Alaska Sockeye Salmon Scale Patterns as Indicators of Climatic and Oceanic Shifts in the North Pacific Ocean, 1922–2000

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Abstract: Climate regime shifts can alter the community structure of marine species in the North Pacific Ocean. In this study, we use a regime shift detection algorithm to determine whether regime shifts are recorded as shifts in the mean fish length indices at the smolt, juvenile, immature, and mature life stages based on measurements of increments on scales of adult age-2.2 sockeye salmon (*Oncorhynchus nerka*) that returned to the Karluk River, Kodiak Island over a 77-year time period (1924–2000). Fish length was expected to increase with cool-to-warm climate shifts (1926, 1958, 1977, and 1998) and decrease with warm-to-cool climate shifts (1943, 1947, 1971, and 1989). Regime shifts were not consistently observed as statistical shifts in the time series of fish length indices. At contemporaneous lags, shifts in the mean temperature of the North Pacific were detected as shifts in length in 1958 (+), but not in 1926 (+), 1943 (-), 1971 (-), and 1977 (+). Shifts in the atmospheric circulation and sea level pressure of the North Pacific were detected as negative shifts in length in 1989 (-), but not in 1926 (+), 1947 (-), 1977 (+), 1998 (+). Shifts in length indices were associated with the 1957-58 El Niño, the warm-to-cool shift in 1989, and preceded the 1976–77 climate shift in the North Pacific Ocean. Fish length indices from salmon scales may be useful predictors for major and more recent shifts in the status of the ecosystem of the North Pacific Ocean.

Keywords: sockeye salmon, scale, climate, regime shifts

INTRODUCTION

In the 20th century, climate and oceanic conditions shifted between cool and warm regimes in the North Pacific Ocean (Mantua et al. 1997; Yasunaka and Hanawa 2005). Warm regimes (1925–46, 1977–88, 1998–2000) were characterized by a more intense and eastward Aleutian Low pressure cell, increased cyclonic circulation, increased Ekman pumping velocity, cooler conditions in the central North Pacific Ocean, and warmer conditions in the eastern North Pacific Ocean. Cool regimes (1947–1976 and 1989–97) showed opposite trends (Mantua et al. 1997).

Changes in the ecology of the North Pacific Ocean also occurred in response to these climatic regime shifts. Following the 1976–77 cool-to-warm shift, the commercial harvest increased for Pacific halibut (*Hippoglossus stenolepis*), Pacific cod (*Gadus macrocephalus*), walleye pollock (*Theragra chalcogramma*), and Pacific salmon (*Oncorhynchus* spp.), and decreased for shrimp, capelin (*Mallotus villosus*), and Pacific herring (*Clupea pallasii*) (Hare and Mantua 2000). The mid-1940s and mid-1970s climate regime shifts were identified in tree ring growth, a proxy for temperature at coastal land-based stations along the Gulf of Alaska (Wilson et al. 2006).

Climatic and oceanic conditions affect the marine growth rates of Pacific salmon. For sockeye from the Karluk River on Kodiak Island, Alaska, the scale growth during the middle and later part of the marine juvenile growing season was correlated with summer sea surface temperatures in the Gulf of Alaska ($r = 0.49$, $P < 0.01$, n = 40) (Martinson 2004). The 1976–77 regime shift was associated with a positive change in immature marine scale growth when the 1976–77 shift was included as a covariate in the model of growth and population density (Martinson et al. 2008). The positive salmon growth and sea-surface temperature relationship is likely indirectly due to increased food availability from increased transport of warm water and species from south to north and increased sunlight and energy for photosynthesis, plankton growth, and food available for salmon.

Monitoring projects on Pacific salmon provide long-term biological time series with records from the 1920s to the present (Martinson et al. 2008). Biological time series are useful for reconstructing and understanding ecological responses to climate change (Helle and Hoffman 1995;

Ruggerone and Rogers 1998; Isakov et al. 2000; Batten and Welch 2004; Martinson et al. 2008). Relating biological time series to climatic and oceanic time series will help us understand and develop hypotheses on the mechanisms by which climate change might alter large marine ecosystems.

