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## Comment

In a paper recently published in this journal, Farley and Murphy 1997 (hereafter F&M) presented an analysis of the temporal variability in catches of Alaska and British Columbia (BC) sockeye salmon *Oncorhynchus nerka* stocks. On the basis of their analysis of catch time series of 9 sockeye salmon stocks, they concluded that increased catches of most sockeye salmon stocks that began in the late 1970s resulted from a change in escapement policy and not as a response to improved ocean conditions. Throughout the paper F&M make frequent reference to 2 papers of ours (Francis and Hare 1994; Hare and Francis 1995; hereafter FH–HF), where we presented a theory of salmon production regimes driven by interdecadal climatic regimes.

The purpose of this comment is to review the F&M analyses and conclusions and to provide a contemporary assessment of our theory and how it has evolved in the 3 years since the FH–HF papers were published. We state, right at the outset, that we stand by our conclusion that changes in oceanic productivity are largely (though not exclusively) responsible for the decreased Alaska and BC salmon production of the 1950s, 1960s, and early 1970s (relative to the period prior to 1950) and for the increased salmon production after the climate regime shift of 1976/77.

North American salmon catches and productivity have shown enormous variability during the 20th century. There have been numerous studies on the causes of the variability, and explanations have run the gamut from freshwater to oceanic to management influences. In the past 5 years, a new theory has been advanced, which we refer to as the regime-shift productivity theory. One of the main tenets of this theory is that salmon productivity alternates between high and low production regimes in response to decadal-scale climatic regime shifts.

A large number of studies have contributed to the development and refinement of the regime-shift productivity theory. FH–HF summarized many of the papers through 1995 (discussed later). In this comment, we first provide a capsule summary of the FH–HF papers to prime the ensuing critique of F&M.

For the analyses in FH–HF, we assembled catch time series for 4 major Alaskan salmon regional aggregates: western and central Alaska sockeye salmon and central and southeastern Alaska pink salmon. These 4 groups accounted for 80% of the total Alaska salmon catch between 1925 and 1994. We conducted a time series intervention analysis to determine whether these regional salmon stocks showed a response to climatic regime shifts. We found 2 step changes in all 4 time series, a negative step in the late 1940s and a positive step in the late 1970s. These step changes corresponded precisely to abrupt changes found in many climate variables of the North Pacific. We interpreted this result as a bottom-up response by the salmon to changes in the distribution and quantity of secondary productivity in the Alaska Gyre.

F&M argue that the catch data should be analyzed at a finer level (e.g., individual river system) because this would result in a more meaningful interpretation. We do not agree with that assessment, when the larger, regional-scale signal, as was the intent in FH–HF, is of interest. The reason why one should not necessarily expect to see the climate signal at the smaller stock or watershed scale is similar to the reason that the Central Limit Theorem works. At the small scale, there appear to be many local factors both in the freshwater and marine environment that affect salmon production. Because these are local effects, the salmon population may respond either positively or negatively. However, if the climate signal is working on a larger, regional scale, it will be masked by the local scale noise. However, when you look at production on the regional scale, the local effects will be "averaged out," revealing effects occurring at the larger scales. Thus, one would expect the climate signal to become increasingly difficult to discern as the scale of investigation narrows. That does not mean the signal is not present, just that we cannot see it very well. In a sense, we are trying to see the forest, not the individual trees.

We have a number of concerns about the F&M study and the conclusions they draw based on their results. The most obvious improvement that could be made to the FH–HF papers would be to assemble salmon production (catch + escapement) data. This would more directly answer whether changes in production correspond to changes in climate or changes in escapement policy. F&M conclude that changes in escapement policy produced increased catches in the 1970s but provide no supporting data. In fact, Adkison et al. (1996), examined production data for Alaska and BC sockeye salmon and came to the same conclusion as FH–HF; their study, however, was not addressed by F&M.

