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Use of juvenile salmon growth and temperature change indices to predict groundfish post age-0 yr class strengths in the Gulf of Alaska and eastern Bering Sea

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ABSTRACT

Juvenile marine growth (SW1) of salmon and a new temperature change (TC) index were evaluated as ecosystem indicators and predictors for the post age-0 year class strength (YCS) of groundfish in the Gulf of Alaska (GOA) and eastern Bering Sea (EBS). Our hypothesis was that SW1, as measured on the scales of adult Pacific salmon (*Oncorhynchus* spp.), is a proxy for ocean productivity on the continental shelf, a rearing area for young salmon and groundfish. Less negative TC index values are the result of a cool late summer followed by a warm spring, conditions favorable for groundfish YCS. In the GOA, SW1 was a positive predictor of age-1 pollock (*Theragra chalcogramma*), but not age-2 sablefish (*Anoplopoma fimbria*) YCS, indicating that the growth of the Karluk River sockeye salmon that enter Shelikof Strait is a proxy for ocean conditions experienced by age-0 pollock. Contrary to our hypotheses, the TC index was a negative predictor of GOA pollock YCS; and the SW1 a negative predictor of EBS pollock and cod YCS since the 1980s. Recent fisheries oceanography survey results provide insight into possible mechanisms to support the inverse SW1 and YCS relationship. For the EBS, the TC index was a significant positive predictor for pollock and cod YCS, supporting the hypothesis that a cool late summer followed by a warm spring maximizes the over-wintering survival of pollock and cod (*Gadus macrocephalus*), especially since the 1980s. The TC and SW1 index showed value for the assessment of pollock and cod, but not sablefish.

Key words: Bering Sea, groundfish, Gulf of Alaska, indicators, salmon

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INTRODUCTION

Time series that index environmental conditions and fish stock status provide a means to better understand the long-term dynamics and health of marine ecosystems under an ecosystem-based fisheries management (Fluharty *et al.*, 1998). Such indices may also aid in fish stock and fish community assessments by improving our capability to predict post age-0 year class strength (hereafter YCS) and later recruitment to fisheries (Marasco *et al.*, 2007). Currently, the abundance of age-1 pollock (*Theragra chalcogramma*) is estimated from fish survey estimates of age-3 pollock (Ianelli *et al.*, 2010). If the YCS of groundfish is determined during the first year of life (Sigler *et al.*, 2001), then developing hypothesis and ocean-productivity based indices for the age-0 and early age-1 life stage could aid in predicting the abundances of post age-0 fish.

In some situations, YCS and recruitment of a seemingly disparate array of species may be mutually linked and influenced by the same underlying environmental factors and ecological mechanisms. For years 1965–1997, a shift in 1989 towards cooler sea temperatures coincided with reduced productivity of walleye pollock and Pacific cod (*Gadus macrocephalus*) in the North Pacific Ocean (Hare and Mantua, 2000). Similarly, a high to low shift in 1989 occurred in the time series of scale radius growth at the end of the juvenile stage for sockeye salmon (*Oncorhynchus nerka*) from the Karluk River in the Gulf of Alaska (GOA) (Martinson *et al.*, 2009). In such situations, indices for one species or species group may be correlated with and ecologically linked to another species or species group.

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Overlap in the habitat and prey of juvenile salmon (*Oncorhynchus* spp.) and groundfish species with pelagic juvenile stages lends support for the idea that ecological factors affecting the growth, survival, YCS, and recruitment of juvenile salmon in the North Pacific Ocean may also affect groundfish species such as Pacific cod, pollock, and sablefish (*Anoplopoma fimbria*) through effects on growth and survival of their pelagic juvenile stages. The YCS of salmon and groundfish is determined early in life, often in the first year (Mortensen *et al.*, 2000; Sigler *et al.*, 2001). During their first year at sea in the eastern Bering Sea (EBS) and the GOA, both salmon and groundfish juveniles distribute mainly in waters above the continental shelf, an important rearing area (Hartt and Dell, 1986; Mecklenburg *et al.*, 2002). Pelagic juvenile groundfish species and salmon consume similar prey items such as euphausiids, shrimp, and small fish (Auburn and Ignell, 2000; Andrews *et al.*, 2009; Moss *et al.*, 2009; Coyle *et al.*, 2011). The environmental conditions on the continental shelf are important in determining overwinter survival to the next age for these pelagic juvenile species (Mortensen *et al.*, 2000; Beamish and Mahnken, 2001; Sigler *et al.*, 2001).

Sea temperatures may play a role in determining YCS of salmon and groundfish in both the EBS and GOA. In the EBS, a cool late summer period is associated with reduced metabolic demand, higher energy prey (such as larger zooplankton), and higher energy reserves in the fish that improve the over-wintering survival of juvenile salmon and age-0 pollock (Moss *et al.*, 2005; Andrews *et al.*, 2009; Coyle *et al.*, 2011). Warm sea temperatures in spring lead to an earlier ice retreat and a later thermal stratification induced spring bloom at an optimal time for feeding for pelagic fish such as age-0 and age-1 pollock and juvenile salmon (Stabeno and Hunt, 2002). Although Mueter *et al.* (2011) found no relationship between spring temperatures during the age-0 stage of pollock and variations in brood survival, they found a reduction in pollock survival as summer sea temperatures increased above 9°C during the age-0 life stage (Mueter *et al.*, 2011). More information is needed on the effects of seasonal temperature during the age-0 and age-1 stages for pollock, cod, and sablefish on their YCS. In the GOA, a warm sea surface layer in the spring (late March–early April) leads to thermal stratification that helps initiate the spring bloom (Goering *et al.*, 1973). The timing, intensity, and duration of the spring phytoplankton bloom determines the annual biomass of copepods (Eslinger *et al.*, 2001), a prey item for salmon and groundfish. The temperature change between late summer and the following spring, or TC index, may index these environmental changes in the EBS (range: −7.14 to 1.70) and GOA (range: −9.23 to −4.77). A less negative TC index values in the EBS and GOA represents a cool late summer followed by a warm spring.

