On the Coherence of Salmon Abundance Trends and Environmental Factors

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Salmon catches from Pacific rim countries have shown a high degree of consistency in trend over time. This pattern is exhibited over wide spatial and temporal scales suggesting a significant influence of the marine environment. The relationships among all-nation catches of sockeye, pink and chum salmon and three indices of atmospheric conditions are considered in this paper. Time series models are employed to remove the trend component of the data as well as any autocorrelation. Cross-correlation analyses of the residuals from each of the models are used to identify plausible links between salmon catches and the various climate indices. Significant relationships were observed between the all-nation salmon catch time series and each of the climate indices. The Atmospheric Circulation Index (ACI) exhibited a downward change around 1990 and if the relationship holds, this may indicate all-nation salmon production could be reduced in the near future.

INTRODUCTION

There is clear and mounting evidence that variations in the size and distribution of marine fish stocks are related to changes in the marine environment (see for example Beamish 1995; Beamish and Bouillon 1991, 1993; Beamish et al. 1997b; Hare and Francis 1995; Steele 1996). In general, traditional stock assessment methods do not adequately incorporate (either explicitly or implicitly) environmental change in population models and this does not usually pose a serious problem provided environmental conditions are relatively stable or change slowly over a reasonable time scale. Abrupt shifts in the ecosystem as characterized by dramatic changes in the population dynamics of fish stocks often result in spectacular failures of assessment models and sub-optimal management decisions that could have serious consequences for fish stocks in both the short and long term. Incorporation of key environmental signals into assessment models or at least the development of environmental indices that mimic or predict general trends in fish production would be helpful to individuals wishing to adopt a risk adverse approach to fisheries management.

In this paper, we statistically examine three climate indices for the north Pacific Ocean to determine if they are related to trends in the production of Pacific salmon (Beamish et al. 1997a). The models employed are necessarily simplistic and do not attempt to account for the different life strategies of the various salmon species and the consequences of variable management regimes employed in each region in the Pacific rim. Time series models are employed to remove the trend component for each of the data series as well as to model any observed autocorrelation. Cross-correlation analyses of the residuals from each of the models are used to identify plausible links between salmon production and each of the climate indices. Finally, transfer function models incorporating both all nation salmon catch and environmental data are developed.

MATERIALS AND METHODS

Salmon Data

All nation catches of sockeye (*Oncorhynchus nerka*), pink (*O. gorbuscha*), and chum (*O. keta*) salmon are used to represent salmon production trends in the north Pacific Ocean. The catch of these three species represents about 90 percent of the total salmon catch in the north Pacific and exploitation rates for these species are relatively and consistently high (40 to 80 percent) over time. While total production requires catch and escapement estimates for each stock, these data are not generally available and are of quite variable quality. For these reasons, total catch is viewed as a reasonable surrogate of salmon production trends and the use of such data is consistent with approaches used in previous studies (Beamish and Bouillon 1993).

Climate Indices

Three climate indices are used in this study. The Aleutian Low Pressure Index (ALPI) was developed by Beamish and Bouillon (1991, 1993) and represents the area of the low pressure region less than or equal to 100.5 kPa averaged over the period from December to May. The ALPI used in this study is the modified index described in Beamish et al. (1997a). It can be considered as a measure of the mid-ocean upwelling in the north Pacific that influences plankton production in that area. Periods of intense Aleutian lows general result in increased primary production and in turn lead to increases in salmon production in subsequent years (Beamish and Bouillon 1993).

The second climate index employed was developed by Trenberth and Hurrell (1995). Their North Pacific Index (NPI) represents the deviation from the long-term mean sea level pressure over a fixed area in the north Pacific Ocean that generally includes the area occupied by the Aleutian low. Like the ALPI, trends in the NPI may represent trends in primary productivity resulting from changes in upwelling or other biological or physical processes. While one could argue the use of a fairly large fixed geographic area provides a more inclusive picture of the climate in the north Pacific, the NPI may also be less informative than ALPI which varies in size and shape annually.

The last climate index used in this study is an Atmospheric Circulation Index (ACI) (Beamish et al. 1997a). The ACI represents the intensity of the prevailing climate pattern over the upper northern hemisphere in a particular year. Daily weather patterns are categorized as one of three general types and the dominant pattern for the year becomes the climate type for that year. The number of days for the dominant pattern in the year determines the intensity of the index for that year. As with the other indices, the ACI is viewed as a surrogate measure of the complex biological and physical process that influence primary production in the ocean and subsequently fish production (Beamish et al. 1997a). The ACI is a more general index than either the ALPI or the NPI since climatic conditions in the Northern Hemisphere are considered simultaneously.