Prior to modeling, F&M apply a logarithmic transformation to their data. Both Quinn and Marshall (1989) and FH–HF found square-root transforms appropriate for some sockeye salmon catch time series. Also, the display of the log-transformed time series (as in F&M, Figure 3) contains erroneous values along the y-axes.

One of the pitfalls of time series analysis is that when a large number of parameters are being estimated, a wide variety of possibly wildly different models can provide almost the same statistical fit. To some extent, this can be alleviated by the use of objective criteria (AIC, Akaike 1974; SBC, Schwarz 1978). F&M present only an RSE (residual standard error) statistic, which is guaranteed to decrease as parameters are added. When several different types of outliers are being permitted in the models, it becomes critical that added explanatory power be documented.

Rather than attempting an a priori approach where some response in the time series is hypothesized and then tested, F&M found a number of different types of outliers and then searched for an explanation for those outliers. It is generally comforting when statistics confirm a trend or pattern that the eye detects. Examining some of the plots (F&M Figures 8, 9), it is very difficult to visualize what is significant about points they identify as significant outliers (e.g., see Egegik and Alitak systems). Perhaps this is the major explanation for why they could not find explanations for most of the temporary change and additive outliers they identified. It is further surprising that the resulting fits are not illustrated anywhere in their paper. We would have appreciated seeing to what extent their final model fits tracked the catch time series.

We believe that the third conclusion in F&M requires clarification and further discussion. The conclusion reads: "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." Although F&M acknowledge that environmental conditions play an important role in salmon catch dynamics, their findings and conclusion seem to discount the regime-shift productivity theory of FH–HF and they attribute the increase in catches to a change in escapement policy.

We contended in our papers that the 1970s regime shift was tied to favorable environmental conditions that increased the production of Alaska salmon and that the shift between regimes was likely to persist for decades. F&M note that forecasts for Bristol Bay sockeye salmon returns implicitly recognize the regime-shift impact by omitting data prior to 1978. Thus, it is not clear what favorable environmental conditions they are referring to or how they benefit salmon. Finally, the conclusion that increased escapement was responsible for increased production is not supported by any data analysis.

In the 3 years since the FH–HF papers, a number of other studies have been published, refining and expanding the regime-shift productivity theory. Adkison et al. (1996), fit a variety of climate models to Bristol Bay and Fraser River sockeye salmon production data. They concluded that the best explanation for the observed variation in Bristol Bay stocks was an abrupt shift in the productivity parameter of the Ricker stock-recruitment relationship. This same result was also obtained by Hare (1996). Adkison et al. (1996) could not find a model that explained much of the variability in Fraser River sockeye salmon productivity. In a different study, however, Beamish, Neville (1997), using total return and marine survival data, found a significant positive shift (using intervention analysis) in the productivity of Fraser River sockeye stocks beginning with the 1975 brood year (migrating to sea in 1977).

A number of studies have also examined the response of other species of salmon, as well as those from other regions, to the climate regime shift of 1976–1977. Beamish et al. (1995) found an abrupt decline in survival of chinook salmon from Strait of Georgia and Fraser River hatcheries after 1977. Anderson (*in press*) shows that Columbia and Snake River chinook salmon catch responded to the climate regime shift as the high catches of 1945–1976 were replaced by the low catches that have persisted since then. In a superb review paper on salmon production and ocean regimes, Pearcy (1997) notes that production of both wild and hatchery coho salmon from coastal Oregon "decreased dramatically between the 1975 and 1976 smolt release years." Downton and Miller (*in press*) fit multivariate time series transfer function models to catch time series of Alaskan sockeye, pink, and chum salmon. All 3 species show statistically significant shifts in both the late 1940s and late 1970s, in synchrony with the climatic regime shifts. In a recent paper, an inverse relationship between catches of Alaskan and U.S. West Coast salmon was demonstrated (Hare et al. *in press*). Abrupt transitions occurred in 1947 and 1977 and approximately 50% of the total catch variability was attributed to climate-regime-driven shifts in productivity. Noakes et al. (1998) showed that salmon catches from around the Pacific Rim have shown a "high degree of consistency" in trend over time. Beamish, Mahnken (1997) examined the role of hatchery production in the jump in salmon catches after the mid 1970s.

