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Patterns of Change in Climate and Pacific Salmon Production

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Abstract.—For much of the 20th century a clear north-south inverse production pattern for Pacific salmon had a time dynamic that closely followed that of the Pacific Decadal Oscillation (PDO), which is the dominant pattern of North Pacific sea surface temperature variability. Total Alaska salmon production was high during warm regimes of the PDO, and total Alaska salmon production was relatively low during cool regimes of the PDO. Leading hypotheses for the link between climate and Pacific salmon production have focused on changes in early ocean survival for juvenile salmon, but it is clear that climate also affects freshwater life stages and influences productivity. Over broad spatial scales, the PDO-related patterns in climate and Pacific salmon production were less prominent in the period 1990–2004 than in earlier decades of the 20th century, yet the regional associations between salmon production and temperatures were generally the same: warm periods coincided with high salmon production in Alaska, and cool periods off the west coast of the continental U.S. and British Columbia coincided with high salmon production in those regions. A case study of Norton Sound pink salmon provides one regional perspective on the links between changes in climate and salmon production. In the period 1962–1995, anomalously warm winter and spring climate in western Alaska and warm spring/summer temperatures in the eastern Bering Sea generally coincided with high pink salmon production. However, especially warm conditions for freshwater and early marine life stages for Norton Sound pink salmon coincided with both high and low levels of recruits per spawner for brood years 1996–2003, a period that experienced large inter-annual variations in Bering Sea, North Pacific, and tropical Pacific Ocean conditions.

Introduction

Previous studies report compelling evidence for variations in Pacific climate as primary causes for large-scale variations in Pacific salmon abundance during the 20th century (Beamish and Bouillon 1993; Hare and Francis 1995; Mantua et al. 1997). These studies and others have demonstrated that interannual to interdecadal variations in the Pacific Decadal Oscillation (PDO), the dominant pattern of sea surface temperature (SST) variations in the North Pacific, coincided with an inverse relationship in Pacific salmon production for most of the 20th century. When the PDO pattern is in its warm phase, the Aleutian Low atmospheric pressure cell is strong in winter and spring, bringing warm moist air into western North America and north into Alaska from the northwestern

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portion of the continental U.S. Under these atmospheric conditions, SSTs are typically warmer than average along the entire Pacific coast of western North America, including the Bering Sea and Gulf of Alaska, while at the same time being cooler than average in the eastern and central North Pacific between 30° and 50°N latitude (Mantua et al. 1997). Salmon production in Alaska was generally high during warm phases of the PDO from 1925–1946 and 1977–1998, while in these same periods salmon production for the west coast of the continental U.S. was generally low (Hare et al. 1999).

The regional salmon catch records showing the strongest correlation with the large-scale Pacific Decadal Oscillation (PDO) index are those for western Alaska sockeye salmon *Oncorhynchus nerka* and pink salmon *O. gorbuscha*, where the time series of the PDO explains over 50% of the variability for 1925 to 1996 (Hare et al. 1999). In contrast, a series of studies provide evidence that much of the interannual coherence between different salmon stocks is manifest at spatial scales from a few hundred to perhaps a thousand km (Myers et al. 1997; Peterman et al. 1998; Pyper et al. 2001, 2002; 2005). Hilborn et al. (2003) show that underlying what appears to be a broad regional coherence in western Alaska sockeye salmon population changes are complex patterns of productivity changes at the scale of the major fishing districts and watersheds in Bristol Bay, wherein watersheds that were once dominant producers for decades lose their importance, while formerly unproductive watersheds suddenly become sustained major producers for the region as a whole.

In this study, a brief review of large-scale and regional-scale perspectives on the patterns of linked climate and salmon production variations are offered from analyses that focus on spatial scales of coherence in salmon production ranging from 1000s to 100s of km. The analysis strategy adopted in this study is to use time series for salmon abundance and productivity to define years of interest, and then to conditionally sample the Pacific climate record to develop maps and time series indicating the space-time patterns of environmental covariations. Once the environmental patterns of interest are identified, the relative influences of the El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and the global average temperature are assessed. Understanding the relative importance for these three large-scale patterns of climate variations is crucial for projecting the likely changes in North Pacific climate important for Pacific salmon in the next few decades and centuries. Beamish and Sweeting (2009, this volume) and Moss et al. (2009, this volume) argue that analysis of environmental variables in both freshwater and marine systems is needed to better understand what controls salmon productivity in the North Pacific and Arctic-Yukon-Kuskokwim region. Following this same perspective, indicators related to both freshwater and early marine environment are evaluated for evidence of robust relationships with salmon productivity.

Methods

The environmental data sets examined in this study are gridded sea and land surface temperatures and selected large-scale indices important for North Pacific climate. Monthly surface air temperature and precipitation for 1950–1999 were from the 0.5° latitude by 0.5° longitude gridded and interpolated fields from the University of Delaware (Willmott and Matsuura1995). Monthly sea surface temperatures for 1900–2006 were from Version 2 of NOAA's Extended Reconstructed 2° latitude by 2° longitude gridded fields of Smith and Reynolds (2004). Three large-scale climate indices examined here were the UK Met Office global surface air temperature record from 1900–2006, Mantua et al.'s (1997) PDO index (JISAO 2009), and the Niño3.4 index from Kaplan et al. (1998). Sea surface temperature fields from the gridded data of Smith and Reynolds (2004) and observed monthly air temperatures from Nome archived by NOAA's Western Regional Climate Center (WRCC 2008) were used to provide regional perspectives for ocean and air temperatures for the eastern Bering Sea and Norton Sound region.

