Climate Indicators of Salmon Survival[1][2]

James J. Anderson[3] and Richard A. Hinrichsen[2]
School of Fisheries and Center for Quantitative Science
University of Washington[4]

Abstract

Using studies from the Columbia River, salmon survival and catch measures were correlated with several Pacific Northwest climate indices. Spring chinook survival rate and catch were varied with the Pacific Northwest climate index (PNI), which characterizes temperature and precipitation cycles in the Pacific Northwest. Cool / wet conditions were associated with higher survival and catch while warm / dry conditions were associated with lower stock measures. At a finer temporal scale, the survival of spring chinook from smolt to adult was correlated with the arrival time of smolts into the estuary and the spring transition date, which signals the beginning of spring and coastal upwelling. A match / mismatch hypothesis is suggested to explain how variation in spring transition and estuary entry dates can effect stock survival. The effects of hatchery production and hydrosystem passage on year class strength is also considered in terms of the match / mismatch mechanism.

Introduction

The decline of salmon fisheries has been attributed to cumulative human activities and a cyclic environment. Although impacts of human activities are easily identified, the impact of climate on declining stocks is only recently appreciated. How climate alters salmon productivity is poorly understood and how anthropogenic changes alter a stock's response to climate variations even less so. These issues have been studied to identify causes for the decline of Columbia River salmon.

Columbia River salmon have declined principally from human activity including: harvest, mining, logging and hydroelectric development. Although hydroelectric dams are identified as a major factor, catch decline began about 1920, which was prior to the development of the hydroelectric system (Fig. 1). In the 1970s a hatchery program was initiated to increase salmon production. In spite of this and other efforts to improve fish passage, the stocks have continued to decline. Recent studies, designated the Process for Analyzing and Testing Hypotheses (PATH), have focused on identifying the individual contributions of harvest, habitat, hydro, hatcheries and climate to stock declines (Marmorek et al 1996). Through PATH, progress is being made to understand the effect of climate on fish and how human activities might have altered the response of salmon stocks to climate.

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[3] Columbia Basin Research, University of Washington, Box 358218, Seattle WA, 98195
[4] e-mail jim@fish.washington.edu, hinrich@cqs.wasahington.edu

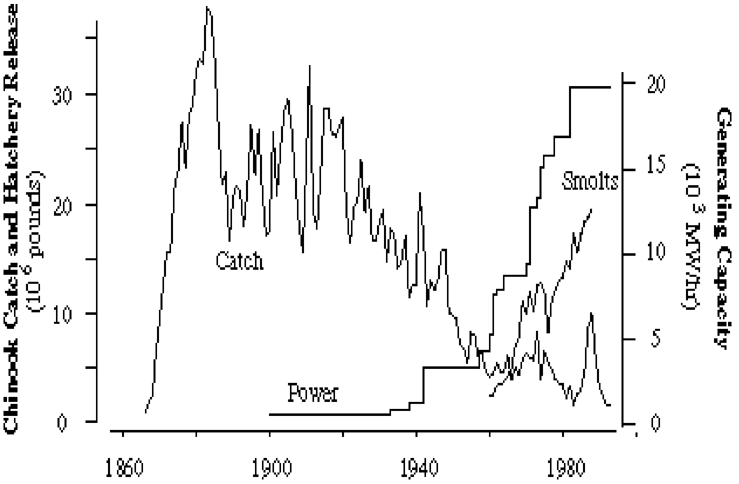

Fig. 1 Trends in Columbia River spring chinook catch, hydroelectric generating capacity and hatchery smolt production.

In general, human development produces a gradual and continuing decline in salmon productivity while climate variations produce cycles (Anderson 1996). Together the two processes can generate an oscillatory stock decline where succeeding peak population levels are smaller than previous ones resulting in a "ratchet-like" decline as observed in the Columbia River salmon (Fig. 1). This ratchet-like decline can be produced by an increasing anthropogenic-derived mortality rate and an oscillatory climate-derived mortality rate (Fig. 2).

