Pergamon

Progress in Oceanography 47 (2000) 103–145

Progress in Oceanography

www.elsevier.com/locate/pocean

Empirical evidence for North Pacific regime shifts in 1977 and 1989

Steven R. Hare [a,*], Nathan J. Mantua [b]

[a] *International Pacific Halibut Commission, P.O. Box 95009, Seattle, WA 98145-2009, USA*
[b] *Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, Box 354235, Seattle, WA 98195-4235, USA*

Abstract

It is now widely accepted that a climatic regime shift transpired in the North Pacific Ocean in the winter of 1976–77. This regime shift has had far reaching consequences for the large marine ecosystems of the North Pacific. Despite the strength and scope of the changes initiated by the shift, it was 10–15 years before it was fully recognized. Subsequent research has suggested that this event was not unique in the historical record but merely the latest in a succession of climatic regime shifts. In this study, we assembled 100 environmental time series, 31 climatic and 69 biological, to determine if there is evidence for common regime signals in the 1965–1997 period of record. Our analysis reproduces previously documented features of the 1977 regime shift, and identifies a further shift in 1989 in some components of the North Pacific ecosystem. The 1989 changes were neither as pervasive as the 1977 changes nor did they signal a simple return to pre-1977 conditions. A notable feature of the 1989 regime shift is the relative clarity that is found in biological records, which contrasts with the relative lack of clear changes expressed by indices of Pacific climate. Thus, the large marine ecosystems of the North Pacific and Bering Sea appear to filter climate variability strongly, and respond nonlinearly to environmental forcing. We conclude that monitoring North Pacific and Bering Sea ecosystems may allow for an earlier identification of regime shifts than is possible from monitoring climate data alone. © 2000 Published by Elsevier Science Ltd.

Contents

* Corresponding author. Tel.: +1 (206) 634-1838; fax: +1 (206) 632-2983.
E-mail address: hare@iphc.washington.edu (S.R. Hare).

0079-6611/00/$ - see front matter © 2000 Published by Elsevier Science Ltd.
PII: S0079-6611(00)00033-1

1. Introduction

In the early 1990s, a wide array of evidence began accumulating that a major climate event had transpired in the mid-1970s, which had widespread consequences for the biota of the North Pacific Ocean and Bering Sea. The event was eventually termed a ‘regime shift’ and several studies have documented the climatic (Graham, 1994; Miller, Cayan, Barnett, Graham & Oberhuber, 1994) and ecosystem (Francis &

Hare, 1994; Hare & Francis, 1995; Francis, Hare, Hollowed & Wooster, 1998; McGowan, Cayan & Dorman, 1998) changes that took place. A particularly influential study was that of Ebbesmeyer, Cayan, McLain, Nichols, Peterson and Redmond (1991) who assembled 40 environmental time series and demonstrated that a statistically significant 'step' change occurred in a composite of the time series in the winter of 1976–77.

There is no common definition of a regime shift, but certain aspects are generally agreed upon. A regime implies a characteristic behavior of a natural phenomenon (sea level pressure, recruitment, etc.) over time. A shift suggests an abrupt change, in relation to the duration of a regime, from one characteristic behavior to another. Although climate variability occurs across a broad spectrum of spatial and temporal scales, in the context of the current discussion a regime spans a decade or more, whereas a shift occurs within a year or so. There is also an important distinction between regime shift and *random walk* type variability. In a random walk model of climate variability, which involves gradual random change over time, there is no mean (average) state and, in the absence of negative feedback, variance increases with time.

Recognition of the 1976–77 regime shift has opened the question of whether that event was unique or merely the latest in a sequence of regime shifts in the historical record. Based on analyses of temperature, pressure, tree ring and salmon catch records, several researchers have hypothesized that earlier climate shifts in the North Pacific occurred in the early 1920s and mid 1940s (Kondo, 1988; Mantua, Hare, Zhang, Wallace & Francis, 1997; Zhang, Wallace & Battisti, 1997; Minobe, 1997; Ingraham, Ebbesmeyer & Hinrichsen, 1998). Mantua et al. (1997) coined the term 'Pacific Decadal Oscillation' (PDO) to describe this interdecadal climate variability. They described the PDO as a long-lived El Niño–Southern Oscillation (ENSO) like pattern of Pacific climate variability. As seen with ENSO, extremes in the PDO pattern are marked by widespread variations in Pacific Basin and North American climate. Viewed from another perspective, extremes in the (tropical) ENSO cycle often influence North Pacific climate in PDO-like ways. The exceptional El Niño of 1997–1998 is a clear case in point, wherein changes in tropical rainfall and atmospheric circulation 'forced' strong and persistent climate anomalies over the North Pacific (Barnston et al., 1999). Two main characteristics distinguish the PDO from ENSO. First, typical PDO 'events' have shown remarkable persistence relative to that attributed to ENSO events — in this century, major PDO regimes have persisted for 20 to 30 years. Second, the climatic fingerprints of the PDO are most visible in the North Pacific/North American sector, while secondary signatures exist in the tropics — the opposite is true for ENSO.

It is of great interest to determine whether or not the Pacific has undergone a further climatic regime shift since the 1976–77 event, both for practical and for theoretical reasons. Within the field of fisheries, recognition of the impact of the 1976–77 regime shift has influenced management decisions. For example, certain salmon runs are now managed and optimal catch levels computed under the assumption that data collected prior to the mid 1970s is no longer relevant to modeling the dynamics of present-day salmon runs (Beverly Cross, Alaska Department of Fish and Game, personal communication). Similarly, investigations of the optimal harvest rate for the Pacific halibut fishery use regime shift models as one expression of the recruitment process (Clark, Hare, Parma, Sullivan & Trumble, 1999). To a large extent, however, most fisheries management is based on models that either 1) ignore environmental influences on population dynamics processes; 2) assume them to be random and without trend; or 3) subsume influences into an additive error term. Several high profile fisheries management failures (e.g., North Atlantic cod) have highlighted the fact that our current understanding and modeling of commercial fish populations are inadequate. We believe that only by adopting a more holistic view, including the incorporation of environmental forcing, will we increase our understanding of fish population dynamics and so be able to manage them so as to optimize the tradeoffs better between harvest and sustainability.

In this study we evaluate empirical evidence for North Pacific regime shifts in the 1965–1997 period, with a focus on 1989 as a year of special interest. As noted, many studies offer convincing evidence for the occurrence of an important North Pacific regime shift in 1977. Subsequent studies (published in the mid-to-late 1990s) have suggested that another regime shift occurred in the winter of 1988–89 (Polovina, Mitchum, Graham, Craig, DeMartini & Flint, 1994; Mackas, 1995; Sugimoto & Tadokoro, 1998; Watanabe & Nitta, 1999; Overland, Adams & Bond, 1999; Beamish, Noakes, McFarlane, Klyashtorin, Ivanov & Kurashov, 1999; Brodeur, Mills, Overland, Walters & Schumacher, 1999; Welch, Ward, Smith & Eveson, 2000), whereas others have suggested that the post-1977 regime persisted through (at least) 1997 (Mantua et al., 1997; McGowan et al., 1998; Ingraham et al., 1998). Assessments of some of the Pacific climate indicators that were sensitive to the 1977 regime shift have contributed to the controversy over the existence of a 1989 regime shift. For example, Beamish et al. (1999) used four Northern Hemisphere climate indices to form a single ‘regime index’ to examine the late 1980s–early 1990s period for evidence of a regime shift, and their results were equivocal. Our approach follows that of Ebbesmeyer et al. (1991), in which a diverse array of physical and biological data are examined to determine the statistical significance of regime changes.

2. Data and methods

For this study we assembled 100 physical and biological time series. We attempted to select a broadly representative set of environmental indicators. However, availability (or lack thereof) inevitably shaped the selection process. Additionally, several time series were chosen because they have been used by other researchers as indicators of decadal scale climate/ecosystem change. Our region of interest is the North Pacific Ocean and Bering Sea, i.e., regions that have demonstrated previous regime shift type responses. Thus we selected time series that represented this geographic range. Our physical time series (total of 31) represent atmospheric and oceanic processes while the biological time series (total of 69) are all oceanic species ranging from zooplankton to salmon and groundfish.

In the Appendix, we provide a brief description and plot of all 100 time series so the reader can generally assess their temporal variability, importance and relevance. For each time series we provide a citation or Internet address, and interested readers are encouraged to refer to these sources for more complete descriptions. Each of the time series was normalized prior to plotting and statistical analysis. We restricted our analysis to the period 1965–1997 and for each series computed the mean and standard deviation from the data during this period only. Using this time period, we can examine both the proposed 1988–89 regime shift, that of 1976–77, together with any others that might have occurred during this period. We have also minimized potential biases related to the extreme 1997–1998 El Niño event by curtailing our analysis in 1997. Most of the physical time series are winter averages while most biological time series represent annual values. None of the time series has been smoothed in any fashion except for that which occurs in the computation of seasonal or annual means. While smoothing is a fairly common practice, it is inevitably subjective and manipulative of the data. Further, the detection of trends without smoothing tends to lend greater weight to such interpretations of the data.

A list of all 100 time series is provided in Table 1, along with the abbreviations and coding numbers used in subsequent figures. We computed means for the three time periods of interest: 1965–1976, 1977–1988, and 1989–1997. The change in means between successive periods is also listed in Table 1. In Fig. 1, the time series are displayed geographically at approximately the location where they are measured, to assist in the interpretation of the spatial footprint of both the 1977 and the hypothesized 1989 regime shift.

We analyzed the environmental data using two statistical methods. The first was Principal Component Analysis (PCA) which was used to isolate the most important modes of variability in the data. PCA has a long history of use in climatology, so the methodology will not be extensively reviewed here, as numerous books and articles have been written on the subject (e.g., Priesendorfer, 1988; Hare, 1996; Von Storch & Zwiers, 1999). The goal of PCA is to concentrate most of the variance of a large dataset into a small number of physically interpretable patterns of variability. A PCA generates three types of outputs: principal components (PCs, also called scores), eigenvectors (also termed loadings), and eigenvalues, which are interpreted in sets. In climatological analysis, the PCs give the temporal variability of the isolated climate patterns. The patterns are illustrated by the loadings on the PCs. Positive loadings indicate that a variable bears a large, positive, correlation with the PC; a negative loading indicates a negative association. The eigenvalues are used to determine the fraction of total data variance explained by each PC and its eigenvector. The first PC–eigenvector pair explains the greatest amount of total variance and each successive pair explains the greatest amount of the residual variance left after that explained by earlier pairs has been removed.

The second statistical method is the same as that employed by Ebbesmeyer et al. (1991) to illustrate the magnitude of the 1977 regime shift. We applied their methodology to quantify environmental change around both 1977 and 1989. This involved two separate analyses according to the type of data normalization that is used. Thus, to test the 1977 shift, we compared the years 1965–1976 with the years 1977–1988, and to test the 1989 shift we compared the years 1977–1988 with the years 1989–

Table 1
The 100 time series used in the analysis. The time series are plotted geographically in Fig. 1. Means were computed for each time series for three periods: 1965–1976 (regime 1), 1977–1988 (regime 2), and 1989–1997 (regime 3). The 1977 change is the difference between regime 1 and regime 2, and the 1989 change is the difference between regime 3 and regime 2. No difference was computed if there were less than five years data in one of the regimes

No.	Abbreviation	Full name	1977 change	1989 change
1	NPATMOS	North Pacific Atmospheric Pressure Index	1.18	−0.66
2	PDOWIN	Pacific Decadal Oscillation — winter index	1.60	−0.95
3	PDOSUM	Pacific Decadal Oscillation — summer index	1.11	0.27
4	SOI	Southern Oscillation Index	−0.86	0.24
5	NINO34WIN	ENSO3.4 — winter index	0.50	−0.27
6	NINO34SUM	ENSO3.4 — summer index	0.10	0.44
7	AO	Arctic Oscillation index	−0.17	1.37
8	KSAT	King Salmon, AK air temperature	1.70	−0.61
9	CBAT	Cold Bay, AK air temperature	0.96	−0.40
10	KUSSTR	Kuskokwim River stream flow	−0.29	0.78
11	PISST	Pribilof Islands sea surface temperature	0.40	−1.33
12	BSICE	Bering Sea ice cover	1.64	−0.53
13	EBZOO	Eastern Bering Sea zooplankton biomass	−0.64	0.37
14	BSJELLY	Bering Sea jellyfish		1.50
15	EBSPOLL	Eastern Bering Sea walleye pollock recruitment	0.02	−0.16
16	EBSCOD	Eastern Bering Sea Pacific cod recruitment		−0.30
17	EBSYFS	Eastern Bering Sea yellowfin sole recruitment	−0.67	0.66
18	EBSTRBT	Eastern Bering Sea Greenland turbot recruitment	−0.99	−0.85
19	EBSATF	Eastern Bering Sea arrowtooth flounder recruitment	1.58	0.01
20	EBSRSOLE	Eastern Bering Sea rock sole recruitment		−0.69
21	EBSFSOLE	Eastern Bering Sea flathead sole recruitment		−1.32
22	EBSAKPLA	Eastern Bering Sea Alaska plaice recruitment	−0.15	−1.83
23	EBSPOP	Eastern Bering Sea Pacific Ocean perch recruitment	−0.26	0.50
24	EBSHERR	Eastern Bering Sea herring recruitment	1.14	
25	AIATKA	Aleutian Islands Atka mackerel recruitment		−0.70
26	AIPOP	Aleutian Islands Pacific Ocean perch recruitment	1.14	
27	WAK_CH	Western Alaska chinook salmon catch	1.08	−0.27
28	WAK_CM	Western Alaska chum salmon catch	1.11	−1.73
29	WAK_CO	Western Alaska coho salmon catch	1.73	0.03
30	WAK_PI	Western Alaska pink salmon catch	0.48	−0.04
31	WAK_SO	Western Alaska sockeye salmon catch	1.60	0.13
32	EP	East Pacific teleconnection index	−0.85	−0.72
33	KODAT	Kodiak, AK air temperature	1.72	−0.96
34	KENSTR	Kenai River stream flow	0.97	−0.45
35	PAPA	Ocean Station Papa trajectory index	1.05	−0.19
36	GAK1SST	GAK 1 sea surface temperature		−0.47
37	U60N149W	Upwelling at 60N, 149W	−0.59	−0.23
38	U57N137W	Upwelling at 57N, 137W	−0.99	0.69
39	CPZOO	Central Pacific zooplankton biomass	0.63	−0.97
40	EPZOO	Eastern Pacific zooplankton biomass		−0.53
41	GOASHR	Gulf of Alaska shrimp catch	−1.61	−0.78

(continued on next page)

Table 1 (*continued*)

No.	Abbreviation	Full name	1977 change	1989 change
42	GOASAB	Gulf of Alaska sablefish recruitment		−1.10
43	GOAHAL	Gulf of Alaska halibut recruitment	1.72	
44	GOAPOP	Gulf of Alaska Pacific Ocean perch recruitment	0.28	
45	GOATHORN	Gulf of Alaska shortspine thornyhead recruitment	0.33	−0.83
46	GOAPOLL	Gulf of Alaska walleye pollock recruitment	0.09	−0.87
47	GOACOD	Gulf of Alaska Pacific cod recruitment		−0.50
48	GOAATF	Gulf of Alaska arrowtooth flounder recruitment	1.29	0.14
49	PWSHERR	Prince William Sound herring recruitment	0.07	
50	SITHERR	Sitka herring recruitment	0.79	0.01
51	CAK_CH	Central Alaska chinook catch	1.48	0.68
52	CAK_CM	Central Alaska chum catch	1.43	−0.46
53	CAK_CO	Central Alaska coho catch	1.71	0.12
54	CAK_PI	Central Alaska pink catch	1.49	0.37
55	CAK_SO	Central Alaska sockeye catch	1.49	0.55
56	SAK_CH	Southeast Alaska chinook catch	−0.41	−0.56
57	SAK_CM	Southeast Alaska chum catch	0.54	1.65
58	SAK_CO	Southeast Alaska coho catch	1.09	0.97
59	SAK_PI	Southeast Alaska pink catch	1.16	0.76
60	SAK_SO	Southeast Alaska sockeye catch	1.26	0.81
61	SKEESTR	Skeena River stream flow	−0.77	0.54
62	KISST	Kains Island sea surface temperature	1.24	−0.24
63	U51N131W	Upwelling at 51N, 131W	−0.43	0.01
64	NDR	Northern diversion rate	0.94	0.66
65	BC_CH	British Columbia chinook salmon catch	−0.53	−1.61
66	BC_CM	British Columbia chum salmon catch	0.37	0.19
67	BC_CO	British Columbia coho salmon catch	0.05	−1.19
68	BC_PI	British Columbia pink salmon catch	0.58	−0.72
69	BC_SO	British Columbia sockeye salmon catch	0.70	−0.01
70	FORAT	Forks, WA air temperature	0.41	−0.02
71	NEWAT	Newport, OR air temperature	0.66	0.22
72	EURAT	Eureka, CA air temperature	1.22	−0.51
73	COLSTR	Columbia River stream flow	−0.61	0.29
74	8RIVSTR	8 Rivers index	−0.09	−0.54
75	SCRSST	Scripps' pier sea surface temperature	1.21	0.03
76	U48N125W	Upwelling at 48N, 125W	0.26	−1.14
77	U42N125W	Upwelling at 42N, 125W	−1.47	0.24
78	U36N122W	Upwelling at 36N, 122W	−0.72	−0.50
79	CCZOO	CalCOFI Region 2 zooplankton biomass	−0.81	−1.04
80	OCI	Oyster Condition Index	−1.32	−0.45
81	WCMACK	West Coast mackerel recruitment	1.97	−0.42
82	WCSAB	West Coast sablefish recruitment	0.00	−1.22

