
**Time Series Outlier Analysis: Evidence for Management
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ABSTRACT: Autoregressive, moving average models were fit and outliers were identified for commercial catches of 9 major sockeye salmon *Oncorhynchus nerka* stocks in Alaska and northern British Columbia. Distinct patterns in the sample autocorrelation and partial autocorrelation functions indicated stock-specific dynamics. Three types of outliers were considered: level-shift, temporary-change, and additive outliers. Most additive outliers were unexplainable and may represent multiplicative survival at several different life history stages. Additive outliers that could be explained resulted from changes in fishing effort. Temporary-change outliers commonly reflected cold winter temperatures in western Alaska during the early 1970s. Four of nine river systems in our analysis had level-shift outliers, and only one of these had a positive shift in the late 1970s. The level-shift outliers, which indicate a long-term shift in catch levels, appeared to be the result of changes in escapement policy rather than an abrupt change in the production dynamics of the North Pacific.

INTRODUCTION

Sockeye salmon *Oncorhynchus nerka* catches in Alaska have fluctuated greatly over the last 60 years. Although there can be large year-to-year variation in catch levels, an obvious increasing trend is apparent in the commercial catch (Figure 1). Sockeye salmon catches reached their lowest levels between the mid 1940s and mid 1970s but recovered to record highs in the 1990s. This dramatic shift in salmon catches throughout Alaska has sparked renewed interest in explaining and modeling the possible underlying mechanisms responsible for salmon catch trends.

The most recent analyses of Alaska salmon catch have used time series models. Hare and Francis (1995) used univariate models and intervention analyses for sockeye salmon of western and central Alaska and pink salmon *O. gorbuscha* in southeastern Alaska. Quinn and Marshall (1989) used univariate and multivariate time series analyses to model catch of pink and chum *O. keta* salmon in southeastern Alaska. Each study indicated an underlying environmental mechanism as the possible cause for dynamic trends in salmon production.

The focus of previous time series analyses has been on aggregate catch, either by species and region within Alaska (southeastern, central, and western) or total Alaska catch by species. Although aggregate salmon catches contain similar trends during the same periods (Hare and Francis 1995), temporal patterns of catches, disaggregated by separate river systems or management units, may differ. Marshall and Quinn (1987) found patterns or trends in aggregate southeastern Alaska salmon catch data that were difficult to interpret; they recommended analysis on disaggregated salmon catches.

Much of the difficulty in interpreting patterns in the aggregate catch is due to the inability to adequately separate variable effects of environment and management. The geographic scale of environmental influences on salmon production can range from the entire North Pacific to local climate in freshwater rearing areas.

Direct management effects on salmon production are most easily interpreted for individual stocks or river systems, the functional unit often used in management. By maintaining a resolution in the catch data that most closely matches the resolution of management actions,

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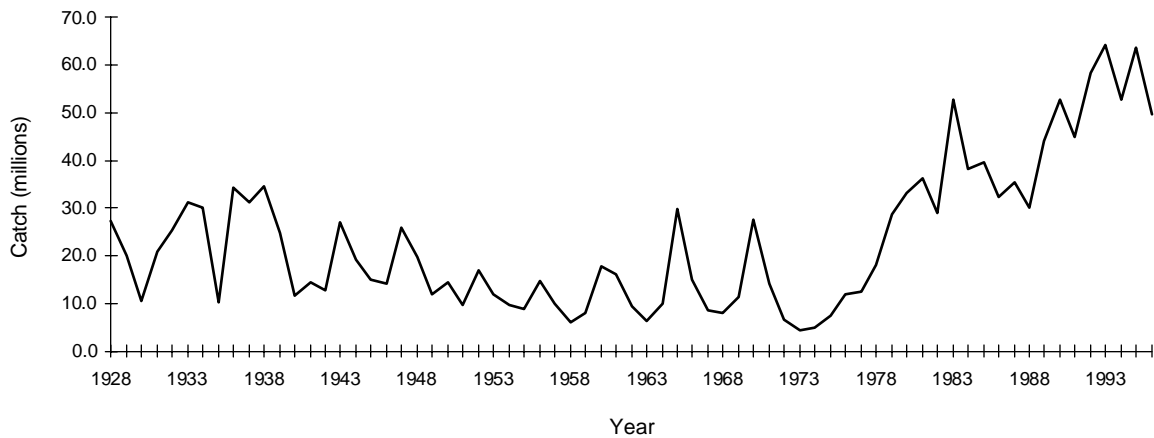


Figure 1. Total Alaska sockeye salmon commercial catch, 1928–1996.

we can more effectively segregate the relative influence of management and environment. In this paper, we examine sockeye salmon catch time series for 9 individual river systems from western, central, and southeastern Alaska and northern British Columbia by analyzing the relationship of data series outliers in terms of management strategies and environmental influences.

METHODS

Our approach to analyzing the catch time series was separated into 3 parts. First, we identified the appropriate univariate model for each river system based on autocorrelation patterns (Box and Jenkins 1976). Then we simultaneously estimated the model parameters and detected the presence of outliers in each data series through an iterative procedure developed by Chen and Liu (1993). Last, we discussed each outlier in terms of management strategy and environmental influences.

Data

We modeled commercial catches of 9 sockeye salmon stocks aggregated into 3 regions: southeastern Alaska including British Columbia (BC), western Alaska, and central Alaska. Catch data for the 9 stocks were from the Skeena River (BC) and the Situk River in southeastern Alaska; the Ugashik, Naknek/Kvichak, and Egegik Rivers in western Alaska (Bristol Bay); and the Alitak, Karluk, Chignik, and Copper Rivers in central Alaska (Table 1; Figure 2). Catch data were not available for the Egegik River in 1942, 1943, and 1945; for the Ugashik River in 1935; and for the Situk River in 1928, 1929, 1932, 1936, 1937, and 1960. Catch data

for the missing years were estimated by the average of the previous 5 annual catches. Catches were log-transformed (Figure 3) to stabilize variance in the catch; catches tended to have a skewed distribution and variance increased as the mean increased.

Univariate Time Series Analysis

Univariate autoregressive integrated moving average (ARIMA) modeling techniques (Box and Jenkins 1976) were used to reveal patterns and relationships in the sockeye salmon catch data. A 3-phase approach for identifying and fitting ARIMA models was used: (1) model identification, (2) estimation of model parameters, and (3) diagnostics and model criticism. Autoregressive (AR) and moving average (MA) models were fit to the data. In AR processes, the present value of a time series depends on preceding values plus a random shock. A p^{th} order AR process, designated ARIMA($p,0,0$) or AR(p), is defined by

$$Z_t = \phi_1 Z_{t-1} + \phi_2 Z_{t-2} + \dots + \phi_p Z_{t-p} + a_t, \text{ or} \\ (1 - \phi_1 B - \phi_2 B^2 - \dots - \phi_p B^p) Z_t = a_t, \quad (1)$$

where ϕ_j is the j^{th} AR, $Z_t = (z_t - \mu)$, μ is the series mean, a_t is the Gaussian white-noise error term at time t , and B is the backward-shift operator where $B^p(Z_t) = Z_{t-p}$. In MA processes, random events produce an immediate effect that dissipates after short periods. The q^{th} order MA model, designated as ARIMA(0,0, q) or MA(q), is defined by

$$Z_t = a_t - \theta_1 a_{t-1} - \dots - \theta_q a_{t-q}, \text{ or} \\ Z_t = (1 - \theta_1 B - \theta_2 B^2 - \dots - \theta_q B^q) a_t, \quad (2)$$

where θ_q is the q^{th} MA parameter.

Table 1. References used to build the sockeye salmon catch data series for each river system.