The goal of this project was to determine the relevance of multiple long-term time series (1978–2005) of the juvenile marine growth of Pacific salmon and the TC index as ecosystem indicators and in forecasting the YCS of selected post age-0 groundfish species. The objectives were to (i) describe the relationships between the SW1 index and YCS of groundfish, (ii) describe the relationships between the TC index and YCS of groundfish, (iii) describe how these relationships change over time, and (iv) compare the TC index and YCS relationships between recent warm (2002–2005) and cold (2006–2010) periods in the EBS.

We hypothesized that the growth of juvenile salmon during their first year in the marine environment (the SW1 index) would be an effective proxy for ocean productivity on the continental shelf, an important common rearing habitat for young salmon and groundfish. Also, we hypothesized that a cool late summer followed by a warm spring (i.e., a higher, or less negative, TC Index) would favor the pelagic early life stages of pollock, Pacific cod, and sablefish in the EBS and GOA and result in greater YCS for these species. If fish have more energy at the start of the fall and winter as a result of a cool late summer and more food available in the spring as a result of warmer seas in the spring, then the likelihood of surviving to the next summer would increase.

METHODS

Salmon growth and groundfish YCS pairings for analysis

Time series of juvenile salmon growth (SW1) in three distinct populations and the YCS of groundfish in the EBS and GOA were paired *a priori* (four pairs) for evaluation based on commonality and overlap of young salmon and pelagic stages of groundfish in rearing areas on the continental shelf. The first pairing, in the EBS, was between the juvenile growth of sockeye salmon that migrate from the Naknek River to Bristol Bay and the continental shelf waters of the EBS in the summer and the estimated YCS of age-1 pollock in the following year based on fisheries survey data and mid-water acoustic-trawl survey data. The Naknek River sockeye growth data was used due to the relatively stable escapement of the population in comparison to the other sockeye populations in the Bristol Bay river system. The second pairing was between the same sockeye growth time series and age-1 cod the following year as estimated from the fisheries survey data. These two pairings were based on evidence from the EBS indicating that juvenile salmon, age-0 pollock, and age-0 cod were captured together in surface trawl tows (0–30 m depth) during August and September (Farley and Moss, 2009). The third pairing, in the GOA, was the juvenile growth of chum salmon (*O. keta*) that leave Fish Creek from February to May to enter Portland Canal, Southeast Alaska, with the estimated YCS of age-2 sablefish in the following year. These fish share common distribution in near shore and shelf waters. The juvenile chum salmon migrate from near shore waters in the spring and spend the summer migrating counterclockwise in waters above the continental shelf of the GOA. Sablefish as age-0 larva drift from the central and eastern GOA to pelagic waters on the continental shelf and inshore in the GOA where they spend the next 2–3 yrs (Rutecki and Varosi, 1997; Sigler et al., 2001). The fourth pairing, in the GOA, was between juvenile growth of sockeye salmon that migrate from the Karluk River on Kodiak Island into Shelikof Strait from March to May and then migrate into waters west of Kodiak, important spawning areas for adults and rearing area for age-0 pollock (Dorn *et al.*, 2010), with the estimated YCS of age-1 pollock the following year.

Salmon growth (SW1) indices

Three distinct times series of SW1 were developed from measurements on the scales of adult fish collected from the three salmon populations (Fig. 1): age 2.2 sockeye salmon from the Naknek River in Bristol Bay in western Alaska from 1979 to 2005 (SW1: 1977–2003), age 0.3 chum salmon from Fish Creek near Hyder, southeast Alaska from 1972 to 2007 (SW1: 1969–2004), and age 2.2 sockeye salmon from the Karluk River on Kodiak Island in south-central Alaska from 1982 to 1999 (SW1: 1980–1997). The GOA age-1 pollock time series extends past 1997, but these data were not included in the analysis in order to match the SW1 Karluk salmon time series which extended only to 1997. Scales were collected by the National Marine Fisheries Service and the Alaska Department of Fish and Game. SW1 was measured as the distance in millimeters in the first ocean zone along a consistent radial axis on the scale for each fish stock. Mean SW1 was calculated for each year. SW1 data were unavailable for years 1980, 1986, and 2000 for the Naknek River sockeye and in 1995 and 1999 for Fish Creek chum salmon; data for these years were estimated using a 3-yr centered average.

Figure 1. Means of the juvenile growth time series for age 0.3 chum salmon from Fish Creek near Hyder Alaska 1969-2004, age 2.2 sockeye salmon from the Karluk River on Kodiak Island 1980-1997, and age 2.2 sockeye salmon from the Naknek River of Bristol Bay 1977-2003.

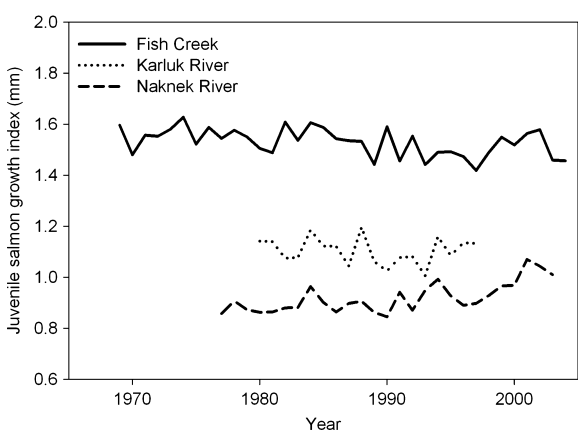
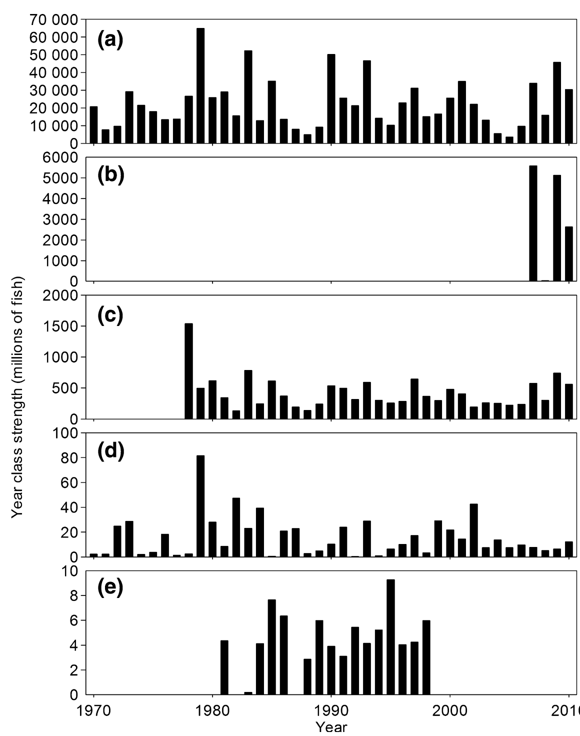


