, log transformed.	<a href="http://www.pcouncil.org/groundfish/gfsafe.html">http://www.pcouncil.org/groundfish/gfsafe.html</a>	1965-2003
87	West coast canary rockfish recruitment	Recruitment of age-0 canary rockfish, log transformed.	<a href="http://www.pcouncil.org/groundfish/gfsafe.html">http://www.pcouncil.org/groundfish/gfsafe.html</a>	1965-2006
88	West coast yellowtail rockfish recruitment	Recruitment of age-4 yellowtail rockfish, by year class, log transformed.	J. Wallace, NWFSC, pers. comm.	1965-1999

**Appendix 1** (continued)

No.	Dataset	Description	Source for update	Time span
89	West coast Pacific hake recruitment	Recruitment of age-0 Pacific hake off British Columbia and U.S. West Coast, log transformed. Recruitment prior to 1967 set to median value, so excluded.	<a href="http://www.pcouncil.org/groundfish/gfsafe.html">http://www.pcouncil.org/groundfish/gfsafe.html</a> .	1967-2005
90	West coast sardine catch	West Coast sardine catches log transformed and lagged 4 years, to correspond with age-0 recruitment of dominant 4 year old age class in fishery. Catch data only available up to 2003 year class. However, log transformed "update" model recruitment estimates for 1982-2003 (lagged one year to correspond to January, as for #81) are highly correlated with catch values (catch = $-0.2664 \times \text{Recruitment}_2 + 4.0765 \times \text{Recruitment} - 10.511$ , $R^2 = 0.91$ ).	<a href="http://www.pcouncil.org/cps/cpssafe.html">http://www.pcouncil.org/cps/cpssafe.html</a> , also K. Hill, SWFSC, pers.comm.	1982-2007
91	West coast Pacific Ocean perch recruitment	Recruitment of age-3 Pacific Ocean perch off Washington and Oregon by year class, log transformed.	<a href="http://www.pcouncil.org/groundfish/gfsafe.html">http://www.pcouncil.org/groundfish/gfsafe.html</a> .	1965-2002
92	Washington chinook salmon catch	Commercial catch, log transformed and lagged 3 years.	<a href="http://www.st.nmfs.noaa.gov/st1/commercial/index.html">http://www.st.nmfs.noaa.gov/st1/commercial/index.html</a>	1965-2004
93	Washington chum salmon catch	Commercial catch, log transformed and lagged 3 years.	<a href="http://www.st.nmfs.noaa.gov/st1/commercial/index.html">http://www.st.nmfs.noaa.gov/st1/commercial/index.html</a>	1965-2004
94	Washington coho salmon catch	Commercial catch, log transformed and lagged 1 year.	<a href="http://www.st.nmfs.noaa.gov/st1/commercial/index.html">http://www.st.nmfs.noaa.gov/st1/commercial/index.html</a>	1965-2006
95	Washington pink salmon catch	Commercial catch, log transformed and lagged 1 year.	<a href="http://www.st.nmfs.noaa.gov/st1/commercial/index.html">http://www.st.nmfs.noaa.gov/st1/commercial/index.html</a>	1965-2006
96	Washington sockeye salmon catch	Commercial catch, log transformed and lagged 2 years.	<a href="http://www.st.nmfs.noaa.gov/st1/commercial/index.html">http://www.st.nmfs.noaa.gov/st1/commercial/index.html</a>	1965-2005

**Appendix 1** *(continued)*

<b>No.</b>	<b>Dataset</b>	<b>Description</b>	<b>Source for update</b>	<b>Time span</b>
97	Oregon chinook salmon catch	Commercial catch, log transformed and lagged 3 years.	<a href="http://www.st.nmfs.noaa.gov/st1/commercial/index.html">http://www.st.nmfs.noaa.gov/st1/commercial/index.html</a> ; <a href="http://www.dfw.state.or.us/fish/commercial/">http://www.dfw.state.or.us/fish/commercial/</a>	1965-2005
98	Oregon coho salmon catch	Commercial catch, log transformed and lagged 1 year.	<a href="http://www.st.nmfs.noaa.gov/st1/commercial/index.html">http://www.st.nmfs.noaa.gov/st1/commercial/index.html</a> ; <a href="http://www.dfw.state.or.us/fish/commercial/">http://www.dfw.state.or.us/fish/commercial/</a>	1965-2007
99	California chinook salmon catch	Commercial catch, log transformed and lagged 3 years.	<a href="http://www.st.nmfs.noaa.gov/st1/commercial/index.html">http://www.st.nmfs.noaa.gov/st1/commercial/index.html</a>	1965-2004