River	Years and Data Sources				
Skeena	1928–1954 ^a	1955–1967 ^b	1968–1972 ^c	1973–1984 ^d	1985–1996 ^e
Situk	1930–1949 ^f	1951–1959 ^g	1960–1996 ^h		
Copper	1928–1991 ⁱ	1992–1994 ^j	1995–1996 ^k		
Alitak	1928–1996 ^l				
Chignik	1928–1966 ^m	1967–1987 ⁿ	1988–1994 ^o	1995–1996 ^k	
Karluk	1928–1996 ^l				
Ugashik	1928–1955 ^p	1956–1995 ^q	1996 ^r		
Naknek/Kvichak	1928–1955 ^p	1956–1995 ^q	1996 ^r		
Egegik	1928–1955 ^p	1956–1995 ^q	1996 ^r		

^a Shepard and Withler (1958)

^b DFF (1970)

^c INPFC (1970 and through 1975)

^d DE (1974 and through 1979); DFO (1980 and through 1985)

^e Data for 1985–1996 c/o John Morris, Department of Fisheries and Oceans, Nanaimo, British Columbia

^f USDIFWS (1930 and through 1949)

^g Simpson (1960)

^h Data for 1960–1996 c/o Ben Van Alen, Alaska Department of Fish and Game, Juneau

ⁱ Rigby et al. (1991)

^j Geiger and Savikko (1993); Geiger and Simpson (1994, 1995)

^k Buls (1996); Shapiro (1997)

^l Data for 1928–1996 c/o Chris Hicks, Alaska Department of Fish and Game, Kodiak

^m Dahlberg (1968)

ⁿ Barrett (1989)

^o Savikko (1989); Savikko and Page (1990); Geiger and Savikko (1991, 1992, 1993); Geiger and Simpson (1994, 1995)

^p INPFC (1979)

^q Data for 1956–1995 c/o Beverly Cross, Alaska Department of Fish and Game, Anchorage

^r Alaska Department of Fish and Game web page — <http://www.state.ak.us/adfg/cfmd/geninfo/finfish/salmon/salmhome.htm>

Both AR and MA models required stationary time series, i.e., no trend in variance or mean values. Trends in mean values were removed by taking successive differences of the data, to create a new series z'_t , where $z'_t = Z_t - Z_{t-1}$. The number of differences required for a stationary series to evolve was denoted by d . Non-stationary variance was remedied by applying a logarithmic transformation (Vandaele 1983; Quinn 1985). Differencing operations and AR and MA models can be combined into a single model known as the autoregressive, integrated, MA model, or ARIMA(p, d, q). The equation for the ARIMA(p, d, q) model is defined by

$$(1 - \phi_1 B - \phi_2 B^2 - \dots - \phi_p B^p)(1 - B)^d Z_t = C + (1 - \theta_1 B - \theta_2 B^2 - \dots - \theta_q B^q) a_t. \quad (3)$$

The term C is related to the mean of the process when the original process is stationary, i.e., $C = \mu(1 - \phi_1 - \dots - \phi_p)$.

Three functions were used in identifying time series models: sample autocorrelation function (SACF), sample partial autocorrelation function (SPACF), and extended sample autocorrelation function (ESACF). The SACF measures the correlation between Z_t and Z_{t+k} , where k is the time lag, whereas the SPACF quantifies the correlation between Z_t and Z_{t+k} after their mutual linear dependency on the intervening variables ($Z_{t+1}, Z_{t+2}, \dots, Z_{t+k-1}$) has been removed (Wei 1990). AR models are characterized by an exponential or oscillatory decay of the SACF and one or more spikes at various lags in the SPACF. The opposite is true for MA models: decaying SPACF and spiked SACF. If the SACF decays very slowly and the SPACF cuts off after lag 1, the series is possibly nonstationary and requires a differencing operation (Wei 1990).

Mixed ARIMA models were identified using the ESACF (Tsay and Tiao 1984). The ESACF table is drawn with X for significant values and O for values that are within 2 standard errors of zero. Tentative models are identified by drawing a triangle whose

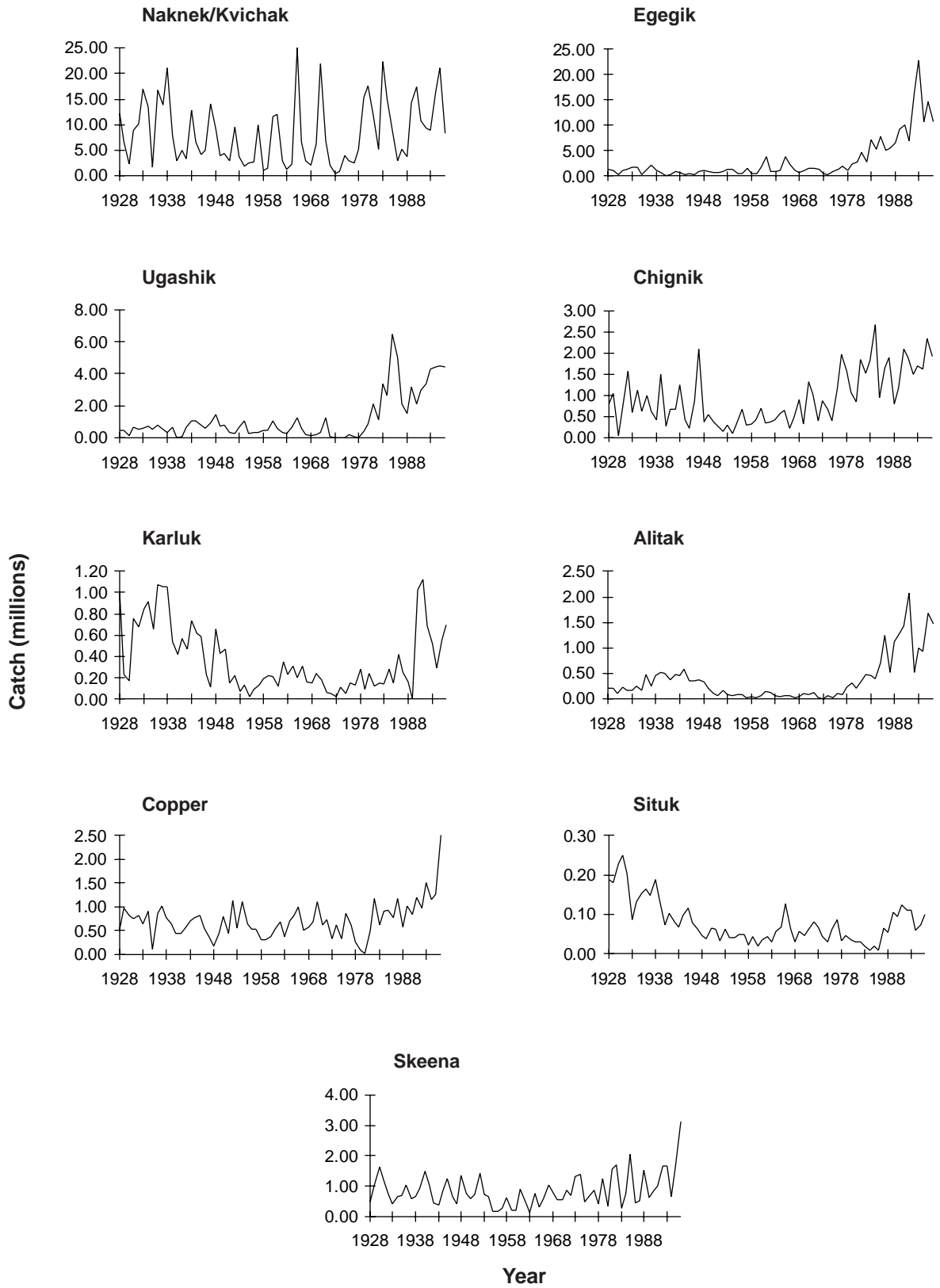


Figure 2. Sockeye salmon commercial catch for 9 major sockeye salmon-producing rivers in Alaska and British Columbia, 1928–1996.