(continued on next page)

1997. Several time series had missing data points either near the beginning or the end of the records. We did not use a time series in the subsequent calculations if there were less than 5 years of data in either regime. Labelling the 1965–1976 years as regime 1, 1977–1988 as regime 2, and 1989–1997 as regime 3, the procedure for quantifying the step between regimes 1 and 2 is as follows:

Table 1 (*continued*)

No.	Abbreviation	Full name	1977 change	1989 change
83	WCDSOLE	West Coast dover sole recruitment	−1.16	
84	WCWIDOW	West Coast widow rockfish recruitment	0.47	−0.89
85	WCCHILI	West Coast chilipepper recruitment	−0.74	−0.01
86	WCBOCACC	West Coast bocaccio recruitment	−0.19	−0.57
87	WCCANARY	West Coast canary rockfish recruitment	−0.56	−0.97
88	WCYTROCK	West Coast yellowtail rockfish recruitment	−0.12	−0.21
89	WCHAKE	West Coast Pacific hake recruitment	0.16	−0.04
90	WCANCHOV	West Coast anchovy recruitment	−0.09	−0.89
91	WCPOP	West Coast Pacific Ocean perch recruitment	0.03	0.30
92	WA_CH	Washington chinook catch	−0.75	−1.62
93	WA_CM	Washington chum catch	1.37	−0.06
94	WA_CO	Washington coho catch	−0.19	−1.65
95	WA_PI	Washington pink catch	−0.13	−0.19
96	WA_SO	Washington sockeye catch	−0.15	−0.84
97	OR_CH	Oregon chinook catch	−0.23	−0.84
98	OR_CO	Oregon coho catch	−0.47	−1.54
99	CA_CH	California chinook catch	−0.12	−0.94
100	CA_CO	California coho catch	−0.82	−1.16

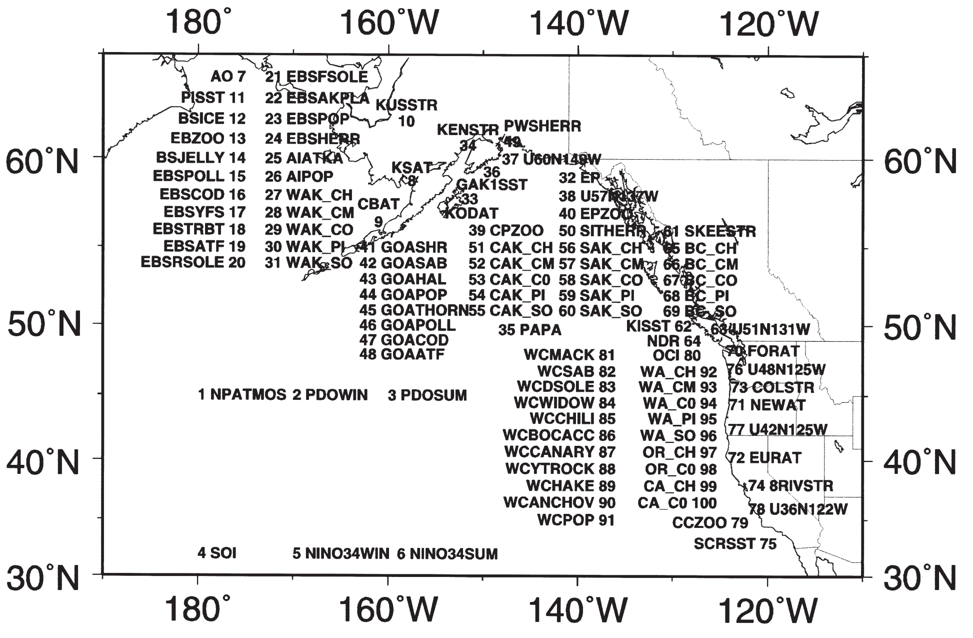

Fig. 1. Numeric and alphabetic abbreviations for the 100 time series used in this study. Geographical arrangement gives a general indication of where each variable is measured or has influence. See Table 1 for a definition of each abbreviation.

1. The data in the two regime time series were normalised. This is done by subtracting the mean across both regimes but then dividing the data for each regime by the standard deviation for that regime. This reduces bias in the parameters by eliminating the effect of the step on the variances.
2. Reverse some series so that all change in the same direction. Most of the time series showed a positive increase with the 1977 regime shift, but a few underwent a step decline between regime 1 and regime 2 (e.g., West Coast salmon). To compute the step's average magnitude they must all be of the same sign. So the sign of a variable was reversed (i. e., it was reversed every year) if the mean for regime 1 was lower than the mean for regime 2.
3. Compute an average value for each year across all 100 time series.
4. Compute regime averages by averaging across years within each regime.
5. Standard errors for each year were computed as $s/\sqrt{n}$, where s is the standard deviation across all variables within a year and n is the number of time series used in the calculation ($\leq$100)

To explore the nature and significance of the 1977 and hypothesized 1989 regime shifts further, we obtained a) the North Pacific gridded Optimally Interpolated sea surface temperature (SST) dataset of Reynolds and Smith (1994); b) the reconstructed SST dataset of Smith, Reynolds, Livezey and Stokes (1996); and c) the sea level pressure (SLP) dataset of Trenberth and Paolino (1980) for the winters and summers of 1965–1997. We selected SLP and SST because they act on large spatial scales, and are generally implicated in regime shifts. Hence they are important indicators of habitat change that is likely to influence biological productivity. From these data, we prepared difference maps, where regime averages are computed at each data point on the grid. By differencing the resulting grids, one obtains the spatial footprint of climate change between regimes.

3. Results

3.1. Principal component analysis

We used principal component analysis (PCA) to isolate objectively the most important patterns of common variability in the 100 physical and biological time series. Eigenvalue analysis indicates that only the first two principal components are meaningful. Error bars for higher order PCs (computed using the formula of North, Bell, Cahalan & Moeng, 1982) overlap indicating that the patterns are potentially mixed and non-interpretable (Fig. 2). Scores for the first two PCs are illustrated in Fig. 3 and the loadings on these two PCs are graphically illustrated in Figs. 4 and 5. The PC loadings are in fact correlations between individual time series and the associated PC score. The first and second PCs account for 24% and 11% of the total variance respectively.

The first principal component (PC1) has a time history that could be interpreted as either a slow oscillation or an abrupt shift. It is negative from 1965 until 1980

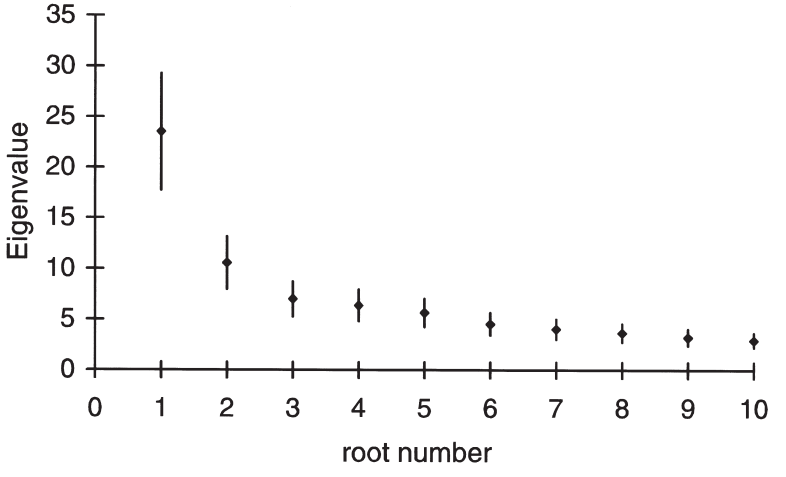

Fig. 2. Eigenvalue scree plot for the principal component analysis of 100 environmental time series. Standard error bars were computed by the formula of North et al. (1982).

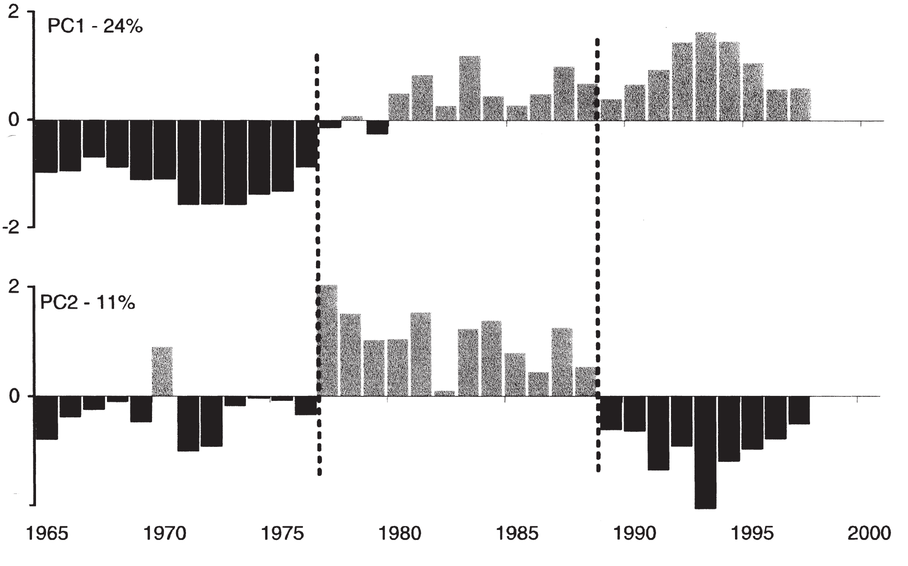

Fig. 3. The first two principal component scores from a principal component analysis of the 100 environmental time series. The scores are normalized time series and vertical bars are shown before the data points for 1977 and 1989.

and then strongly positive until 1997. The time series shows a minimum in 1973 and a maximum in 1993. As an indicator of regime shift, PC1 would signify that the North Pacific remained in the post-1977 regime through (at least) 1997. High loadings ($r>|0.5|$) on PC1 occur for 31 of the physical and biological time series, and another 25 variables have loadings of between $|0.3|$ and $|0.5|$. In particular, a

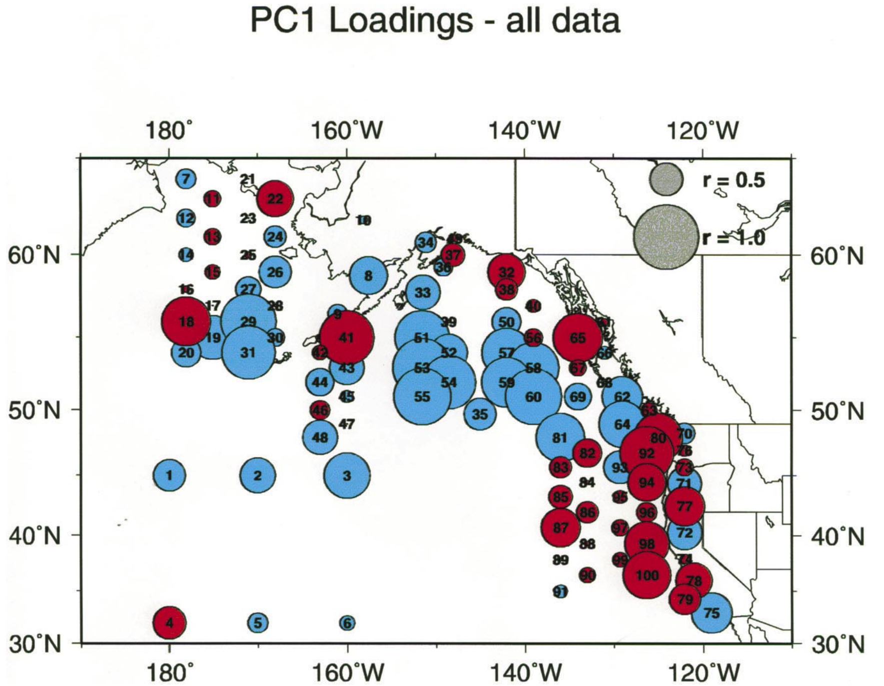

Fig. 4. Loadings on the first principal component (PC1) from a principal component analysis of the 100 environmental time series. The loadings are correlation coefficients between each time series and the first PC score (Fig. 3). Positive correlations are shaded blue, negative correlations are shaded red. Numbers correspond to definitions in Table 1 and Fig. 1. Locations of some of the numbers have been jittered slightly (from locations in Fig. 1) to enhance clarity.

large fraction of the Gulf of Alaska time series show this regime shift signal, whereas a smaller fraction of the Bering Sea and West Coast time series score highly on PC1. Among the large-scale climate variables, the largest loading was on the summer PDO. West Coast and Gulf of Alaska SST and air temperature time series generally also had large loadings. The equatorial indices (SOI, NINO34WIN, NINO34SUM) had negligible loadings on PC1, signifying that the changes seen in 1977 were restricted to the extratropical North Pacific. The Bering Sea climate indices also generally scored low on PC1.

Among the biological indices, Alaskan and West Coast salmon catches had high loadings but were inversely correlated with PC,1 reproducing the inverse production pattern first demonstrated by Hare, Mantua and Francis (1999). Among groundfish, most flatfish stocks (arrowtooth flounder, Pacific halibut, Greenland turbot, rock sole) scored very highly on PC1 whereas the rest of the groundfish complex generally did not. While many of the groundfish stocks did experience a number of strong recruitment years following the 1977 regime shift, this increased productivity does not appear to have been sustained through the 1990s. Several of the miscellaneous biological variables — Gulf of Alaska shrimp, Oyster Condition Index, Northern Diver-

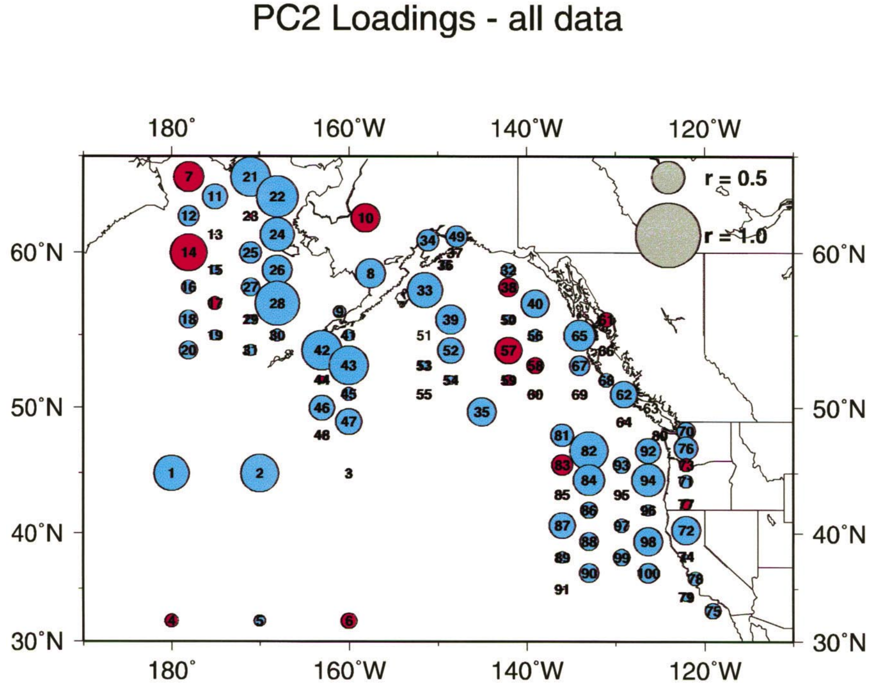

Fig. 5. Loadings on the second principal component (PC2) from a principal component analysis of the 100 environmental time series. The loadings are correlation coefficients between each time series and the second PC score (Fig. 3). Positive correlations are shaded blue, negative correlations are shaded red. Numbers correspond to definitions in Table 1 and Fig. 1. Locations of some of the numbers have been jittered slightly (from locations in Fig. 1) to enhance clarity.

sion Rate, California Current zooplankton — also had loadings greater than |0.5| on PC1.