Figure 2. The estimated year class strengths of age-1 pollock (millions of fish) in the eastern Bering Sea (EBS) 1978-2010 (a), age-1 pollock from the acoustic-trawl survey data in the eastern Bering Sea 2007-2010 (b), age-1 cod in the EBS from Model B 1978-2010 (c), age-2 sablefish in the Gulf of Alaska (GOA) 1970-2005 (d), and the natural logarithm of the age-1 pollock in the GOA 1981-1998 (e). Data are from Ianelli *et al.* (2010), Thompson *et al.* (2010), Hanselman *et al.* (2008), and Dorn *et al.* (2010).



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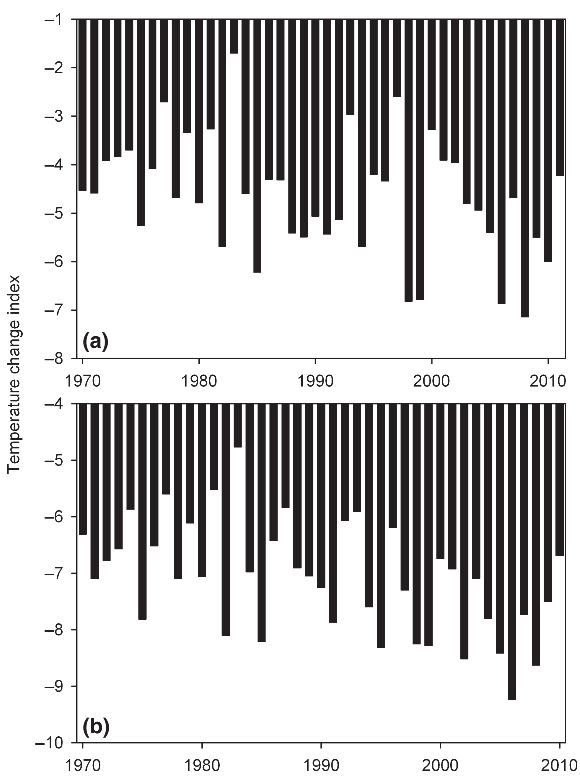
Groundfish YCS indices

Five time series of numerical estimates of YCS values for post age-0 groundfish (millions of fish) in the GOA and EBS were obtained from North Pacific groundfish stock assessment and fishery evaluation reports (Fig. 2): age-1 pollock in the EBS for years 1978–2010 (Table 1.21 in Ianelli *et al.*, 2010), age-1 pollock estimated from the mid-water acoustic trawl survey data in the EBS for 2007–2010 (Table 1.14 in Ianelli *et al.*, 2010), age-1 cod in the EBS for years 1978–2010 (Table 2.25c in Thompson *et al.*, 2010), age-2 sablefish in the GOA for years 1970–2005 (Table 3.9 in Hanselman *et al.*, 2008), and age-1 pollock in the GOA for years 1981–1998 (Table 1.10 in Dorn *et al.*, 2010). Authors used age-structured models and fisheries survey data to make these estimates. The acoustic trawl surveys are typically biannual, but were conducted for four consecutive years (2007–2010) into the Russian zone and covered part of the Navarin Basin (Ianelli *et al.*, 2010). These survey results were included to compare the TC and YCS relationships for with age-1 pollock estimated from bottom trawl and acoustic mid-water data. Due to a large variance in the GOA pollock values, we transformed those data using natural logarithms.

Figure 3. Temperature change index values for the eastern Bering Sea (a) and the Gulf of Alaska (b). Less negative values represent a cold late summer in year t-1 and warm spring in year t, while more negative values represent a warm late summer in year t-1 and a cold spring in year t.



Temperature change (TC) indices

The TC index (Fig. 3) was calculated as the difference in the mean monthly sea temperature in the spring of year *t* and the late summer of year *t*–1 for the EBS (Fig. 3a) and GOA (Fig. 3b). Less negative TC index values represent a cold late summer followed by a warm spring. Time series of average monthly sea surface temperatures were obtained from the NOAA Earth System Research Laboratory Physical Sciences Division website. Sea surface temperatures were based on NCEP/NCAR gridded reanalysis data (Kalnay *et al.*, 1996, data obtained from http://www.esrl.noaa.gov/psd/cgi-bin/data/timeseries/timeseries1.pl).

For the EBS, the average June sea surface temperature was used to represent spring sea temperature due to possible ice coverage into May. August sea surface temperature, the warmest month, was used to represent late summer sea temperature. The EBS sea temperature components were calculated for the south EBS region at 56.2° and 58.1°N latitude by 166.9° and 161.2°W longitude to eliminate bias due to ice and regional variability in sea temperatures.

For the GOA, the average of the April and May sea surface temperatures was used to represent spring sea temperatures to match the timing of the spring phytoplankton bloom and August sea surface temperature to represent the late summer sea temperature. The GOA sea temperature components were averaged for the several regions on the continental shelf around the GOA that included areas near the Alaska Peninsula at 56.2° and 54.3°N latitude by 159.4° and 157.5°W longitude, west of Kodiak Island at 56.2° latitude by 157.5° and 155.6°W longitude, east of Kodiak Island at 58.1°N latitude and 151.9°W longitude, Prince William Sound at 60.0° and 58.1°N latitude by 146.2° and 144.4°W longitude, and near Prince of Whales Island at 56.2°N latitude by 135.0° and 133.1°W longitude.