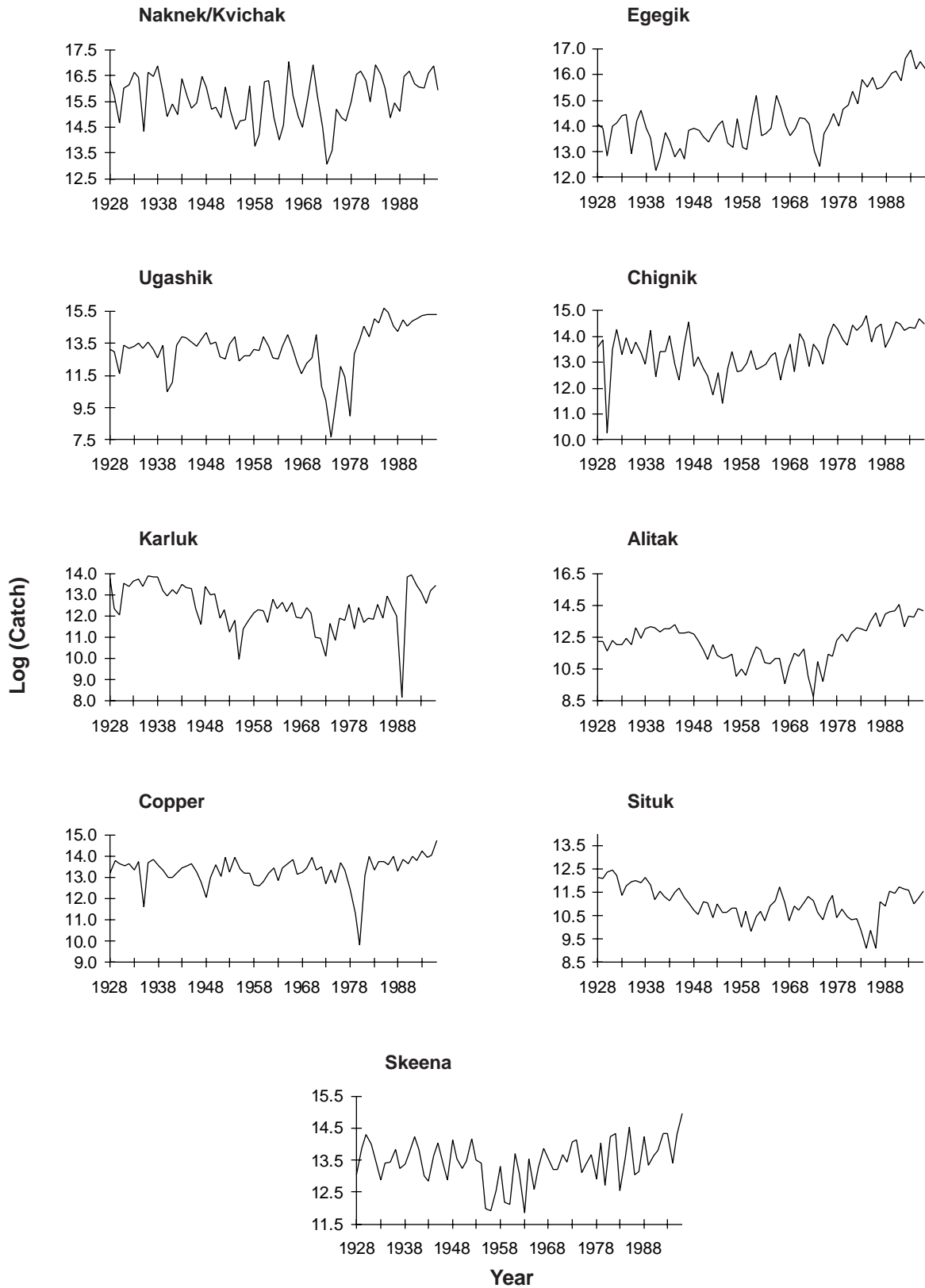


Figure 3. Sockeye salmon logarithm of commercial catch for 9 major sockeye salmon-producing rivers in Alaska and British Columbia, 1928–1996.

vertex is in the position (p_0, q_0) so that all O values in the table are for the (i, j) coordinates in the triangular region, where $i = p_0 + k$ and $j \geq q_0 + k$, $k = 0, 1, 2, \dots$. Examples of ESACF use are found in Tsay and Tiao (1984), Quinn and Marshall (1989), Wei (1990), and Farley (1996).

Model parameters were estimated using the maximum likelihood method. The significance of the model parameters was determined by constructing a test statistic defined by t , the estimate minus the hypothesized value divided by the estimated standard deviation of the estimate.

This statistic was compared to the critical value of the t distribution for the 5% level with $(n - p)$ degrees of freedom. In general, the hypothesis, ϕ_p or $\theta_q = 0$, was rejected when the t value was >1.7 ($n \leq 70$). Diagnostic checks were performed to assess model adequacy by checking whether the model assumptions were satisfied. The basic assumption is that the $\{a_t\}$ values were uncorrelated random shocks with a zero mean and constant variance (Wei 1990). The sample ACF and PACF of the $\{a_t\}$ values were used to determine if the residuals showed any patterns and that autocorrelation at all lags were statistically insignificant (within 2 standard deviations at the 5% level). The presence of large autocorrelations in the SACF of the residuals indicated the model was inadequate.

Outlier Detection

Three types of outliers were considered, including additive outliers (AO), level shifts (LS), and temporary changes (TC; Chen and Liu 1993; Figure 4). An AO is a pulse that affects the time series at one period only. An LS is an event that permanently affects the subsequent level of a series. A TC is an event that decays exponentially according to a prespecified dampening factor.

The AO, LS, and TC occurring at time $t = T$ can be represented as

$$\begin{aligned} \text{AO: } & Y_t = Z_t + \omega_A P_t^{(T)} \\ \text{LS: } & Y_t = Z_t + \omega_L S_t^{(T)} \\ \text{TC: } & Y_t = Z_t + \frac{1}{1 - \delta B} \omega_c P_t^{(T)}, \quad (4) \end{aligned}$$

where $P_t^{(T)}$ is referred to as a pulse function represented in a binary fashion, assuming the value 1 when $t = T$ and 0 otherwise, and $S_t^{(T)}$ is referred to as a step function represented in a binary fashion, assuming the value 0 before $t = T$ and the value 1 thereafter. The values for ω_A , ω_L , and ω_c represent the deviation from

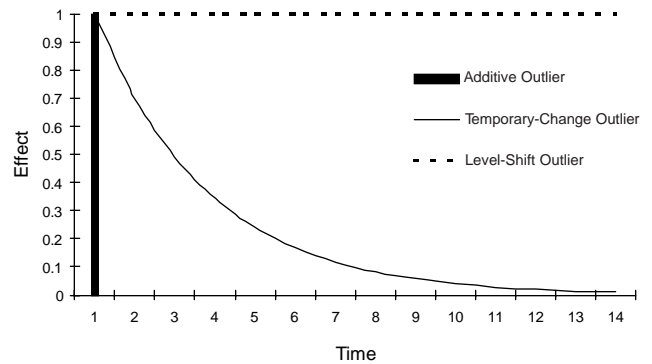


Figure 4. Plot illustrating the effect of an additive outlier, temporary-change outlier with $\delta=0.7$, and level-shift outlier on later periods.

the prior value of Z_t , and the δ parameter is the dampening factor, which can be specified by the analyst but is given a default value of 0.7 (Chen and Liu 1993).

After an ARIMA model was identified, model parameters and outliers within the time series were jointly estimated by an iterative procedure (Chen and Liu 1993). Outliers were detected by calculating 3 test statistics, 1 for each type of outlier. The largest test statistic (in absolute value) for each outlier type was retained and compared with a prespecified critical value. Chen and Liu (1993) suggest a critical value of 3.0 for data series with lengths between 100 and 200; for data series <100 , they suggest a critical value between 2.5 and 2.9. However, they point out that spurious outliers, or the presence of a large number of outliers, may appear when the critical value is too low, and they emphasize the need to validate the outliers through residual plots. We selected the lowest critical value that did not produce spurious outliers and resulted in an adequate model fit. Adequacy of the model fit was evaluated by both the residual pattern and the standard errors of the model parameters.