This study uses annual salmon catch histories as indices of abundance, and stock-recruit indices as measures of annual levels of productivity. While total run-sizes or total biomass are preferable for tracking total salmon production, these data are not widely available. Catch series for Alaska salmon populations have been used extensively as indices of abundance in many previous studies (e.g., Beamish and Bouillon 1993; Hare and Francis 1995; Hare et al. 1999). Catch data were described by Hare et al. (1999) for the five major species of salmon for the period 1910–2004. Salmon productivity indices (SRi), developed as residuals from spawner-recruit relationships, were for pink salmon stocks from Norton Sound for brood years 1962–1995 (Pyper et al. 2001). An index of aggregate recruits-per-spawner for Norton Sound pink salmon based on harvest and escapement data for the Kwiniuk, Niukluk, Nome, Snake, North and El Dorado Rivers was developed from the Banducci et al. (2007) annual catch and escapement estimates for 1995–2005. A record for the minimum annual returns to the Columbia River (lower river catch plus counts over Bonneville Dam) for spring Chinook salmon *O. tshawytscha* was obtained from the Oregon Department of Fish and Wildlife and the Northwest Power Council.

Sub-sample composites of environmental data, conditioned on periods of either high or low salmon abundance or productivity, were created to identify aspects of climate variations that were typically observed during periods of high and low Alaska salmon productivity. The compositing approach used here included (1) ranking the values of the annual SRi according to their magnitude, (2) identifying the fry emergence and smolt migration year for the ten highest and lowest SRi values and grouping them into "high" and "low" productivity sub-samples, (3) creating new time series of the ten-member average monthly surface air temperatures in Nome for the 19-month period that begins in June of the brood year and ends in December of the fry emergence and smolt migration year for the high and low productivity sub-sample, and (4) creating ten-member average SST anomaly maps for May-August conditions representing the average SST anomalies experienced in the first summer for juvenile pink salmon in the high and low productivity groups.

Large Scale Patterns of Climate and Salmon Variations

For much of the 20th century an inverse north-south pattern of Pacific salmon production covaried with the interdecadal variations in the PDO pattern (Hare et al. 1999). Figure 1 shows five-year running averages for the observed catch history for all Alaska salmon from 1910 to 2004, and the observed catch plus escapement for Columbia River spring Chinook salmon from 1938 to 2002. For most of the 20th century these regionally aggregated population groups were negatively correlated ($r = -0.57$ for three-year running averages over 1940–1999), wherein Alaska salmon landings were high from the mid-1920s through 1940s and from the late 1970s until 2004, while Columbia Basin spring Chinook salmon numbers tended to be low from the late 1930s through mid-1940s, high from the 1950s through mid-1970s, and then low from the late 1970s through mid-1990s.

Difference maps provide insights into the large-scale aspects of the relationships between surface temperature and Pacific salmon production changes. May through August averaging was chosen here to focus on a hypothesized “critical” early ocean period for many Pacific salmon stocks where variations in climate were thought to have especially large impacts on smolt-to-adult survival rates (Hare et al. 1999). A difference map showing May through August SST between 1977–1998 and 1950–1976 shows the SST changes that correspond with the large increases in Alaska salmon catches and the period of declining returns for Columbia Basin spring Chinook salmon (Figure 2). SST changes were positive throughout the subarctic regions of the North Pacific, including the Bering Sea, the Gulf of Alaska, and the northeast Pacific. At the same time, SSTs cooled across much of the North Pacific between about 30°N and 50°N latitude. Figure 3 shows seasonal averages for surface air temperature changes between the same periods. For Alaska and the rest of the Pacific Northwest the era of high Alaska salmon production from 1977–1998 was warmer than the era of low salmon production in 1950–1976. The largest temperature differences between these two periods were found in the winter season (January–March), where surface temperatures in Alaska and western Canada were ~2–3°C warmer in the later period. The smallest temperature differences between these periods were found in summer (July–September), where surface temperatures in Alaska were ~0–1°C warmer in the later period. Temperature changes in spring and fall seasons were typically ~1–2°C warmer in the later period.

From a global perspective, the period since the 1970s was notable for the prominent and sustained rises in globally-averaged surface temperature, with especially large warming trends in the high-latitudes of the Northern Hemisphere (Figure 4; IPCC 2007). Wallace et al. (1995) showed that a substantial part of the late 1970s warming in the Northern Hemisphere was related to interdecadal changes in atmospheric circulation, with the pattern of warming in western North America especially influenced by the persistently strong Aleutian Low pressure pattern that was part of the 1977 shift in Pacific climate. From a North Pacific perspective, the patterns of warming shown in Figures 2 and 3 bear a strong resemblance to the patterns of warming associated with the PDO-pattern of interdecadal variability (Mantua et al. 1997; Zhang et al. 1997).

From a North Pacific climate perspective, the period from 1997 through the early 2000s was notable for the rapid basin-scale changes that coincided with the extreme changes in the tropical ENSO. A visual analysis of the three climate indices (Figure 4) shows that ENSO, the PDO, and global average temperatures all underwent large interannual changes in the period since the mid-1990s. The Niño 3.4 index, which tracks ENSO variability, had extreme positive values indicating El Niño conditions from mid-1997 through the winter of 1998, and then rapidly changed to negative values (La Niña conditions) in the spring of 1998 that persisted into mid-2002. Similarly, the PDO index had large positive values from mid-1997 through spring 1998 indicating an extreme warm period for the Bering Sea, Gulf of Alaska, and northeast Pacific Ocean that were also followed by a rapid change to cooler conditions in these locations that persisted into 2002. Overland et al. (2001) showed that atmospheric teleconnections[1] initiated by the tropical ENSO likely altered wind and weather patterns in the North Pacific that resulted in the observed interannual shift in North Pacific SSTs (also see Peterson and Schwing 2003). Finally, global average surface temperatures spiked in association with the extreme 1997–1998 El Niño event, rising up to 0.2°C above the long-term warming trend for a period of about one year.