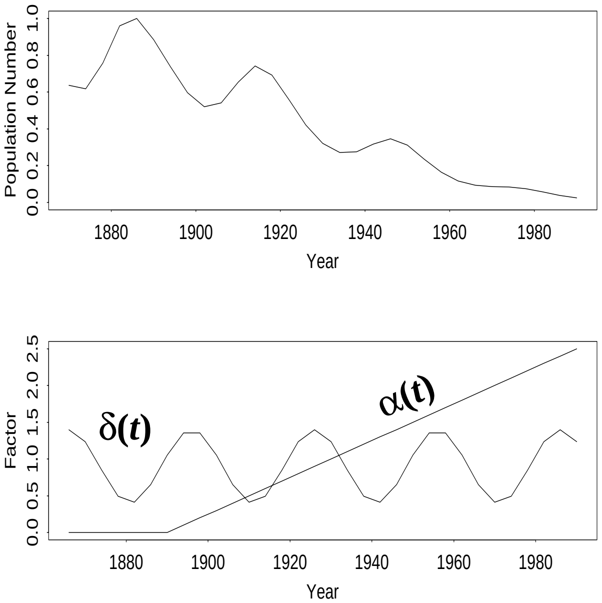

Fig. 2 Salmon decline under ratchet processes is driven by increasing cumulative anthropogenic impacts on mortality, $\alpha(t)$, and a climatic cycle impact $\delta(t)$.

Fish-climate relationships

The problem is to determine the separate contributions of human and climate factors to the decline. A study by Deriso, Marmorek and Parnell (1996) used a Maximum Likelihood Estimator form of a Ricker model on stock-recruitment data from the Columbia River to separate hydrosystem effects from year-to-year effects, which are presumably controlled by the climate (Fig. 3). Variations in the year-to-year mortality rate (δ), which was common to all the Columbia River spring chinook, exhibited a decadal scale pattern that was correlated with the Pacific Northwest Index (PNI) (Ebbesmeyer and Strickland 1995)[1]. In general, the indicators move out of phase: positive PNI values (associated with warm-dry weather) occurred with negative δ values (associated with lower survivals) while negative PNI values (cool -wet weather) occurred with positive δ values (higher survivals).

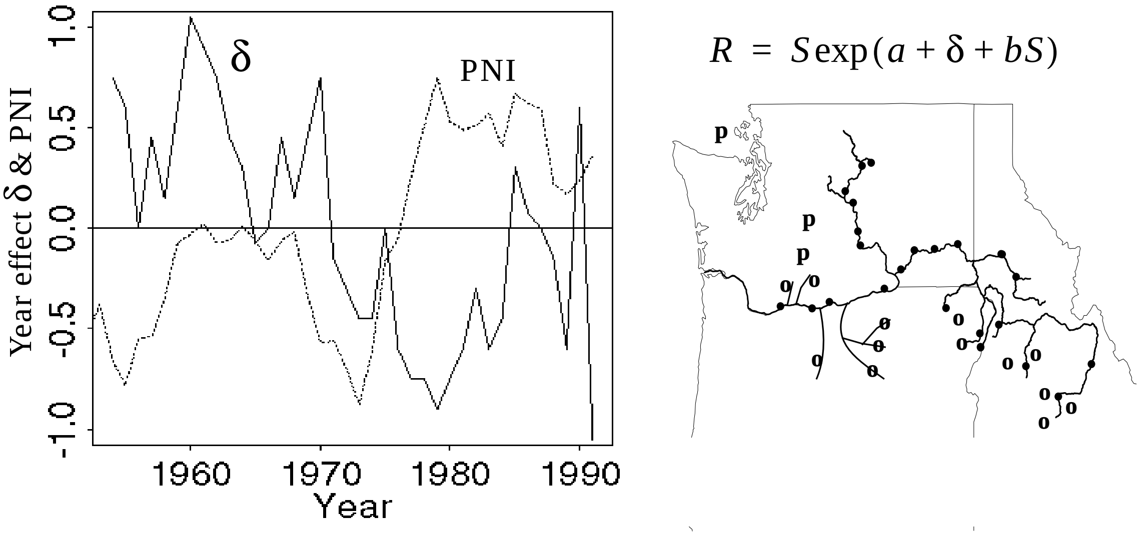

Fig. 3 The survival rate year affect δ and PNI. Locations of spring chinook stock (**o**) and PNI measures (**p**). Ricker density dependent and independent parameters are a and b in a Ricker stock (S) recruitment (R) equation.