RESULTS

Univariate Models

For Naknek/Kvichak (western Alaska), autocorrelation at lags 1 and 5 in the SACF and lags 1, 2, 4, and 6 in the SPACF were significant (Figure 5). The complexity of the autocorrelation function indicated a possible need to difference the data. Differencing the data by 5 produced a less complex autocorrelation function and suggested a possible ARIMA(5,5,0) (Figure 6). The ESACF for differenced data (Figure 7) also suggested a possible ARIMA(5,5,0) model for the

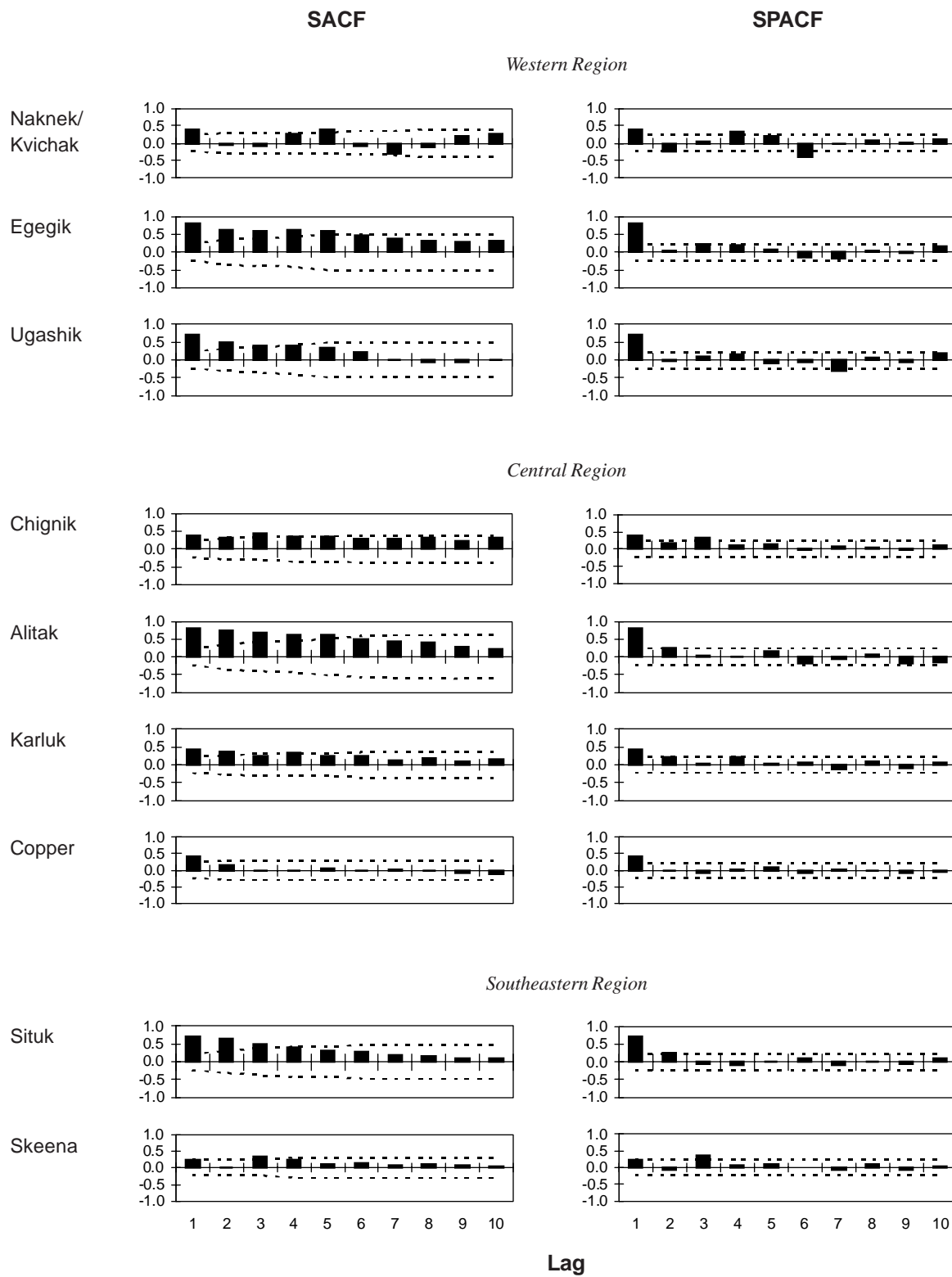


Figure 5. Sample autocorrelation function (SACF) and sample partial autocorrelation function (SPACF) for 9 sockeye salmon catch time series in western, central, and southeastern Alaska. Horizontal dashed lines represent ± 2 standard errors of the sample lag autocorrelation estimates.

Naknek/Kvichak sockeye salmon catch series. The ARIMA(5,5,0) model fit to the data series resulted in statistically insignificant AR terms for lags 2, 3, and 4. Analysis of the residuals indicated serial correlation had been adequately accounted for by the model. Therefore, the ARIMA(5,5,0) $\phi_{2-4}=0$ model was cho-

sen for the Naknek/Kvichak sockeye salmon catch (Table 2).

For Egegik (western Alaska), the SACF decayed slowly, indicating the series needed to be differenced (Figure 5). Differencing the series by 1 produced an SACF that cut off after lag 4 and an SPACF that con-

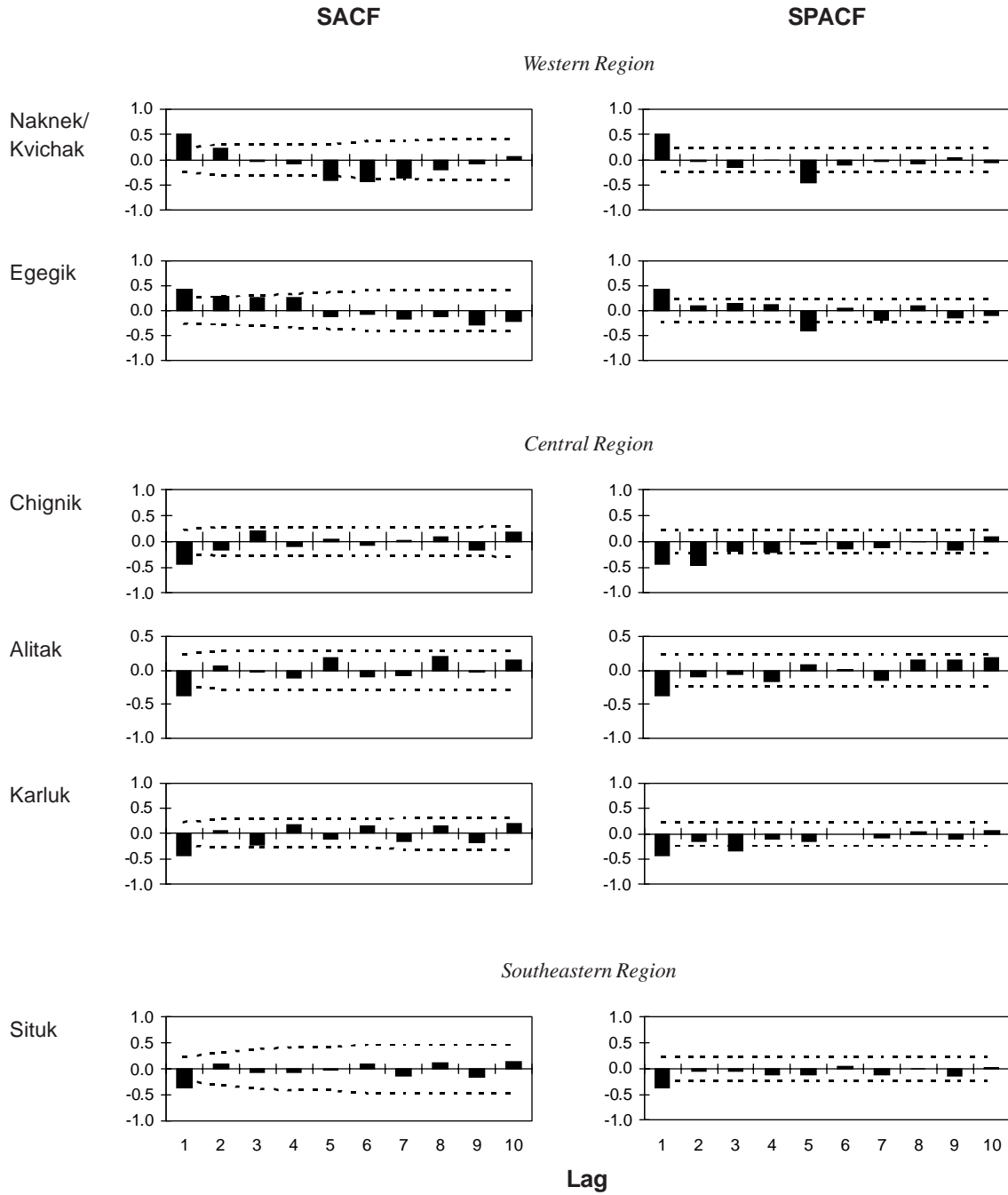
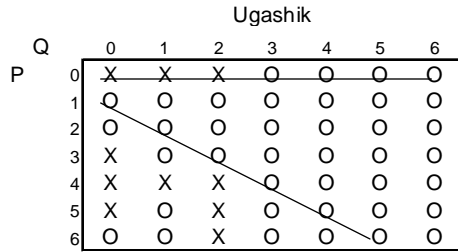
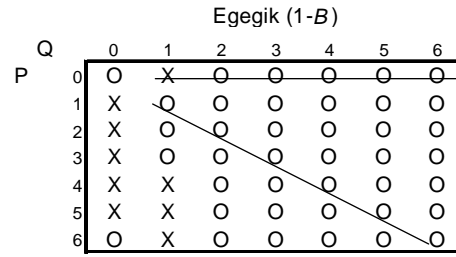
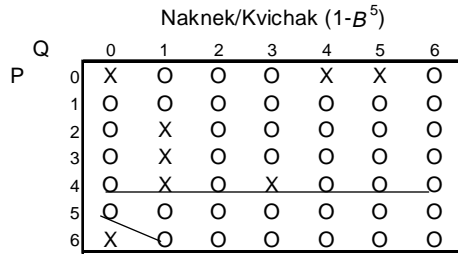
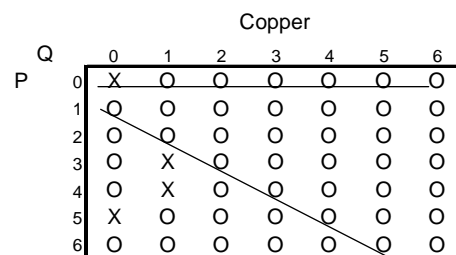
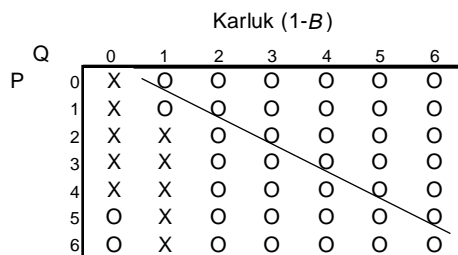
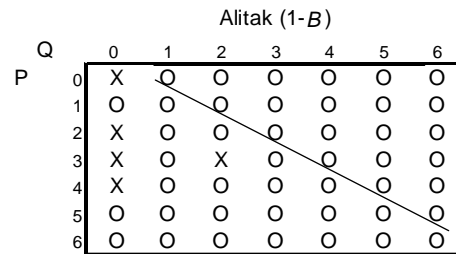
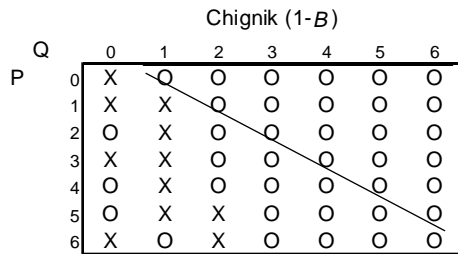