In terms of the conceptual model linking large-scale climate variability and salmon production, several recent papers have progressed beyond the FH–HF papers. Mantua et al. (1997) and Zhang et al. (1997) identified the interdecadal-scale climate pattern associated with the regime shift of 1976/77. They termed this pattern the Pacific Decadal Oscillation (PDO), which has shown 3 reversals in the 20th century: 1924/25, 1946/47, and 1976/77. Francis and Hare (1997) and Francis et al. (1998) present an expanded discussion of the hypothesized bottom-up forcing mechanism driving northeast Pacific oceanic ecosystems. A conceptual extension to this model has recently been advanced (Gargett 1997), the key notion being the possible existence of an optimum window for coastal water-column stability driven by large-scale fluctuations in Pacific basin climate, which affect both light levels and nutrient supply for phytoplankton growth. Assuming that the stability of the coastal northeast Pacific Ocean varies in phase with and in response to decadal-scale variation in the Aleutian Low/PDO process, it is hypothesized that northern (Gulf of Alaska/Bering Sea) and southern (California Current) phytoplankton populations occupy opposite ends of this window, thereby producing variations in primary (and secondary) production in the 2 regions that are out of phase. Perry et al (1998) considered the evidence for bottom-up versus top-down control of epipelagic (principally salmon) fish production in the subarctic Pacific. They concluded that bottom-up control was probably on the interdecadal scale, as well as on an interannual basis.

We believe the debate over the causes behind the enormous fluctuations in salmon production is necessary and important and to that extent we welcome the input from F&M. However, we disagree with their conclusion that a change in escapement policy is responsible for the increased sockeye salmon catches. This disagreement is based, not only on our own work, but on the findings of several other studies and on the lack of escapement data analysis in their paper.

The climatic regime shift of 1976/77 reverberated throughout the large marine ecosystems of the North Pacific. Biological responses to the regime shift have been documented in a wide array of species at all trophic levels, from plankton to fish to marine birds and mammals (see Francis et al. 1998 for a lengthy summary). Salmon populations along the entire coast of North America have shown a remarkably coherent response to the climate regime shift, none more so than the Bristol Bay stocks (FH–HF; Brodeur and Ware 1995; Beamish, Neville 1997; Noakes et al. 1998). Recognition of the importance of ocean conditions and the interdecadal nature of climate variability in establishing those conditions, is an important advance in better understanding the nature of salmon production, and in managing those populations.

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## Response

Hare and Francis state that we concluded "that increased catches of most sockeye salmon *Oncorhynchus nerka* stocks that began in the late 1970s resulted from a change in escapement policy, and not as a response to improved ocean conditions." This interpretation incorrectly expands our analysis of positive level-shift outliers found in 3 river systems to include the enormous fluctuations present in Alaska sockeye salmon production. It is important to point out that sockeye salmon catches increased in all 9 river systems in our analysis, but only 3 of these contained level-shift outliers. In the 6 remaining series, mean catch increased gradually over a period of several years, and the increase was removed from our time series analysis when the data were differenced. For clarity, we reviewed the 3 sockeye salmon stocks that contained positive level-shift outliers.