The purpose of this study was to determine whether shifts in physical atmospheric and oceanic conditions were recorded in the growth patterns on scales of sockeye salmon that originated from the eastern North Pacific Ocean. A regime shift detection algorithm was used to determine whether climatic regime shifts were recorded as abrupt changes, called shifts, in the patterns of scales of sockeye salmon (*Oncorhynchus nerka*) from the Karluk river and lake, on Kodiak Island, Alaska, from 1924 to 2000. Karluk sockeye are distributed primarily on the continental shelf of the eastern North Pacific as juveniles, in the central and western Pacific Ocean during the immature stage, and in the central and eastern North Pacific Ocean as maturing fish (Myers et al. 1996). Because Karluk sockeye originate in the middle of the latitudinal distribution of North American sockeye, we hypothesize that the indices of fish length estimated from scale radius measurements would increase in response to cool-to-warm regime shifts (+) and to decrease in response to warm-to-cool regime shifts (-).

MATERIAL AND METHODS

Fish length indices

Fish lengths at the end of the freshwater period and at times of marine annulus formation were estimated indirectly from incremental measurements on the scales of adult age-2.2 sockeye salmon that returned from the ocean to the weir on the Karluk River system on Kodiak Island, 1924–2000. Historical field notes indicate that scales were taken a few rows above the lateral line using either a scrape method (1924–51) or with forceps (1952–2000). Some bias may have resulted if scrape samples were not taken consistently from an area immediately (2–3 rows) above the lateral line (Clutter and Whitesel 1956; Scarnecchia 1979). In using scale radius to estimate fish length, we assumed that the growth along the radius of the scale was proportional to the increase in fish length and that the distance between adjacent annuli on a scale depicted one year of somatic growth (Dahl 1909; Fukuwaka and Kaeriyama 1997).

One scale per fish was measured, resulting in 30 to 50 scales per year (n = 69 years) for a total of 3,116 scales. Data were missing for the years 1945, 1947, 1958, 1965, 1966, 1969, and 1979. The missing values were estimated using a smoothing technique to establish a continuous time series for the statistical analysis. For each year, scales were selected at equal time intervals throughout the collection period from the early run (May 1–July 21) spawning migration. Mea-

Table 1. Results of the regime shift detection test for smolt (FW), juvenile (L1), immature (L2), and maturing (L3) body length as estimated from scale measurements of age-2.2 sockeye salmon that returned to the Karluk River on Kodiak Island, Alaska, 1924–2000.

Length Variable	Regime			Shift		
	No. of Years	Years	Mean (mm)	Year	Direction	Confidence Interval
FW	14	1922-1935	0.709930			
	63	1936-1998	0.639646	1936	↓	5.58E-06
LI	15	1922-1936	1.712347			
	20	1937-1956	1.673877	1937	↓	0.040799
	17	1957-1973	1.709088	1957	↑	0.12392
	15	1974-1988	1.788408	1974	↑	0.00345
	7	1989-1995	1.672092	1989	↓	0.000692
	3	1996-1998	1.778136	1996	↑	0.035939
L2	50	1923-1972	2.445125			
	27	1973-1999	2.587601	1973	↑	2.05E-09
L3	33	1924-1957	2.735112			
	17	1958-1973	2.837429	1958	↑	0.001023
	17	1974-1990	2.975105	1974	↑	5.39E-05
	8	1991-1998	2.842775	1991	↓	0.000865
	2	1999-2000	2.984582	1999	↑	0.105114

surements were made using imaging software along a reference line drawn from the focus to the edge of the scale along the longest axis of the anterior portion of the scale (Narver 1968). A mark was placed at the end of the freshwater growth zone, at the end of each annulus, and at the edge of the scale.

Four fish length indices were calculated for the analysis. Smolt length (FW) was estimated as the total radius from the focus of the scale to the end of freshwater growth. Juvenile length (L1) was estimated as the total radius from the focus to the end of the 1st marine annulus on the scale. Immature length (L2) was estimated as the total radius from the focus to the end of the 2nd marine annulus. Maturing length (L3) was estimated as the total radius from the focus to the edge of the scale, at the time of capture in river. For each length index, mean values were constructed by year.