The second principal component (PC2) also shows three distinct regimes between 1965 and 1997, with abrupt transitions in both 1977 and 1989. Twelve of the time series had loadings on PC2 of |0.5| or greater, and another 29 had loadings between |0.3| and |0.5|. Most of the highest loadings were on Bering Sea/Aleutian Islands variables, although a number of West Coast variables also had moderate loadings on PC2. The highest climate loadings were on the North Pacific atmospheric and winter PDO indices. Among biological variables, highest loadings were on Bering Sea groundfish, Bering Sea jellyfish and West Coast salmon and groundfish. Of perhaps more acute interest is that 62 of the 69 biological time series have a positive loading on PC2. Since the biological indices are, with the exception of the Northern Diversion Rate, measures of abundance, a positive loading indicates a negative shift to decreased productivity beginning in 1989.

In the PCA, we weighted all the time series equally, i.e., each contributed 1/100th of the total data variance. We attempted to include a geographically representative collection of time series. However, we did not impose a balance between the number of climatic and biological time series, nor did we weight the data matrix to guarantee equal contributions of variance from the physical and ecological time series examined by the PC analysis. There are 31 climate and 69 biological time series, so significantly more of the variance is being derived from the biological time series. By conducting the PCA on the full data matrix, we are explicitly looking for coherence between environmental and biological variables. We were also interested to see if the biological and the climate data, by themselves, would produce leading PCs similar to those obtained from the full environmental-ecological analysis. We conducted separate PCAs on the biological and climate datasets to see if the results that were obtained differed from the combined data PCA.

The leading PCs for the climate-only and biology-only PCAs are illustrated in Fig. 6. They show both broad similarities and significant differences between the two analyses. The biology PCs are very similar to those of the full dataset PC scores. Biology PC1 (27% of total biological variance) shows a two-regime time history with a change occurring sometime in the late 1970s; PC2 (12% of total variance) shows an abrupt change in 1977 and a reversal in 1990. Climate PC1 (27% of total climate variance) also shows an abrupt shift in 1977 and a reversal in 1989. However, the 1989 reversal is short-lived and persists for just three years before returning to post 1977 conditions. The climate PC2 does contains neither of these two temporal trends (i.e., single 1977 shift, or a 1977 and 1989 shift). It accounts for 13% of the total variance, and has large loadings ($r>0.5$) only on the six Bakun upwelling time series. Hence the climate PC2 is identifying a signal that is unique to the upwelling indices. It contains the same general negative trend that is common to each of the Bakun upwelling indices (compare with Appendix Fig. A7). In contrast, the climate PC3 (11% of total variance) resembles PC2 from both the combined and the biology-only data analyses, showing prevailing changes in sign in both 1977 and 1989.

Loadings on the climate and biological variables (not shown) are very similar to those obtained from the combined data analysis. A notable distinction between the physical and biological PC scores is their respective relative smoothness. Note that except at the abrupt transitions the biology-only PC1 and PC2 show remarkable year-to-year persistence, while the climate-only PC1 and PC3 exhibit strong year-to-year variations that are superimposed on the regime scale changes. Thus year-to-year ‘noise’ in the environment appears to be strongly low-passed filtered by the large marine ecosystems represented in our collection of biological time series.

3.2. Estimation of regime shift step magnitude

In our repeat of the regime shift analysis of Ebbesmeyer et al. (1991) we found statistically significant step changes in both 1977 and 1989 in composites of our 100 environmental time series (Fig. 7). For the 1977 test, 91 time series were usable (i.e. had at least five years data in each regime) and 94 time series were usable for the 1989 test. The 1977 step (1.22 standard deviates) was slightly larger than the 1989 step (1.05). There is little apparent interannual trend within the three regimes and the standard errors of the mean annual values varied little from year to year. We applied this test to other years to see if a statistically significant step could be ident-

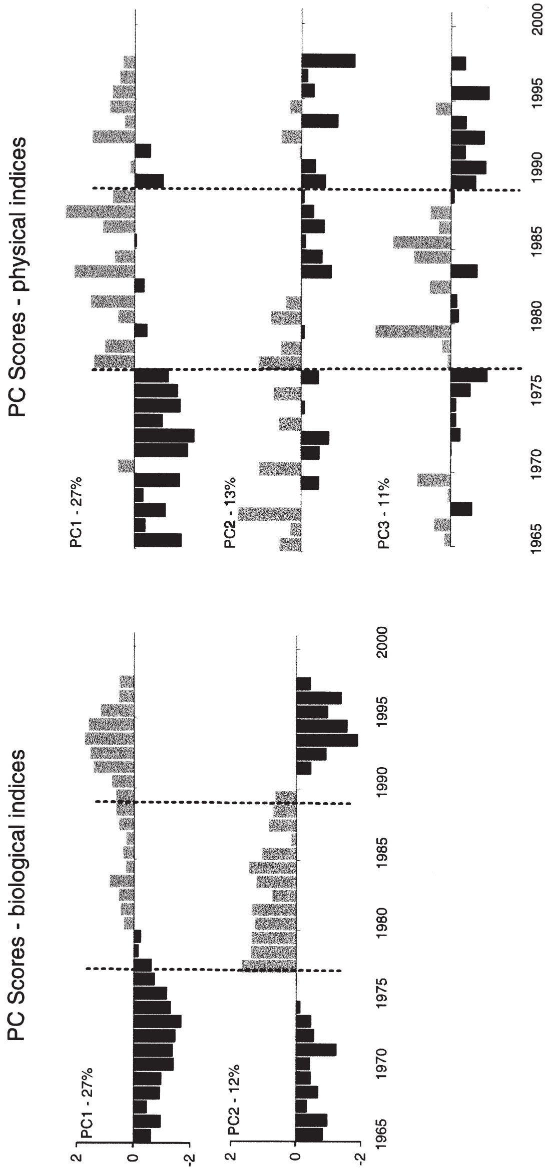

Fig. 6. Principal component (PC) scores from separate principle component analyses of 69 biological time series and 31 climate time series. PC1 and PC2 are show for the biological analysis and PC1, PC2 and PC3 are shown for the climate analysis. The scores are normalized time series and vertical bars are shown before the data points for 1977 and 1989.

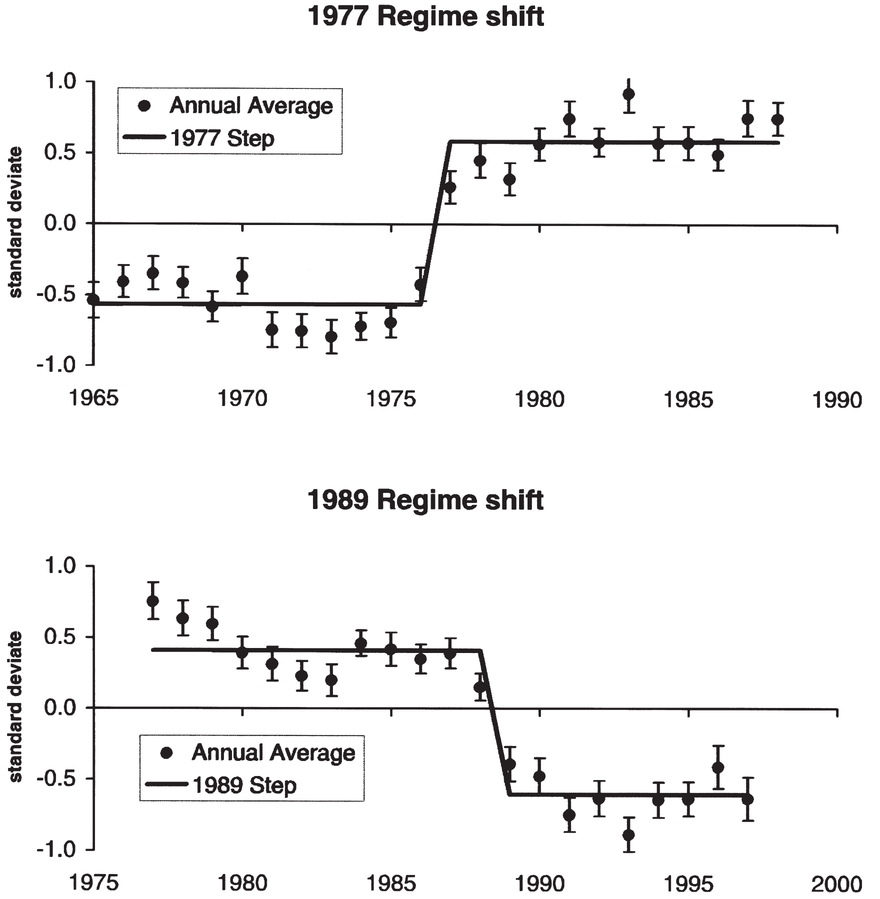

Fig. 7. Results from two regime shift analyses of a composite of the 100 environmental time series. The step passes through the mean standard deviate within each regime. The standard error of the 100 time series is illustrated for each year.

ified. As a consequence of how the data are manipulated (all aligned to change in the same direction) there is always a step change from one chosen regime to the next. What is unique about the 1977 and 1989 years, however, is that none of the standard errors around the annual values cross zero. For the other years we tested at least one annual value would not pass this test. McFarlane, King and Beamish (2000) obtained similar results when they applied this same regime shift test to a composite index based on seven indices that track major components of British Columbia commercial fisheries (see their Fig. 10).

To provide more detailed insights into the 1977 and 1989 regime changes, we have computed differences in the successive regime averaged values for each of the 100 data series (Table 1). Viewed in this simple way, the changes in successive regimes are sometimes expressed as regionally coherent patterns. For instance, during the 1977–88 period there were increases in Alaska salmon catches in 14 of the 15 data sets examined here (the exception being Southeast Alaska chinook). During the same time period, 8 of 9 salmon catch records for California, Oregon, and Washington showed decreases in the regime averaged data (Washington chum being the exception) relative to the 1965–1976 period.

Records that indicate shifts to higher values (productivity, biomass, or catch) occurred in the 1977–88 regime followed by a shift to lower index values in the 1989–97 regime include: western Alaska chinook, chum, and pink salmon; central Pacific zooplankton biomass; recruitment for Gulf of Alaska shortspine, thornyhead and walleye pollack; central Alaska chum salmon; British Columbia coho, pink and sockeye salmon catch; recruitment for West Coast mackerel, widow rockfish, Pacific hake; and Washington chum salmon catch. McFarlane et al. (2000) report that recruitment rates for fish stocks showing this type of behavior include Strait of Georgia, Puget Sound and coastal Oregon coho, Fraser River sockeye salmon, and British Columbia sablefish, and rock and Dover sole.

Data series indicating back-to-back increases in regime-averaged indices are concentrated in Alaskan waters. This subgroup includes: Western Alaska coho and sockeye salmon catch; recruitment of Gulf of Alaska arrowtooth flounder; Central Alaska chinook, coho, pink and sockeye salmon catch; Southeast Alaska chum, coho, pink and sockeye salmon catch; British Columbia chum salmon catch; and West Coast Pacific ocean perch recruitment.

Perhaps the most alarming observation is that some of the stocks show back-to-back decreases in regime averaged recruitment, biomass, or catch. Note that these stocks are concentrated in, but not limited to, the southern end of our study area. This category includes: recruitment for Eastern Bering Sea Greenland turbot and Alaska plaice; Gulf of Alaska shrimp catch; southeast Alaska and British Columbia chinook catch; Washington Oyster Condition Index; CalCOFI Region 2 zooplankton biomass; recruitment of West Coast chilipepper, bocaccio, canary rockfish, yellowtail rockfish, and anchovy; Washington chinook, coho, pink and sockeye salmon catch, Oregon chinook and coho salmon catch, and California chinook and coho salmon catch.

3.3. Climatic difference maps

3.3.1. SST

i. (1977–88)–(1965–76)

Among the most notable changes in North Pacific ocean climate following the 1977 regime shift was the cooling of the central North Pacific and the warming of the Northeast Pacific Ocean. In winter, the warming encompassed a broad band along the Pacific coast of North America. SSTs in 1977–88 were 0.6–1°C warmer than that observed from 1965–76 (Fig. 8a). At the same time, much of the central North Pacific was on average −0.8 to −1°C cooler. The maximum cooling was centered between 39° and 44°N, from 170°E to 175°W.

Differences between summer season (June–August) SSTs for these same years are shown in Fig. 8b. Although much of the Northeast Pacific warmed, and much of

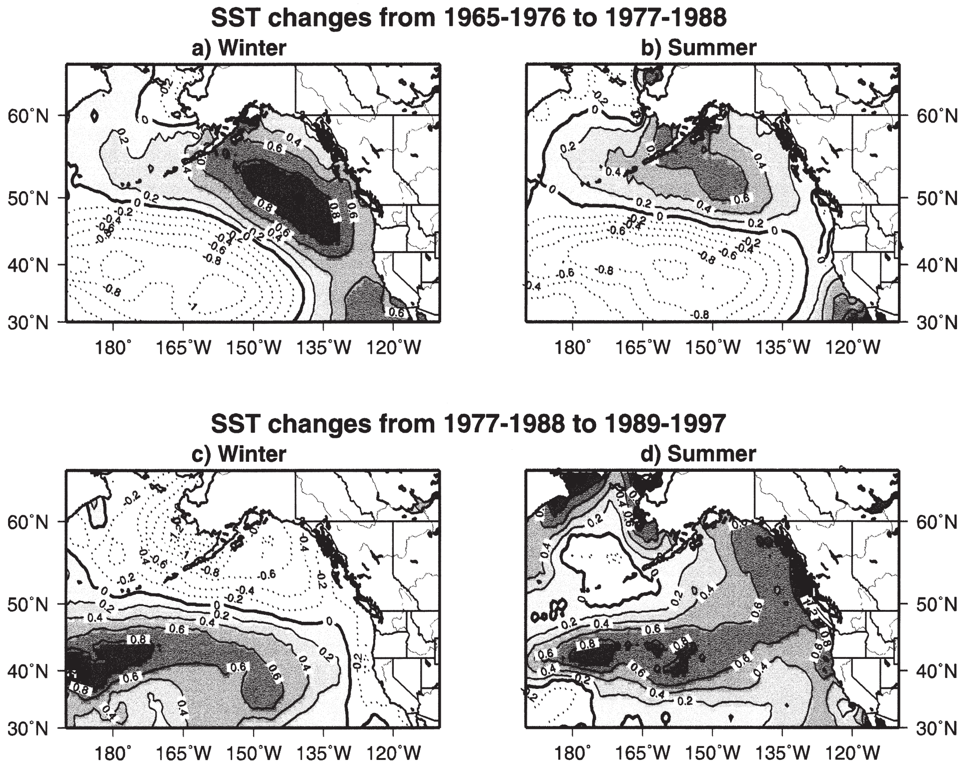

Fig. 8. Difference maps for SST change across two possible regime shifts.

the central North Pacific cooled, between these eras, the pattern of warming and cooling was different from that observed in winter. Summer SST differences show that the greatest warming (~0.6°C) took place in the Gulf of Alaska and eastern Bering Sea, and in triangular region spanning most of the California and Baja California coasts that continued into the eastern tropical Pacific. Summer season SST differences were very small (<0.2°C) off the coasts of Southern British Columbia to the Oregon–California border. Cooling of summer SSTs was centered east of the area most affected in winter, with the greatest changes taking place between 33° and 45°N, 180° and 145°W.

ii. (1989–97)–(1977–88)

Differences between the winter SSTs of 1989–97 and 1977–88 (Fig. 8c) show cooling of −0.4 to −0.6°C in the Northern Gulf of Alaska and Bering Sea, a region of minor cooling (~−0.2°C) off the coast of California, and a broad region of warming in much of the central North Pacific. Warming occurred in two areas: the greatest warming was centred near 172°E, 41°N, and the warming centered near 150°W, 37°N extended over a wider area.