Statistical Models and Procedures

Time series models (Box and Jenkins 1976) were used to remove trends as well as to model any autocorrelation in each of the catch and climate data series. Where appropriate, the time series models incorporated autoregressive or moving average components or both. In an autoregressive process, the catch at time t, C_t, is related in a linear fashion to previous catches (say to lag p) such that

$$(C_t-\mu)=\phi_1(C_{t-1}-\mu)+\phi_2(C_{t-2}-\mu)+\ldots\ldots +\phi_p(C_{t-p}-\mu)+a_t$$

where μ is the mean catch, ϕ_i, $i = 1,2,\ldots,p$ are the p autoregressive parameters for the model, and a_t is an error term assumed to be normally and independently distributed with mean 0 and constant variance σ_a^2. In a moving average process, the catch at time t, C_t, is linearly related to past errors (say to lag q), $a_{t-j,\ j=1,2,\ldots,q}$, such that

$$(C_t-\mu)=a_t+\theta_1 a_{t-1}+\theta_2 a_{t-2}+\ldots\ldots +\theta_q\ a_{t-q}$$

where θ_j, $j=1,2,\ldots,$ q are the q moving average parameters. Combining both autoregressive and moving average components in the model provides a robust approach to modelling autocorrelated time series and this family of models has been shown to be useful in fisheries (see for example Campbell et al. 1991; Fogarty 1988; Hare and Francis 1995) as well as economics (Makridakis et al. 1982; Granger and Newbold 1977) and environmental science (Hipel and McLeod 1994).

To identify models that incorporate both salmon catch and climatic indices, cross-correlations were calculated using the model residuals from each time series (Haugh 1976; Haugh and Box 1977; Hipel et al. 1982, 1985). Employing model residuals instead of the raw data minimizes the chances of obtaining spurious correlations. Once tentative models and appropriate lags have been identified, transfer function models linking salmon catch to climate indices were developed such that

$$(C_t-\mu)=\omega_0 X_t+\omega_1 X_{t-1}+\ldots..+\omega_v X_{t-v} + N$$

where X_t is the climate index ω_k, $k = 1,2,\ldots\ldots, v$ are the parameters associated with the transfer function component of the model, and N is the stochastic noise component of the model which includes the appropriate autoregressive and moving average terms as well as the random error term, a_t.

RESULTS

Salmon Data Models

All nation sockeye, pink, and chum salmon catch data are available for the period 1926-95 inclusive (Fig. 1a). Catches were in the 700,000 t range from 1926 until about 1940, decreased to about 350,000 t between 1940 and the mid-1970s, and have increased steadily since the mid-1970s to their current level of approximately 875,000 t in 1995. In spite of the obvious year to year variability, there are strong and persistent trends in the data. The persistence in the time series may indicate a high degree of autocorrelation in the data and it may be possible to account for the trends using an autoregressive model. However, it may also be necessary to remove the trends as part of the overall model. One common approach to removing trends is to difference the data and fit a model to the differenced time series, D_t, such that

$$D_t = C_t - C_{t-1}$$

where D_t is the difference between successive observations. For the salmon catch data, the differenced log transformed data (Fig. 1b) show no residual trend.

A number of potential models were considered and the residuals from each model were examined to ensure key statistical assumptions were satisfied. In each case, the data were log transformed to provide a closer approximation to normality. The best two or three models (one model included differencing the data) were all quite similar and included a single moving average component at lag one and significant weight being given to catches two years previous (indicative of the important role pink salmon plays in the total catch). The general overall model for catch is given as

$$\ln (C_t)=\phi_2 \ln (C_{t-2})+a_t + \theta_1 a_{t-1} + \text{constant}$$

where C_t and C_{t-1} are catch at time t and t-1, a_t and a_{t-1} are the error terms at time t and t-1, ϕ_2 (= 0.9) and θ_1(= 0.4) are the autoregressive and moving average parameters, respectively, and the constant is the weighted mean of the log transformed catch data $[(1 - \phi_2)\ \mu = 0.6]$. Overall, this model (and other similar candidate models) accounted for approximately 80 % of the variance of the raw data.

Climate Index Models

NPI data were only available for the period 1926 - 1994. No significant autocorrelation was detected for either the ALPI (Fig. 2) or the NPI (Fig. 3) so the best predictor of each is the series mean. Given the similar basis for the ALPI and NPI, a significant linear relationship (R^2 = 0.74) exists between ALPI and NPI (Fig. 4).