**Appendix 2.** Eigenvectors (loadings) for individual variables from biology-only PCA.

Variable	PC1	Variable	PC2
SAK_CM	-0.20	WAK_CM	-0.25
WCSARD	-0.19	EBSRSOLE	-0.23
SAK_CO	-0.18	WCMACK	-0.23
CAK_PI	-0.18	WAK_CH	-0.22
CAK_SO	-0.18	WAK_CO	-0.21
SAK_PI	-0.18	CCZOO	-0.21
EBSATF	-0.17	BC_SO	-0.20
CAK_CO	-0.17	WA_CM	-0.20
CAK_CH	-0.16	BC_CO	-0.19
WAK_SO	-0.16	WAK_SO	-0.18
GOAHAL	-0.16	CAK_CO	-0.18
NDR	-0.16	BC_PI	-0.17
SAK_SO	-0.15	BC_CM	-0.17
WAK_CO	-0.14	PWSHERR	-0.16
WAK_PI	-0.14	AIPOP	-0.16
GOAATF	-0.14	WA_SO	-0.16
CAK_CM	-0.12	WAK_PI	-0.15
GOAPOP	-0.11	BC_CH	-0.15
AIPOP	-0.11	SAK_SO	-0.15
EBSRSOLE	-0.10	WCYTROCK	-0.15
BSJELLY	-0.10	CAK_CH	-0.13
SITHERR	-0.09	CAK_SO	-0.13
WCDSOLE	-0.09	WA_CO	-0.12
GOACOD	-0.08	CPZOO	-0.10
WCMACK	-0.06	WCWIDOW	-0.10
GOASAB	-0.05	GOATHORN	-0.10
WA_CM	-0.05	WCCANARY	-0.09
GOATHORN	-0.03	WCSAB	-0.09
EBSHERR	-0.03	GOAHAL	-0.07
EBSCOD	-0.02	CAK_PI	-0.07
AIATKA	0.00	OR_CO	-0.07
EBSFSOLE	0.00	EBZOO	-0.06
EBS POLL	0.02	SAK_PI	-0.06
WAK_CM	0.03	EBSFSOLE	-0.06
WCPOP	0.03	WCBOCACC	-0.06
WCCHILI	0.04	GOAPOLL	-0.05
CPZOO	0.04	EBSHERR	-0.04
BC_CM	0.05	WCCHILI	-0.04
WA_PI	0.05	SAK_CO	-0.04
CCZOO	0.05	GOASAB	-0.04

**Appendix 2** (continued)

Variable	PC1	Variable	PC2
EBZOO	0.05	WCPOP	-0.03
SAK_CH	0.05	GOACOD	-0.03
CA_CH	0.06	CA_CH	-0.02
WCWIDOW	0.07	EBS POLL	-0.02
BC_SO	0.07	WA_CH	-0.02
OCI	0.07	SITHERR	-0.01
WCYTROCK	0.08	EBSCOD	-0.01
BC_PI	0.08	EBSYFS	0.00
WCHAKE	0.08	OR_CH	0.01
EBSAKPLA	0.09	NDR	0.01
WAK_CH	0.10	GOAATF	0.01
WCBOCACC	0.11	PAPAZOO	0.02
OR_CH	0.12	WA_PI	0.02
PWSHERR	0.12	GOAPOP	0.03
EBSYFS	0.12	CAK_CM	0.03
WCCANARY	0.13	AIATKA	0.03
WA_SO	0.13	WCHAKE	0.03
GOAPOLL	0.13	EBSATF	0.05
BC_CO	0.14	SAK_CM	0.05
WCSAB	0.14	SAK_CH	0.05
WA_CO	0.18	EBSTRBT	0.05
EBSTRBT	0.19	WCSARD	0.06
BC_CH	0.19	GOASHR	0.06
WA_CH	0.19	WCDSOLE	0.14
OR_CO	0.19	EBSAKPLA	0.14
GOASHR	0.19	OCI	0.16
PAPAZOO	0.20	BSJELLY	0.26