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[1] Teleconnection in atmospheric science refers to climate anomalies being related to each other at large distances (typically thousands of kilometers).

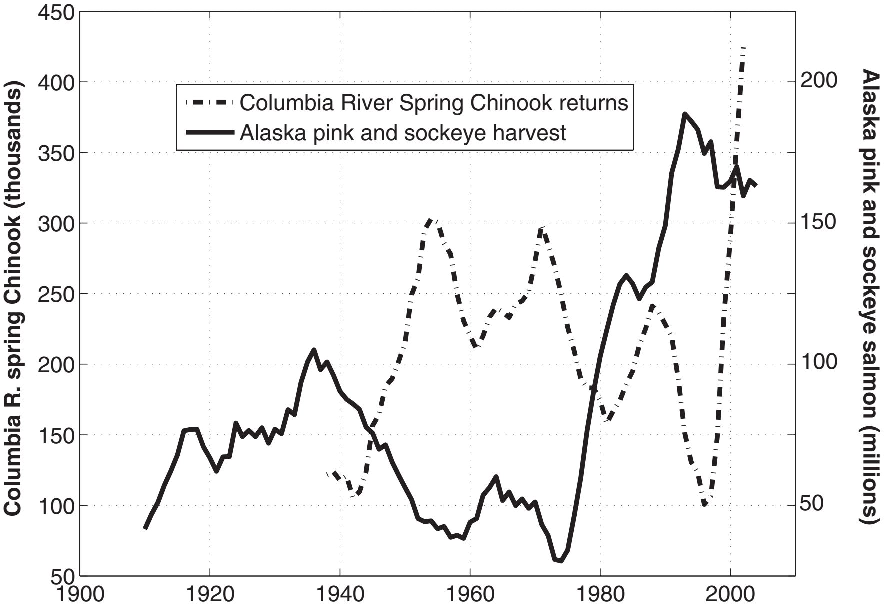

FIGURE 1. Historical salmon landings for Alaska from 1925–2004 and total Columbia River Spring Chinook returns from 1938–2002.

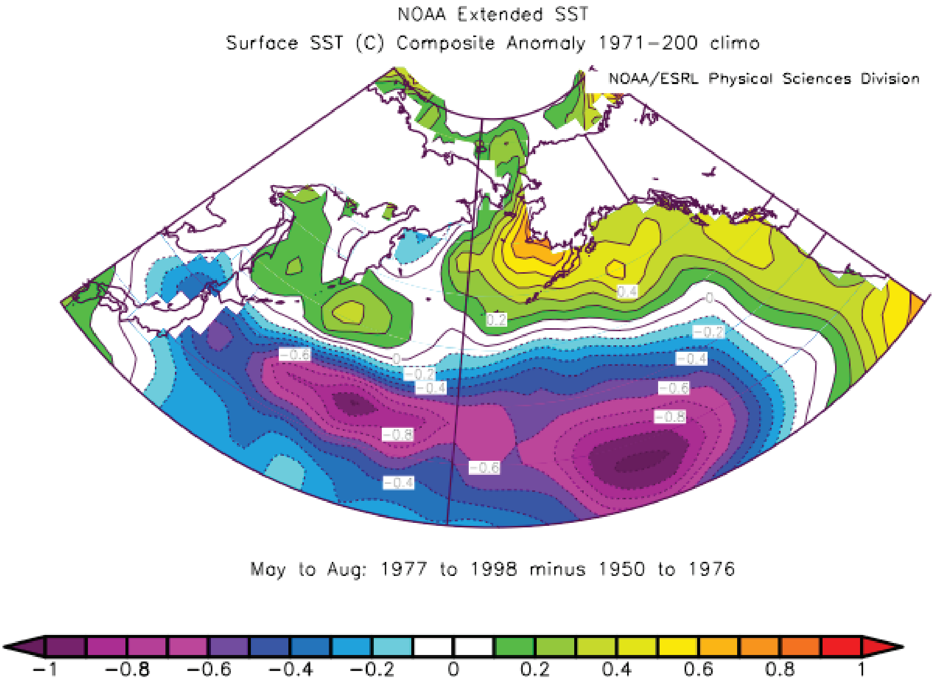

FIGURE 2. May-to-August SST anomalies (in °C) for 1977–1998 minus 1950–1976. Contour interval is 0.1 °C. Image provided by the NOAA/ESRL Physical Sciences Division, Boulder Colorado from their Web site: http://www.cdc.noaa.gov/.