Data analysis

Linear regression models were used to describe groundfish YCS in year *t* as a function of SW1 in year *t*–1 and TC index in year *t*. All hypotheses under investigation postulated positive relationships between the SW1 and TC indices and the YCS indices of pollock, cod, and sablefish. A model of the form

$$\mathrm{YCS}_t = b_0 + b_1\,\mathrm{SW1}_{t-1} + b_2\,\mathrm{TC}_t + \mathrm{error} \qquad (1)$$

would not properly test the various hypotheses since the temperature variable shifts the model adjusted intercept (defined as the estimated intercept plus the TC index times its coefficient) up and down while holding the coefficient of SW1 fixed.

We sought to test whether the coefficient of the SW1 variable changed sign depending on whether the data came from colder or warmer regimes or changed over time. One way to proceed would be to arbitrarily assert the dates of colder or warmer regimes and estimate the model in the two periods. Such an approach assumes that any changes observed are seen as abrupt shifts in the SW1 and YCS relationships. We used a less restrictive way by not assuming specific climate regime dates and letting the data determine when and or if any change occurred in the signs of coefficients in the models. As a more formal test, we used the Quandt Likelihood ratio (Brown *et al.*, 1975; Stokes, 1997) to determine any break points in the data. Break points are defined as relative minimums of the Quandt Likelihood ratio λ_t for models that break at observation t as

$$\lambda_t = 0.5t\ln(\sigma_1^2) + 0.5(T-t)\ln(\sigma_2^2) - 0.5T\ln(\sigma^2), \quad (2)$$

where T is the number of observations in the data and σ_1^2, σ_2^2 and σ^2 are the variances of the regressions fitted to the first t observations the last T–t observations and the whole T observations. When t is at the break point the estimated Quandt likelihood ratio will be at a minimum since the model for data up to period t will be distinct from the model after period t. The fact that the model is distinct implies that one or more coefficients have changed before and after the break point. In the case where there was no break point $0.5t\ln(\sigma_1^2)+0.5(T-t)\ln(\sigma_2^2) \approx 0.5T\ln(\sigma^2)$ while if there had been a break point having different coefficients in the two periods would result in $0.5t\ln(\sigma_1^2)+0.5(T-t)\ln(\sigma_2^2) < 0.5T\ln(\sigma^2)$. More specifically, a lower value or shift in the Quandt likelihood values indicate that the models produced from the data before and after and or including the break point year have coefficients that differ the most. We caution that shifts in the break points near the beginning and end of the time series could be spurious due to the lack of sufficient data in the end points.

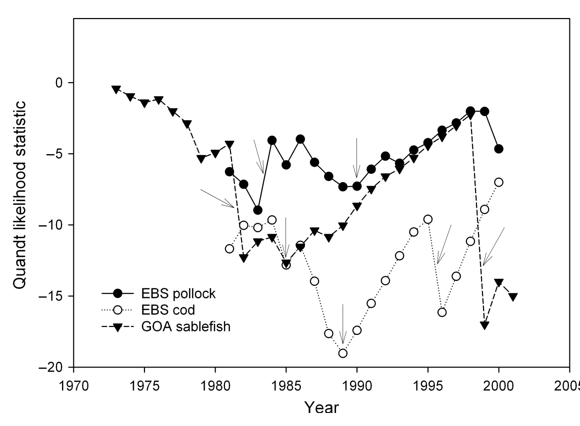
Scatter plots of the SW1 and YCS indices were created for each matching pair: age-1 EBS pollock and Naknek River sockeye salmon SW1, age-1 EBS cod and Naknek River sockeye salmon SW1, age-2 GOA sablefish and Fish Creek chum salmon SW1, and age-1 GOA pollock and Karluk sockeye salmon SW1. The relationships between SW1 and YCS were assessed for the entire periods and by time periods, as determined from the break point analysis.

Scatter plots of the TC and YCS indices were created for each matching pair: age-1 EBS pollock and the EBS TC index, age-1 EBS cod and EBS TC index, age-2 GOA sablefish and GOA TC index, and age-1 GOA pollock and GOA TC index. The relationships between TC and YCS were assessed within and among time periods, as determined from the break point analysis of the YCS and SW1 relationships.

Based on the break point analysis results we divided the data and fit multiple regression models. We fit the multiple regression models to describe YCS as a function of the SW1 and TC indices for all matches. The goodness-of-fit of the regression models were expressed as the probability values of the statistical F-test (P values) and the coefficient of determination (R^2). Multicollinearity among predictor variables for all models was examined using the Pearson correlation method.

Scatter plots were also used to visually compare the relationships between TC and YCS for EBS pollock and EBS cod during the warm (2002–2005) and cold (2006–2010) periods. SW1 data was not available for these years and was not included in the analysis. Simple linear regression models were used to describe EBS pollock YCS as a function of the TC index. The YCS variables in the models were based on the fishery survey data in the recent warm (2002–2005) and cold (2006–2010) years, and the four consecutive years of mid-water acoustic-trawl survey data in a cold year period (2007–2010). Again, the goodness-of-fit of the

Figure 4. Quandt likelihood statistics for the eastern Bering Sea (EBS) pollock 1978-2004, EBS cod 1978-2004, and Gulf of Alaska (GOA) sablefish 1970-2005 models. Arrows show the break points in model structure for EBS pollock in 1983-84 and 1990, EBS cod in 1989 and 1995-1996, and GOA sablefish in 1981-1982, 1985, and 1998-1999.