Figure 6. Sample autocorrelation function (SACF) and sample partial autocorrelation function (SPACF) of the differentiated sockeye salmon catch time series in western, central, and southeastern Alaska. Horizontal dashed lines represent ± 2 standard errors of the sample lag autocorrelation estimates.

Western Region



Central Region



Southeastern Region

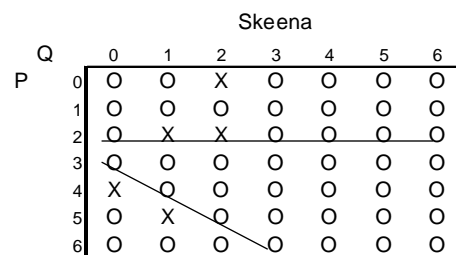
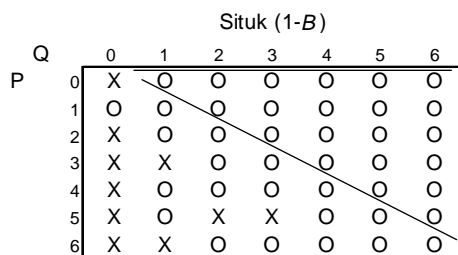


Figure 7. Extended sample autocorrelation function (ESACF) for 9 sockeye salmon catch time series in western, central, and southeastern Alaska. The letter “O” represents values that are ± 2 standard errors of zero.

Table 2. Parameter and adjusted parameter estimates, T values in parentheses, and residual standard errors (RSE) for both univariate time series models (ARIMA) and models that include outliers.

River	ARIMA Model	Univariate		Outlier	
		Parameter Estimates	RSE	Parameter Estimates	RSE
Naknek/ Kvichak	(5,5,0) $\phi_{2,4=0}$	$\phi_1 = 0.48$ (4.8) $\phi_5 = -0.37$ (-3.7)	0.780	$\phi_1 = 0.50$ (5.5) $\phi_5 = -0.44$ (-4.8)	0.724
Egegik	(5,1,1) $\phi_{1-4=0}$	$\theta_1 = 0.53$ (4.9) $\phi_5 = 0.34$ (2.9)	0.592	$\theta_1 = 0.52$ (4.7) $\phi_5 = 0.43$ (3.7)	0.525
Ugashik	(1,0,0)	$\phi_1 = 0.74$ (8.7) $C = 13.28$ (27.2)	1.056	$\phi_1 = 0.31$ (2.5) $C = 13.15$ (125.8)	0.591
Chignik	(0,1,1)	$\theta_1 = 0.80$ (10.4)	0.714		
Alitak	(0,1,1)	$\theta_1 = 0.41$ (3.7)	0.668	$\theta_1 = 0.35$ (3.0)	0.442
Karluk	(0,1,1)	$\theta_1 = 0.72$ (8.4)	0.923	$\theta_1 = 0.78$ (9.1)	0.474
Copper	(1,0,0)	$\phi_1 = 0.43$ (3.8) $C = 13.30$ (92.4)	0.679	$\phi_1 = 0.25$ (1.9) $C = 13.30$ (226.5)	0.364
Situk	(0,1,1)	$\theta_1 = 0.39$ (3.5)	0.471	$\theta_1 = 0.49$ (4.6)	0.413
Skeena	(3,0,0) $\phi_{2=0}$	$\phi_1 = 0.26$ (2.3) $\phi_3 = 0.36$ (3.2) $C = 13.48$ (70.7)	0.585	$\phi_3 = 0.36$ (2.9) $C = 13.56$ (134.7)	0.524

tained significant autocorrelation at lags 1 and 5, suggesting a possible ARIMA(5,1,0). The ESACF of the differenced series suggested a possible ARIMA(1,1,1) for the series (Figure 7). The ARIMA(1,1,1) model fit to the data series produced a statistically insignificant AR term for lag 1. The residual analysis of the ARIMA(0,1,1) model contained significant correlation at lag 5. The ARIMA(5,1,1) model fit to the data produced statistically insignificant AR terms for lags 1 through 4. The residual analysis of the ARIMA(5,1,1) $\phi_{1-4=0}$ model indicated serial correlation had been adequately accounted for by the model. Therefore, the ARIMA(5,1,1) $\phi_{1-4=0}$ was chosen for this series (Table 2).

For Ugashik (western Alaska), the SACF and SPACF indicated a possible ARIMA(1,0,0) model for the series (Figure 5). The ESACF also suggested a possible ARIMA(1,0,0) model for the sockeye salmon catch series (Figure 7). The ARIMA(1,0,0) model fit to the data series produced a statistically significant AR term for lag 1. Analysis of the residuals indicated that serial correlation for the series was adequately accounted for by the model. Therefore, the ARIMA(1,0,0) model was chosen for this series (Table 2).

For Chignik (central Alaska), the SACF decayed slowly, indicating the series should be differenced

(Figure 5). Differencing the series by 1 produced an SPACF that decayed exponentially and an SACF that contained statistically significant correlation at lag 1 (Figure 6), suggesting a possible ARIMA(0,1,1). The ESACF of the differenced series also indicated a possible ARIMA(0,1,1) model (Figure 7). The ARIMA(0,1,1) model fit to the data series produced a significant MA term for lag 1. Analysis of the residuals for the ARIMA(0,1,1) model indicated that serial correlation was adequately accounted for by the model. Therefore, the ARIMA(0,1,1) model was chosen for this series (Table 2).

For Alitak (central Alaska), the SACF decayed slowly, indicating the series should be differenced (Figure 5). Differencing the series by 1 produced an SPACF that decayed exponentially and an SACF that contained significant correlation at lag 1 (Figure 6), suggesting a possible ARIMA(0,1,1). The ESACF for the differenced series also indicated a possible ARIMA(0,1,1) model (Figure 7). The ARIMA(0,1,1) produced an adequate model, and analysis of the residuals indicated no other serial correlation. Therefore, the ARIMA(0,1,1) model was chosen for this series (Table 2).