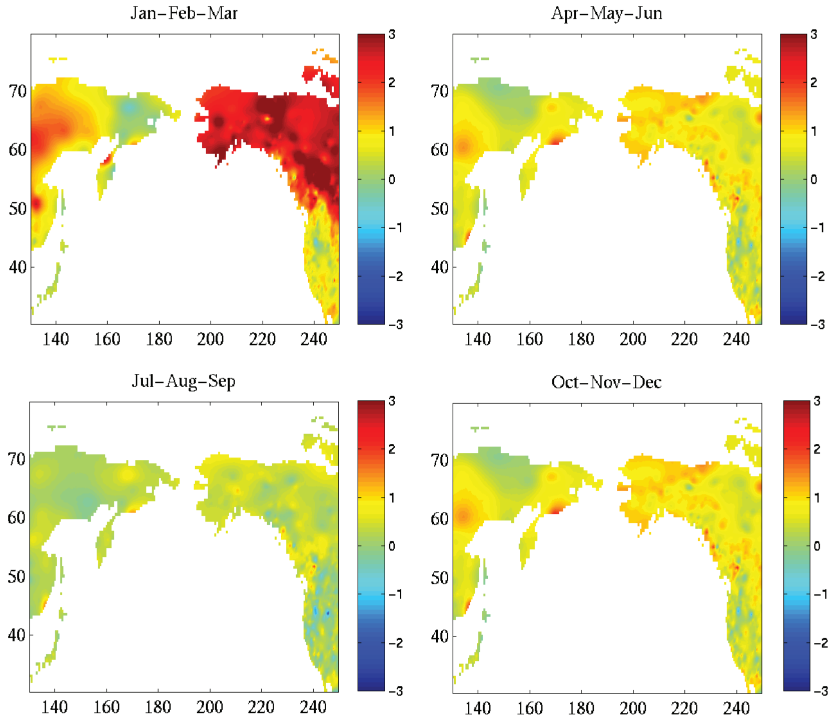

FIGURE 3. 1977–1998 minus 1950–1976 surface air temperatures (in °C) for (a) January-to-March, (b) April-to-June, (c) July-to-September, and (d) October-to-December.

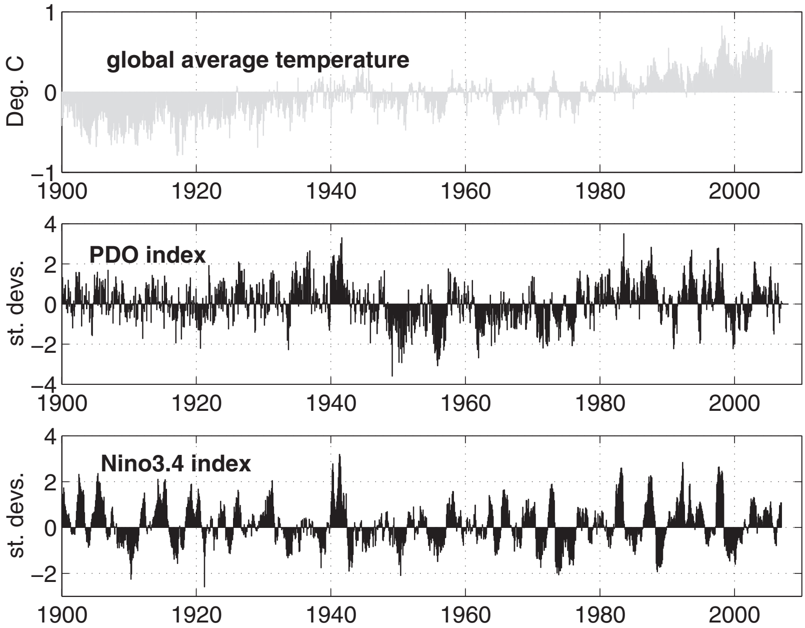

FIGURE 4. Time series monthly Global average temperature (top), Pacific Decaadal Oscillation (PDO) index (middle), and Niño3.4 index (bottom).

The combination of continued long-term global warming trends and large amplitude interannual climate changes associated with the change from tropical El Niño to La Niña conditions in 1998 contributed to North Pacific SST changes that were in part unlike the canonical PDO pattern (Figure 5). During the 1999–2002 period, important SST changes for Pacific salmon included a strong cooling of the northeast Pacific, especially west of Oregon, Washington, and British Columbia, and a moderation of the warm SSTs in the Gulf of Alaska and the Bering Sea. However, SSTs in the Bering Sea and Gulf of Alaska remained warmer than those in the cool PDO and the poor salmon production era of 1950–1976. More precisely, the cool-season (November–March) SST changes in the late 1990s projected strongly onto the second mode of North Pacific SST variations, and only weakly onto the PDO-pattern (Bond et al. 2003). Additionally, the average warm-season (May–August) PDO index value for 1999–2002 was similar to that for the 1950–1976 period. The switch to a coherent north-south salmon production pattern from the late 1990s through the early 2000s can be interpreted in part as a consequence of the breakdown in the PDO-related large-scale spatial coherence in the changing climate and ocean conditions of the northeast Pacific. The state of the climate system in seasons other than winter was likely to be important to the marine ecosystem and to salmon, and the nature of even large-scale climate variations important for salmon was richer than formerly appreciated.

Regional Patterns of Climate and Salmon Variations

To develop insights into the relationships between changes in salmon productivity and climate at regional spatial scales, we now shift our attention to a time series representing the composite annual fluctuations in Norton Sound pink salmon productivity. Pyper et al. (2001) developed the Norton Sound spawner-recruit index (SRi) for brood years 1962 to 1995 from the composite average for variations in spawner-to-recruit survival rates for pink salmon from four stocks or districts in Norton Sound (Nome, Golovin, Moses Point and Norton Bay, and Unalakleet) (Figure 6). This time series depicts a productivity history with large year-to-year and multiyear variations.

Differences between 19-month composite surface temperature time series that span the spawning, incubation, and seaward migration period observed during the ten highest and ten lowest brood years, in the 1962 to 1995 period, are shown in Figure 7. Temperature differences between the high and low productivity years were generally small and variable during the spawning period. In contrast, large and persistent differences were found for the incubation, fry emergence, and seaward migration months of January through May. All differences were positive for the months of January through November of the seaward migration year. A bivariate scatterplot of January through May average air temperature at Nome versus the Norton Sound RSi for the previous (brood) year showed a generally linear relationship between these indices, with a correlation coefficient $r = 0.52$ (Figure 8).