Like the all nation catch of sockeye, pink, and chum salmon, the ACI time series exhibited distinct trends over time (Fig. 5). Differencing was required to remove the trend (Fig. 6a, b) before various combinations of autoregressive and moving average models were fitted to the differenced data. The best model was of the form

$$ACI_t = \phi_1\ ACI_{t-1} + \phi_3\ ACI_{t-3} + a_t$$

where the autoregressive parameters, ϕ_1 and ϕ_3, were 1.5 and -0.5, respectively.

Transfer Function Models

The model residuals from the catch and climate time series were used to calculated cross-correlations for both positive and negative lags to identify plausible links between all nation sockeye, pink, and chum catch and the three climate indices. These analyses indicated possible links between catch and both ALPI and NPI at a lag of three years. That is, ALPI and NPI may be useful in predicting catch up to three years in advance. Similar analysis, indicated ACI may be useful in predicting catch one year in advance. Transfer function models were fitted to the data and in all cases the parameter linking the climate index and catch was significant at the 5% level. All transfer function models provided modest improvements in fit over using catch data alone. Of all the indices, the ACI appears to track salmon catch reasonably well (Fig. 7). The relationship between all nation sockeye, pink, and chum salmon catch and

Fig. 1a All nation catch of sockeye, pink and chum salmon (solid line) from 1926-1995. The trend line (dashed) is a loess smooth of the data.

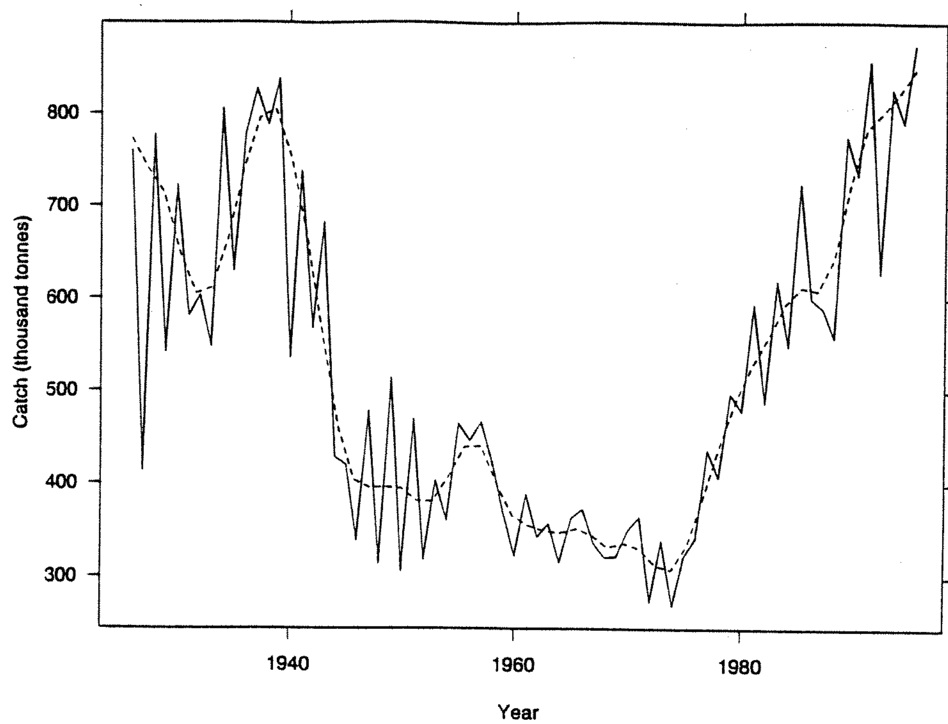


Fig. 1b Differenced and log transformed all nation catch of sockeye, pink, and chum salmon from 1926-1995.