Statistical Analysis

The hypotheses we tested were that fish length indices would increase in response to cool-to-warm (+) climate

shifts (1926, 1958, 1977, and 1998) and decrease in response to warm-to-cool (-) climate shifts (1943, 1947, 1971, and 1989). The North Pacific Ocean mean winter SST shifted in 1926 (+), 1943 (-), 1958 (+), 1971 (-) and 1977 (+) (Yasunaka and Hanawa 2005). North Pacific atmospheric circulation and sea level pressure shifted in 1926 (+), 1947 (-), 1977 (+), 1989 (-), and 1998 (+) (Mantua et al. 1997). We expected eight shifts in each of the four fish length indices time series for a total of 32 possible shifts. All four time series were assumed independent.

To statistically detect shifts in the mean state of each fish length index time series we used a sequential *t*-test analysis of regime shifts (STARS) (Rodionov 2005). The STARS program automatically detects shifts in the time series as the sequential data points enter the model and estimates the magnitude of the shift over the duration of the regime (Rodionov 2004). The confidence level of the difference between the mean values of neighboring regimes is based on the Student's two-tailed *t*-test with unequal variance (TTEST procedure in Excel) at a 90% significant level and a default cutoff length of 10 years. For the one-tailed test and hypotheses
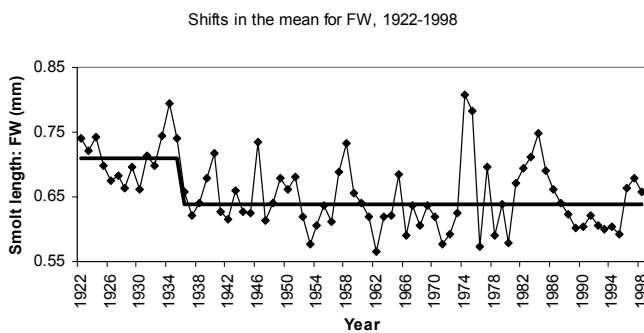

Fig. 1. Regime shift detection for smolt length (FW) in years 1922-1998 estimated from scale measurements of age-2.2 sockeye salmon that returned to the Karluk River on Kodiak Island, Alaska, 1924–2000. A shift occurred in 1936. Data are missing for 1943, 1945, 1956, 1963, 1964, 1967, 1977.
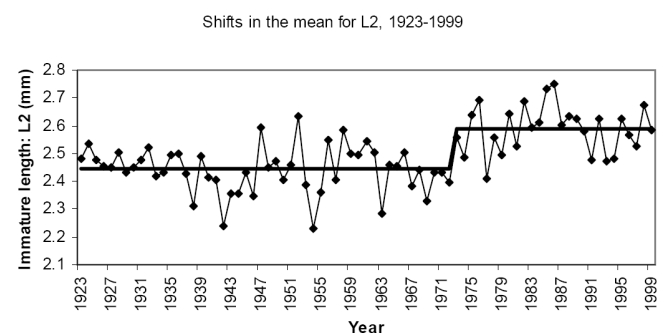

Fig. 3. Regime shift detection for immature length (L2) in years 1923-1999 estimated from scale measurements of age-2.2 sockeye salmon that returned to the Karluk River on Kodiak Island, Alaska, 1924–2000. A shift occurred in 1973. Data are missing for 1944, 1946, 1957, 1964, 1965, 1968, 1978.
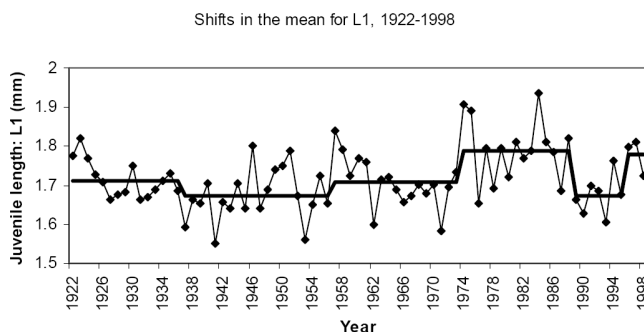