Positive level-shift outliers were found in Situk, Ugashik, and Copper Rivers. In the Situk River stock, sockeye salmon escapement goals were reduced from 80,000–100,000 to 45,000–55,000 in 1987 (B. Van Alen, Alaska Department of Fish and Game [ADF&G] Juneau, personal communication); this change in escapement policy was identified as a possible source of the positive level-shift outlier in the catch time series during 1987. In the Ugashik River stock, we found a positive level-shift outlier in 1979. This positive level shift appeared to follow the 1976–1977 regime-shift hypothesis proposed by Hare and Francis (1995); however, other contributing factors suggested by Eggers et al. (1984), such as increased escapement levels in the early 1970s for river systems in Bristol Bay and reduced Japanese high seas interception rate of Bristol Bay sockeye salmon during 1978, were also identified as possible sources for the level-shift outlier. In the Copper River stock, we found a positive level-shift outlier in 1982. The dominant ocean age for Copper River is 3 years (Burgner 1991). If Copper River stock had responded to the 1976–1977 regime shift proposed by Hare and Francis (1995), we would have expected to see a positive level shift in catch during 1980. We suggested that low escapements between 1974 and 1976 (S. Morestead, ADF&G, Cordova, personal communication) may have delayed this system's full response to favorable ocean conditions.

Our third conclusion states that "changes in escapement policy during favorable environmental conditions appeared to be the most common source of positive level-shift outliers." We did not mean, as Hare and Francis interpreted, that a change in escapement policy was responsible for the increased sockeye salmon catches in Alaska, nor did we propose an alternative hypothesis to that presented by Hare and Francis (1995) and Francis and Hare (1994) for explaining the fluctuations in Alaskan sockeye salmon production. Rather we concluded that when Alaskan sockeye salmon catch is examined at the individual stock level, changes in escapement policy (a local affect) appear to play a role in determining the presence of positive level-shift outliers, or changes in stock production.

Hare and Francis comment that we failed to provide data supporting our conclusion that changes in escapement policy resulted in increased (Alaskan sockeye salmon) catches in the 1970s. Once again, we must point out that our conclusion regarding possible relationships between increased sockeye salmon catch and escapement policies was restricted to 3 river systems (Situk, Ugashik, and Copper Rivers) that contained positive level-shift outliers. We did not expand our conclusion to include sockeye salmon catch for the other 6 river systems examined or for Alaskan sockeye salmon catch as a whole.

Hare and Francis correctly note that although Adkison et al. (1996) examined production data for Alaska, we failed to address their study. This was an unintended omission to our discussion. Adkison et al. (1996) found that the best model of the productivity of Bristol Bay sockeye salmon was a one-time change in the parameters of the Ricker stock–recruitment model that first affected the 1972 brood year. Of the 9 Bristol Bay river systems investigated by Adkison et al. (1996), Ugashik had the largest increase in both the $\alpha$ and $\beta$ parameters of the Ricker model. Because the most common age groups returning to Ugashik are 4- and 5-year-old sockeye salmon (Burgner 1991), the increase in the productivity parameter of the Ricker model for the 1972 brood year should have affected catch levels during 1976 or 1977. We found a level shift in the sockeye salmon catch time series in the Ugashik stock several years later (1979). In addition to the changes in the Ricker parameters (Adkison et al. 1996), escapements increased (Eggers et al. 1984), both or either of which may have produced the level shift in catch during 1979.

Our use of a logarithmic transformation was also contested by Hare and Francis. To stabilize the variance in catch, we applied a logarithmic transformation to the sockeye salmon catch time series; a transformation commonly used in analyzing fisheries data. To test the appropriateness of the logarithmic transformation, we applied a Box-Cox transformation (Box and Cox 1964) to each of the 9 sockeye salmon catch time series. The results indicated that a square root or logarithmic transformation were equally appropriate for these river systems.

Objective criteria such as Akaike Information Criterion (AIC) and Schwartz's Bayesian Criterion (SBC; see Wei 1990 for examples) are useful when comparing the statistical fit of a wide variety of models that contain different numbers of model parameters. The focus of our original paper was on identifying outliers within our sockeye salmon catch time series, not on model selection. Nevertheless, we have computed the SBC for each of the models, and all the ARIMA models that contained outliers produced lower SBC values than ARIMA models without outliers (Table 1).