**Appendix 3.** Eigenvectors (loadings) for individual variables from climate-only PCA.

Variable	PC1	Variable	PC2	Variable	PC3	Variable	PC4
PDOWIN	-0.29	U42N125W	-0.37	BSICE	-0.35	X8RIVSTR	-0.38
KODAT	-0.29	U51N131W	-0.36	FORAT	-0.32	U57N137W	-0.32
NPATMOS	-0.27	U60N149W	-0.35	NEWAT	-0.30	U51N131W	-0.25
EURAT	-0.26	U48N125W	-0.32	NPATMOS	-0.23	U60N149W	-0.20
KSAT	-0.26	KUSSTR	-0.28	EURAT	-0.21	ENSOWIN	-0.20
SCRSSST	-0.26	GAK1SST	-0.26	U51N131W	-0.19	U48N125W	-0.20
KISST	-0.25	U57N137W	-0.23	X8RIVSTR	-0.19	COLSTR	-0.19
NEWAT	-0.24	KENSTR	-0.22	PAPA	-0.17	ENSOSUM	-0.13
PISST	-0.23	U36N122W	-0.18	COLSTR	-0.13	PDOSUM	-0.11
PAPA	-0.23	KISST	-0.11	KISST	-0.12	CBAT	-0.07
FORAT	-0.22	PISST	-0.09	EP.NP	-0.12	PISST	-0.06
ENSOWIN	-0.21	SOI	-0.05	SCRSSST	-0.11	KODAT	-0.05
CBAT	-0.19	KSAT	-0.04	U42N125W	-0.09	SCRSSST	-0.04
PDOSUM	-0.19	CBAT	-0.04	ENSOWIN	-0.09	EURAT	-0.01
KENSTR	-0.18	FORAT	-0.04	U60N149W	-0.09	KSAT	0.05
GAK1SST	-0.06	PDOWIN	-0.03	U57N137W	-0.08	PDOWIN	0.05
ENSOSUM	-0.02	ENSOWIN	-0.02	AO	-0.06	NPATMOS	0.06
U48N125W	-0.01	KODAT	0.00	U48N125W	-0.05	KUSSTR	0.07
X8RIVSTR	0.00	NEWAT	0.02	KUSSTR	0.02	KISST	0.11
U51N131W	0.01	SCRSSST	0.03	KENSTR	0.02	NEWAT	0.12
KUSSTR	0.01	SKEESTR	0.05	U36N122W	0.05	BSICE	0.13
U60N149W	0.04	EP.NP	0.06	PDOWIN	0.06	U42N125W	0.13
U42N125W	0.05	NPATMOS	0.06	SOI	0.08	PAPA	0.14
U57N137W	0.06	BSICE	0.08	SKEESTR	0.08	FORAT	0.16
SKEESTR	0.06	ENSOSUM	0.09	GAK1SST	0.10	AO	0.18
AO	0.08	X8RIVSTR	0.09	PDOSUM	0.12	U36N122W	0.20
U36N122W	0.10	PAPA	0.10	KODAT	0.16	KENSTR	0.20
BSICE	0.14	EURAT	0.11	ENSOSUM	0.19	EP.NP	0.21
COLSTR	0.16	AO	0.11	PISST	0.22	SOI	0.23
EP.NP	0.16	COLSTR	0.23	KSAT	0.26	SKEESTR	0.25
SOI	0.21	PDOSUM	0.29	CBAT	0.41	GAK1SST	0.32