Fig. 2. Regime shift detection for juvenile length (L1) in years 1922-1998 estimated from scale measurements of age-2.2 sockeye salmon that returned to the Karluk River on Kodiak Island, Alaska, 1924–2000. Shifts occurred in 1937, 1957, 1974, 1989, 1996. Data are missing for 1943, 1945, 1956, 1963, 1964, 1967, 1977.
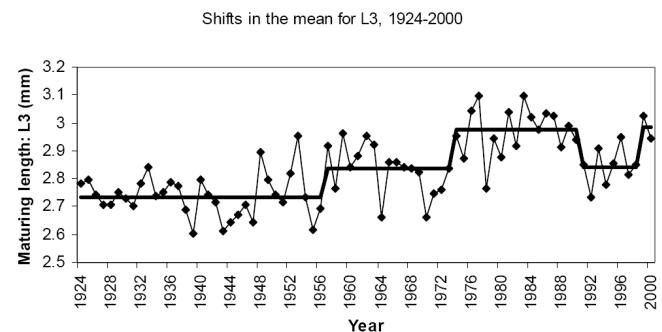

Fig. 4. Regime shift detection for maturing length (L3) in years 1924-2000 estimated from scale measurements of age-2.2 sockeye salmon that returned to the Karluk River on Kodiak Island, Alaska, 1924-2000. Shifts occurred in 1958, 1974, 1991, and 1999. Data are missing for 1945, 1947, 1958, 1965, 1966, 1969, 1979.

there is a 5% probability that two of the 32 shifts will occur by random chance. A significant shift means there is a difference in the mean level between the two regimes. The STARS algorithm was written in Visual Basic and is available from the Bering Climate website (http://www.beringclimate.noaa.gov/regimes/index.html).

RESULTS

Of the 32 possible shifts, only two shifts occurred in the same year and direction that was hypothesized (Table 1). A hypothesized positive shift occurred in 1958, but not 1926, 1977, and 1998. In this shift, the maturing fish length index (L3) had a significant positive shift in 1958 from 2.73511 mm in a 33-year regime (1924–1957) to 2.8374 mm in a 17-year regime (1958–1973). A hypothesized negative shift occurred in 1989, but not 1943, 1947, and 1971. In this shift, the juvenile fish length index (L1) had a significant negative shift in 1989 from 1.78841 mm in a 15-year regime (1974–1988) to 1.67210 mm in a seven-year regime (1989–1995). Similarly, with a one-year time lag between regime shift and fish length shift, an additional match between climate and length shifts occurred in 1958. This low frequency of matches in regime shifts and fish length shifts by exact year and a one-year lag is about the same as expected by random chance.

Of the eleven fish length shifts observed among the four time series, nine occurred in years with no specific hypothesis for shifts. Smolt length (FW) had a negative shift in 1936 (Fig. 1). Juvenile length (L1) had positive shifts in 1957, 1974, and 1996, and negative shifts in 1937 and 1989 (Fig. 2). Immature length (L2) had a positive shift in 1973 (Fig. 3). Maturing length (L3) had positive shifts in 1958, 1974, and 1999 and a negative shift in 1991 (Fig. 4). None of the eleven shifts occurred in the opposite direction than was hypothesized.

DISCUSSION

Climate regime shifts in the North Pacific Ocean were not consistently observed as statistical shifts in the time series of indices of fish length for sockeye salmon that returned to the Karluk River on Kodiak Island, Alaska. At contemporaneous lags, shifts in the sea surface temperatures in the North Pacific Ocean were detected as shifts in fish length in 1958 (+), but not in 1926 (+), 1943 (-), 1971 (-) and 1977 (+) (Yasunaka and Hanawa 2005). Shifts in the atmospheric circulation and sea level pressure of the North Pacific were detected as shifts in length in 1989 (-) , but not 1926 (+), 1947 (-), 1977 (+), and 1998 (+) (Mantua et al. 1997). The influence of underlying and interacting cycles (i.e. predators, prey, competitors, generation length) and density-dependent effects on the growth of salmon may confound the exact year when a regime shift affected the marine growth of Karluk sockeye (Martinson et al. 2008). Despite the low number of matching shifts, some patterns in shifts were found. The

shifts in fish length indices coincided with the 1957–58 El Niño, the 1989 warm-to-cool regime shift, and preceded the 1976–77 cool-to-warm regime shift in the North Pacific Ocean.