For Karluk (central Alaska), the SACF decayed slowly, indicating the series should be differenced

(Figure 5). The SACF and SPACF of the differenced $(1-B)$ series indicated a possible ARIMA(0,1,1) model for the series (Figure 6). The ESACF of the differenced series also suggested a possible ARIMA(0,1,1) model for the series (Figure 7). The ARIMA(0,1,1) produced an adequate model, and analysis of the residuals indicated no other serial correlation for the model. Therefore, the ARIMA(0,1,1) model was chosen for the Karluk sockeye salmon catch (Table 2).

For Copper (central Alaska), the SACF and SPACF patterns were slightly different from the 3 other river systems in central Alaska. The SACF did not slowly decay but cut off after lag 1, and the SPACF also contained significant correlation at lag 1 (Figure 5). The ESACF indicated an ARIMA(1,0,0) model for the series (Figure 7). The ARIMA(1,0,0) model fit to the data series produced a significant AR term for lag 1. The residual analysis indicated no other serial correlation for the model. Therefore, the ARIMA(1,0,0) model was chosen for this series (Table 2).

For Situk (southeastern Alaska), the SACF decayed slowly, indicating the series should be differenced (Figure 5). The SACF and SPACF of the differenced series $(1-B)$ indicated a possible ARIMA(0,1,1) (Figure 6). The ESACF of the differenced series also suggested a possible ARIMA(0,1,1) model (Figure 7). The ARIMA(0,1,1) model fit to the data series produced a significant MA term for lag 1. Analysis of the residuals indicated the serial correlation had been adequately accounted for by the model. Therefore, an ARIMA(0,1,1) was chosen for Situk (Table 2).

For Skeena (southeastern Alaska), the SACF and SPACF contained significant lags 1 and 3 (Figure 5), and the ESACF indicated a possible ARIMA(3,0,0) model (Figure 7). Fitting an ARIMA(3,0,0) model to the Skeena sockeye salmon catch series produced an insignificant AR term for lag 2. Removing the AR term for lag 2 and analyzing the residuals from the fitted ARIMA(3,0,0) $\phi_{2=0}$ model indicated the serial correlation had been adequately accounted for by the model. Therefore, an ARIMA(3,0,0) $\phi_{2=0}$ was chosen for Skeena (Table 2).

Outlier Analysis

For Naknek/Kvichak (western Alaska), the iterative outlier search produced a positive additive outlier for 1983 (Table 3). The addition of the outlier to the time series model reduced the residual standard error by 7% over the univariate model (Table 2). The additive outlier in 1983 (Figure 8) did not correspond to any major shift in catch. However, the large catch in 1983

occurred for an off-cycle year and stands out as an outlier in the residual series because the ARIMA model, which accounts for the 5-year cycle, could not explain it.

For Egegik (western Alaska), 2 outliers were detected and jointly estimated with the model parameters. A positive additive outlier was identified for 1961 and a negative additive outlier was identified for 1974 (Figure 8; Table 3). The addition of the outliers to the time series model reduced the residual standard error by 11% over the univariate model (Table 2).

For Ugashik (western Alaska), more than 10 outliers were identified using the critical value of 2.6, and some appeared to be spurious. A critical value of 2.7 reduced the number of outliers and gave more credence to the results. The outliers identified include negative additive outliers for 1940, 1941, and 1978; negative temporary changes in 1972 and 1974; and a positive level shift in 1979 (Figure 8; Table 3). The inclusion of outliers greatly improved the fit of the time series

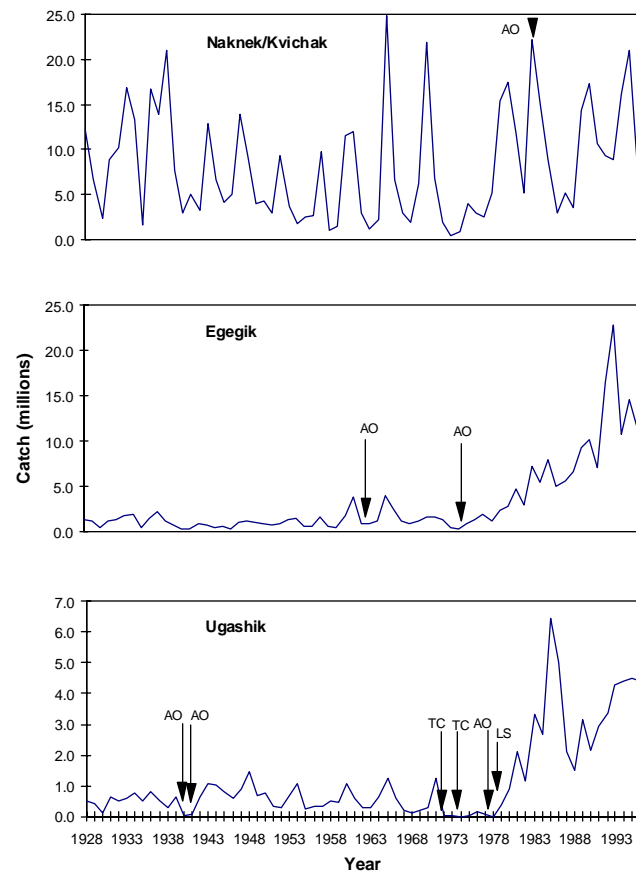


Figure 8. Western Alaska sockeye salmon catch, 1928–1996; level shift (LS), temporary change (TC), and additive outliers (AO) are identified for each river system.

Table 3. Dates, parameter estimates, *T* values {date (estimate; *T* value)}, and critical values for the level shift (LS), temporary change (TC), and additive outliers (AO) identified for each sockeye salmon catch time series.

River	Critical Value	Outliers		
		LS	TC	AO
Naknek/ Kvichak	[2.6]			1983 (1.86; 3.3)
Egegik	[2.6]			1961 (1.36; 3.3) 1974 (-1.35; -3.2)
Ugashik	[2.7]	1979 (1.74; 8.8)	1972 (-3.05; -5.6) 1974 (-3.48; -6.3)	1940 (-2.74; -4.7) 1941 (-2.15; -3.6) 1978 (-2.63; -4.6)
Alitak	[2.6]		1957 (-1.36; -3.3) 1967 (-1.68; -4.1) 1972 (-1.85; -4.4) 1992 (-1.19; -2.9)	1973 (-1.79; -4.8) 1975 (-1.57; -4.3)
Karluk	[2.6]	1951 (-1.22; -4.1)	1971 (-1.40; -3.5) 1990 (1.67; 3.9)	1947 (-1.52; -3.3) 1955 (-1.95; -4.3) 1973 (-1.29; -2.8) 1989 (-4.24; -9.2)
Copper	[2.9]	1982 (0.58; 4.8)		1935 (-1.87; -5.3) 1948 (-1.05; -3.0) 1979 (-1.78; -4.9) 1980 (-3.38; -9.3)
Situk	[2.6]	1987 (1.74; 4.8)		
Skeena	[2.6]		1955 (-1.97; -4.9)	

model and reduced the residual standard error by 44% (Table 2).

For Chignik (central Alaska), no outliers were detected.

For Alitak (central Alaska), negative additive outliers were found for 1973 and 1975, as well as negative temporary changes for 1957, 1967, 1972, and 1992 (Figure 9; Table 3). The inclusion of outliers in the time series model reduced the residual standard error by 34% over the univariate time series model (Table 2).

For Karluk (central Alaska), negative additive outliers were found for 1947, 1955, 1973, and 1989; both negative and positive temporary changes were found for 1971 and 1990, respectively; and a negative level shift was found for 1951 (Figure 9; Table 3). The drop in catch for 1989 can be attributed to loss of fishing due to the Exxon Valdez oil spill. Inclusion of the outliers in the time series model reduced the residual stan-

dard error by 48% over the univariate time series model (Table 2).