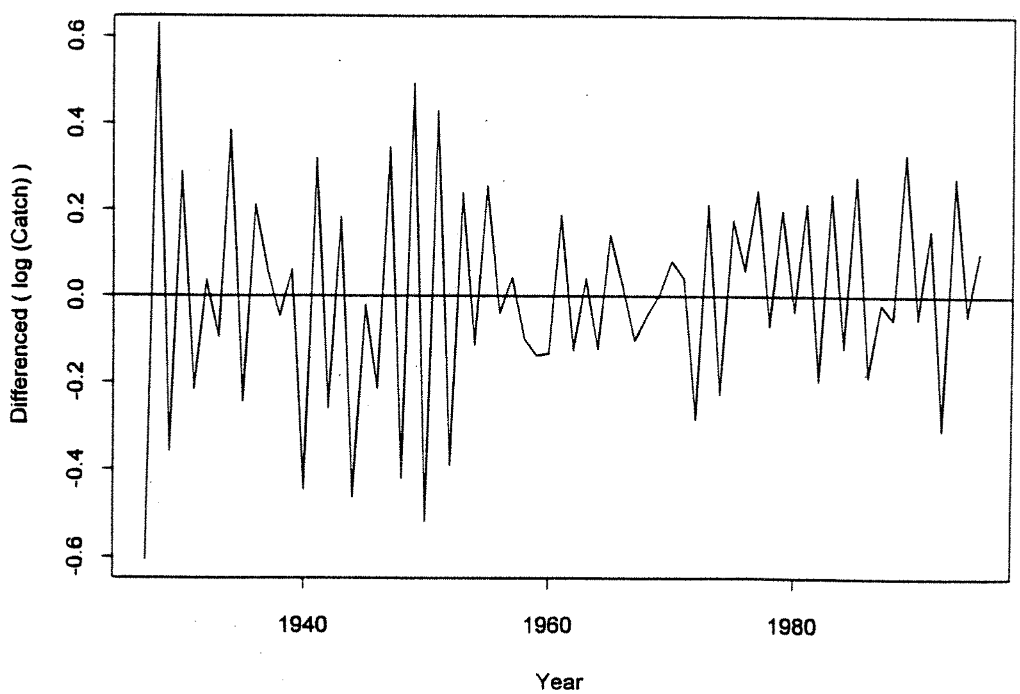


Fig. 2 December - May Aleutian Low Pressure Index (ALPI) from 1926-1995.

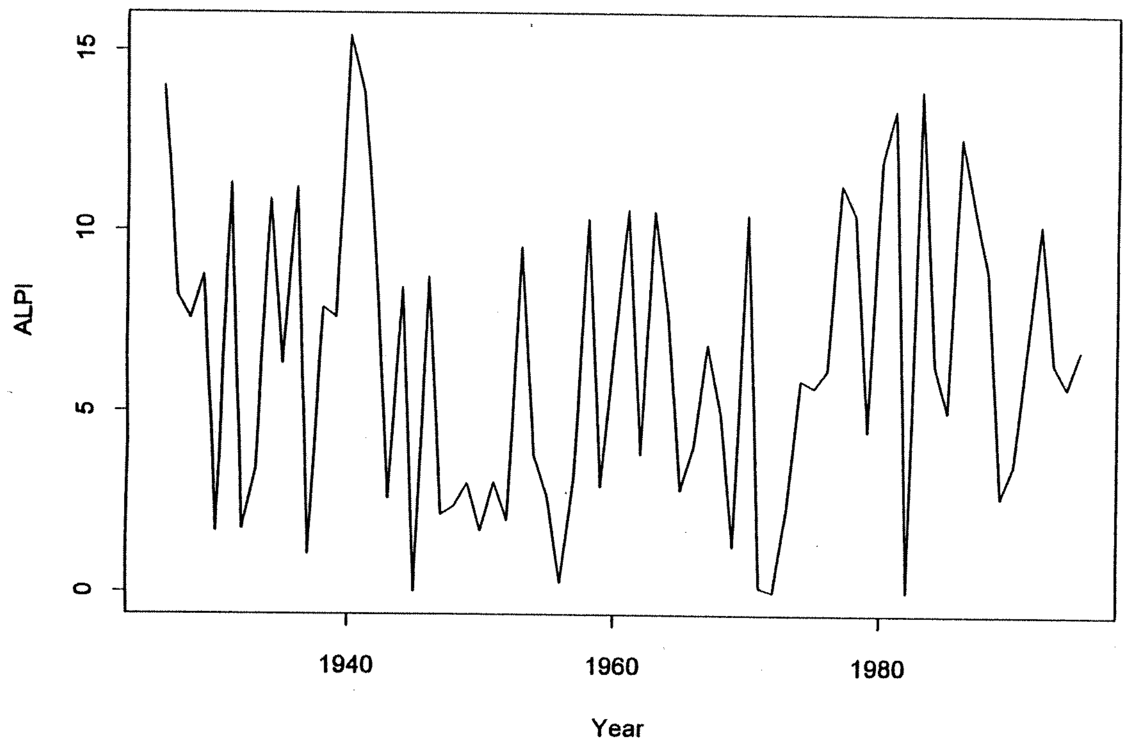


Fig. 3 North Pacific Index (NPI) from 1926-1994.

