Opposite Effects of Sea-Surface Temperature on Survival Rates of Pacific Salmon from Northern and Southern Areas

Franz J. Mueter[1], Brian J. Pyper[1], Randall M. Peterman[1], Chris C. Wood[2], and **David J. Blackbourn[3]**
[1]School of Resource and Environmental Management,
Simon Fraser University, Burnaby, B.C., V5A 1S6, Canada
[2]Fisheries and Oceans Canada, Nanaimo, B.C., V9R 5K6, Canada
[3]562 Bradley St., Nanaimo, B.C., V9S 1C1, Canada

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Environmental conditions cause large variations in productivity of Northeast Pacific salmon (*Oncorhynchus* spp.). Management of salmon stocks could be improved by better understanding the sources of environmentally driven variability in their productivity. Large-scale climatic and oceanographic variability has been related to aggregate catches of Northeast Pacific salmon (Downton and Miller 1998; Hare et al. 1999). However, catch data may not reveal changes in productivity because catch reflects the confounded effects of fishing effort, spawner abundance, and hatchery production, and, if aggregated across stocks, may be dominated by changes in the most abundant stocks in a given area. Therefore, to identify environmental effects on recruitment, we used survival rates from eggs to adult recruits, adjusted for the effect of spawner abundance, as a more appropriate measure of productivity. Recent analyses show that such survival rates are positively correlated among stocks across local or regional spatial scales of several hundred kilometers, but not at larger scales (Peterman et al. 1998; Pyper et al. 2001; Pyper et al. in press). Coastal sea-surface temperatures (SST) have similar spatial correlation scales, suggesting that covariation in survival rates among salmon stocks is driven by regional-scale processes in the coastal ocean (Mueter et al. in press). The objectives of this study were to quantify SST effects on survival rates of pink (*O. gorbuscha*), chum (*O. keta*), and sockeye salmon (*O. nerka*) across multiple stocks, to examine differences in these effects among stocks from different areas, and to determine the relative importance of regional and large-scale measures of ocean temperature for explaining variability in survival rates.

Identifying environmental effects on survival rates of individual stocks are hampered by high variability in spawner and recruit data and short time series. To improve our understanding of effects of temperatures on salmon productivity, we examined relationships between recruitment and potential explanatory variables across a large number of stocks. We adopted a multi-stock approach similar to Myers et al. (1999) to estimate the effects of environmental variability, specifically sea surface temperature (SST), on multiple stocks of three species of salmon. We modeled stock-specific survival rates ($\log_e$(recruits-per-spawner)) as a function of spawner abundance (to account for density-dependent effects) and regional measures of SST. We used 120 stocks of pink (43 stocks), chum (40), and sockeye (37) salmon, with ocean-entry points ranging from Washington to western Alaska, as "replicates" to help identify the effects of SST more clearly than is possible with single-stock analyses. We averaged SST anomalies across the coastal areas occupied by a given stock during the first four months of ocean life. Monthly SST anomalies for selected coastal 2x2° grids were obtained from the COADS database (available at http://ferret.wrc.noaa.gov/las/main.html).

To model variations in $\log_e$(recruits-per-spawner), we fit a mixed-effects model to stock-recruit data for all stocks of a species and area (northern or southern) simultaneously. A mixed-effects model corresponding to the generalized Ricker model may be written as:

$$\log_e(R/S) = \alpha + a_i + \beta_i S + \gamma SST + g_i SST \quad (1)$$

In this multi-stock model, the Ricker-*a* parameter consists of an overall fixed intercept (α) that is common to all stocks in a given area and a random, stock-specific deviation from the fixed intercept (a_i) that reflects the relative productivity of stock *i*. The stock-specific a_i values are assumed to follow a normal distribution. Similarly, the SST effect has two components: a common effect of SST (γ) that affects all stocks within an area equally and a stock-specific SST effect (g_i) that differs among stocks.

Initial parameter estimates for individual stocks showed strong geographical gradients in the SST effect across stocks for all three species. Specifically, SST had a different effect on stocks in Alaska (northern area) compared to stocks in British Columbia and Washington (southern area). We allowed for potential differences by assuming two area-specific mean effects of SST (γ), and stock-specific components (g_i) that vary around the common mean within

All correspondence should be addressed to R. Peterman.
e-mail: Peterman@sfu.ca

each of the two areas. Here we report the estimated mean SST effects for each geographical area and the estimated variability of the SST effect among stocks.

We found strong geographical differences in estimated effects of SST on survival rates for all three species (Mueter et al. 2002). Warm anomalies in coastal temperatures were associated with increased survival rates of all salmon stocks in Alaska and with decreased survival rates of pink and sockeye salmon stocks in Washington and British Columbia. No apparent effects of SST on survival rates were found for chum salmon in the southern area. The magnitude of the SST effect differed among species and was strongest for pink salmon. The estimated effect suggests that an increase in SST corresponding to one standard deviation (~ 1°C) results, on average, in a 45% increase in recruits-per-spawner for Alaska pink stocks, and a 20% decrease in recruits-per-spawner for southern pink stocks. Our results suggest that temperature effects are much more consistent across adjacent stocks than indicated by single-stock analyses, and provide precise estimates of mean SST effects within each area.

To determine the relative importance of regional and large-scale measures of ocean temperature for explaining variability in survival rates, we used the Pacific Decadal Oscillation (PDO), a large-scale index of SST anomalies across the Northeast Pacific, as an alternative to regional SST in equation 1. Generally, regional-scale SST was a much better predictor of survival rates than PDO, suggesting that coastal conditions during the first few months at sea have a larger effect on survival rate and subsequent recruitment of salmon than large-scale variability related to the PDO index (Mueter et al. 2002).

We conclude that survival rates of pink, sockeye, and northern chum salmon are strongly affected by coastal processes related to variations in regional-scale SST during early ocean life, and that northern and southern stocks of Northeast Pacific pink and sockeye salmon respond in opposite ways to variations in coastal SST. Most likely, SST is a proxy for indirect effects on survival related to oceanographic differences between the two areas. Nevertheless, regional measures of SST may be useful predictors of salmon survival rates and future recruitment.

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