Summer SST differences, shown in Fig. 8d, were much more uniformly distributed in the Northeast Pacific. Most of the interior North Pacific north of 36°N warmed by 0.2–0.8°C. Warming was also observed in a broad belt off the coast of southern and Baja California, which extended all the way south into the tropical eastern Pacific.

Winter season SST differences for the eras starting in 1977 and 1989 show a large degree of symmetry, while those in the summer season do not. An asymmetry is noted for the amplitude of SST changes between the winter season eras. In most of the Northeast Pacific, widespread warming in the 1977–88 era was followed by only small SST changes, some of which cooled SSTs by 0.4 to 0.6°C in the northern Gulf of Alaska and Bering Sea. On average, Northeast Pacific SSTs warmed by 0.4 to ~1°C from 1965–76 to the 1989–97 periods (not shown). Also notable is the fact that Northeast Pacific summer SSTs warmed in both eras, although with slightly different spatial patterns.

3.3.2. SLP

i. (1977–88)–(1965–76)

Hemispheric SLP change patterns for the eras of interest are shown in Fig. 9.

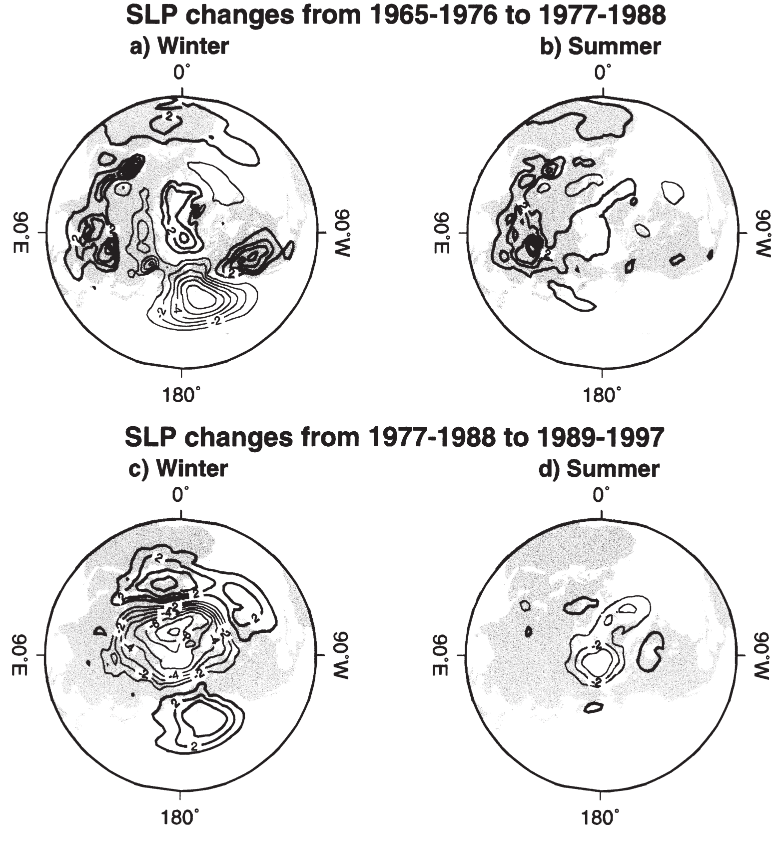

Fig. 9. Difference maps for SLP change across two possible regime shifts.

Differences between observed winter SLPs in the 1977–88 period relative to those observed in 1965–76 highlight the well-documented shift to a deeper Aleutian Low (Fig. 9a, Graham, 1994; Trenberth and Hurrell, 1994). Smaller changes to increased SLP are evident over the western US, the central Arctic, northern Africa, and northern Asia. In summer (Fig. 9b), the largest SLP changes between 1977–88 and 1965–76 were located over the central Arctic, northern Africa and northern Asia, where SLPs were lower by 1–4 mb.

ii. (1989–97)–(1977–88)

Much of the Arctic region experienced a large drop of winter mean SLPs in the 1989–1997 period (Fig. 9c). The lower Arctic SLPs coincided with increased SLPs centered over much of the North Pacific, North Atlantic, and Northern Europe. Thompson and Wallace (1998) have noted that recent trends in both the Arctic and Antarctic extend throughout the troposphere and coincide with stratospheric cooling over both polar regions. They have labeled these features as the Arctic and Antarctic Oscillations (AO and AAO, respectively). In summer, changes to higher SLPs were observed over the central Arctic, where SLPs were lower by 1–4 mb over a small region near the North Pole.

As noted with SSTs, some aspects of the winter SLP changes are symmetrical with those noted from 1977–88. Likewise, the amplitude of the 1989–97 changes was smaller than that of those in the 1977–88 period. Relative to the 1965–76 period, the Aleutian Low is more intense with central SLPs 3–4 mb lower; the winter season Arctic vortex was also much more intense in the 1989–97 period, with central pressures 5–8 mb lower than those observed in the 1977–88 period, and 3–6 mb lower than those for the 1965–76 period.

4. Discussion

We have employed an objective statistical method — Principal Component Analysis (PCA) — to identify temporally coherent changes in indices for parts of the large marine ecosystems of the North Pacific and Bering Sea. PCA requires no a priori assumptions about specific years in the historical record. As a second metric for the significance of regime shift changes, we have employed Ebbesmeyer et al.'s (1991) method, which does require an a priori specification of regime years. The results from both approaches identify statistically significant regime shifts occurred in the large marine ecosystems of the North Pacific/Bering Sea in the period 1965–1997. A late-1970's regime shift explains the greatest fraction of the total variance in our climate and ecosystem data matrix. Independent analyses of climate-only and biology-only data matrices point to the 1977 changes being pervasive throughout the Pacific climate and marine ecosystems. A 1989 regime shift also explains a significant portion of the total variance in our combined climate–biological data matrix. The analysis of biological data by itself offers strong support for a 1989 regime shift, but our analysis of climate data alone is less convincing, though still suggestive.

It is also important to note that the 1989 change was not a simple reversal of climate and ecosystem conditions established after the 1977 regime.

The outstanding features of the leading PCA pattern from our combined climate-biological data analysis include: a late 1970s regime shift to an intensification of the wintertime Aleutian Low, a year-round cooling of the central North Pacific Ocean, and a year-round warming of the coastal Northeast Pacific Ocean and Bering Sea. Following this regime shift, most Alaskan salmon populations increased, while there were decreases in Alaskan shrimp populations; most west coast salmon populations decreased, as did California Current zooplankton abundance, and in the (Washington Coast) Oyster Condition Index.

In contrast, the outstanding features of the second PCA pattern from our analysis include: three distinct regimes with abrupt transitions in 1977 and 1989. Subsequent to 1989, there was a winter cooling of the coastal waters in the northern Gulf of Alaska and Bering Sea, a winter warming of the central North Pacific Ocean, an intensification of the winter and summer Arctic vortex, a weakened winter Aleutian Low, and a summer warming throughout much of the central North Pacific and coastal Northeast Pacific Ocean. Ecologically important changes coherent with this second PCA pattern include declines in Bering Sea groundfish recruitment, Western Alaska chinook, chum, and pink salmon catch, British Columbia coho, pink and sockeye salmon catch, West Coast salmon catches and groundfish recruitment, and increases in Bering Sea jellyfish biomass.

While the 1977 regime shift was coherent with a near-equal balance between fish stocks showing increases and decreases in abundance, the 1989 regime shift was largely expressed as step decreases in productivity in nearly a third of the data series examined, with very few indices showing shifts to higher values. In a related study, McFarlane et al. (this volume) present evidence pointing to 1989 as a year marking widespread changes in British Columbia marine fisheries that included major declines in salmon and groundfish production while at the same time ushering in production booms for sardines and Pacific hake.

A number of climate studies support the notion that two energetic interdecadal-scale climate oscillations, one at a period of about 50–70 years, the other at a period of 15–25 years, have been operating in the Pacific sector in the past century (e.g. Minobe, 1999; Enfield & Mestas-Nuñez, 1999; Mestas-Nuñez & Enfield, 1999). Minobe (1999, 2000) has shown that both oscillations are strongly expressed in broad scale indices used to track North Pacific sea surface temperatures (e.g., the PDO index) and the intensity of the Aleutian Low. Minobe (1999) also demonstrated that on several occasions during the 20th century these two oscillations became superposed in ways that have caused major and minor regime shifts. Such an interaction may explain the existence of both the 1977 and the 1989 regime shifts discussed here and in other studies. It is tempting to interpret our findings as further evidence that whereas both oscillations reversed in 1977, in 1989 only the 15–25-year oscillation reversed.

Are we improving our ability to identify regime shifts? Although the 1976–77 shift has been studied in great detail, it was not widely recognized as having been a significant event until more than a decade had elapsed. Recognition (and acceptance) of a 1989 North Pacific regime shift may be following a similar history. One interpretation is that environmental changes beginning in 1989 triggered dramatic changes in some of the large marine ecosystems in the North Pacific and Bering Sea. In particular, an intensification of the Arctic vortex was noted for most years between 1989 and 1997, as were anomalously warm summertime coastal SSTs from Scripps Pier north to the Gulf of Alaska. However, during this period, relatively large year-to-year variations in most other measures of Pacific climate have made it difficult to identify any larger scale coherence in post-1989 environmental changes. One alternative explanation for the persistent changes in biota calls for a nonlinear reorganization in Northeast Pacific and Bering Sea ecosystems in response to relatively short-lived environmental changes. Can anomalous climate forcing lasting just one to a few years be enough to trigger longer lasting ecosystem changes?

Whatever the case may be, the indices that track variations in the large marine ecosystems of the North Pacific and Bering Sea vary more slowly than most climate indices. This may offer great utility for discerning important ecosystem signals from less ecologically important climate noise. We believe that closely monitoring ecosystem variations offers an avenue for identifying regime shifts sooner than may be possible from climate monitoring alone. Unfortunately, retrospective analysis of ecosystem data still requires a lag time for identifying regime changes, and offers no help in skillfully predicting future regime shifts. Generally speaking, as long as the mechanisms that give rise to interdecadal climate variations remain unknown, efforts to identify persistent regime shifts as they unfold will require at least as much faith as objectivity. Skillfully forecasting regime shifts without a physical basis built on

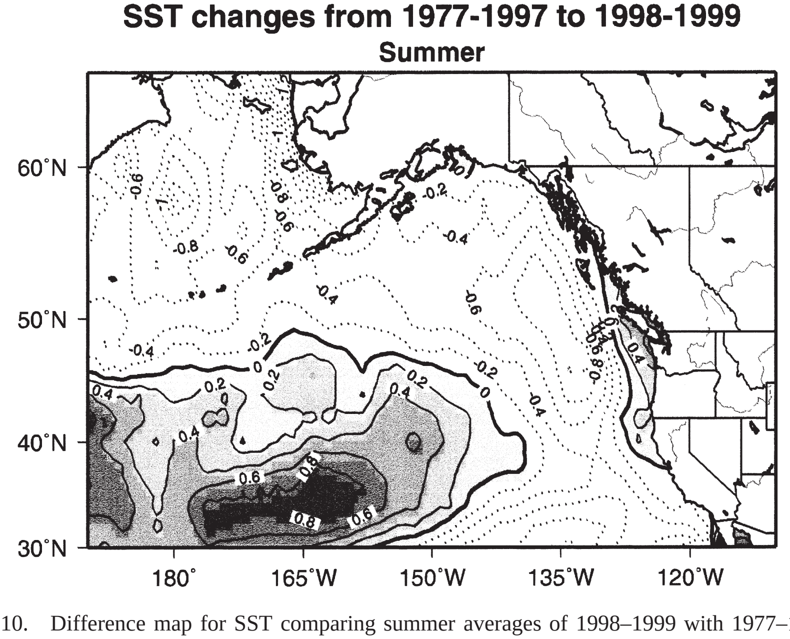

Fig. 10. Difference map for SST comparing summer averages of 1998–1999 with 1977–1996.

conceptual and theoretical models, in combination with a comprehensive monitoring system, appears to be hopeless.

Changes in Pacific climate observed from late 1998 through February 2000 suggest that the post-1977 era of unusually warm coastal ocean SSTs may have ended (Fig. 10). Coincident with the demise of the extreme 1997–98 El Niño event, SSTs all along the Pacific coast of North America have cooled to below average values, and they have generally remained at below average values through February 2000. Recent climate forecasts, based largely on expectations for continued moderate strength (tropical) La Niña conditions, suggest that the cool coastal SSTs are likely to persist through at least the boreal spring of 2000. Are we on the cusp of yet another regime shift? Will we, sometime in the next decade, be looking back at 1998 as the year the PDO pattern reversed and North Pacific climate returned to a pre-1977 state? Would such a climate shift halt or reverse the declines in Pacific fish stocks — and at the same time arrest the production increases — that began in the late 1970s? It appears that only time will answer these questions with certainty.

Acknowledgements

This work was motivated by discussions and presentations held during a series of informal meetings — on the subject of climate impacts on marine resources — held in Seattle between 1997 and 1999. We wish to thank the 20–30 scientists involved in those meetings, many of whom contributed time series used in our analysis. These time series, along with meeting summaries, are available at http://www.iphc.washington.edu/Staff/hare/html/decadal/post1977/post1977.html. We especially wish to acknowledge detailed reviews by Robert Francis, Curt Ebbesmeyer and Bruce Leaman that helped us to substantially improve the manuscript. N. Mantua was funded through the NOAA Office of Global Programs project titled ‘An Integrated Assessment of the Dynamics of Climate Variability, Impacts, and Policy Response Strategies’. This research was funded in part by the Joint Institute for the Study of the Atmosphere and Oceans (JISAO) under NOAA Cooperative Agreement No. NA67RJ0155, Contribution No. 734. The views expressed herein are those of the authors and do not necessarily reflect the views of NOAA or any of its subagencies.

Appendix A. 100 physical and biological time series used in the analysis

A.1. Atmospheric indices

Changes in the character of the wintertime Aleutian Low appear to be at the heart of regime shift dynamics in the North Pacific. There are three commonly used measures of Aleutian Low variability; and we describe these three individually.

A.1.1. Pacific/North American teleconnection index

The Pacific/North American (PNA, Fig. A1a) pattern is a prominent mode of Northern Hemisphere atmospheric variability and has four centers of action one of which lies over the sea level pressure defined Aleutian Low. Wallace and Gutzler (1981) developed the PNA index as a linear combination of the 500 mb height at four latitude–longitude locations. Barnston and Livezey (1987) derived the PNA index, as well as a dozen other teleconnection indices, from a rotated principal component analysis of monthly mean 700 mb height anomalies. The teleconnection time series, anomaly maps, and calculation methods are updated monthly and are available at http://nic.fb4.noaa.gov:80/data/teledoc/telecontents.html. Here, we compute a winter PNA index as an average of the December–February values.