The PNI and the Columbia River spring chinook catch are also related, with the high catch occurring with negative PNIs and low catch occurring with positive PNIs (Fig. 4). For both PNI vs. spring chinook catch index[2] and PNI vs. δ, the data fall mostly within two quadrants: a Warm regime quadrant (PNI > 0, δ and catch index < 0) and a Cool regime quadrant (PNI < 0, δ and catch index > 0). Transitions between the two regimes occurred about 1945 and 1975. For both comparisons, the regressions have negative slopes and correlation coefficients, $|r| > 0.5$ (Fig. 5). These correlations, although weak, do suggest that climate produces long-term variations in stock productivity by possibly altering the terrestrial and nearshore habitat of the fish.

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[1] The PNI is a terrestrial climate index containing three measures: yearly averaged air temperature, rainfall and snowpack. For each measure, the yearly value is subtracted from the mean of the series and divided by the standard deviation. The three measures are averaged to yield the yearly values which are then smoothed with a five-year running average to yield the PNI.

[2] Yearly catch is subtracted from the mean of the series and divided by the standard deviation.

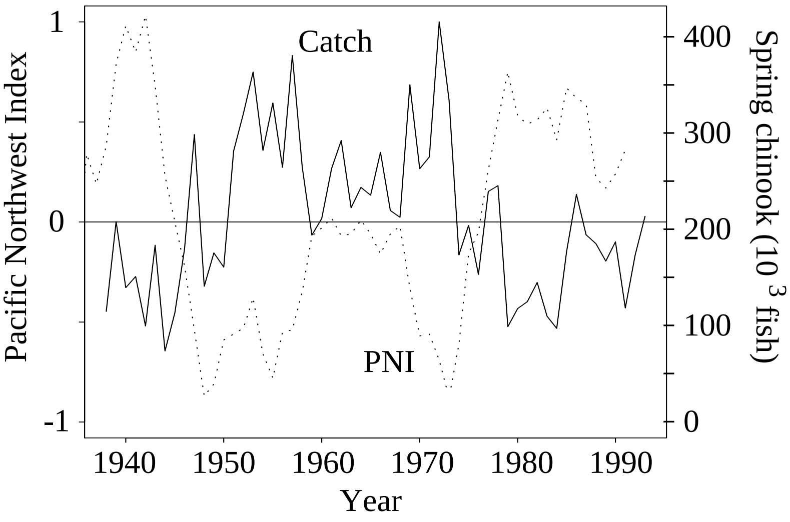


Fig. 4 Columbia River spring chinook catch and PNI over years.