To develop insights into the characteristics of coastal ocean temperatures that typically covary with variations in the Norton Sound pink salmon RSi, composite maps for the early ocean period (May–August) for the ten highest and ten lowest brood years are shown in Figure 9. The high productivity composite has warm SST anomalies throughout the Bering Sea, with the largest anomalies found in the near-shore waters of the eastern Bering Sea. In contrast, the low productivity composite has cold SST anomalies throughout most of the Bering Sea, with the largest anomalies also found in the near-shore waters of the eastern Bering Sea.

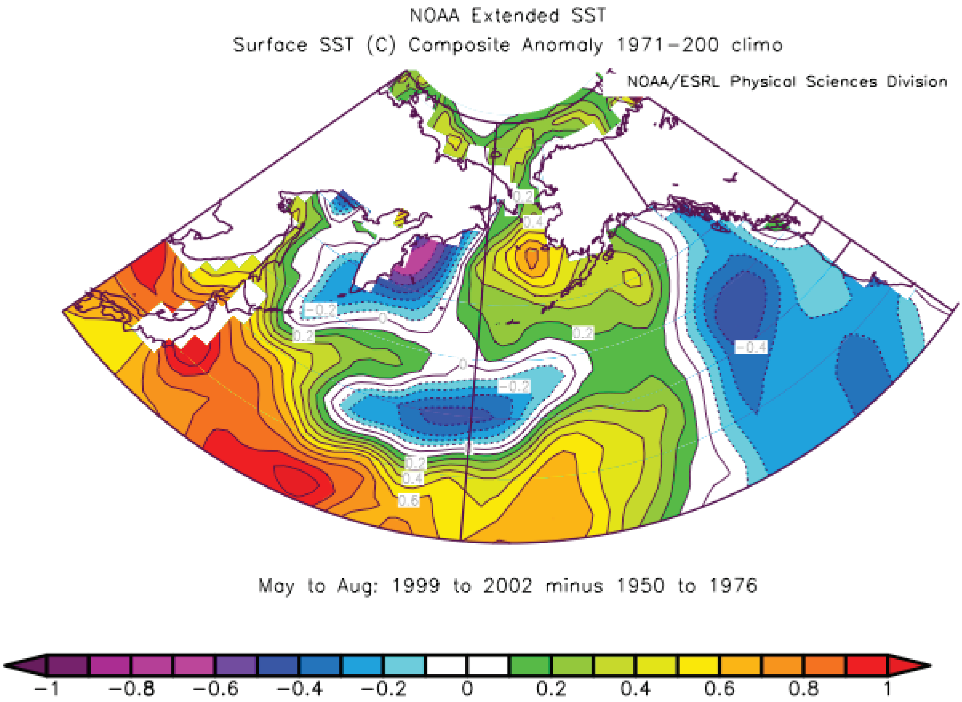

FIGURE 5. May-to-August SST differences (in °C) for 1999–2002 minus 1950–1976. Contour interval is 0.1 °C. Image provided by the NOAA/ESRL Physical Sciences Division, Boulder Colorado from their Web site at http://www.cdc.noaa.gov/.

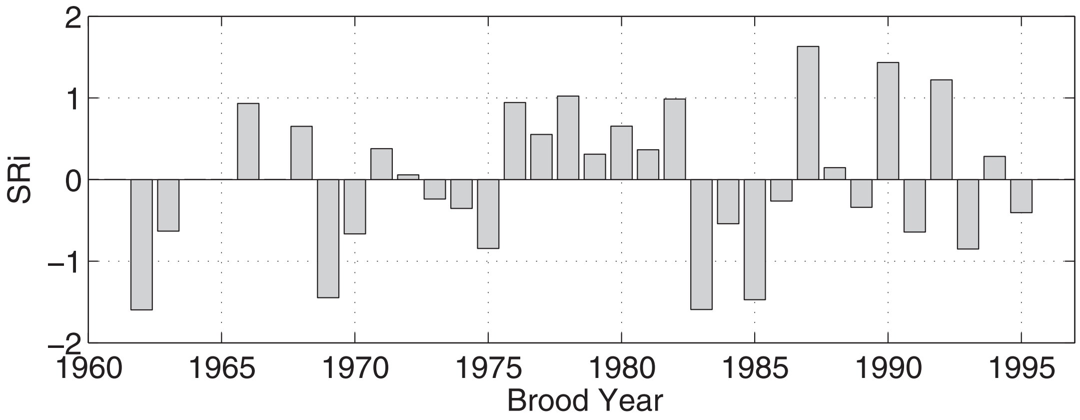

FIGURE 6. Annual Norton Sound pink salmon composite Stock-Recruit survival indices (SRi's) for brood years 1962–1995 (from Pyper et al. 2001).

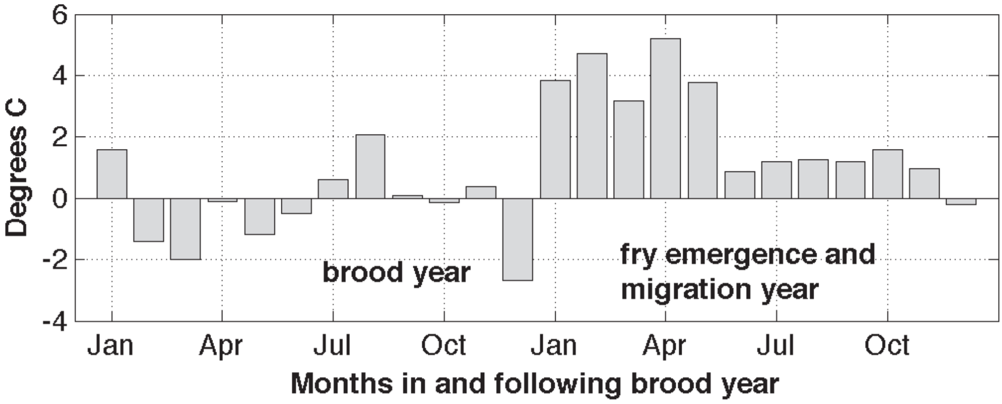

FIGURE 7. Differences between the monthly average surface air temperature in Nome, Alaska, for composites of the 10 highest and 10 lowest Norton Sound pink salmon SRi values for brood years 1962 to 1995.