First, the 1957–58 El Niño event that warmed the Gulf of Alaska and North Pacific Ocean was shown as positive shifts in the juvenile and maturing length and as a positive outlier in the smolt length index. During the 1998 El Niño, immature chum salmon were larger and had an earlier growing season than in the cooler waters of the 1999 La Nina in the central North Pacific Ocean (Martinson and Helle 2000). For Karluk sockeye salmon, the El Niño events were not consistently associated with increases in fish length. However, the 1958, 1983, and 1998 El Niño events were observed as positive outliers in the smolt length index rather than in the length incurred in salt water.

Second, the 1989 negative shift in the L1 index corresponded with reduced atmospheric circulation and sea level pressure shift in the North Pacific Ocean (Mantua et al. 1997). Both the 1989 shift and the mid-1990s shift in L1 corresponded with shifts in the Arctic Oscillation, an index of atmospheric pressure in the Bering Sea (www.beringclimate.noaa.gov).

Third, all three marine fish length indices had shifts during the early 1970s. Several possible reasons could explain the occurrence of shifts three and four years (1973–74) prior to the 1977 cool-to-warm regime shift and following two very cold winters in 1971–72. First, the 1971–72 cold winters increased winter winds and storms in the Gulf of Alaska. Storms bring nutrients from deep layers to the surface at an upwelling rate of 10–30 m/yr in the middle of the Alaska gyre. Upwelled nutrients are then transported to the continental shelf by Ekman flow away from the gyre center (Coyle and Pinchuk 2003). Nutrients in the form of nitrates are also transported by deepwater flow to the shelf (Coyle and Pinchuk 2003). Second, 1973 was also an El Niño year. Regime shifts are correlated with and appear to begin as El Niño events (Yasunaka and Hanawa 2005). Third, the one-year time lag between the L2 shift in 1973 and the L1 and L3 shifts in 1974 may be due to an offshore process in the central or western North Pacific Ocean that propagated into the Gulf of Alaska. Therefore, these indices of fish length may be useful predictors several years in advance of future changes in the ecosystem structure in the North Pacific Ocean.

Two possible brood-year effects occurred in the time series where shifts in body size during an earlier life stage were detected as shifts during a later life stage. For example, the negative shift in L1 in 1989 corresponded with a negative shift in L3 in 1991 and the positive shift in L2 in 1973 corresponded with a positive shift in L3 in 1974. In addition, waters in the Gulf of Alaska were cold in 1991 and warm in 1974 (Hare and Mantua 2000). A combined brood-year effect and temperature-related anomalies in production in the Gulf of Alaska may account for the shifts in length.

The coherence in the timing of the shifts in L1 and

L3 time series indicates that a similar process affected the growth of juvenile and maturing sockeye salmon from the Karluk River. Both juvenile and maturing salmon spend a portion of their life in the eastern North Pacific Ocean, while immature salmon occur in the central and western North Pacific Ocean (Myers et al. 1996). In addition, fewer shifts in the L2 than the L1 and L3 time series indicate that fish in the central North Pacific Ocean may occupy a more stable environment than fish in coastal waters of the Gulf of Alaska and the eastern North Pacific Ocean.

From a regional perspective, similar shifts occurred in the indices of fish length at maturing of sockeye salmon that returned to the Karluk River in the Gulf of Alaska and to Bristol Bay in the eastern Bering Sea. For example, the mid-1970s and the late 1980s shifts in the L3 time series for Karluk sockeye salmon were also detected as shifts in the mean age-specific length of adult Bristol Bay sockeye, however only after the data were filtered for the effects of sockeye and pink salmon abundance (Ruggerone et al. 2007). Coherence in the response of length changes in sockeye salmon from the Gulf of Alaska and Bering Sea indicate that similar processes affected recent shifts in the final body size at maturity of sockeye salmon in the two regions.

Even though most shifts in the fish length indices did not match shifts in climate regime indices, the indices of fish length have some potential as predictors of major ecosystem change in the North Pacific Ocean. For example, shifts in juvenile, immature, and maturing lengths occurred several years in advance of the 1976–77 major climate and ecosystem change in the North Pacific Ocean. The overall increases in the fish length indices over time and especially around the 1958 El Niño and the 1976–77 regime shift indicates that further increases in sea-surface temperatures would possibly increase the body length of these sockeye salmon originating from the eastern North Pacific.

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