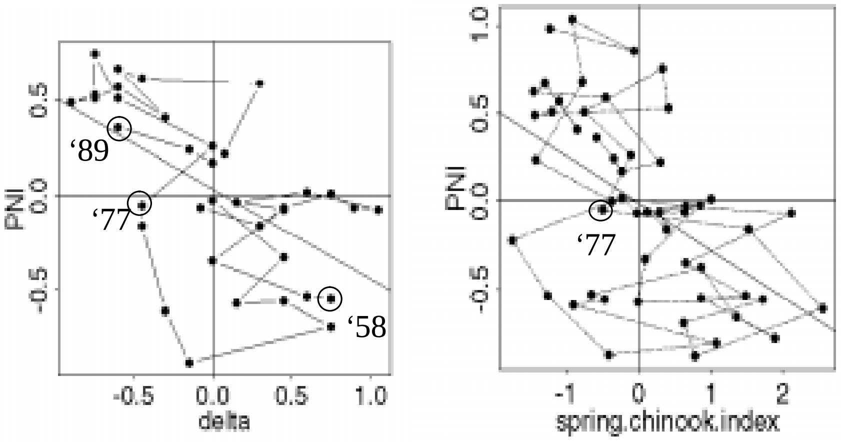
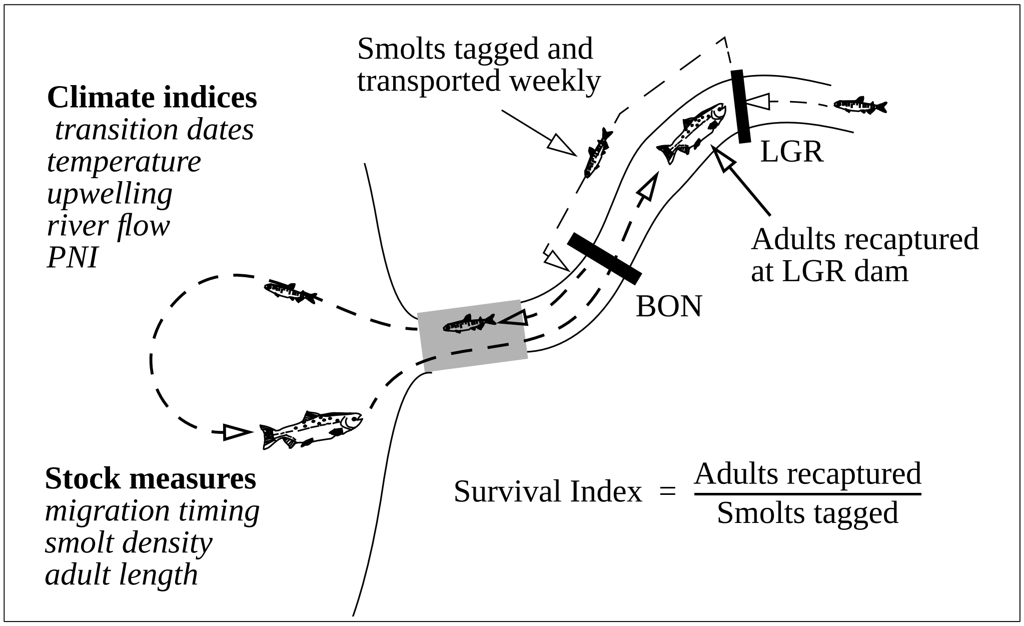


Fig. 5 PNI vs. delta (1958-1991) and PNI vs. spring chinook index (1938-1993) catch. Data falls into two quadrants (PNI > 0, δ and catch index < 0) and (PNI < 0, δ and catch index > 0).

To understand possible causes of fish and climate correlations we consider the early ocean stage of salmon, which is thought to dominate the year class strength since jack salmon returning in the first year of ocean residence often have a strong positive relationship with adults returning several years later (Pearcy 1992). In particular, we have tested whether the timing of smolt entry into the estuary has a significant correlation with adult survival using information on the survival of adult spring chinook salmon released as juveniles above the Columbia River estuary. These survival data were collected as part of the smolt transportation program which barges migrating smolts from the Snake River dams to below Bonneville Dam (the last hydroelectric project on the Columbia). During the spring migration smolts were collected, tagged and transported to below Bonneville Dam on a weekly basis. Between 1983 and 1990 over 350,000 smolts were tagged with coded wire tags and adults were recovered in the fishery, at the dams and in the hatcheries (Fig. 6).



$$\text{Survival Index} = \frac{\text{Adults recaptured}}{\text{Smolts tagged}}$$

Fig. 6 Configuration of fish transportation system from which survival data was obtained. Also indicated are variables used in the GLM analysis.

The data revealed that the survival index (Fig. 6), a surrogate for survival from transport release to adult recovery, was related to migration timing. Of the juveniles marked, those migrating late in the season had a two-fold increase in the survival index over the early migration fish. The highest contrast was seen in 1990, when there was a five-fold increase in the survival index for late versus early migrants.