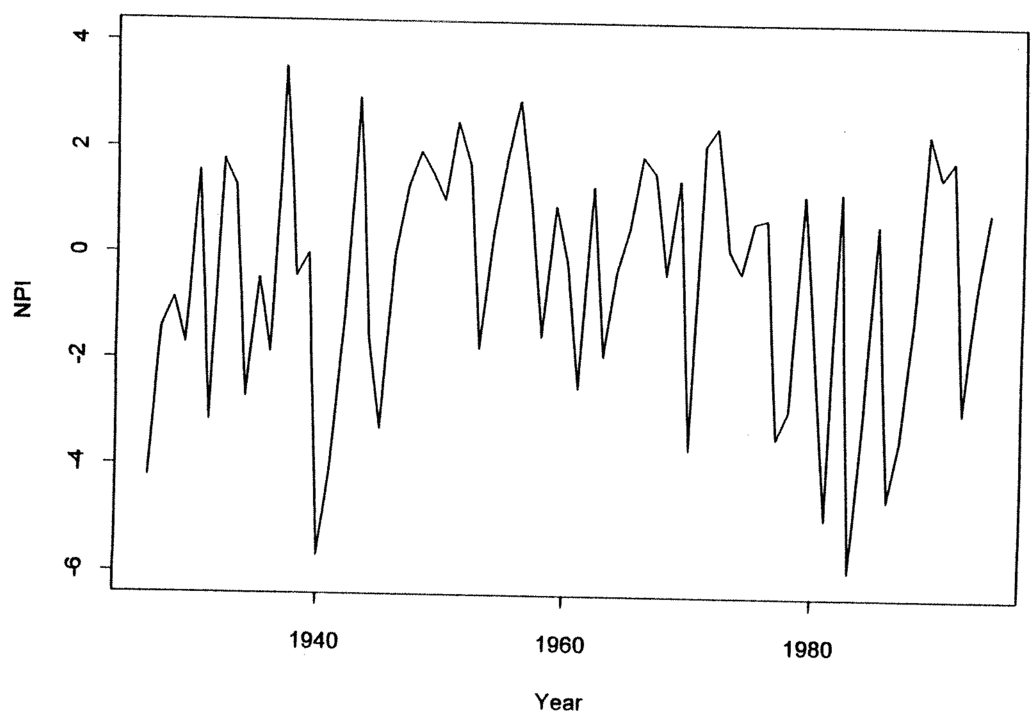


Fig. 4 Relationship between ALPI and NPI, 1926-1994.