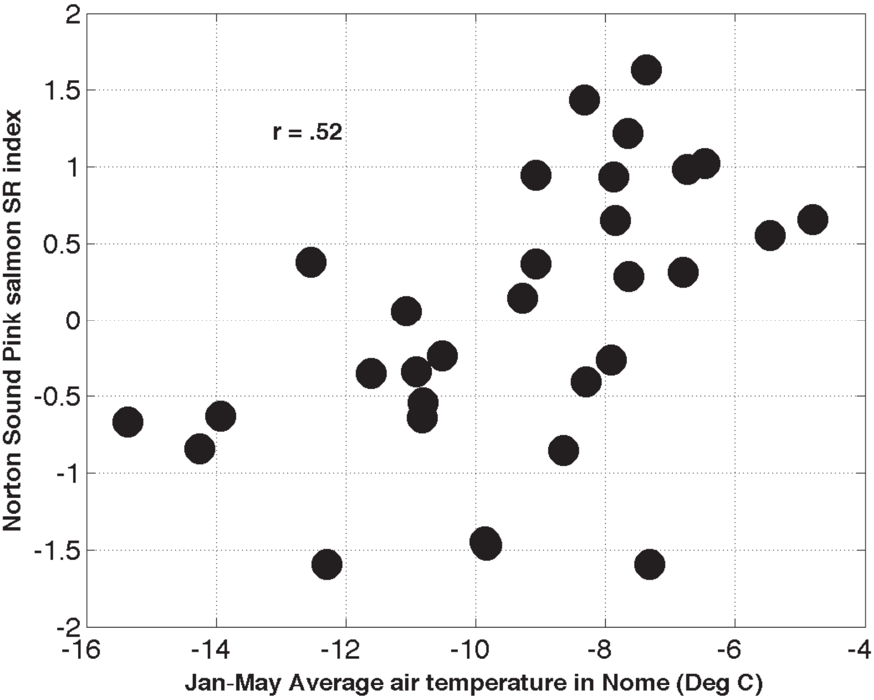

FIGURE 8. Bivariate scatterplot of annual Norton Sound pink salmon SRi values versus annual January-to-May averaged Nome, Alaska, air temperatures in the following year. These two series are correlated at a level of *r* = +0.52.