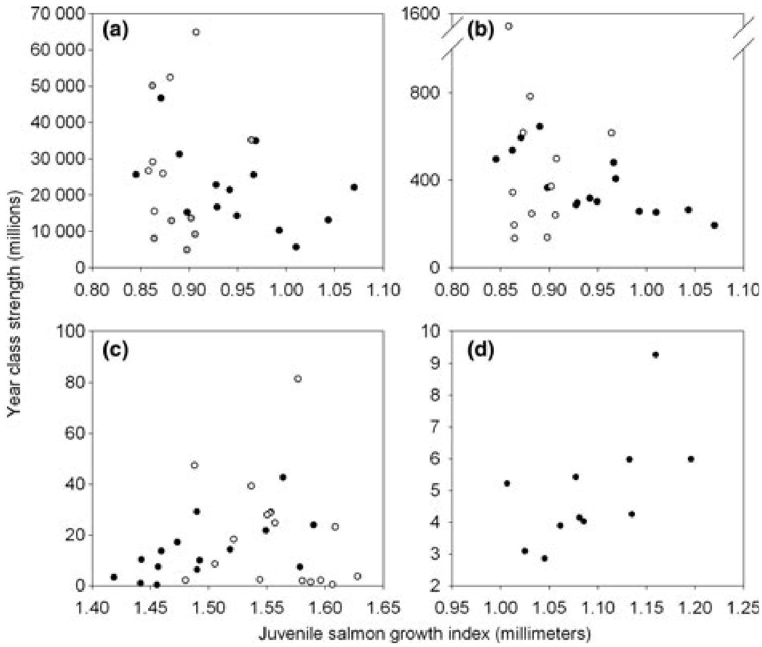


Figure 5. Relationships between groundfish year class strength (YCS) in year t and estimates of juvenile salmon growth indices (SW1) in year t-1 for pre- (open circles), middle (grey circles) and post- (filled circles) break point periods. Figures include the relationship between SW1 measured on scales of age 2.2 sockeye salmon from the Naknek River and the YCS of age-1-pollock in the eastern Bering Sea (EBS) 1978-1983, 1984-1990, and 1990-2004 (a), age 2.2 sockeye salmon from the Naknek River and the YCS of age-1 cod in the EBS 1978-1989 and 1989-2004 (b), age 0.3 chum salmon from Fish Creek and the YCS of age-2 sablefish in the GOA 1970-1985 and 1985-2005 (c), and age 2.2 sockeye salmon from the Karluk River and the natural logarithm transformed YCS of age-1 pollock in the Gulf of Alaska 1981-1998 (d).

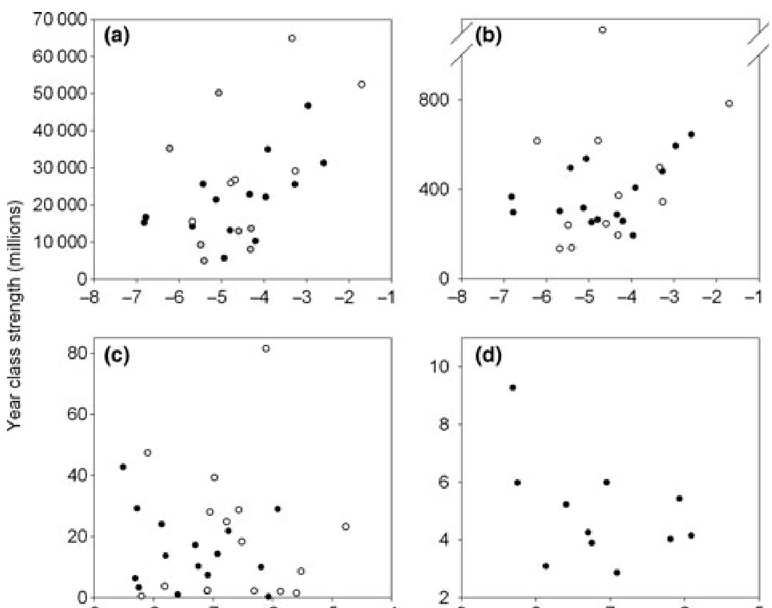


Figure 6. Relationships between groundfish year class strength (YCS) estimates and the Temperature Change (TC) indices for the eastern Bering Sea (EBS) and Gulf of Alaska (GOA) for pre- (open circles), mid- (grey circles), and post- (filled circles) break periods. Figures include the relationship between the EBS TC index and the YCS of age-1 pollock in the EBS 1978-83, 1984-1990, and 1990-2004 (a), the EBS TC index and the YCS of age-1 cod in the EBS 1978-1989 and 1989-2004 (b), the GOA TC index and the YCS of age-2 sablefish in the GOA 1970-1985 and 1985-2005 (c), and the GOA TC index and YCS of age-1 pollock in the GOA 1981-1998 (d).

regression models were expressed as the probability values of the statistical *F*-test (*P* values) and the coefficient of determination (R^2).

RESULTS

Changes in the predictive capability of the juvenile salmon growth index (SW1) with respect to the year class strength (YCS) of groundfish occurred in the 1980s and 1990s (Fig. 4). Break points or statistical changes in the SW1 and groundfish YCS relationships, as indicated by shifts and minimum values of the Quandt Likelihood Statistic, were observed for EBS pollock in 1983–1984 and 1990, for EBS cod in 1989 and 1995–1996, and for GOA sablefish in 1981–1982, 1985, and 1998–1999. For the GOA pollock dataset, a break point was not possible to reliably assess because there were only 11 consecutive observations.

The SW1 index was not visibly related to the YCS of groundfish for all years of data combined, except for

Table 1. Multiple linear regression model coefficients for predictor variables (SW1 and TC), test statistic (t) of the coefficients, coefficient of variation (R^2), F-test statistic of R^2, and the probability of the F-test statistic [Prob(F)] for year class strength (YCS) described as a function of juvenile salmon growth (SW1) and the temperature change (TC) index. YCS is the estimated abundance of age-1 pollock (millions) in the eastern Bering Sea, 1978–2010.