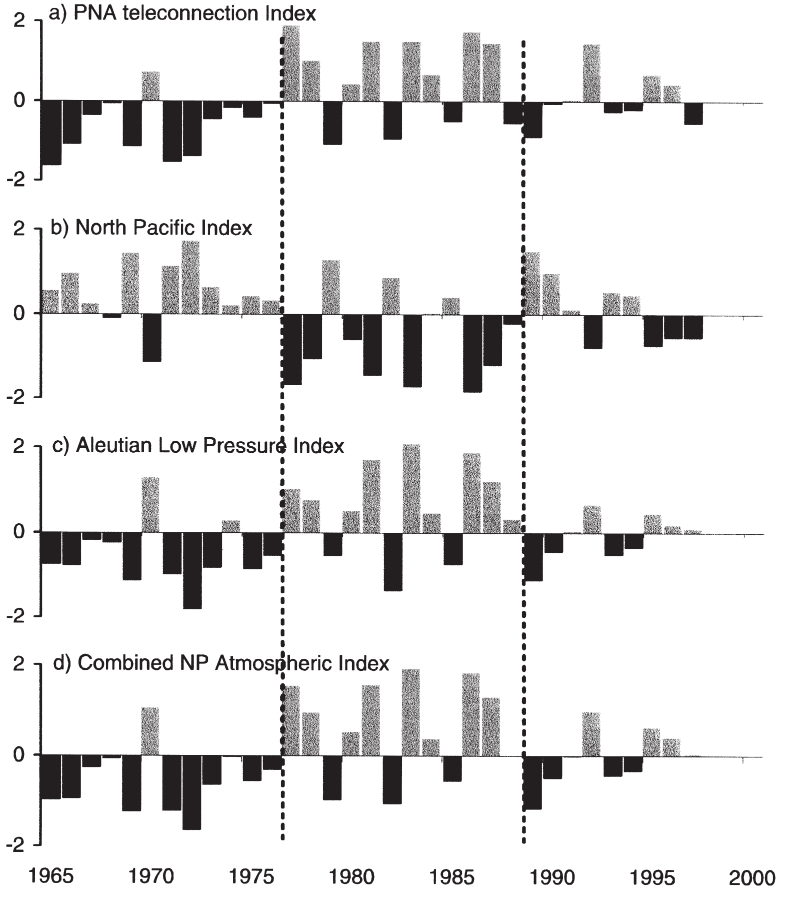

Fig. A1. Three indices of the winter Aleutian Low pressure cell and a North Pacific atmospheric index created by averaging the three indices. All time series have been normalized and are plotted for the period 1965–1997.

A.1.2. North Pacific index

The North Pacific Index (NPI, Fig. A1b), as developed by Trenberth and Hurrell (1994), is the area-weighted mean sea level pressure over the region 30° to 65°N, 160°E to 140°W. We averaged the months of December–February to form a winter time series. The NPI is essentially a mirror image of the PNA; the correlation between the two time series is −0.91 for the period 1965–1998.

The Aleutian Low Pressure Index (ALPI, Fig. A1c) was developed by Beamish and Bouillon (1993) as another measure of the winter Aleutian Low. To form the winter ALPI index, SLP maps are prepared for the months December–March. The surface area inside the 1005 mb (i.e., with a lower SLP than 1005 mb) contour is computed for each month and then summed.

While these three indices measure slightly different aspects of winter season Aleutian Low variations, it would be redundant to include all three in a compilation of North Pacific climate indices. We derived a wintertime North Pacific atmospheric index by averaging the three indices (after reversing the sign of the NPI) and then renormalizing the resulting time series (Fig A1d). This index had a correlation coefficient greater than 0.96 with each of the individual series. We refer to this new times series as our North Pacific Atmospheric Index.

A.1.3. Other Pacific atmospheric indices

Atmospheric variability in the tropical and extratropical North Pacific and Arctic (independent of the Aleutian Low) may play a role in climate regimes in the North Pacific. Here we describe indices used to track variability in three other well known atmospheric patterns.

A.1.4. Southern oscillation index

The Southern Oscillation Index (SOI, Fig. A2a) is a measure of the atmospheric pressure gradient across the tropical Pacific. Originally developed in the early 1920s by Sir Gilbert Walker (1924), its relation to El Niño–La Niña cycles was not widely recognized until the 1960s (Bjerknes, 1969). This version of the SOI is the difference in normalized sea level pressure between Tahiti and Darwin, Australia. When negative, i.e., anomalously high pressure in Darwin and anomalously low pressure in Tahiti, the easterly trade winds weaken or even reverse, this situation typically accompanies the anomalous warming in the eastern equatorial Pacific recognized as El Niño. A positive SOI is associated with enhanced easterly trade winds and typically cooler than average SSTs in the eastern equatorial Pacific (La Niña).

A.1.5. Arctic oscillation

In a recent publication, Thompson and Wallace (1998) described the Arctic oscillation (AO, Fig. A2b) as “the surface signature of modulations in the strength of the polar vortex aloft”. The AO is derived as the leading principal of global winter sea level pressure. This version of the index is an average of the January–March values.

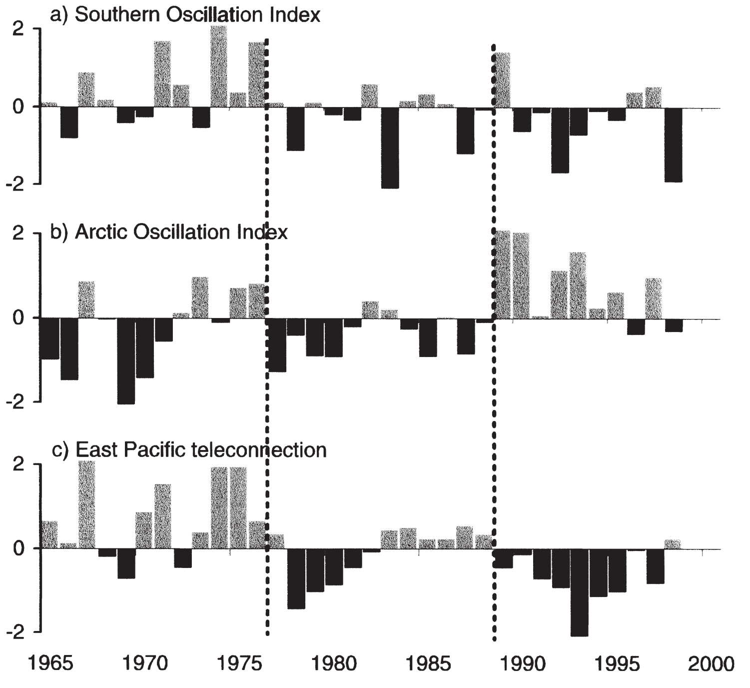

Fig. A2. Three commonly used indices of winter atmospheric pressure variability over the Pacific Ocean. All time series have been normalized and are plotted for the period 1965–1997.

A.1.6. East Pacific teleconnection

The East Pacific (EP, Fig. A2c) teleconnection pattern is a north-south dipole of 700 mb height anomalies over the northeastern Pacific (Barnston & Livezey, 1987). The north pole is generally located over central Alaska, the south pole is centered just east of Hawaii. This index, which we obtained from the same source as the PNA index, is an average of the monthly values for December–February.

A.2. Terrestrial indices

A.2.1. North American coastal air temperatures

Monthly air temperatures for several thousand U.S. cities, many dating back 100 years or more, have been assembled, quality controlled, and made freely available by the National Climate Data Center as part of the U.S. Historical Climate Network (USHCN, web site http://www.ncdc.noaa.gov/ol/climate/research/ushcn/ushcn.html). For this study, we selected one coastal station from each West Coast state: Forks, WA; Newport, OR and Eureka, CA. Historical monthly air temperatures for Alaska are available from the Alaska Climate Research Center (http://climate.gi.alaska.edu/). Long-term continuous time series are available for three coastal cities: King Salmon, Kodiak and Cold Bay. These six winter air temperature time series are plotted in Fig. A3.

A.2.2. North American stream flows

We opted to use stream flow volume rather than precipitation values since stream flow integrates climate conditions (primarily precipitation and temperature, but also snow pack, soil moisture and evaporation) and is much less noisy. We obtained values for 5 major river systems along the Pacific coast of North America (Fig. A4). To focus on the year-to-year time scales of variability, we computed annual water year stream flow indices for each river by summing October–September gauge flows. Stations included in this part of the analysis include: the Kuskokwim River at Crooked Creek Alaska; the Kenai River at Soldotna, Alaska; the Skeena River at Usk (station 08JA010), British Columbia, Canada; the Columbia River at The Dalles, Oregon; and the 8 Rivers Index from the Sacramento/San Joaquin drainage in California. Gauge flows for the Kuskokwim and Kenai rivers were obtained from the US Geological Survey's web-site http://www.h2o.usgs.gov. Records for the Skeena River were originally obtained from the PACLIM data archives (http://meteora.ucsd.edu/PACLIM), and are also available from Environment Canada (http://www.ec.ca). Columbia River stream flows were obtained from the Bonneville Power Administration (BPA, personal communication). The 8 Rivers Index was obtained from the California Water Department (personal communication).

Our Columbia River data represents 'naturalized' monthly stream flow to account for the effects of the extensive hydrosystem development (BPA, personal communication). Generally speaking, differences between the water year gauge and naturalized flows at the Dalles range from 2 to 5%, depending on the year, and typically year-to-year and decade-to-decade flow variability is well-captured by either raw gauge data or the naturalized flow records.

A.3. Oceanic indices

A.3.1. Pacific Ocean sea surface temperatures

Sea surface temperature (SST) is one of the most widely observed variables in the ocean environment. We assembled several indices from across the north Pacific Ocean and Bering Sea to examine recent trends in SST variability. For a basin-wide perspective, we used indices of the El Niño–Southern Oscillation (ENSO) and Pacific Decadal Oscillation (Fig. A5). For ENSO, we obtained the 'Nino3.4' time series — a block average of SSTs between 5°N–5°S, 170°W-−120°W (available at http://nic.fb4.noaa.gov:80/data/cddb/). The PDO (available from the authors) is defined as the first principal component of extratropical North Pacific Ocean SST anomalies (Mantua et al., 1997; Zhang et al., 1997). Both are monthly time series and we prepared both winter (December–February) and summer (June–August) indices.

To portray the history of coastal SST variations in the Northeast Pacific, we selected four sites along the North American coast with lengthy time series: Scripps' Pier in La Jolla CA (McGowan et al., 1998); Kains Island, British Columbia (BC lighthouse data available at http://pices.ios.bc.ca/data/dataf.htm); the 'GAK 1' line south

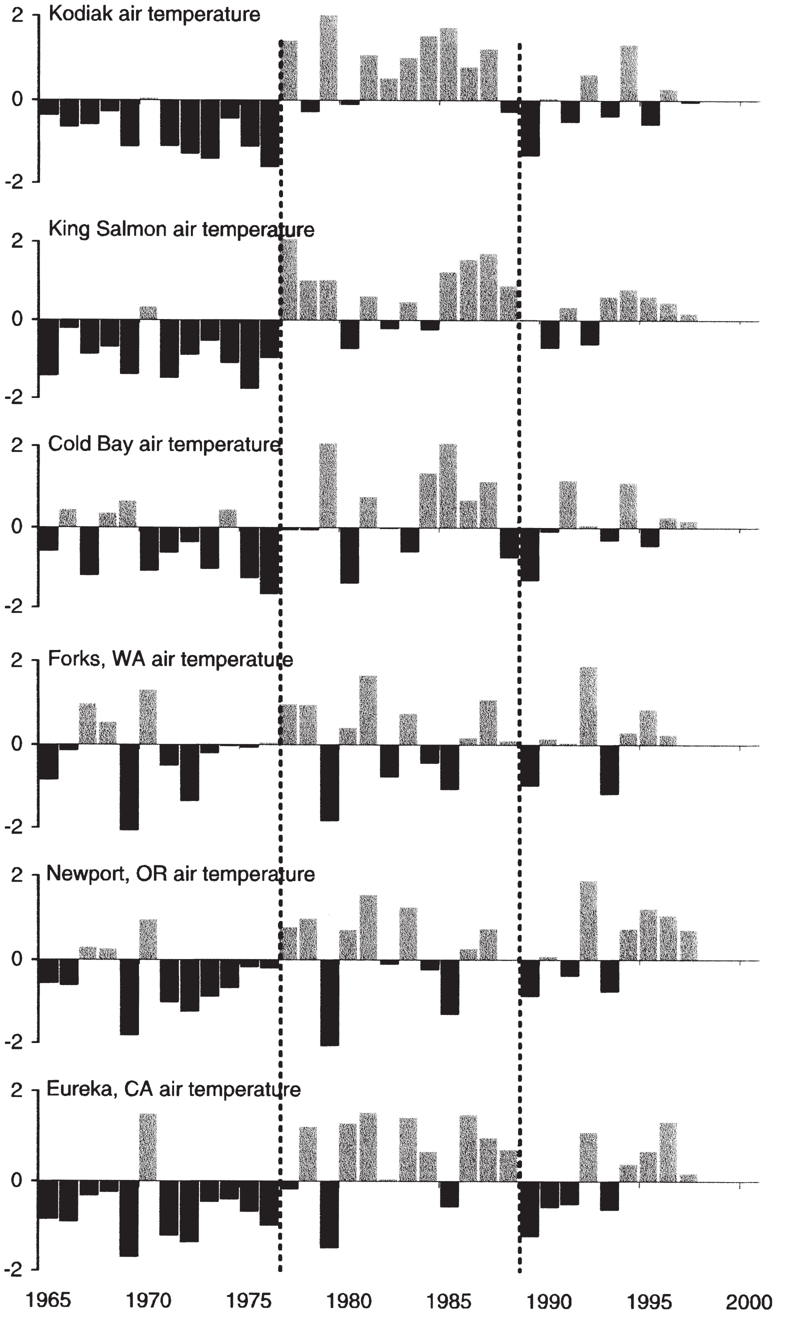

Fig. A3. North American coastal winter air temperatures. All time series have been normalized and are plotted for the period 1965–1997.

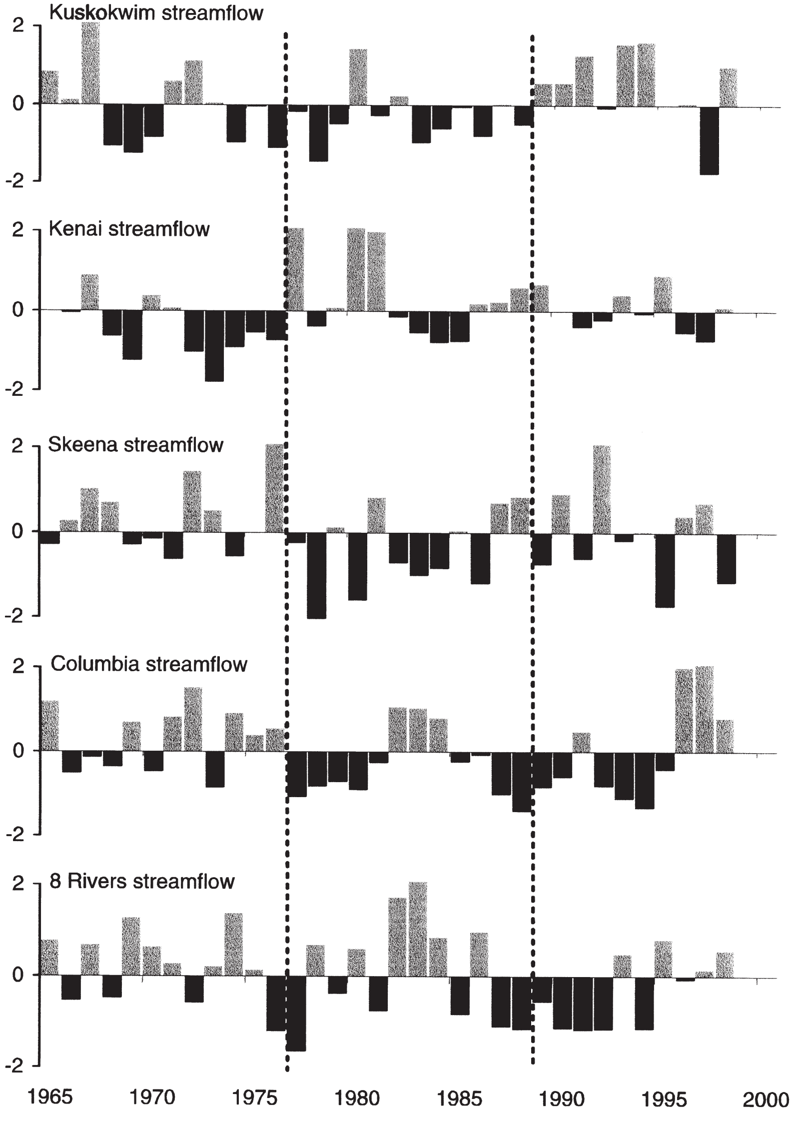

Fig. A4. North American coastal annual stream flows. All time series have been normalized and are plotted for the period 1965–1997.

of Seward Alaska (Royer, 1989); and the Pribilof Islands in the Bering Sea (Fig. A6). The time series for the Pribilof Islands was constructed from the Reynolds Reconstructed SST data set (available at http://www.cdc.noaa.gov/cdc/data.reynolds_sst.html). We used the monthly averages for the region 56°–58°N, 176°–172°W to compute average SST around the Pribilof Islands.