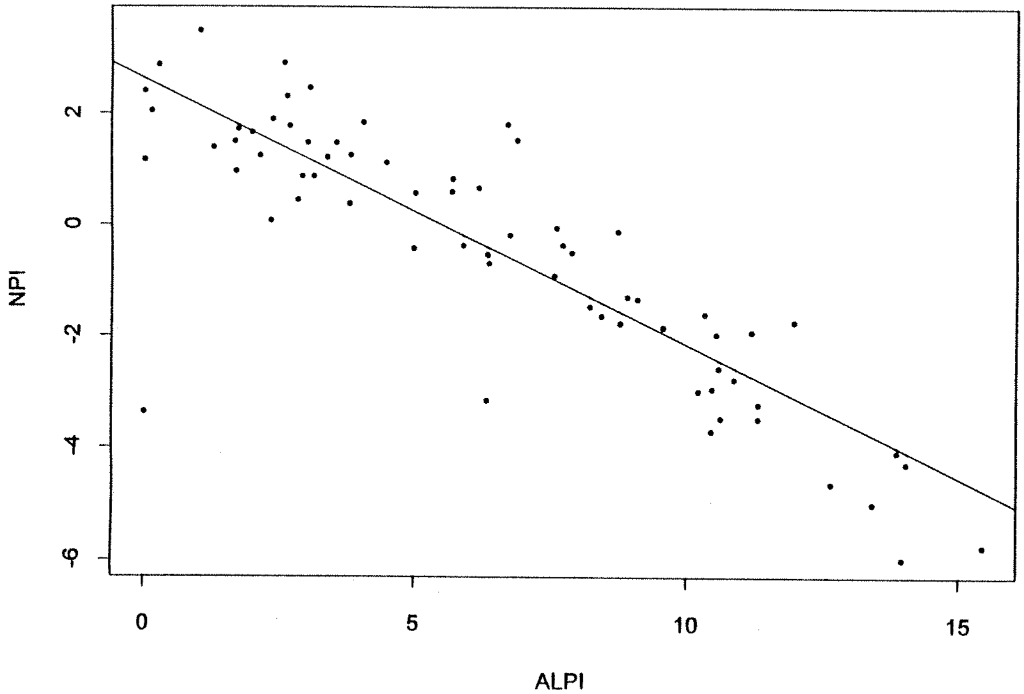


Fig. 5 Atmospheric Circulation Index (ACI) from 1926-1995

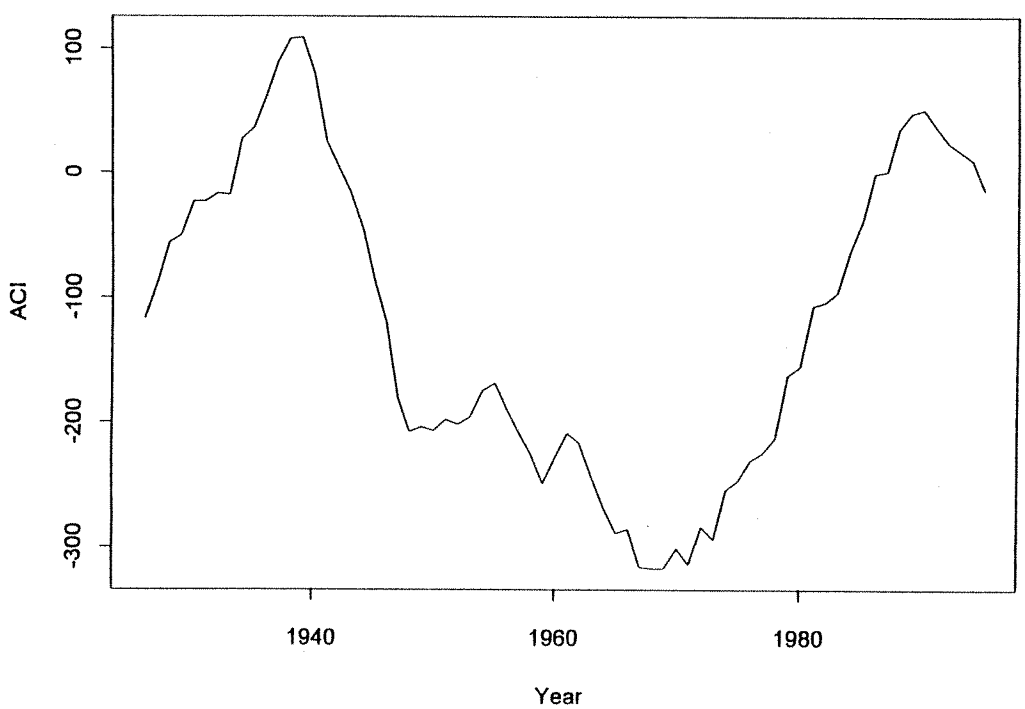


Fig. 6a First order differencing of ACI.

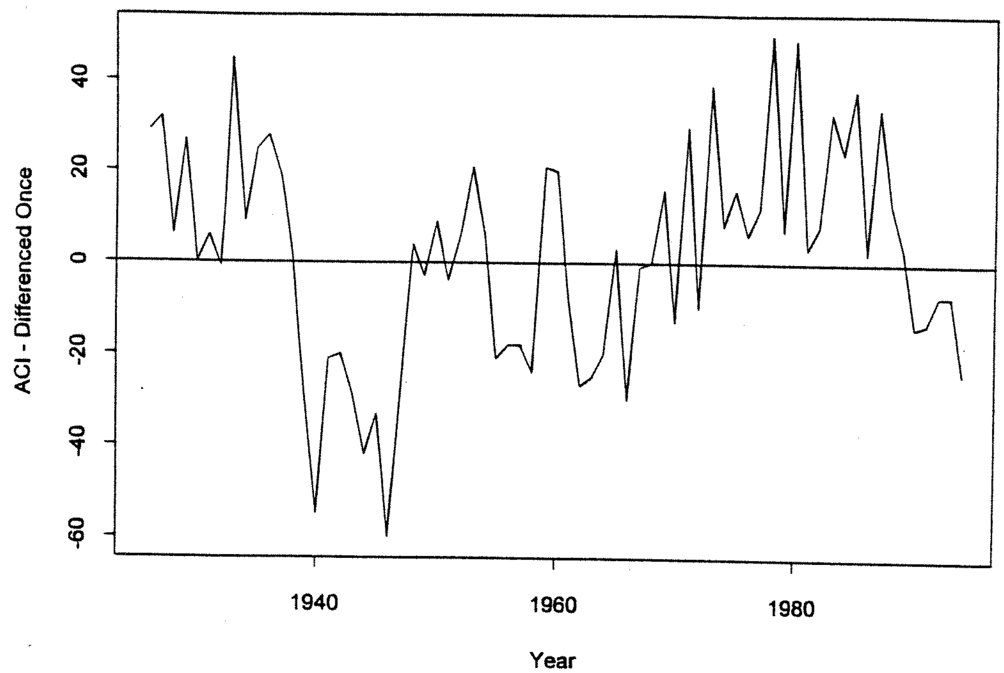


Fig. 6b Second order differencing of ACI.