Years	1978–2004	1978–1983	1984–2004	1984–1990	1990–2004	2002–2005	2006–2010	2007–2010
SW1	**−58517**	**720041**	−50439	−188177	**−121325**			
t	**−1.346**	**5.069**	−1.106	−0.562	**−3.359**			
TC	**6221**	**5961**	3638	−15188	**5109**	**13382**	11552	**2405**
t	**2.957**	**3.325**	1.478	−0.928	**2.673**	**4.761**	2.292	**5.203**
Constant	**106582**	**−570454**	85387	111108	**162170**	**75018**	96959	**17374**
t	**2.616**	**−4.477**	1.902	0.454	**4.475**	**5.559**	3.151	**6.370**
R^2	**0.314**	**0.955**	0.152	0.184	**0.582**	**0.919**	0.637	**0.931**
F	**5.488**	**31.731**	1.608	0.452	**8.345**	**22.668**	5.254	**27.074**
Prob(F)	**0.011**	**0.010**	0.228	0.665	**0.005**	**0.041**	0.106	**0.035**

The best fit models have probability values of the F-statistics <0.05, shown in bold text.

Table 2. Multiple linear regression model coefficients for predictor variables (SW1 and TC), test statistic (t) of the coefficients, coefficient of variation (R^2), F-test statistic of R^2, and the probability of the F-test statistic [Prob(F)] for year class strength (YCS) described as a function of juvenile salmon growth (SW1) and the temperature change (TC) index. YCS is the estimated abundance of age-1 cod (millions) in the eastern Bering Sea, 1978–2010.

Years	1978–2004	1978–1989	1989–2004	1989–1995	1996–2004	2002–2005	2006–2010
SW1	−1561	−500	**−1641**	**−2136**	**−1645**		
t	−1.784	−0.108	**−5.919**	**−4.028**	**−4.079**		
TC	56.111	62.968	**63.893**	**67.058**	**60.091**	−27.662	166.564
t	1.325	0.569	**4.371**	**2.260**	**3.394**	−0.856	2.313
Constant	2115	1203	**2218**	**2660**	**2222**	101	1490
t	2.579	0.303	**7.944**	**5.331**	**5.409**	0.651	3.387
R^2	0.178	0.047	**0.788**	**0.846**	**0.804**	0.268	0.641
F	2.592	0.221	**24.115**	**11.061**	**12.293**	0.733	5.350
Prob(F)	0.096	0.806	**0.000**	**0.024**	**0.008**	0.482	0.104

The best fit models have probability values of the F-statistics <0.05, shown in bold text.

GOA pollock (Fig. 5). For the EBS, the SW1 was inversely related to pollock and cod YCS in the post-break point periods, but not related in the pre- and middle break periods (Fig. 5a,b). For the GOA, no visible relationship occurred between SW1 and sablefish YCS for any period (Fig. 5c). For the GOA pollock, SW1 was directly related to YCS in the 1981–1998 period (Fig. 5d).

The temperature change (TC) index was directly related to the EBS pollock (Fig. 6a), but not visibly related to EBS cod (Fig. 6b), GOA sablefish (Fig. 6c), or GOA pollock (Fig. 6d) YCS. For EBS pollock, the direct relationships between TC and YCS were visible in the 1978–1983 and 1990–2004 period, but not the 1984–1990 period.

For EBS pollock, YCS was described as a significant positive function of the TC index, but not SW1, for the entire year period (R^2 = 0.314, P = 0.011) (Table 1). Dividing the data at the 1983 and 1984 break point, SW1 and TC indices were positive predictors of YCS for years 1978–1983 (R^2 = 0.955, P = 0.010) and non-significant predictors in the 1984–2004 period (R^2 = 0.152, P = 0.228). Further dividing the 1984–2004 data at the 1990 break point, the TC and SW1 indices were not significant predictors of pollock YCS for the 1984–1990 period (R^2 = 0.184, P = 0.665). However, the TC index was correlated with SW1 for this period (r = 0.75, t = 2.54, P = 0.038), but removing each predictor did not change the results. For the 1990–2004 period, SW1 was a significant negative and TC a significant positive predictor of pollock YCS (R^2 = 0.582, P = 0.005), with similar signs of the coefficients as the entire year period.

For EBS cod, the TC and SW1 indices were significant predictors of YCS from the late 1980s to the

Table 3. Multiple linear regression model coefficients for predictor variables (SW1 and TC), test statistic (t) of the coefficients, coefficient of variation (R^2), F-test statistic of R^2, and the probability of the F-test statistic [Prob(F)] for year class strength (YCS) described as a function of juvenile salmon growth (SW1) and the temperature change (TC) index. YCS is the estimated abundance of age-2 sablefish (millions) in the Gulf of Alaska, 1970–2005.

Years	1970–2005	1970–1985	1970–1981	1982–1985	1985–2005	1985–1998	1999–2005
SW1	64.37	−109.39	21.67	−422.71	92.79	80.55	166.82
t	1.038	−0.683	0.101	−2.589	2.345	1.923	2.253
TC	−0.435	1.229	4.552	7.045	−0.839	3.156	−10.947
t	−0.121	0.166	0.355	1.180	−0.330	0.296	−2.249
Constant	−84.75	198.49	13.28	736.72	−132.90	−87.62	−319.78
t	−0.798	0.758	0.039	2.660	−2.022	−1.269	−2.410
R^2	0.033	0.035	0.014	0.870	0.234	0.335	0.640
F	0.570	0.235	0.065	3.352	2.754	2.773	3.548
Prob(F)	0.571	0.794	0.937	0.360	0.090	0.106	0.130

Coefficient and models were not statistically significant.

Table 4. Multiple linear regression model coefficients for predictor variables (SW1 and TC), test statistic (t) of the coefficients, coefficient of variation (R^2), F-test statistic of R^2, and the probability of the F-test statistic [Prob(F)] for year class strength (YCS) described as a function of juvenile salmon growth (SW1) and the temperature change (TC) index. YCS is the natural logarithm transformed estimated abundance of age-1 pollock (millions) in the Gulf of Alaska, 1981–1998.

Years	1981–1998
SW1	**19.012**
t	**2.994**
TC	**−1.081**
t	**−3.194**
Constant	**−23.589**
t	**−3.379**
R^2	**0.640**
F	**11.585**
Prob(F)	**0.001**

The best fit models have probability values of the F-statistics <0.05, shown in bold text.

mid-2000s (Table 2). The multiple regression models that describe YCS as a function of SW1 and TC were not significant for the entire period (R^2 = 0.178, P = 0.096) or the earlier 1978–1989 period (R^2 = 0.047, P = 0.806). In more recent years, YCS was described as a significant negative function of SW1 and positive function of TC for the 1989–2004 period (R^2 = 0.788, P = 0.00004), the 1989–1995 period (R^2 = 0.846, P = 0.024), and the 1996–2004 period (R^2 = 0.804, P = 0.008).