Using a generalized linear model (GLM) Hinrichsen et al. (1996) identified variables that correlated with the survival index. The variables included river flow, solar radiation, wind velocity, the PNI, migration timing, the date of the spring and fall transitions, adult fish length and a measure of upwelling through coastal wind velocity (Fig. 6). Of these variables migration timing and spring transition explained the most year-to-year variation in the survival index. The PNI was not significant over the short period of the data (1983-1990). From the analysis Hinrichsen et al.(1996) concluded:

- Most fish returned at age 4 (8% at age 3, 58% at age 4, and 33% at age 5).
- Within a season, later migrants (19 Apr-8 Jun) had a higher adult survival index (0.29%) than earlier migrants (16-22 Apr) (0.11%).
- Spring transition date was the best predictor among those explaining year-to-year variation (as opposed to within-year variation). All else being equal, an earlier spring transition gave higher survival indices.
- A longer summer during out migration (spring transition date - fall transition date), was less favorable to survival than a shorter summer.
- Higher river flows were negatively correlated with the survival index.
- Larger Snake River hatchery releases were negatively correlated with the survival index.

- The Pacific Northwest Index, solar radiation, age-specific length of returning fish, and wind velocity (which drives coastal upwelling) were not significantly related to the survival index. Some of these variables, such as the PNI, may be important only over longer time scales than the 8 years in the study.

The spring transition and smolt migration dates were the most significant predictors of the year-to-year variation in fish survival. The spring transition date is identified by the reversal of winds, which marks the beginning of spring and the onset of coastal upwelling (Pearcy 1992). Prior to the spring transition, the average north-south component of the wind is from the south; after the spring transition the component is from the north. The spring transition moves up the coast as the year progresses and conversely the fall transition moves down the coast in the autumn. These yearly movements are illustrated in Fig. 7, which shows fifty-year averaged isopleths of the north-south wind component along the coast as a function of latitude and month. The dates of the spring and fall transitions at any latitude change from year to year and may vary by over three months (Ebbesmeyer, Hinrichsen and Ingraham 1996).