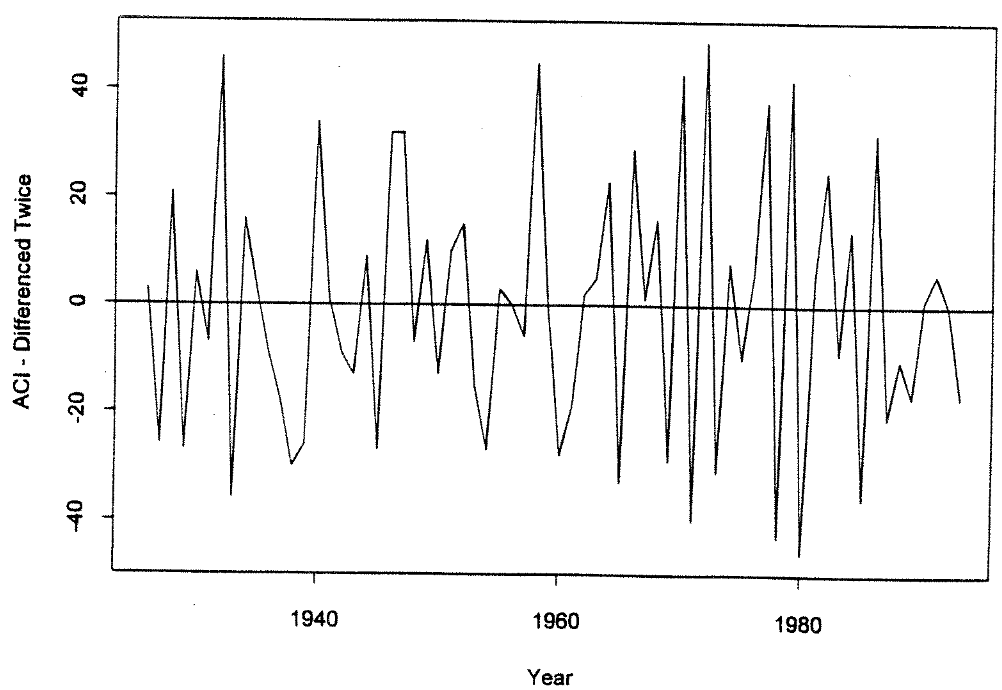
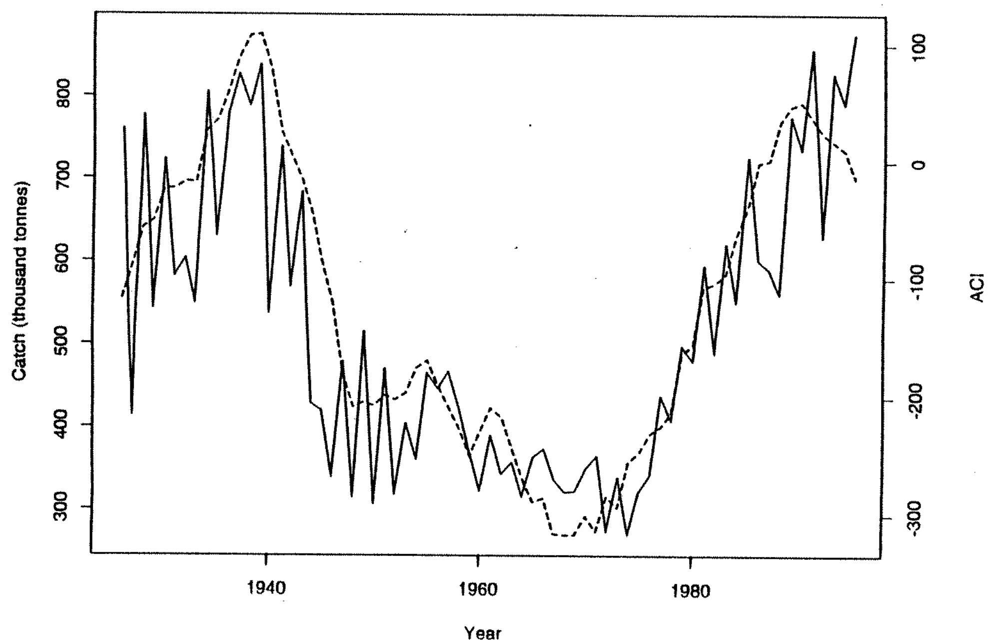


Fig. 7 All nation catch of sockeye, pink and chum salmon (solid line) and ACI (dashed line) for the period 1926-1995.



the ACI also appears to be well approximated by a linear function (Fig. 8).