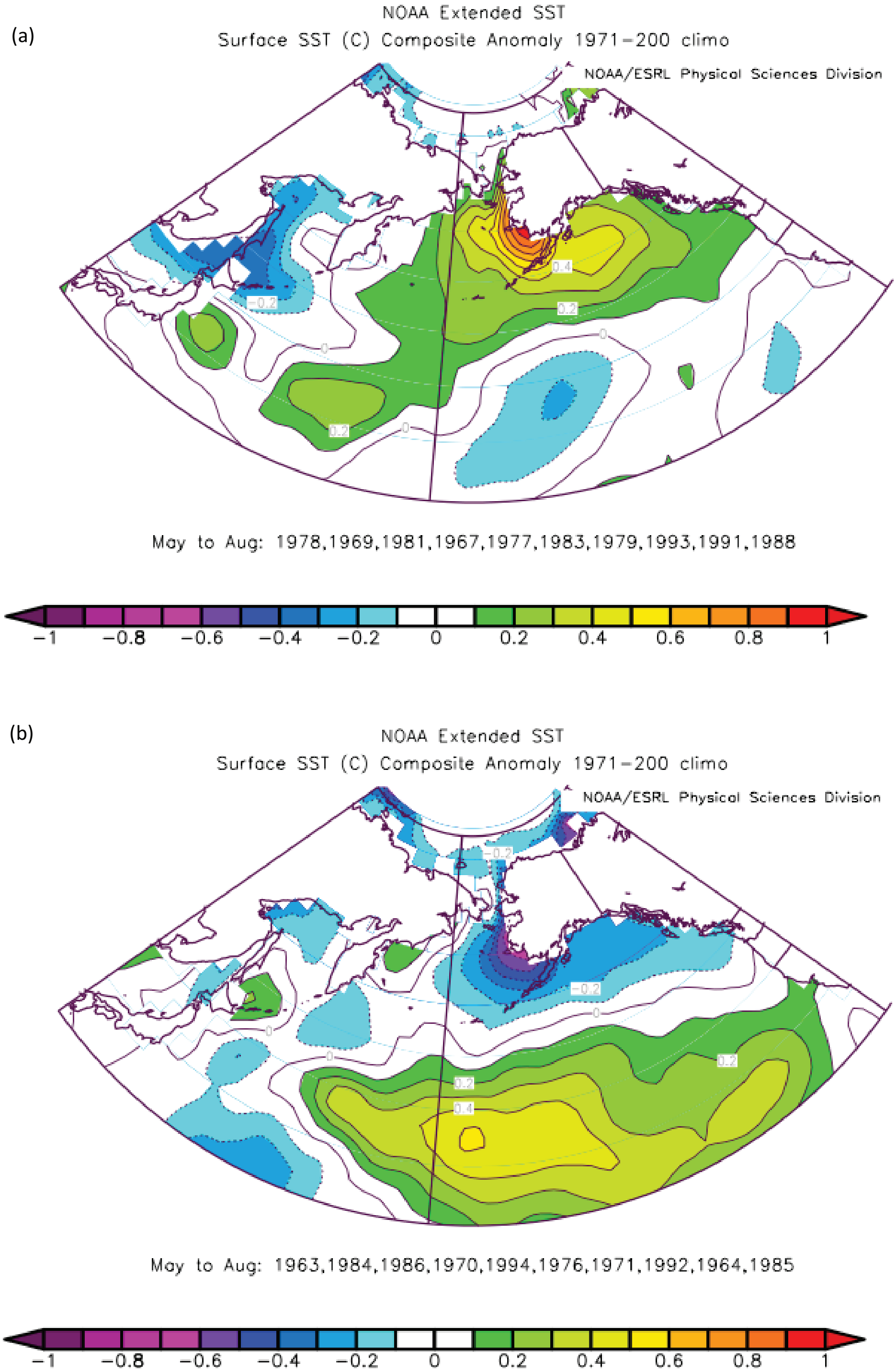

FIGURE 9. Composite May-to-August SST anomalies for years showing (a) the averages for the 10 highest and (b) 10 lowest SRi values for Norton Sound pink salmon productivity in the period 1962–1995. Anomalies are computed with respect to the 1971–2000 May-to-August climatology. Contour interval is 0.1 °C. Image provided by the NOAA/ESRL Physical Sciences Division, Boulder Colorado from their Web site at http://www.cdc.noaa.gov/.

An aggregate recruits-per-spawner index developed from the Banducci et al. (2007) annual catch and escapement estimates for the Kwiniuk, Niukluk, Nome, Snake, North and El Dorado Rivers for 1995–2005 is shown in Figure 10a (see also Menard et al. 2009; this volume). In this period, productivity exceeded two recruits-per-spawner for brood years 1995, 2001, 2002, and 2003, while productivity was less than one recruit-per-spawner for brood years 1997 and 1998. Note that no attempt was made to fit a stock-recruit curve to these data because of the short length of this time series, so no attempt was made to remove possible impacts of density dependent processes.

Figure 10b shows a bivariate scatterplot between January–May average surface air temperatures in Nome (corresponding to the fry emergence and ocean migration year) and the recruits-per-spawner index. A notable feature of these data were that especially warm conditions for freshwater and early marine life stages for Norton Sound pink salmon coincided with both high and low levels of recruits-per-spawner for brood years 1996–2003. May–August SSTs in the eastern Bering Sea were warmer than average in 1997 and 1998, especially cold in 1999, near average in 2000, and slightly cooler than average in 2001, yet there were less than two recruits-per-spawner for each of these broods. For these years little evidence existed for a coherent relationship between productivity and winter-spring air temperatures or spring-summer near-shore ocean temperatures. Ocean entry years 2002, 2003, and 2004 did, however, have warm conditions in winter, spring, and summer, and greater than two recruits-per-spawner for each year.

Discussion

Co-varying patterns of climate and salmon production variations depend upon the spatial scale of interest. Aggregating catch data across large regions like the state of Alaska leads to the identification of climate patterns with comparable scales of coherence, namely across the entire North Pacific Ocean and western North America. At this scale, Alaska salmon abundance for all five commercially harvested species covaries among regional populations through time, and the PDO index accounts for nearly 50% of the interannual to interdecadal variance in Alaska salmon abundance (Hare et al. 1999). A regional perspective based on the ten highest and ten lowest years of Norton Sound pink salmon productivity identifies regional patterns of climate variation that were nearly mirror images in character between the high and low productivity subsamples. A key finding in this analysis was that the high productivity years in the 1962–1995 period were associated with warmer than average winter-spring air temperatures and summertime SST, while the low productivity years were more strongly associated with cold periods in winter-spring air temperatures and summer SST. However, especially warm conditions for freshwater and early marine life stages for Norton Sound pink salmon coincided with both high and low levels of recruits-per-spawner for brood years 1996–2003, a period that experienced large interannual variations in Bering Sea, North Pacific, and tropical Pacific ocean conditions.

The north-south inverse production pattern for North Pacific salmon, along with the PDO pattern of North Pacific climate variability, was prominent in the period from 1925 through the mid-1990s, but less prominent in the period from the late 1990s to early 2000s. This latter period was marked by sustained warming trends at the global scale, throughout the Arctic, and over Alaska. Statewide Alaska salmon production remained near historic highs, although some large population groups (like Yukon River Chinook and chum salmon, and Norton Sound pink salmon)