Figure 7. The estimated abundance (millions) of (a) age-1 pollock and (b) age-1 cod in the eastern Bering Sea in relation to the Temperature Change (TC) index for pollock (R^2 = 0.919, P = 0.041) and cod (R^2 = 0.268, P = 0.482) in recent warm years 2002-05 (filled circles) and for pollock (R^2 = 0.637, P = 0.106) and cod (R^2 = 0.641, P = 0.104) in cold years 2006-10 (open circles). The cold year models and the 2011 TC value −4.23 predicts 48,094 million age-1 pollock and 785 million age-1 cod for 2011 (black x).

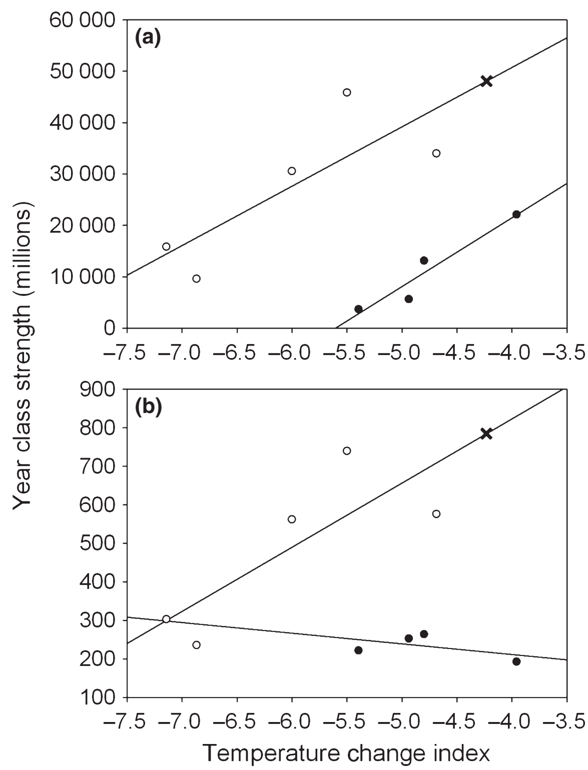
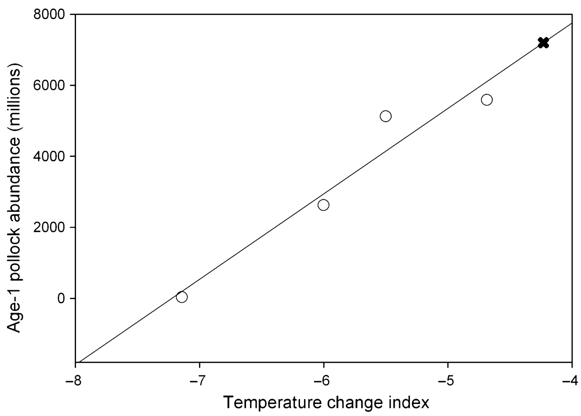


Figure 8. The NMFS summer mid-water acoustic-trawl survey estimates of the abundances (millions) of age-1 pollock in the Bering Sea in relation to the Temperature Change index for cold years 2007-2010 ($R^2 = 0.931$, $P = 0.035$). The current model and the 2011 TC index value −4.23 predicts 7,198 million age-1 pollock for 2011 (black x).



For the GOA time series, the SW1 and TC indices were significant predictors of pollock YCS, but not sablefish YCS (Tables 3 and 4). For sablefish, the predictive ability of the indices was low for the entire period ($R^2 = 0.033$, $P = 0.571$), but increased over time. TC was correlated with SW1 for the entire period ($r = 0.34$, $t = 2.13$, $P = 0.039$), but removing each predictor did not change the results. SW1 and TC were less related to YCS during the 1970–1985 period ($R^2 = 0.035$, $P = 0.794$), than the 1985–2005 period ($R^2 = 0.234$, $P = 0.090$). Sablefish YCS was not significant related to SW1 or TC for the 1970–1981, 1982–1985, and 1999–2005 periods. GOA pollock YCS was described as a significant positive function of SW1 and a negative function of the TC index for the 1981–1998 yrs ($R^2 = 0.641$, $P = 0.001$) (Table 4).

For recent warm (2002–2005) and cold (2006–2010) periods in the EBS, a cool late summer followed by a warm spring in the EBS was linked to higher YCS values for age-1 pollock (Fig. 7a) and age-1 cod (Fig. 7b), except for cod during warm years in the EBS. For YCS estimates based on fishery survey data, the model coefficient for the TC index were significant for pollock during the 2002–2005 warm period ($R^2 = 0.919$, $P = 0.041$), but not significant for pollock during the 2006–2010 cold period ($R^2 = 0.637$, $P = 0.106$), for cod during the 2002–2005 warm period ($R^2 = 0.268$, $P = 0.482$), or for cod during the 2006–2010 cold period ($R^2 = 0.641$, $P = 0.104$). For the cold year models, the TC index had a better fit with the estimates of age-1 pollock made from the mid-water acoustic-trawl survey data (Fig. 8) than those based on fisheries survey data (Fig. 7a). Overall, the best fit model used the TC index to predict EBS pollock ($R^2 = 0.931$, $P = 0.035$) as estimated from the acoustic trawl survey data for the cold 2007–2010 period (Table 1).