For Copper (central Alaska), analysis of the residuals from the outlier analysis with a critical value of 2.6 suggested an inadequate ARIMA model for the series. After estimating several different ARIMA models and analyzing residuals, an appropriate model could not be found. Increasing the critical value to 2.9 stabilized the model and produced satisfactory parameter estimates and residuals. Negative additive outliers were found for 1935, 1948, 1979, and 1980, and a positive level shift was identified for 1982 (Figure 9; Table 3). The inclusion of outliers to the time series model greatly improved the residual standard error, reducing the residual standard error to 46% of the univariate time series model (Table 2).

For Situk (southeastern Alaska), a positive level shift was identified for 1987 (Figure 10; Table 3). The residual standard error for the time series model was

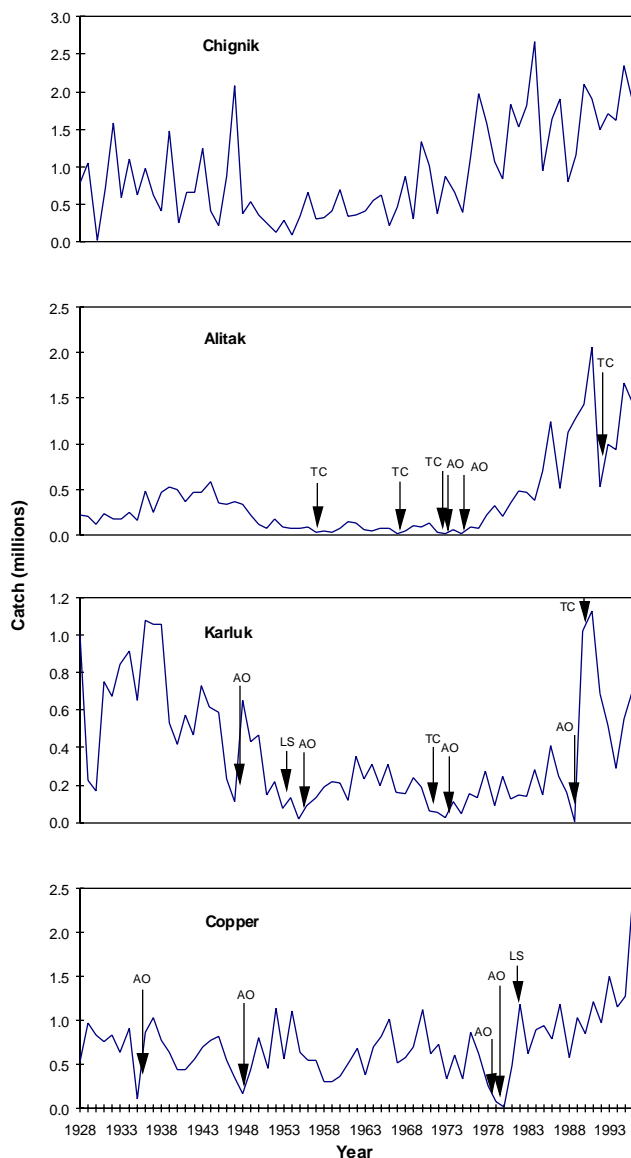


Figure 9. Central Alaska sockeye salmon catch, 1928–1996; level shift (LS), temporary change (TC), and additive outliers (AO) are identified for each river system.

reduced by 12% when the outliers were included in the time series model (Table 2).

For Skeena (southeastern Alaska), the outlier identification process with a critical value of 2.6 suggested a different model from the previous $ARIMA(3,0,0)$ $\phi_{2=0}$ model. The AR term for lag 1 became insignificant after the outliers in the model were estimated. The outlier search for the $ARIMA(3,0,0)$ $\phi_{1,2=0}$ model identified a negative temporary-change outlier for 1955 (Figure 10; Table 3). The residual standard error was reduced by 10% when the outlier was included in the time series model (Table 2).

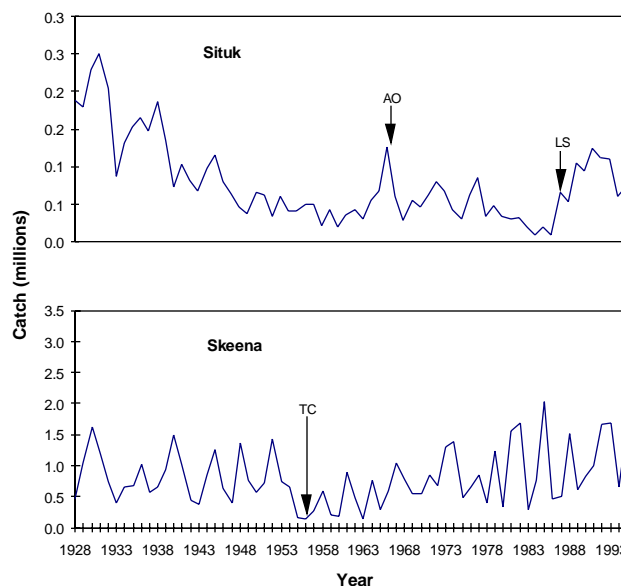


Figure 10. Southeastern Alaska sockeye salmon catch, 1928–1996; level shift (LS), temporary change (TC), and additive outliers (AO) are identified for each river system.

DISCUSSION

Alaska Salmon Production

Over the past 60 years, sockeye salmon catches have fluctuated widely from a low of roughly 4.5 million in 1973 to >64 million in 1993 (Figure 1). Changes in both management policy and environmental conditions have been hypothesized as contributing factors in these fluctuations.

Management policies affecting catch levels include variable escapement strategies (Eggers et al. 1984), high seas interceptions (Eggers et al. 1984; Rogers 1984; Pella et al. 1993), improved access to spawning grounds (Van Cleve and Bevan 1973), lake fertility (Stockner 1987), and direct manipulation of spawning ground habitat (Sprout and Kadowaki 1987; West and Mason 1987). Environmental influences on catch range in scale from changes in regional climatic conditions, such as winter air temperatures (Mathisen and Poe 1981; Eggers et al. 1984; Rogers 1984), to ocean basin-scale shifts in the North Pacific environment (Mysak 1986; Francis and Hare 1994; Beamish and Bouillon 1995; Hare and Francis 1995).

Basin-scale climatological conditions in the Gulf of Alaska are related to the intensity of the Aleutian Low Pressure System: greater intensity corresponds with increased precipitation (Cayan and Petersen 1989), wind stress and Eckman transport (Thompson

1981; Trenberth 1991), and vertical mixing (Thompson 1981; Lau 1988; Rogers and Raphael 1992), all of which may provide linkages between basin-scale climate and salmon production. Evidence for linkages between salmon production and the intensity of the Aleutian Low can be seen in their parallel decrease in the late 1940s and increase in the late 1970s (Beamish and Bouillon 1995).

Hare and Francis (1995) hypothesized the sockeye salmon catch in western and central Alaska was impacted by a large-scale climate change reflected in North Pacific atmospheric-oceanic regime shifts during 1946–1947 and 1976–1977. They used intervention analysis to determine if significant level shifts were present in Alaska sockeye salmon catches. Negative level shifts in western and central Alaska sockeye salmon occurred during 1949 and 1950, and positive level shifts occurred during 1979 and 1980. Hare and Francis (1995) concluded level shifts found in sockeye salmon catches imply an abrupt change or “snap” in the biological production dynamics of the North Pacific.

The impact of large-scale climate shifts in the marine environment has important implications for fisheries management. Increased escapements or artificial enhancement can be successful in increasing catch levels during favorable regime shifts; however, attempts to rebuild stocks through increased escapements or artificial enhancement are unlikely to be successful during periods of low ocean productivity. To effectively evaluate management policies regarding escapement and artificial enhancement, it is important to recognize changes in productivity regimes in the oceanic environment (Beamish et al. 1997). For example, forecasts produced for sockeye salmon returns to Bristol Bay omit data prior to 1978 because models based on most recent data more accurately reflect current trends in sockeye salmon production (Cross et al. 1993).

Analyses comparing large-scale climate shifts to sockeye salmon production have been based primarily on aggregate catch levels. However, stock-specific production dynamics play an important role in determining catch levels. This can be seen in the substantially different catch patterns of sockeye salmon stocks (Figure 2). Harvest and escapement strategies vary from system to system (Eggers and Rogers 1987), which also emphasize the need to examine catch data at the individual management unit or stock level. Still, the large range of factors that influence catch levels will confound the interpretation of catch trends, even at the individual stock level. Changes in management practices are much more readily identified, but their

influence on catch levels can often be confounded with the changing environment (Eggers et al. 1984).