In examining some of our sockeye salmon catch time series, Hare and Francis indicated that they found the significance of our "significant outliers" difficult to visualize. We used an iterative outlier detection procedure developed by Chen and Liu (1993) that is applied to the residuals of the empirically built model. The procedure begins by examining the residual series for outliers, adjusts the original series by removing the effects of outliers according to the types of detected outliers and their effects, re-estimates model parameters, and then examines the residuals from the

Table 1. Schwarz's Bayesian criterion (SBC) values for univariate ARIMA models and ARIMA models that included outliers.

| River | SBC Values | |
|---|---|---|
| | Univariate | Outlier |
| Naknek/Kvichak | -23.49 | -28.86 |
| Egegik | -58.79 | -65.84 |
| Ugashik | 15.85 | -37.77 |
| Alitak | -51.44 | -83.03 |
| Karluk | -6.82 | -69.15 |
| Copper | -44.21 | -107.91 |
| Situk | -99.67 | -113.57 |
| Skeena | -58.2 | -72.74 |

adjusted model for other outliers. Because the procedure uses the residuals from the empirical model to detect outliers, it may not be possible to distinguish outlier effects within the original time series. For example, the additive outlier we noted for Naknek/Kvichak in 1983 did not correspond to a distinguishable 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.

Hare and Francis also were curious about how well our final model fits tracked the catch time series. We include the model fits in Figure 1. During the second review process, we 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($p$,$d$,$q$) · ($P$,$D$,$Q$)$s$, 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 $(5,0,0)(0,1,0)_5\ f_{2\text{-}4=0}$.

Unexpected or uncontrolled events (outliers) often affect time series and, depending on their nature, may have moderate or substantial impact on the interpretation of a time series (Liu et al. 1994; see Beamish, Neville 1997 for an example.). We considered 3 types of outliers (level shift, temporary change, and additive) when examining the 9 sockeye salmon catch time series. We found 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 only considering level-shift outliers may be susceptible to misclassification of the outlier type (Chen and Liu 1993).

Hare and Francis (1995) found significant positive interventions in sockeye salmon catch levels during 1979 for western Alaska and during 1980 for central Alaska stocks in response to the 1976–1977 regime shift. Of the 9 sockeye salmon catch time series we examined, only 3 had positive level-shift outliers: 1979 (Ugashik), 1982 (Copper), and 1987 (Situk). The positive level shift found in Ugashik appeared to follow the regime-shift hypothesis proposed by Hare and Francis (1995); however, given the 8-year period spanning positive level shifts in these 3 river systems, we suggested that factors other than the 1976–1977 regime shift may also be contributing to the timing and presence of positive level shifts in these river systems. These factors may be the influence of localized stock-specific production dynamics.

Direct management effects on salmon production are not easily discerned for aggregate catches. By maintaining a resolution in production data that most closely matches the resolution of management actions, we can more effectively segregate the relative influence of management and environment (e.g., Adkison et al. 1996). It is important to examine processes affecting fish production at a number of spatial and temporal scales to fully understand their population dynamics. However, ultimately the processes must be brought to the scales used by management before they can advance the management of fish populations.

Lack of positive level-shift outliers during the late 1970s in the other 6 sockeye salmon catch time series we examined does not necessarily preclude the existence of linkages between the Gulf of Alaska climate and sockeye salmon production. However, it does suggest the linkages that are present may gradually affect fish production over a period of years in the form of a trend or moving average, rather than in a form of a level-shift outlier. Five of the 9 sockeye salmon river systems examined in our analysis contained autoregressive (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 producing good years after good years and bad years after bad years (T. J. Quinn II, University of Alaska Fairbanks, personal communication). Climate change may affect sockeye salmon catch gradually, in the form of autocorrelation in catch; rapidly, in the form of shifts in mean catch levels; or both. A distinction between these two are important