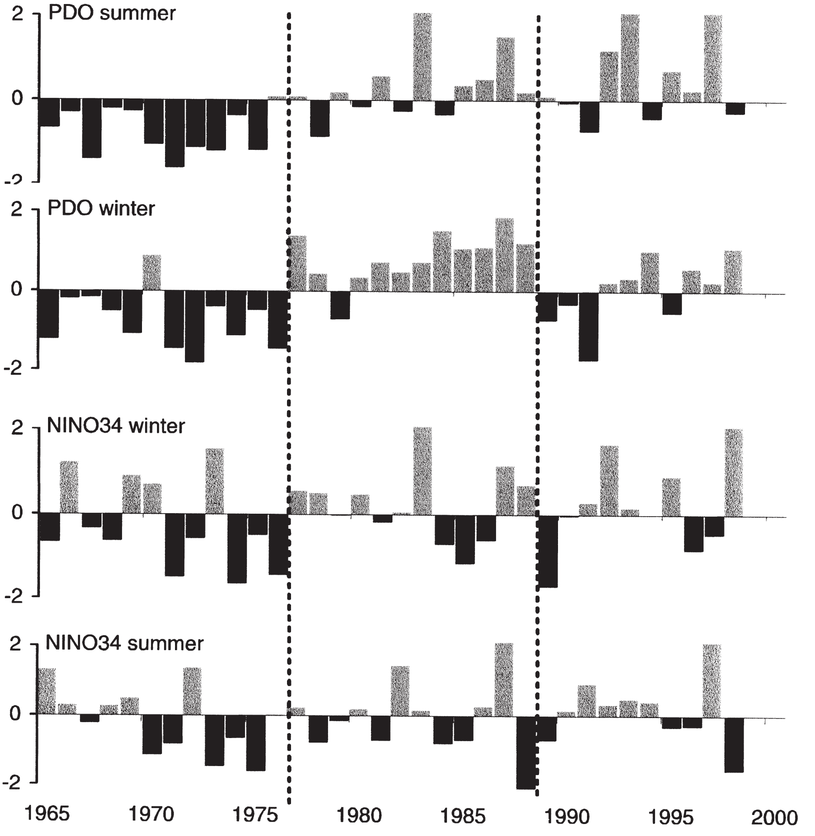

Fig. A5. Winter and summer indices for the Pacific Decadal Oscillation (PDO) and El Niño Southern Oscillation (ENSO). All time series have been normalized and are plotted for the period 1965–1997.

A.3.2. Bakun upwelling indices

Coastal Bakun upwelling indices have been developed at the Pacific Fisheries Environmental Laboratory for 15 locations along the West Coast of North America. These data are available as monthly values from January 1946 to the present at the location http://www.pfeg.noaa.gov/products/upwell.html. These upwelling indices have been used as indirect indicators of coastal upwelling, with positive anomalies indicating an increase in upwelling. We computed spring-summer anomaly time series for 1965–1997, normalizing each time series by its mean over this period. These spring-summer time series were highly correlated with shorter spring (March–May) averages. The locations we selected include two Alaska stations, one off of BC, and three along the U.S. West Coast (Fig. A7).

A.3.3. Miscellaneous northeast Pacific climate indicators

We assembled three other indices that have been used to illustrate climate and ecological variability in the Northeast Pacific.

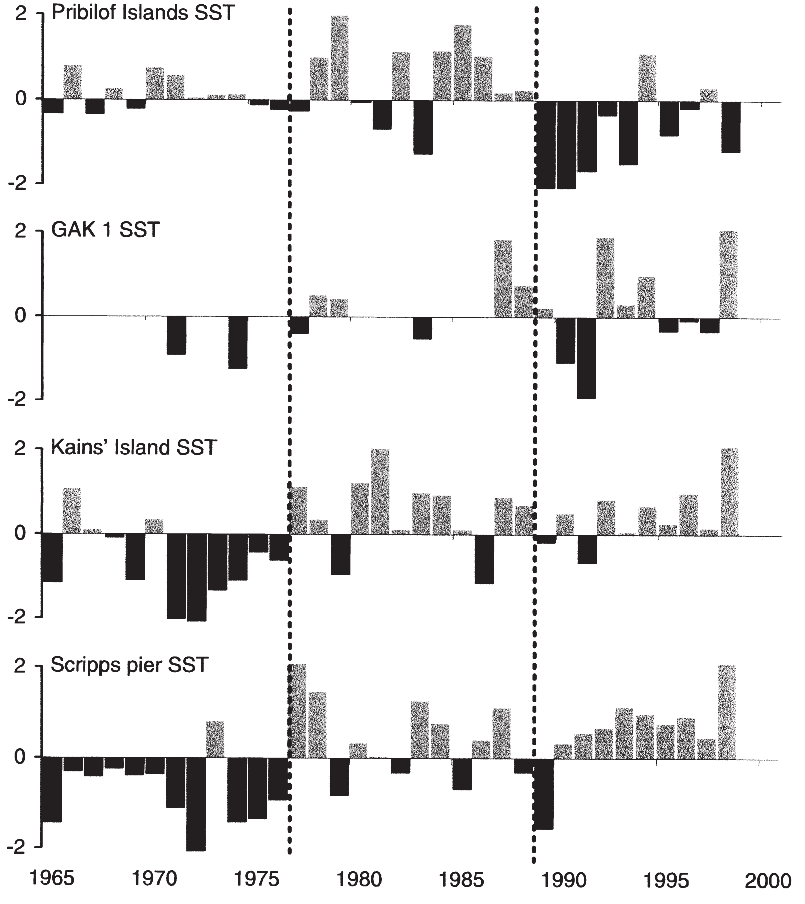

Fig. A6. Winter sea surface temperatures at four locations along coastal North America. All time series have been normalized and are plotted for the period 1965–1997.

Bering Sea ice cover has important consequences for marine fish distributions (Wyllie-Echevarria & Wooster, 1998). A time series for the period 1972–1997 has been developed that measures the southernmost extent of winter sea ice along 169°W (Fig. A8a).

OSCURS is an Ocean Surface CURrent Simulator (Ingraham & Miyahara, 1989) that computes Langrangian drift in the oceanic surface layer from daily atmospheric surface pressures. Using OSCURS, Ingraham et al. (1998) developed the 'Papa Trajectory Index' (PTI, Fig. A8b) as a measure of the strength of the winter Alaska Gyre circulation. To compute the PTI, a passive 'drifter' is 'released' at Ocean Weather Station Papa (50°N, 145°W) on December 1 and its movement in the surface currents simulated for 90 days. The latitude of the drift end point is the PTI for that year. Ingraham et al. (1998) showed that the PTI for 1950–1997 tended to have two

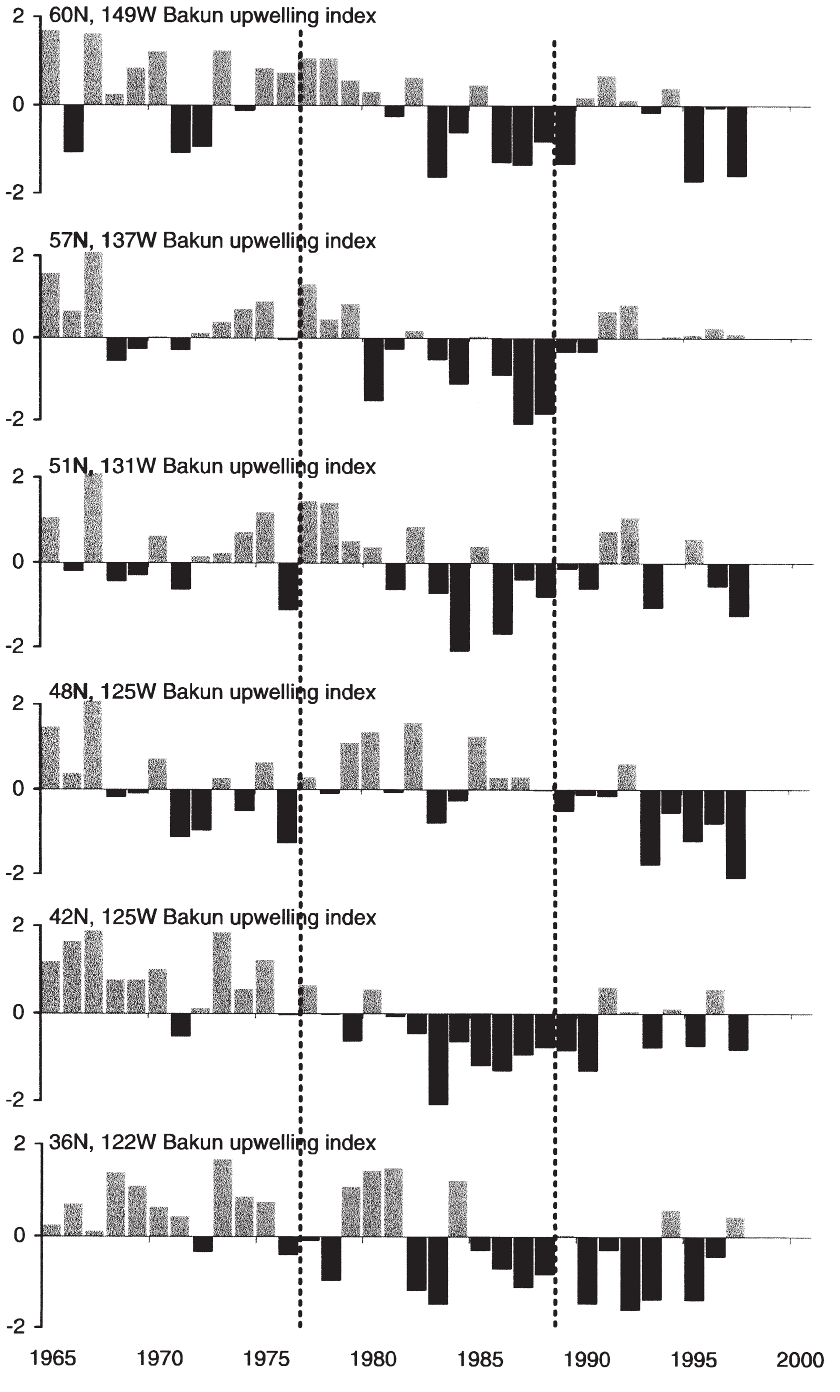

Fig. A7. Bakun upwelling indices at six locations along the west coast of North America. All time series have been normalized and are plotted for the period 1965–1997.

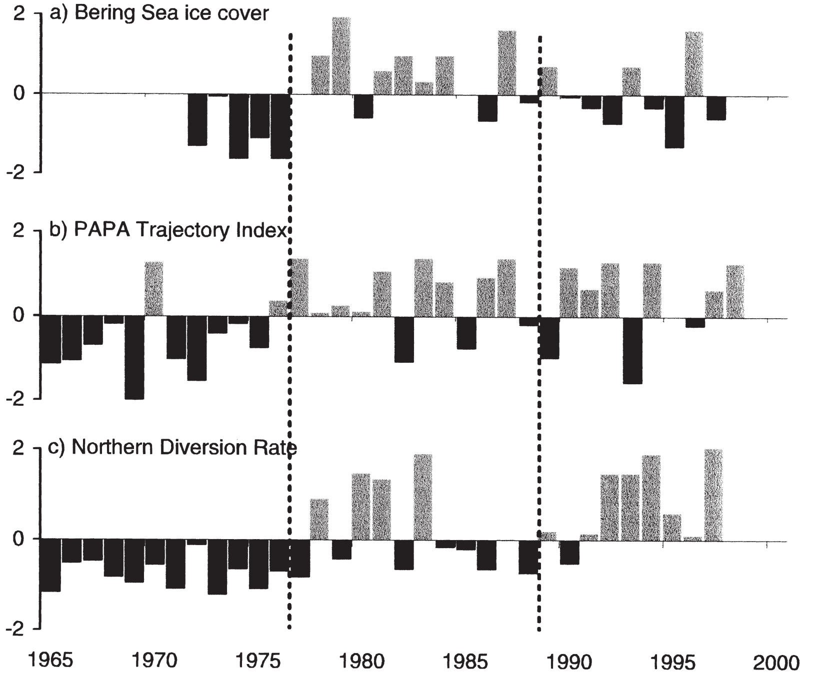

Fig. A8. Three indices of environmental variability in the Northeast Pacific and Bering Sea. See text for definitions. All time series have been normalized and are plotted for the period 1965–1997.

distinct modes, a northern mode where the end points were in the central Gulf of Alaska, and a southern mode with endpoints off of British Columbia.

Fraser River sockeye salmon undergo a homeward migration each year from the central Gulf of Alaska to the Fraser River. As they near land, a variable fraction of the fish return via Johnstone Strait on the northeastern side of Vancouver Island, presumably as a response to environmental conditions. This 'Northern Diversion Rate' (NDR, McKinnell, Freeland & Groulx, 1999, Fig. A8c) has important ramifications for fisheries management as the smaller the NDR, the greater the number of Fraser River sockeye that may be intercepted by U.S. fishermen as they swim through the Strait of Juan de Fuca and San Juan Islands.

A.4. Biological indices

A.4.1. Zooplankton biomass

We assembled the few available time series of zooplankton biomass for the Pacific Ocean and Bering Sea. Sugimoto and Tadokoro (1997) generated time series for several large regions of the Pacific Ocean and Bering Sea from samples collected aboard Hokkaido University research vessels from 1954 through 1994. We have updated their time series for the Eastern Bering (Bering shelf, west of 180°, north of the Aleutian chain), Central Pacific (region between 170°E and 160°W, 40°N and the Aleutian chain), and Eastern Pacific (region east of 160°W and north of 45°N). We also obtained zooplankton biomass data from the CalCOFI program for the period 1951–1998. CalCOFI Area 2 (roughly between Pt. Conception and San Diego out to 200 miles offshore) is the most consistently sampled and these are the data we use. A recent review and description of CalCOFI zooplankton data is provided in Roemmich and McGowan (1995) and Brodeur, Frost, Hare, Francis and Ingraham (1996). There are a few other Pacific zooplankton time series — notably from Ocean Weather Station Papa — but they are too incomplete to be useful. Even the time series we have assembled have large gaps in them, relatively large annual coefficients of variation, and may not be reliable as indicators of secondary oceanic productivity. Nonetheless, they are the best data available and we examine them for evidence of variability indicative of radical ecosystem changes.

We computed average summer biomasses (June–August) for each time series. Summer averages were used as the large majority of the data are collected in the

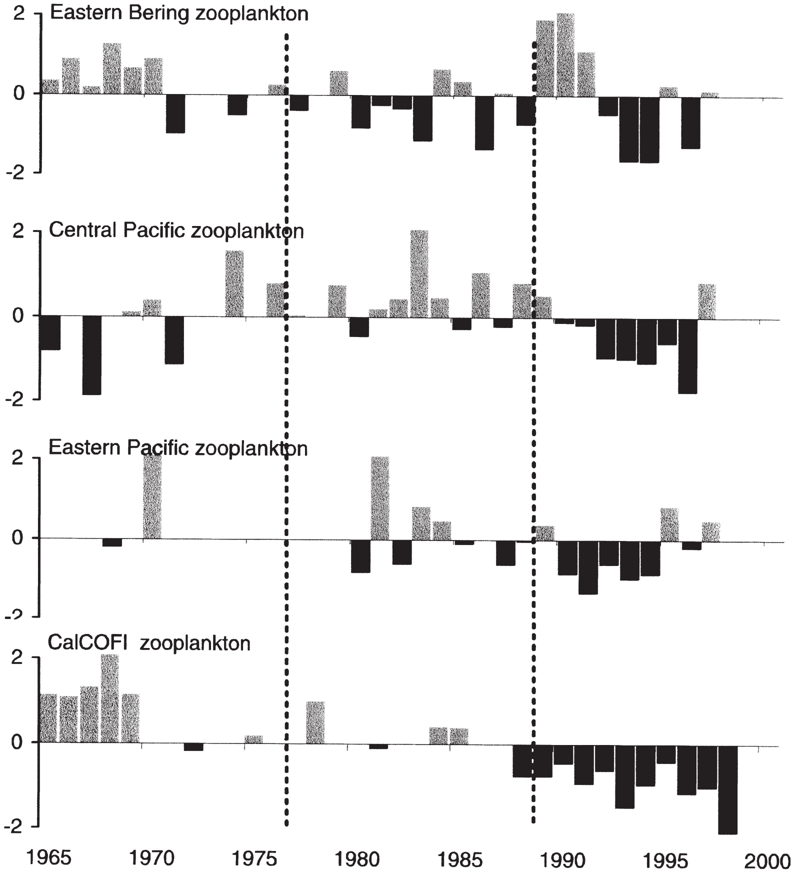

Fig. A9. Summer zooplankton biomass time series for large regions of the Northeast Pacific and Bering Sea. All time series have been normalized and are plotted for the period 1965–1997.

summer and it is generally the period of peak seasonal biomass (Brodeur et al., 1996). The zooplankton biomass data were log-transformed prior to any statistical summarization or analysis as has been the custom with these data (Brodeur et al., 1996) due to their highly skewed distribution. The four time series are plotted in Fig. A9.