ARIMA Models

The nonstationary nature of most river systems required differencing by 1 or 5 years. The Chignik, Alitak, Karluk, and Situk Rivers were differenced by 1 year, which simplified the ARIMA process and resulted in MA models. Differencing the data by 1 year produced a mixed ARIMA model for the Egegik River. For Naknek/Kvichak Rivers, differencing the data by 5 produced less complex patterns in the SACF and SPACF and simplified the modeling process. Only 3 rivers, Ugashik, Copper, and Skeena, did not require a differencing operator to produce a stationary time series.

Time series models for Naknek/Kvichak, Egegik, Ugashik, Copper, and Skeena Rivers contained AR terms. AR terms form the basis for incorporating serial correlation or “memory” present in the time series data. Time series models that contain a significant AR term for lag 1 may represent environmental effects, where good years are followed by good years and bad years are followed by bad years (T. J. Quinn II, University of Alaska Fairbanks, personal communication). Models that contained significant AR terms for lag 5 (Table 2) may represent the effect of parent escapement on catch. The significant AR term for the 5-year lag in the Naknek/Kvichak system is probably due to the obvious 5-year cycle found in the Kvichak stock. The cyclic pattern of the Kvichak stock is sustained by its predominate 5-year age of return and escapement goals that are set to follow the cycle, i.e., lower escapements in off-peak years and higher escapements in peak years (Mathisen and Poe 1981; Eggers and Rogers 1987).

Outliers Analysis

Unusual observations or outliers often provide insight into the processes governing catch levels not available to analyses that only consider mean values or trends. However, particular attention needs to be given to the methodology used to identify outliers. Unlike methods used to compute the mean or trend, methods or approaches to defining and identifying outliers can be quite variable. The variable approaches to identifying outliers will inevitably lead to variable interpretations of the data. We used an iterative procedure recently developed by Chen and Liu (1993) to estimate the magnitude, significance, timing, and type of outliers occurring within each of the catch time series. Our outlier

analysis is quite different from intervention analysis (Hare and Francis 1995), where the magnitude and significance of an outlier is estimated but requires the timing and type of outlier be known a priori. We found almost twice as many temporary changes and 4 times as many additive outliers as level shifts in our catch time series. The relative infrequency of level-shift outliers suggests that analyses that only consider level-shift outliers may be susceptible to misclassification of the outlier type (Chen and Lui 1993).

Level-Shift Outliers

The positive level shifts found in our analysis all occurred during and after the late 1970s, which corresponded with the period of increased intensity of the Aleutian Low. Positive level shifts found in Ugashik, Copper, and Situk occurred during 1979, 1982, and 1987, a period of 8 years. This was not consistent with the hypothesis that salmon production has undergone a rapid increase to new production levels in response to the physical regime shift in 1976–1977 (Hare and Francis 1995) and suggests that other factors may be contributing to the timing and presence of positive level shifts.

The timing and presence of the positive level shifts found in our analysis may reflect the influence of management decisions on catch. In 1987, sockeye salmon escapement goals were reduced from 80,000–100,000 to 45,000–55,000 in the Situk (B. Van Alen, Alaska Department of Fish and Game, personal communication). Because the average Situk River sockeye salmon catch prior to 1987 was approximately 45,000 fish, this new goal produced substantially higher catches in subsequent years. Escapement levels for river systems in Bristol Bay, other than the Kvichak, increased in the early 1970s, and the Japanese high seas interception rate of Bristol Bay sockeye salmon was markedly reduced for returns in 1978 and later (Eggers et al. 1984). Therefore, increased escapement levels and reduced interception rates also may have contributed to the 1979 positive level shift in the Ugashik. Enhancement efforts beginning in 1978 by the Gulkana Hatchery may have contributed to the 1982 level shift in Copper River sockeye salmon.

Inevitably, management and environmental influences on catch levels are confounded (Pella 1979). Eggers et al. (1984) concluded that the combined effects of both favorable climate, decreased high seas interception, and increased escapement led to increased catch levels for non-Kvichak stocks in Bristol Bay after 1978. The 1982 positive level shift in the Copper River may be the result of favorable climatic conditions after 1979; however, low escapements between

1974 and 1976 may have delayed this system's full response to favorable conditions.

Only 4 of the 9 river systems in our analysis had level-shift outliers, and only 1 river system (Ugashik) had a positive level shift during the late 1970s. The lack of level-shift outliers during the late 1940s and late 1970s does not necessarily preclude the existence of linkages between the Gulf of Alaska climate and fish production. However, it does suggest the linkages that are present may gradually affect fish production over a period of years rather than in a form of a level-shift outlier, where the full magnitude of the effect is realized within 1 year. Level-shift outliers, when they were found in our analysis, appeared to be most commonly the result of changes in escapement policy.

Temporary-Change Outliers

In western and central Alaska, cold winter temperatures may be an important factor in producing unusually poor survival. Four of the eight temporary-change outliers in western Alaska occurred during the early 1970s (1971–1974), which coincides with a period of cold winter temperatures in western Alaska (Mathisen and Poe 1981; Eggers et al. 1984). The only temporary-change outlier found in southeastern Alaska stocks occurred during 1955 in the Skeena River. This outlier was most likely due to a rock slide on the Babine River, which severely reduced escapements into Babine Lake in 1951 and 1952 (Sprout and Kadowaki 1987). The absence of negative temporary-change outliers in southeastern Alaska during the early 1970s may be due to warmer winter temperatures in southeastern Alaska.

The one positive temporary-change outlier in 1990 may be due to increased escapement goals into the Karluk River in 1985 (C. Hicks, Alaska Department of Fish and Game, Kodiak, personal communication). Because the predominant age of return is 5 for Karluk, this increased escapement would have its largest affect on the 1990 returns. It is unclear why the increased escapement resulted in a temporary change and not a level shift. However, our ability to distinguish between temporary-change and level-shift outliers is limited at the end of a time series, and therefore the significance of the outlier type should be interpreted with caution.

Additive Outliers

Many of the additive outliers were unexplainable and may simply represent the multiplicative effect of good or poor survival at several different life history stages. Most of the additive outliers that were explainable were related to changes in fishing effort, not survival. Fish-

ers went on strike during the 1935 fishing season on the Copper River, and the sockeye salmon fishery was closed in 1980 because of a poor anticipated run. These events presumably explain the negative additive outliers in 1935 and 1980. Due to the Exxon Valdez oil spill, the 1989 fishing season for Karluk sockeye salmon was closed, which most likely produced the negative additive outlier in 1989. The negative additive outlier in 1974 for Egegik is possibly due to the cold winter in Bristol Bay during 1971. Similar to the pattern observed in Bristol Bay (Mathisen and Poe 1981; Eggers et al. 1984), the low catches and negative additive outliers found in 1973 for Karluk and Alitak may be the result of an exceptionally cold winter in 1971.

CONCLUSIONS

1. Catch data analyzed at the stock level provides a more meaningful interpretation of catch patterns

because of differences in production dynamics between salmon stocks and because effective management requires decisions based on the individual stock level.

2. Most of the abrupt departures from our time series models of sockeye salmon catch were classified as temporary changes or additive outliers, both of which represent a short-lived shift in catch levels. Cold winter temperatures in western Alaska appeared to be the most common source of temporary-change outliers. The few additive outliers we could explain were related to decreased fishing effort.
3. Changes in escapement policy during favorable environmental conditions appeared to be the most common source of positive level-shift outliers, rather than an abrupt change in the production dynamics of the North Pacific in response to the 1970s regime shift.

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Postnote

- ▶ 98 Jul 24 — Edward V. Farley, Jr. and James M. Murphy.

We recently discovered an error in the ARIMA model given for Naknek/Kvichak. The model should have been written in the form of a seasonal model $ARIMA(p, d, q) \cdot (P, D, Q)_s$, where p , d , and q are defined in Farley and Murphy (1997), P , D , and Q are the orders of the seasonal components, and s is the seasonality (Wei 1990). Therefore, the ARIMA model for Naknek/Kvichak should have been written as $(5, 0, 0)(0, 1, 0)_5 \Phi_{2-4=0}$.

- ▶ 98 Oct 10 — editor's note

A comment and response to this paper were published in Alaska Fishery Research Bulletin 5(1):67–73. ([View the comment and response.](#))

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