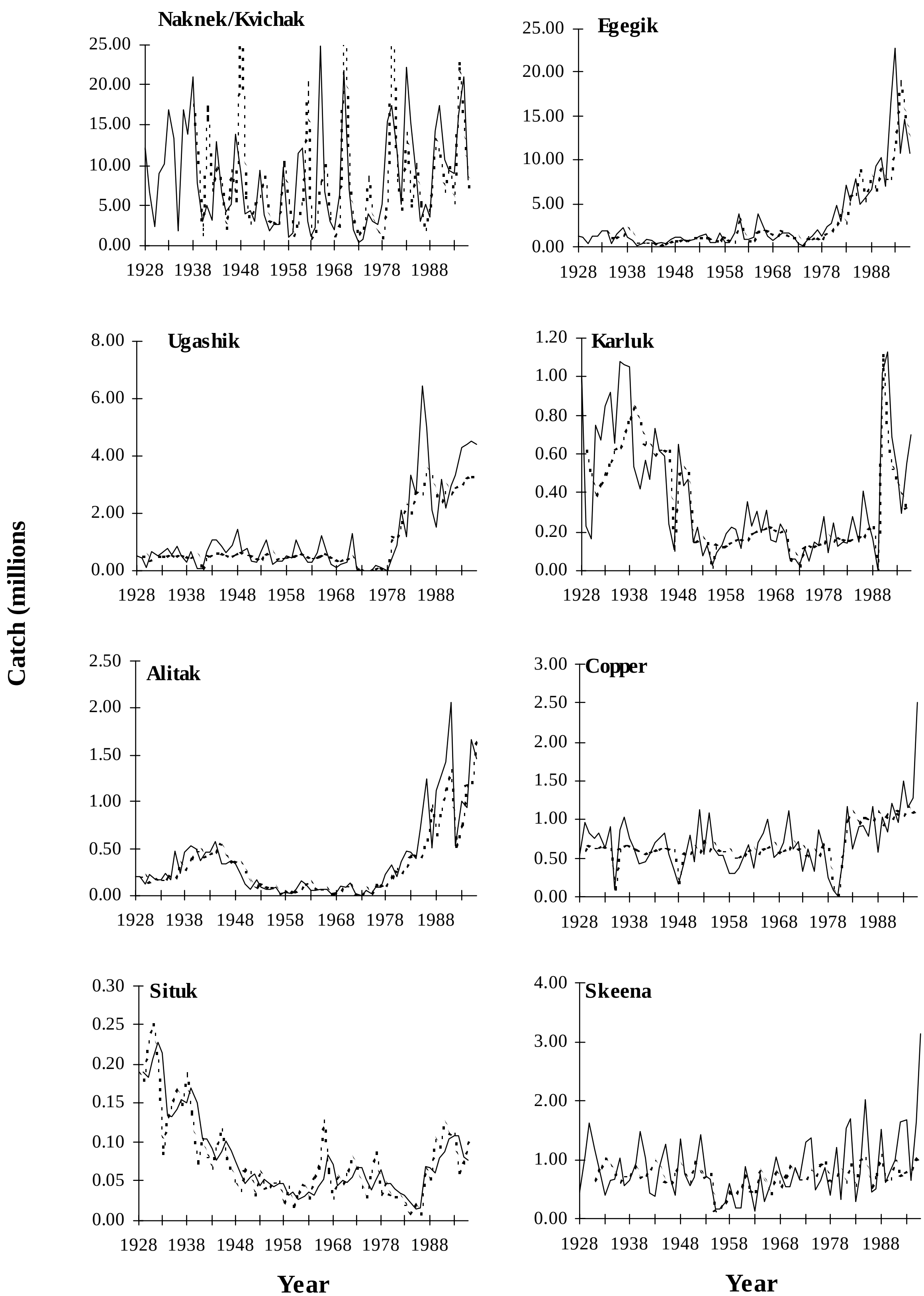


Figure 1. Sockeye salmon commercial catch (solid line) and fitted ARIMA models that included outliers (dashed lines) for 8 major sockeye salmon rivers producing in Alaska and British Columbia, 1928–1996.

when interpreting changes in sockeye salmon catch time series.

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