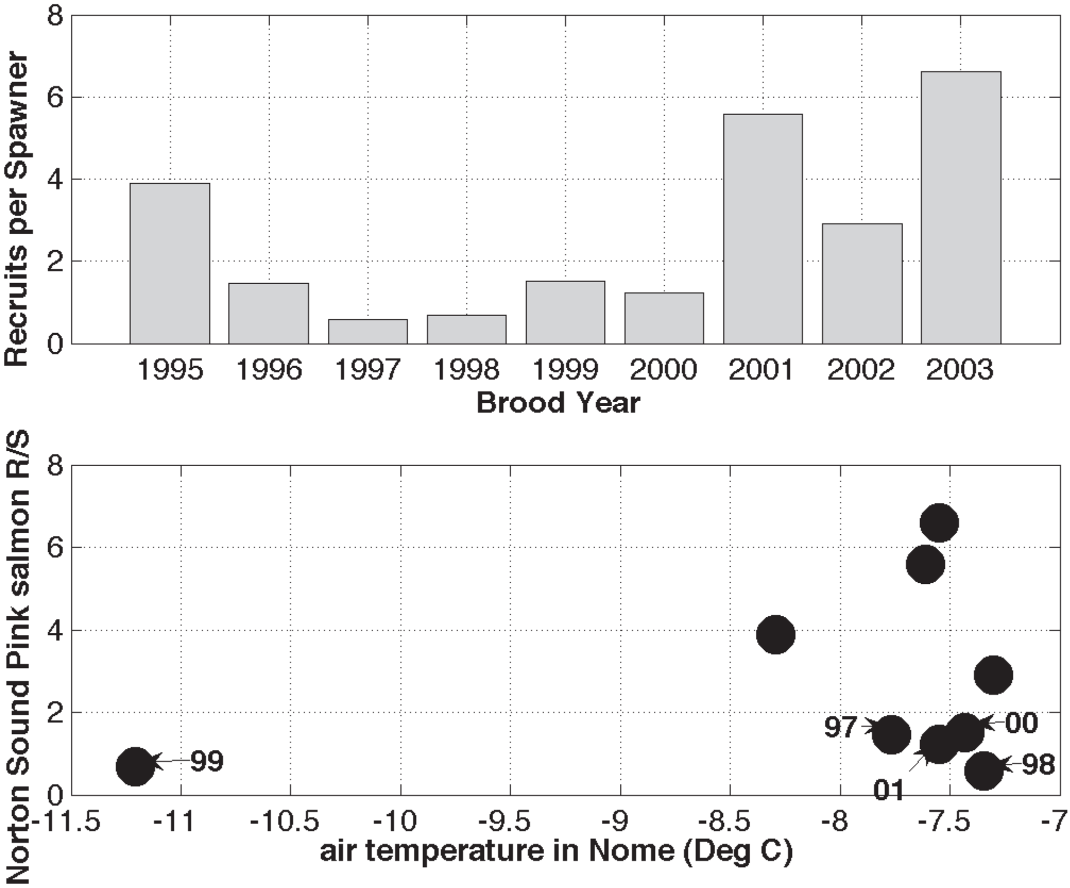

FIGURE 10. (a) Aggregate recruits-per-spawner index developed from Banducci et al's (2007) annual catch and escapement estimates for the Kwiniuk, Niukluk, Nome, Snake, North and El Dorado Rivers for 1995–2005. (b) Bivariate scatterplot of Norton Sound pink salmon recruits-per-spawner values versus annual January-to-May averaged Nome, Alaska, air temperatures corresponding to the fry emergence and ocean migration period.

experienced periods of very low abundance and productivity in some years. As shown by Hilborn et al. (2003) and discussed by Schindler and Rogers (2009), the same regional-scale climate forcing can contribute to a wide diversity of productivity responses in the same species but across different population groups. This diversity of sensitivity at the stock and watershed level poses a substantial challenge for those interested in predicting future changes in salmon productivity in response to a changing climate.

Leading hypotheses for the link between climate variations and Pacific salmon production have focused on changes in early ocean survival for juvenile salmon, but it is clear that climate also affects freshwater life stages and influences productivity. For example, warm winter and spring temperatures extend the ice-free period in Alaska's lakes and streams, and can contribute to increased productivity in freshwater environments that lead to more rapid growth rates for rearing juvenile salmon (Schindler and Rogers 2009, this volume). Warming winter and springtime surface temperatures in the 1948–2000 period have been linked with advanced runoff timing in many snowmelt watersheds in western North America (Stewart et al. 2004). Changes in hydrologic regimes can be important for the reproductive success of salmon in freshwater. For example, Battin et al. (2007) found that for Washington State's Snohomish River Basin, future climate favors a transition to more winter precipitation falling as rain and less as snow, which in turn increases peak winter flows while eggs are incubating; these projected hydrologic changes caused large decreases in the simulated reproductive success for Chinook salmon in that watershed. A finding here shows, in recent decades, anomalously warm temperatures in both the freshwater and marine regions that juvenile Alaska salmon use while rearing has been associated with periods of high abundance for Alaska salmon as a whole. At the scale of Norton Sound, this pattern was evident for brood years 1962–1995, but less clear for brood years 1996–2000 when highly variable environmental conditions coincided with sustained low productivity.

Monitoring of both physical and ecological changes in freshwater and marine environments is a necessary step for better understanding the relative importance of climate on freshwater and marine productivity for salmon, yet this kind of monitoring is relatively rare around the Pacific Rim. An improved understanding for climate on salmon also begs for studies integrating research efforts around the full lifecycle of salmon, because it is lifecycle survival and productivity that contributes to their population dynamics.

A strong scientific consensus has emerged that global average temperatures will continue to rise in the coming century because of human-caused increases in atmospheric greenhouse gas concentrations (IPCC 2007). Based on climate model projections, global average temperatures are expected to rise from 1–6°C by 2100, and western Alaska's surface temperatures are expected to rise at substantially greater rates (IPCC 2007; Schindler and Rogers 2009).

For Alaska salmon populations that currently occupy habitats that are far from thermal stress levels in freshwater and marine environments, additional warming may serve to benefit productivity for some years into the future. Based on recent periods of anomalously warm ocean temperatures in the subarctic North Pacific and Bering Sea, and periods of warm winter and spring surface air temperatures over Alaska, relatively small amounts of warming in the future will likely continue to favor high productivity for Alaska salmon. However, more extreme ocean warming like that observed in 1997 and 1998 may push North Pacific and Bering Sea ecosystems into states that no longer favor high productivity for Alaska salmon.

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