DISCUSSION AND CONCLUSIONS

The marine environment clearly has a significant influence on fish stocks and this study provides additional evidence to support that thesis. Statistically significant linear relationships were found between all of the climate indices employed in this study and all nation sockeye, pink and chum salmon catch. The inclusion of these climate data provided modest improvements in fit compared to models developed using catch data alone and each index acted as a leading indicator of catch. Of the three indices examined, the ACI appears (visually) to track all nation salmon catch reasonably well and the relationship between catch and ACI appears to be approximately linear (Fig. 8).

There have been significant salmon enhancement activities in the Pacific rim over the last twenty years and there is no doubt these activities have impacted (at least locally) the dynamics of some salmon populations. Recent changes in the size of returning salmon (Ricker 1995) and the leveling off of salmon catches in recent years may indicate the ocean ecosystem is reaching the practical carrying capacity for some salmon species in some areas of the ocean. If true, it may be possible to detect and quantify changes in the marine environment and to relate these shifts to changes in fish population. Beamish et al. (1997a) showed there was an obvious change (from an increasing to a decreasing trend) in the climate around 1990 and this may indicate a change in ocean conditions to what would be expected to be a less productive state in terms of salmon production. So far, all nation catch has not dropped significantly but the rate of growth in catch has clearly decreased. It may also be possible that these shifts may only impact some populations. Certainly, some salmon populations in Washington, Oregon and British Columbia have not returned at expected levels in the early 1990s and this trend appears to be due to decreased marine survival since smolt and fry production has generally remain stable or increased during the same period.

The models employed in this paper are necessarily simplistic because we have neither the understanding of the biological or physical processes nor the necessary data to construct more comprehensive and complex models at this time. Our retrospective analysis suggest we might expect a modest increase in our ability to predict future catches by including these climate indices in our models.

ACKNOWLEDGEMENT

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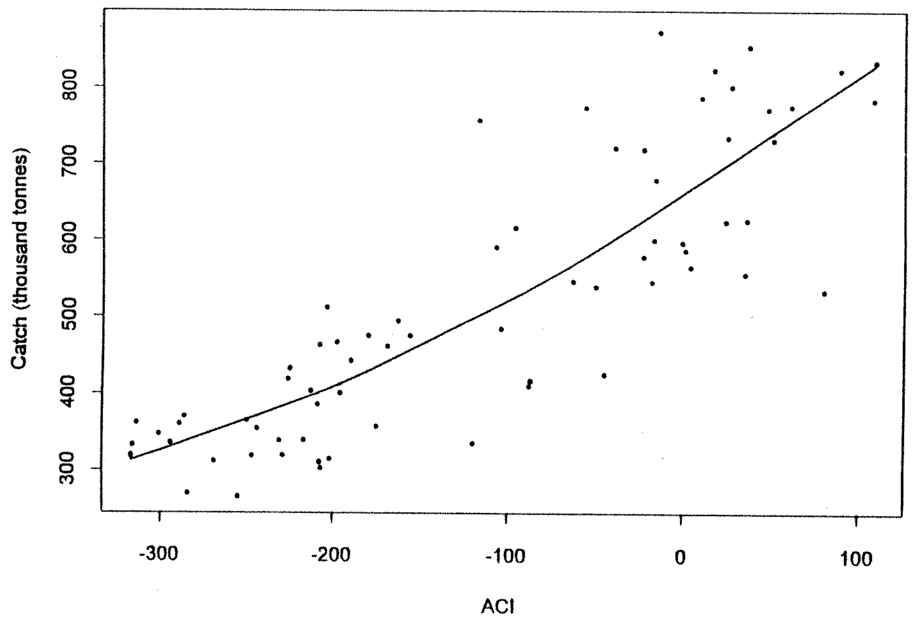
Fig. 8 **Relationship (solid line is a loess smooth) between all nation catch of sockeye, pink, and chum salmon and the ACI for the period 1926-1995.**



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