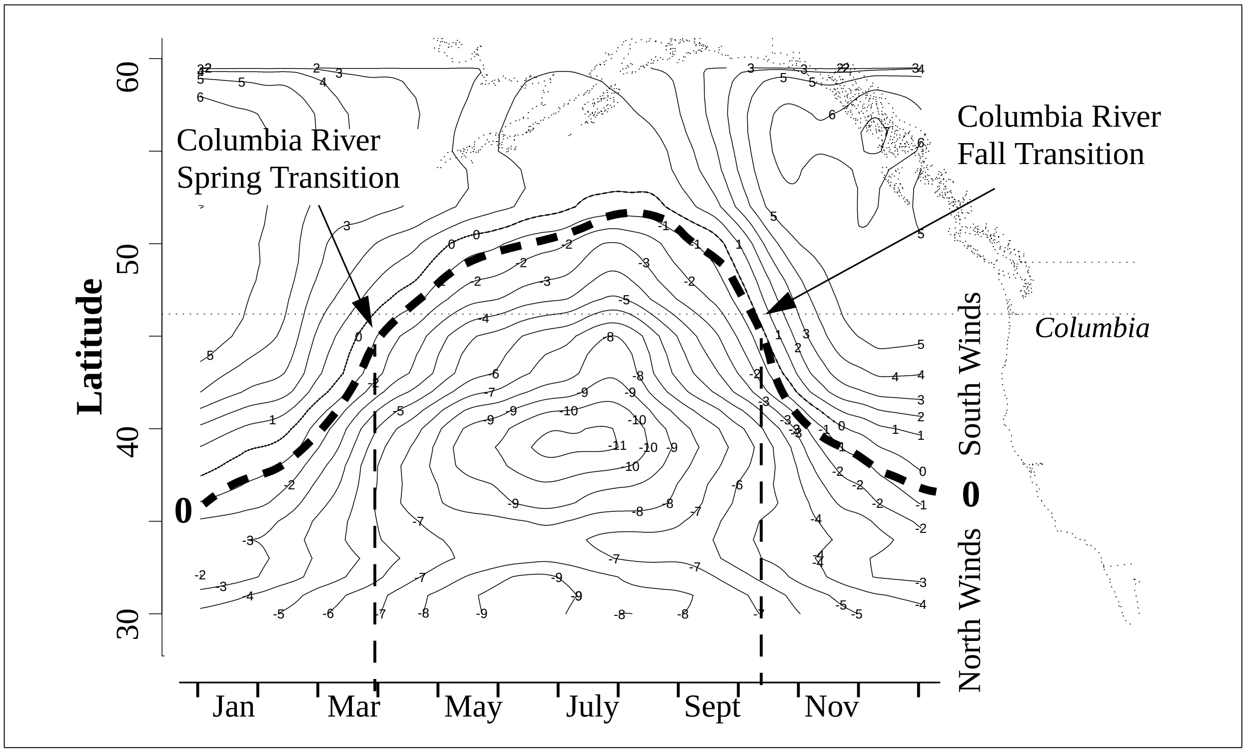


Fig. 7 Isopleths of north-south component of coastal wind velocity (m/s) by month and latitude averaged over years 1946-1994. Positive velocity (southerly wind component) designates winter and fall seasons, negative velocity (northerly wind component) designates spring and summer seasons. Transitions at 0 isopleth.

Hypothesis

The relationship between the timing of smolt migration and the spring transition may be a critical element in the correlation between salmon survival and climate. The work of Hinrichsen et. al (1996) indicates a relationship with survival likely exists. The work of Ebbesmeyer et al. (1996) indicates the transition has a decadal scale pattern that may involve both climate and anthropogenic effects. These relationships suggest stock year class strength may, in part, be formed through a match / mismatch mechanism similar to that proposed by Cushing (1975) for North Sea herring. In this hypothesis the herring spawn within a fixed period of time so larval survival and consequentially year class strength depend on the matching or mismatching of spawning to the local plankton production, which is highly variable and may vary by six weeks in British waters. For Columbia River smolt survival, the possibility of a match / mismatch process is even greater since the spring transition can vary by over three months and the arrival time of certain stocks varies considerably less. The implications for hatchery production is especially significant since hatchery smolts are typically released on a given day. Furthermore, the smolt transportation program, may truncate smolt arrival timing to the estuary and thus may alter the response of fish to the estuary's natural variations. A match / mismatch process may also contribute to the recent decadal scale pattern of stock variations since the date of the spring transition has increased since the early '60s (Ebbesmeyer et al 1996).

The potential effect of human activities in the Columbia River system on a match / mismatch process is illustrated in Fig. 8. If smolt survival is determined by when smolts arrive in the estuary and the spring transition date, then any human activities that affect estuary arrival would affect the smolt survival response to spring transition variations. In Fig. 8 a hypothetical Snake River stock, composed of hatchery fish which are transported from Snake River dams, arrive in the estuary over a narrow period of time while a lower river wild stock, which migrates to the estuary through the lower river, arrives over a protracted period. If the period of favorable estuary survival is variable from year-to-year then the match of the hatchery stock to the favorable period would be less likely than for the wild stock. As a result, the hatchery stock could exhibit more variability in year class strength as a result of the activities that truncate its estuary entry dates.

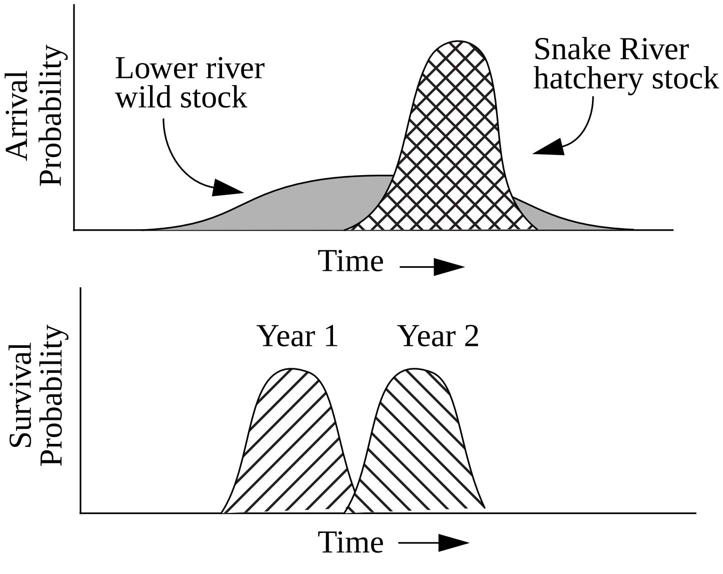


Fig. 8 Hypothetical comparison of arrival time of a wild and hatchery stock and variations in estuary survival conditions over two years.

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