A.4.2. Miscellaneous biological time series

In addition to the zooplankton and fish time series, we obtained data on three other lower trophic level marine populations that may serve as indicators of ecosystem trends or regime shifts.

A.4.3. Bering Sea jellyfish

Bottom trawl surveys have been conducted annually in the Bering Sea since 1972, and have followed a standardized set of stations on a fixed grid since 1979. Brodeur et al. (1999) computed an index of biomass estimates of large medusae (jellyfish or gelatinous zooplankton) in the Bering Sea (Fig. A10a).

A.4.4. Gulf of Alaska shrimp

Small-mesh trawl surveys have been conducted annually by the National Marine Fisheries Service and Alaska Department of Fish and Game since 1953. At that time,

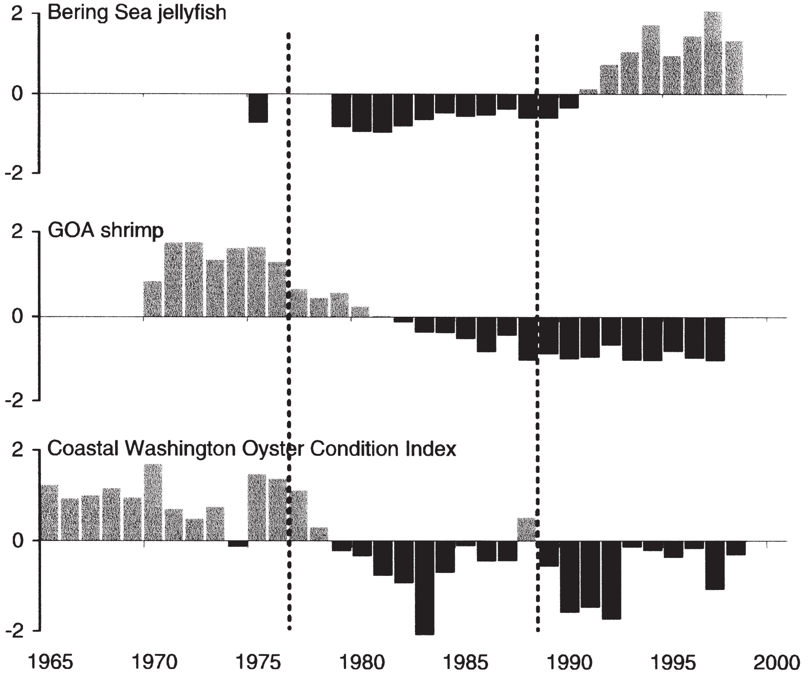

Fig. A10. Three lower trophic level populations from the Northeast Pacific and Bering Sea. All time series have been normalized and are plotted for the period 1965–1997.

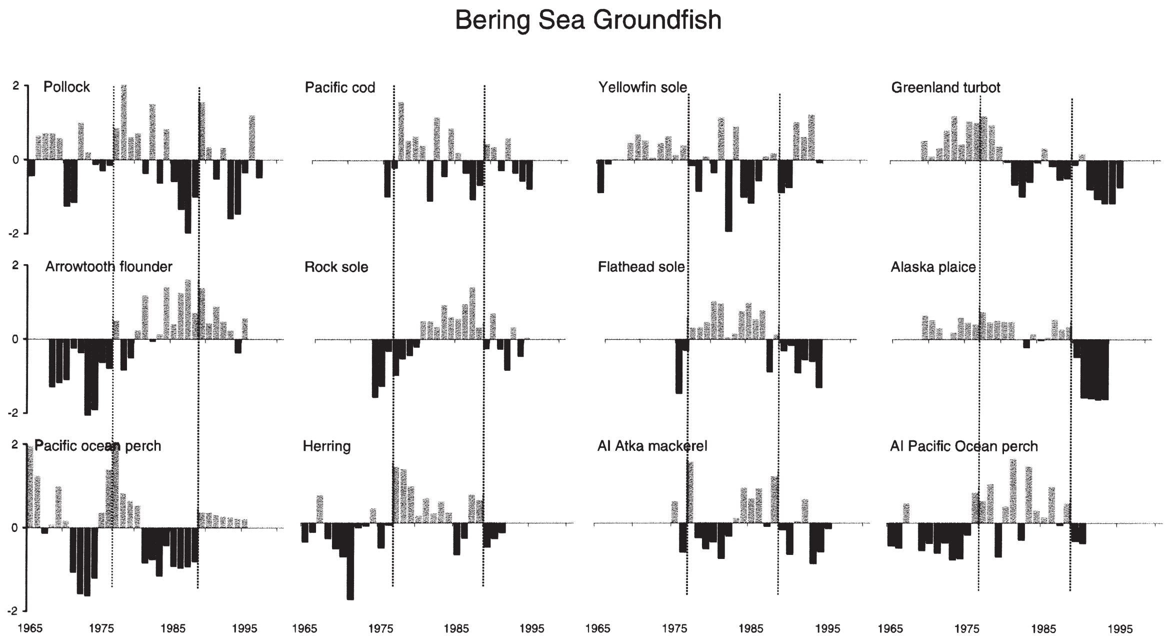

Fig. A11. Annual recruitment time series for the major commercially exploited groundfish populations of the Bering Sea. All time series have been log-normalized and are plotted for the period 1965–1997.

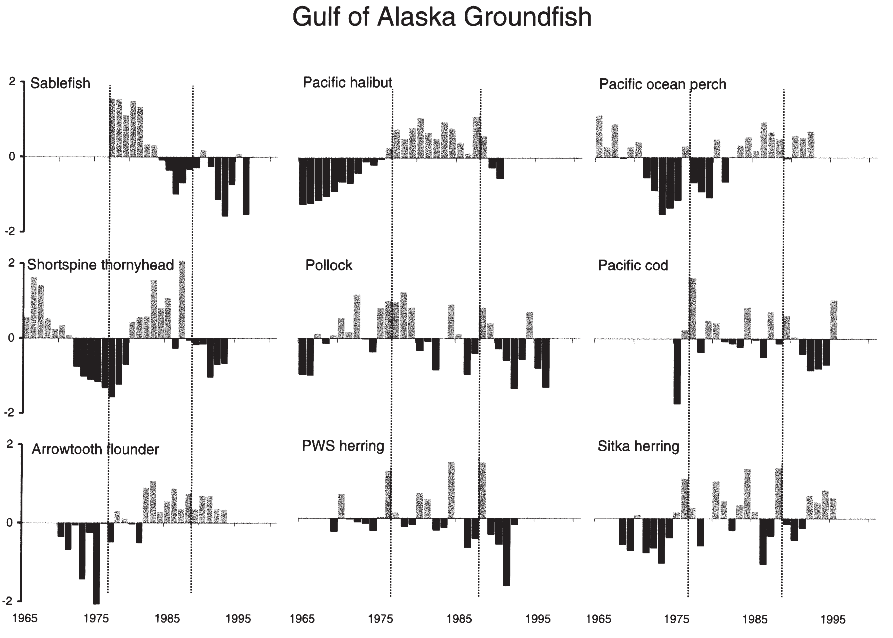

Fig. A12. Annual recruitment time series for the major commercially exploited groundfish populations of the Gulf of Alaska. All time series have been log-normalized and are plotted for the period 1965–1997.

trawl locations were all known major shrimp locations in the western and central Gulf of Alaska. Standardized methods were implemented in 1972 and data from that point forward are considered comparable. Anderson and Piatt (1999) computed the average fraction of shrimp (by weight) in the annual survey catches for 1970–1997 (Fig. A10b)

A.4.5. Coastal Washington oyster condition index

The condition of Pacific oysters (*Crassostrea gigas*) in Willapa Bay on the west coast of Washington state has been monitored since the mid-1950s. The most commonly used 'Oyster Condition Index' (OCI) is the ratio of dry meat weight to shell cavity. The lower the index, the greater the number of oysters that must be harvested to provide the same yield (Schoener & Tufts, 1987). We obtained the OCI for four regional oyster-growing locales (Oysterville, Parcel A, Stackpole, and Stony Pt.) from the Washington Department of Fish and Wildlife (Bruce Kauffman, personal communication). Measurements are made monthly though there are data gaps ranging from 15–19% of the total possible months with most gaps occurring in the early 1980s. We computed standardized annual anomalies for each time series from 1965–1998 and averaged these to form a single index (Fig. A10c). Temporal trends at all four locations were highly correlated ($r>0.8$ for all time individual time series with composite series).

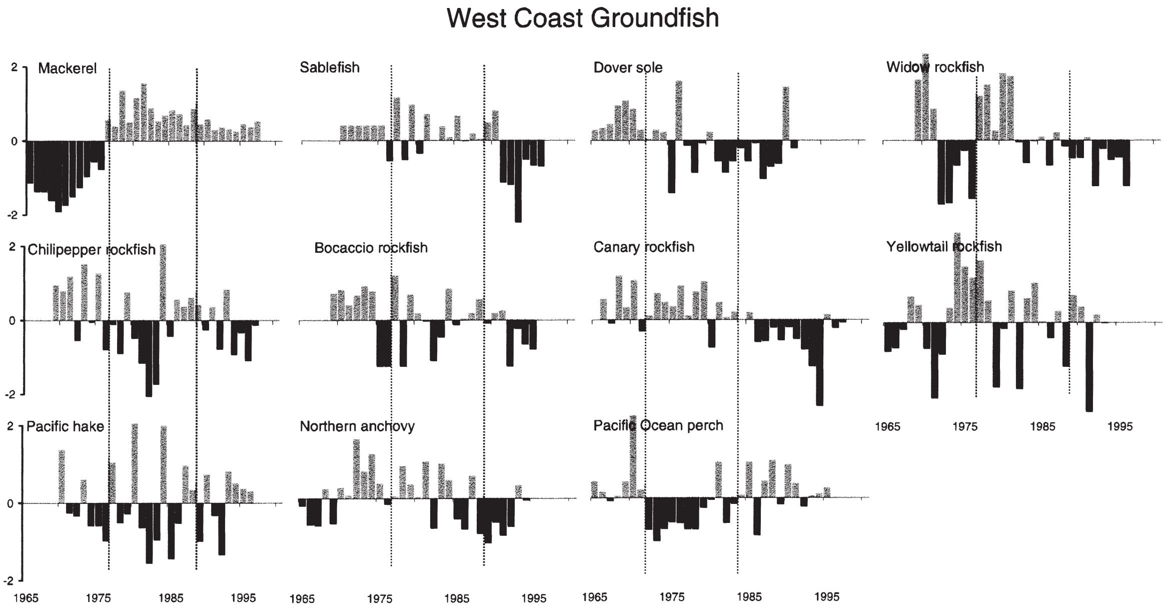

Fig. A13. Annual recruitment time series for the major commercially exploited groundfish populations off the West Coast of the U.S. All time series have been log-normalized and are plotted for the period 1965–1997.

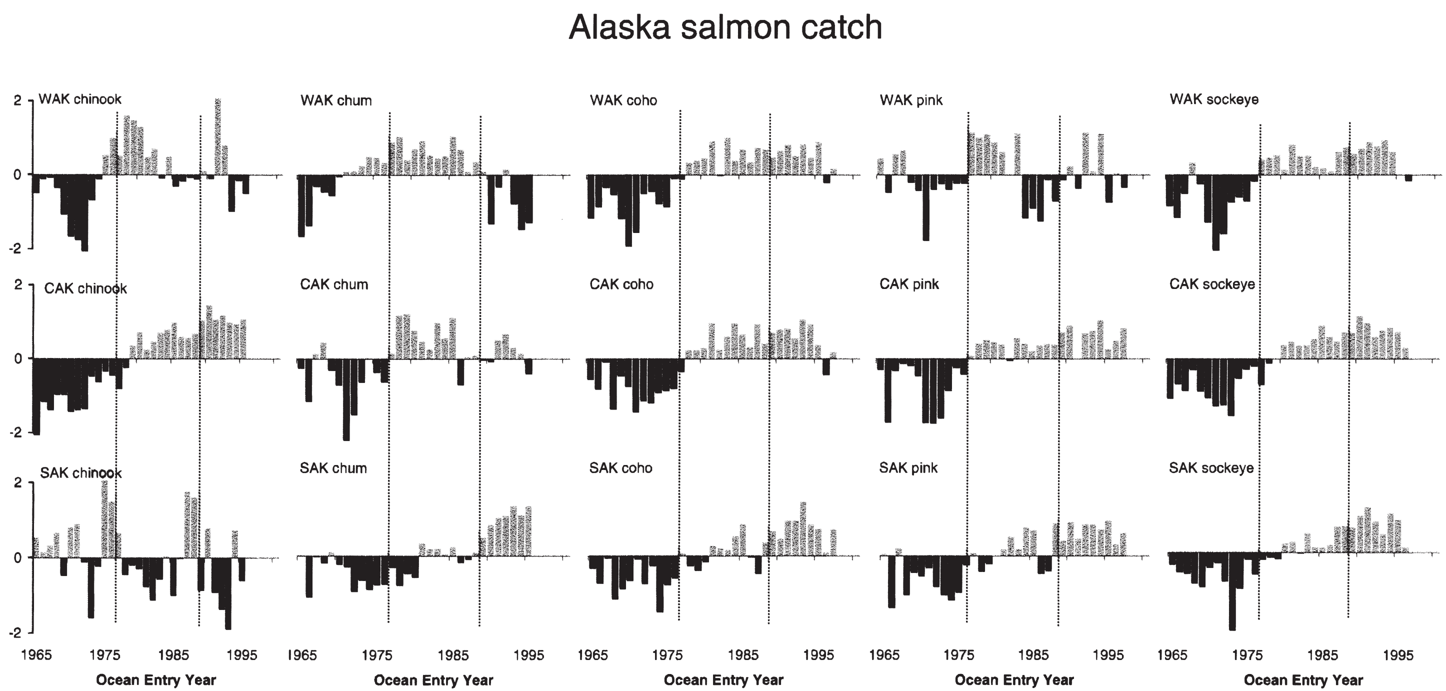

Fig. A14. Annual salmon catches for three regions in Alaska. WAK, CAK and SK represent Western Alaska, Central Alaska and Southeast Alaska respectively. All time series have been log-normalized and are plotted for the period 1965–1997.

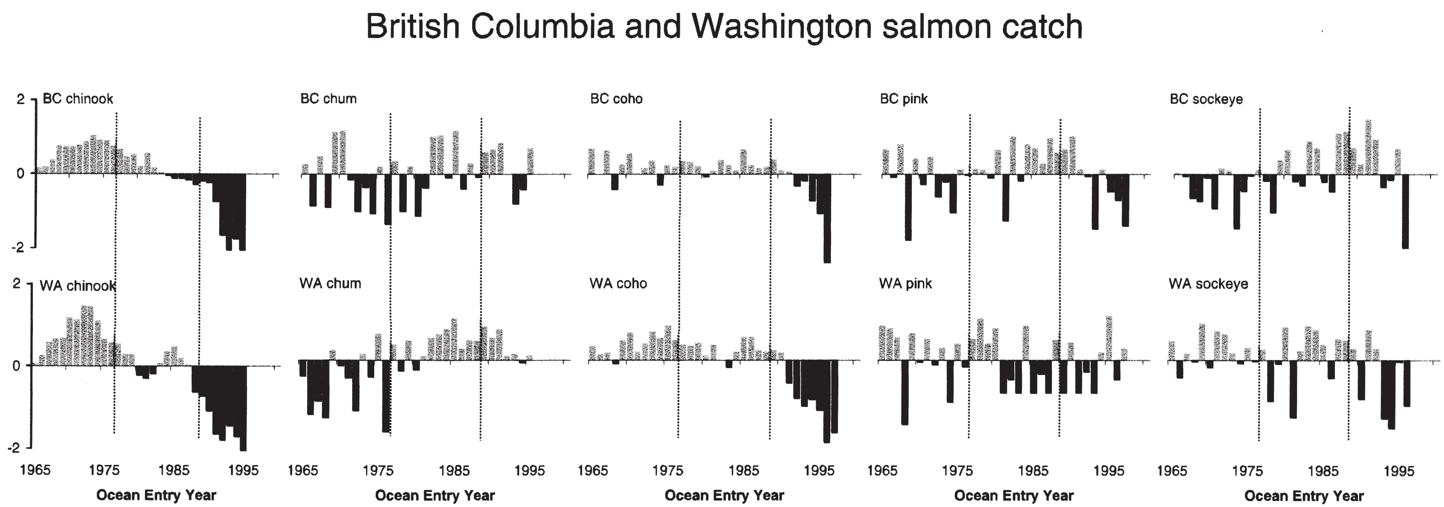

Fig. A15. Annual salmon catches in British Columbia and Washington. All time series have been log-normalized and are plotted for the period 1965–1997.

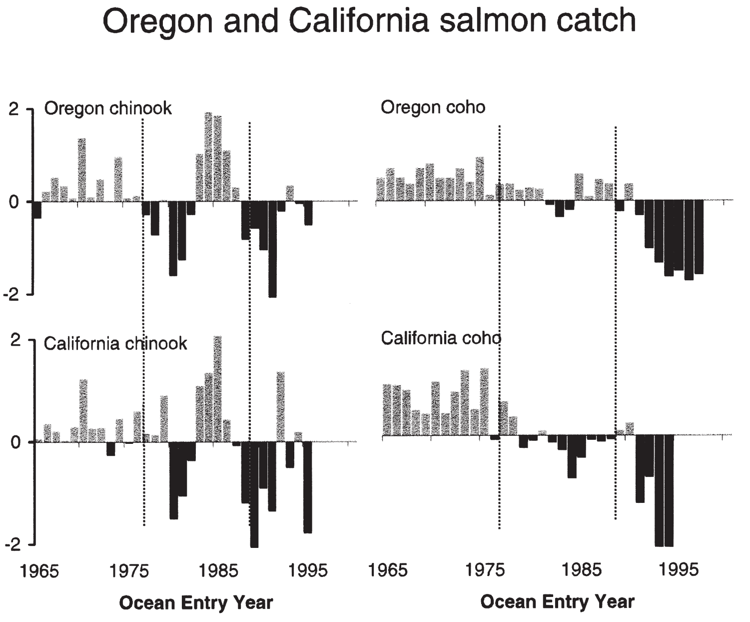

Fig. A16. Annual salmon catches in Oregon and Washington. All time series have been log-normalized and are plotted for the period 1965–1997.

A.4.6. Groundfish recruitment

The Northeast Pacific is home to a diverse array of pelagic and demersal fish populations (collectively termed groundfish here), supporting some of the largest fisheries in the world. Management responsibility for the offshore (>3 miles) populations is coordinated by the North Pacific Fishery Management Council and Pacific Fishery Management Council. Research on the status of the fish stocks is conducted by several federal, state and international agencies. In a study of groundfish recruitment trends in the northeast Pacific, Hollowed, Hare and Wooster (1998) obtained recruitment time series for the 32 major exploited populations from the Bering Sea to California (excluding British Columbia). The time series are divided among three geographic (and management) areas: the Bering Sea (12 time series, Fig. A11), the Gulf of Alaska (9 stocks, Fig. A12) and the U.S. West Coast (11 stocks, Fig. A13).

Recruitment time series are notoriously noisy, subject to large measurement and/or modeling errors, and often of relatively short duration. None of the recruitment times series spans the entire period 1965–1998, with year denoting year class. This is due to several factors. Data from earlier years are missing for many time series because serious management and survey efforts were not initiated until the 1970s. Data from more recent years are absent because the animals are not yet at an age where reliable estimates of recruitment year class strength can be made. Pacific halibut recruitment, for example, is measured at age eight thus the 1990 year class strength was first estimated in 1998. Further details on the recruitment time series and the sources of data are given in Hollowed et al. (1998).

A.4.7. Salmon catches

Catches of Pacific salmon have been used as indicators of ecosystem (ecological+climate) variability by numerous investigators. In a recent study, Hare et al. (1999), assembled catch histories of the five major species of salmon (chinook, coho, sockeye, chum, and pink) from seven geographic regions (western Alaska, central Alaska, southeastern Alaska, British Columbia, Washington, Oregon, California). The data were lagged such that the species were aligned by year of ocean entry rather than catch year. Thus, relative to the catch year, pink and coho salmon were lagged one year, sockeye salmon were lagged two years, and chinook and chum salmon were lagged three years. Using principal component analysis, they showed a historical inverse production pattern between Alaska salmon stocks and those from the U.S. West Coast.

For this analysis, we use the same time series as in Hare et al. (1999), truncated to the ocean entry years of 1965–1995 and log transformed. Not all species are taken in all areas and there are a total of 29 salmon catch time series. To help assess regional variability we plotted them by geographical region: Alaska (Fig. A14), British Columbia and Washington (Fig. A15), and Oregon and California (Fig. A16).

References

Anderson, P. J., & Piatt, J. F. (1999). Community reorganization in the Gulf of Alaska following ocean climate regime shift. *Marine Ecology Progress Series*, *189*, 117–123.

Barnston, A. G., & Livezey, R. E. (1987). Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. *Monthly Weather Review*, *115*, 1089–1112.

Barnston, A. G., & co-authors. (1999). NCEP forecasts of the El Niño of 1997–98 and its US impacts. *Bulletin of the American Meteorological Society*, 80, 1829–1852.

Beamish, R. J., & Bouillon, D. R. (1993). Pacific salmon production trends in relation to climate. *Canadian Journal of Fisheries and Aquatic Science*, *50*, 1002–1016.

Beamish, R. J., Noakes, D. J., McFarlane, G. A., Klyashtorin, L., Ivanov, V. V., & Kurashov, V. (1999). The regime concept and natural trends in the production of Pacific salmon. *Canadian Journal of Fisheries and Aquatic Science*, *56*, 516–526.

Bjerknes, J. (1969). Atmospheric teleconnections from the equatorial Pacific. *Monthly Weather Review*, *97*, 163–172.

Brodeur, R. D., Frost, B. W., Hare, S. R., Francis, R. C., & Ingraham, W. J. Jr. (1996). Interannual variations in zooplankton biomass in the Gulf of Alaska and covariation with California Current zooplankton. *California Cooperative Oceanic Fisheries Investigation Report*, *37*, 80–99.

Brodeur, R. D., Mills, C. E., Overland, J. E., Walters, G. E., & Schumacher, J. D. (1999). Evidence for a substantial increase in gelatinous zooplankton in the Bering Sea with possible links to climate change. *Fisheries Oceanography*, *8*, 296–306.

Clark, W. G., Hare, S. R., Parma, A. M., Sullivan, P. J., & Trumble, R. J. (1999). Decadal changes in growth and recruitment of Pacific halibut (*Hippoglossus stenolepis*). *Canadian Journal of Fisheries and Aquatic Science*, *56*, 242–252.

Ebbesmeyer, C. C., Cayan, D. R., McLain, D. R., Nichols, F. H., Peterson, D. H., & Redmond, K. T. (1991). 1976 step in the Pacific climate: forty environmental changes between 1968–1975 and 1977–1984. In J. L. Betancourt, & V. L. Tharp (Eds.), *Proceedings of the Seventh Annual Climate (PACLIM) Workshop, April 1990* (pp. 115–126). California Department of Water Resources. Interagency Ecological Studies Program Technical Report 26.

Enfield, D. B., & Mestas-Nuñez, A. M. (1999). Multiscale variabilities in global sea surface temperatures and their relationships with tropospheric climate patterns. *Journal of Climate*, *12*, 2719–2733.

Francis, R. C., & Hare, S. R. (1994). Decadal-scale regime shifts in the large marine ecosystems of the North-east Pacific: a case for historical science. *Fisheries Oceanography*, *3*, 279–291.

Francis, R. C., Hare, S. R., Hollowed, A. B., & Wooster, W. S. (1998). Effects of interdecadal climate variability on the oceanic ecosystems of the NE Pacific. *Fisheries Oceanography*, *7*, 1–21.

Graham, N. E. (1994). Decadal-scale climate variability in the tropical and North Pacific during the 1970s and 1980s: observations and model results. *Climate Dynamics*, *10*, 135–162.

Hare, S. R. (1996). *Low frequency climate variability and salmon production*. Ph.D. Dissertation. University of Washington, School of Fisheries. 306 pp.

Hare, S. R., & Francis, R. C. (1995). Climate change and Salmon production in the Northeast Pacific Ocean. In R. J. Beamish (Ed.), *Ocean climate and northern fish populations* (pp. 357–372). *Canadian Special Publication of Fisheries and Aquatic Science*, 121.

Hare, S. R., Mantua, N. J., & Francis, R. C. (1999). Inverse production regimes: Alaskan and West Coast Salmon. *Fisheries*, *24*, 6–14.

Hollowed, A. B., Hare, S. R., & Wooster, W. S. (1998). Pacific-basin climate variability and patterns of Northeast Pacific marine fish production. In G. Holloway, P. Muller, & D. Henderson (Eds.), *Proceedings of the 10th 'Aha Huliko' a Hawaiian Winter Workshop on Biotic Impacts of Extratropical Climate Variability in the Pacific, January 26–29, 1998* (pp. 89–104). NOAA Award No. NA67RJ0154, SOEST Special Publication.

Ingraham, W. J. Jr., Ebbesmeyer, C. C., & Hinrichsen, R. A. (1998). Imminent climate and circulation shift in Northeast Pacific Ocean could have major impact on marine resources. *EOS*, *79*, 197–201.

Ingraham, W. J., & Miyahara, R. K. (1989). Tuning the OSCURS numerical model to ocean surface current measurements in the Gulf of Alaska. U.S. Department of Commerce. *NOAA Technical Memorandum* NMFS F/NWC-130. 155 pp.

Kondo, J. (1988). Volcanic eruptions, cool summers and famines in the northeastern part of Japan. *Journal of Climate*, *1*, 775–788.

Mackas, D. L. (1995). Interannual variability of the zooplankton community off southern Vancouver Island. In R. J. Beamish (Ed.), *Climate change and northern fish populations* (pp. 603–615). *Canadian Special Publication of Fisheries and Aquatic Science*, 121.

Mantua, N. J., Hare, S. R., Zhang, Y., Wallace, J. M., & Francis, R. C. (1997). A Pacific interdecadal climate oscillation with impacts on salmon production. *Bulletin of the American Meteorological Society*, *78*, 1069–1079.

McFarlane, G. A., King, J. R., & Beamish, R. J. (2000). Have there been recent changes in climate? Ask the fish. *Progress in Oceanography*, *47*, 147–169.

McGowan, J. A., Cayan, D. R., & Dorman, L. M. (1998). Climate–ocean variability and ecosystem response in the Northeast Pacific. *Science*, *281*, 210–217.

McKinnell, S., Freeland, H. J., & Groulx, S. D. (1999). Assessing the northern diversion of sockeye salmon returning to the Fraser River, B. C. *Fisheries Oceanography*, *8*, 104–114.

Mestas-Nuñez, A. M., & Enfield, D. B. (1999). Rotated global modes of non-ENSO sea surface temperature variability. *Journal of Climate*, *12*, 2734–2746.

Miller, A. J., Cayan, D. R., Barnett, T. P., Graham, N. E., & Oberhuber, J. M. (1994). The 1976–77 climate shift of the Pacific Ocean. *Oceanography*, *7*, 21–26.

Minobe, S. (1997). A 50–70 year oscillation over the north Pacific and north America. *Geophysical Research Letters*, *24*, 683–686.

Minobe, S. (1999). Resonance in bidecadal and pentadecadal climate oscillations over the North Pacific: role in climatic regime shifts. *Geophysical Research Letters*, *26*, 855–858.

Minobe, S. (2000). Spatio-temporal structure of the pentadecadal variability over the North Pacific. *Progress in Oceanography*, *47*, 381–408.

North, G. R., Bell, T. L., Cahalan, R. F., & Moeng, F. J. (1982). Sampling errors in the estimation of empirical orthogonal functions. *Monthly Weather Review*, *110*, 699–706.

Overland, J. E., Adams, J. M., & Bond, N. A. (1999). Decadal variability of the Aleutian Low and its relation to high-latitude circulation. *Journal of Climate*, *12*, 1542–1548.

Polovina, J. J., Mitchum, G. T., Graham, N. E., Craig, M. P., DeMartini, E. E., & Flint, E. N. (1994). Physical and biological consequences of a climate event in the central North Pacific. *Fisheries Oceanography*, *3*, 15–21.

Priesendorfer, R. W. (1988). *Principal components analysis in meteorology and oceanography*. Elsevier, 425 pp.

Reynolds, R. W., & Smith, T. M. (1994). Improved global sea surface temperature analyses using optimum interpolation. *Journal of Climate*, *7*, 929–948.

Roemmich, D., & McGowan, J. (1995). Climatic warming and the decline of zooplankton in the California Current. *Science*, *267*, 1324–1326.

Royer, T. C. (1989). Upper ocean temperature variability in the northeast Pacific Ocean: is it an indicator of global warming? *Journal of Geophysical Research*, *94*, 18175–18183.

Schoener, A., & Tufts, D. F. (1987). Changes in oyster condition index with El Niño–Southern Oscillation events at 46°N in an eastern Pacific bay. *Journal of Geophysical Research*, *92*, 14429–14435.

Smith, T. M., Reynolds, R. W., Livezey, R. E., & Stokes, D. C. (1996). Reconstruction of historical sea surface temperatures using empirical orthogonal functions. *Journal of Climate*, *9*, 1403–1420.

Sugimoto, T., & Tadokoro, K. (1997). Interannual–interdecadal variations in zooplankton biomass, chlorophyll concentration and physical environment in the subarctic Pacific and Bering Sea. *Fisheries Oceanography*, *6*, 74–93.

Sugimoto, T., & Tadokoro, K. (1998). Interdecadal variations of plankton biomass and physical environment in the North Pacific. *Fisheries Oceanography*, *7*, 289–299.

Thompson, D. W. J., & Wallace, J. M. (1998). The Arctic Oscillation signature in the winter time geopotential height and temperature fields. *Geophysical Research Letters*, *25*, 1297–1300.

Trenberth, K. E., & Hurrell, J. W. (1994). Decadal atmosphere–ocean variations in the Pacific. *Climate Dynamics*, *9*, 303–319.

Trenberth, K. E., & Paolino, D. A. Jr. (1980). The northern hemisphere sea-level pressure data set: trends, errors and discontinuities. *Monthly Weather Review*, *108*, 855–872.

Von Storch, H., & Zwiers, F. W. (1999). *Statistical analysis in climate research*. Cambridge University Press, 494 pp.

Walker, G. T. (1924). Correlation in seasonal variations of weather. IX. A further study of world weather. *Memorandum of the Indian Meteorology Department*, *24*, 275–332.

Wallace, J. M., & Gutzler, D. S. (1981). Teleconnections in the geopotential height field during the Northern Hemisphere winter. *Monthly Weather Review*, *109*, 784–812.

Watanabe, M., & Nitta, T. (1999). Decadal changes in the atmospheric circulation and associated surface climate variations in the northern hemisphere winter. *Journal of Climate*, *12*, 494–510.

Welch, D. W., Ward, B. R., Smith, B. D., & Eveson, J. P. (2000). Temporal and spatial responses of British Columbia steelhead (*Oncorhynchus mykiss*) populations to ocean climate shifts. *Fisheries Oceanography*, *9*, 17–32.

Wyllie-Echevarria, T., & Wooster, W. S. (1998). Year-to-year variations in Bering Sea ice cover and some consequences for fish distributions. *Fisheries Oceanography*, *7*, 159–170.

Zhang, Y., Wallace, J. M., & Battisti, D. S. (1997). ENSO-like interdecadal variability: 1900–93. *Journal of Climate*, *10*, 1004–1020.