DISCUSSION

Our indices differ from indices most often used in assessing the year class strength of fish in that we integrated pre- and post- winter ocean conditions into one index and developed salmon growth as a proxy for ocean productivity and used both indices to predict the overwintering survival of groundfish. More often the recruitment of groundfish is linked to individual climate variable during a specific life stage. For example, higher YCS of age-2 pollock was linked to warmer than average annual and seasonal air temperatures near the Pribilof Islands ($r = 0.527$, $P < 0.05$) and less annual ice cover in the Bering Sea ($r = -0.445$, $P < 0.05$) during the age-1 life stage for years 1964–1990 (Quinn and Niebauer, 1995). For years 1964–2001, the log-transformed estimates of the abundances of age-2 pollock was higher when the spring bloom was later during age-1 stage and when the surface winds were stronger during age-0 stage, possibly due to the transport larvae away from adult predation (Mueter *et al.*, 2006). Our findings that the TC index was a positive predictor for EBS groundfish YCS supports the hypothesis that a cool late summer during the age-0 stage followed by a warm spring during the age-1 stage maximize the conditions for over-wintering survival of young pollock and cod in the EBS.

Temporal changes in SW1 and TC indices as predictors of groundfish post age-0 YCS

The 1980s timing of change in the SW1 and YCS relationships for EBS groundfish coincided with a restructuring of the ecosystem dynamics in the EBS. For the EBS pollock, the SW1 and YCS relationship was direct from the late 1970s to mid-1980s, weak from the mid- to late 1980s, and inverse from the late 1980s to mid-2000s. In the mid-1980s, Bailey (2000) observed a shift in the important life stage driving the recruitment of pollock from the larval to the juvenile stage in the Bering Sea. In addition, for years 1965–1997, Hare and Mantua (2000) found a positive shift in the recruitment of GOA and EBS pollock in 1977 was followed by a negative shift in the recruitment of pollock and cod in the EBS in 1989. Our findings support the evidence for a restructuring of ecosystem dynamics in the EBS in the 1980s.

SW1 and groundfish post age-0 YCS

For the Gulf of Alaska, the index for growth in body length of juvenile salmon was a positive predictor of age-1 pollock, but not age-2 sablefish, indicating that juvenile salmon growth has potential as a proxy for favorable ocean conditions experienced by age-0 pollock (i.e., the year prior to their contributing to the YCS indices used in this paper). For groundfish in the Gulf of Alaska, above-average temperatures and faster growth rates relate to higher recruitment success for groundfish (Sigler *et al.*, 2001). In addition, the body size of both species is important in determining over wintering survival (Beamish and Mahnken, 2001; Sigler *et al.*, 2001). The proposed purpose of attaining a larger body size during the first year at sea is to avoid predation during the early summer (Beamish and Mahnken, 2001). The positive SW1 and YCS relationship indicates that the early marine growth of Karluk sockeye salmon may be an informative indicator for rearing conditions of age-0 pollock in the Gulf of Alaska.

Based on the results for the Gulf of Alaska, it would be expected that SW1 might be a positive predictor of groundfish YCS for the EBS, because juvenile salmon share similar prey resources and habitat as groundfish in the GOA and the EBS (Auburn and Ignell, 2000; Sigler *et al.*, 2001). However, we found an inversely relationship between SW1 for Naknek River sockeye and EBS groundfish YCS. Recently published results from fisheries oceanography surveys in the EBS provide insight into the possible mechanisms to explain the inverse SW1 and YCS relationship seen since the late 1980s. Juvenile pink (*O. gorbuscha*), sockeye, and chum salmon captured with a trawl net in the upper 35 m in the EBS were longer during warm summers (2002 and 2003) and shorter during cold summers (2006, 2007) (Andrews *et al.*, 2009; Farley and Moss *et al.*, 2009; Farley and Moss, 2009; Farley and Trudel, 2009; Farley *et al.*, 2011). However, the energy density of juvenile pink salmon was higher during cold late summers (2004 and 2005) and lower during warm late summers (2006 and 2007) (Andrews *et al.*, 2009). Similarly, age-0 pollock were more energy dense (kJ g^{-1}) and consumed higher energy prey (amphipods, euphausiids, and copepods) during cold summers than during warm summers (Moss *et al.*, 2009; Coyle *et al.*, 2011). The partitioning of energy to lipid reserves, rather than growth in length, was important in determining the overwintering survival of age-0 pollock in the Bering Sea (Moss *et al.*, 2009; Hunt *et al.*, 2011) and could explain the inverse relationship between SW1 index and pollock and cod YCS since the late 1980s.

TC index and groundfish post age-0 YCS

For the Gulf of Alaska, the finding that the TC index was a significant negative predictor for pollock YCS and not a significant predictor for sablefish YCS contradicted our hypothesis. The inverse relationship between GOA pollock YCS and the TC index indicates that a warm fall followed by a cool spring favors the overwintering survival of pollock in the Gulf of Alaska. Other studies were successful in addressing the variation in GOA groundfish recruitment with climate indices. For sablefish off Vancouver Island, McFarlene and Beamish (1992) found that a multi-year cool period followed by a warm year produced strong year classes of sablefish in 1941, 1953, 1958, 1967, and 1977. The strong sablefish YCSs were linked to a more intense Aleutian Low pressure (R^2 = 0.53, P < 0.001) and higher copepod abundances (R^2 = 0.45, P < 0.001). A stronger Aleutian Low pressure during the warm years transported cool nutrient-rich waters from the central North Pacific to near shore waters by the more intense cyclonic atmospheric and oceanic circulation and Ekman transport (McFarlene and Beamish, 1992). For GOA sablefish, above average year classes were linked to warmer sea temperatures and northerly winter ocean currents, but not linked to diets, El Nino events, or eddy activity (Sigler *et al.*, 2001). Authors express the need for more detailed studies on sablefish ecology.

For the eastern Being Sea, the finding that the temperature change index was a significant positive predictor for the YCS of groundfish supports the hypothesis that a cool late summer during the age-0 stage followed by a relatively warm spring during the age-1 stage are coupled to maximize the over-wintering survival of pollock and cod in the EBS. In 2002, the hypothesis was proposed that a warm spring, an earlier ice retreat, and a later spring bloom of phytoplankton led to the production of food in the pelagic zone at a time when zooplankton and prey of zooplankton, such as age-0 pollock and juvenile salmon could utilize the pelagic production (Hunt *et al.*, 2002; Stabeno and Hunt, 2002). In recent years, colder late summer temperatures (2006–2010) during the age-0 stage were linked to higher energy prey (crustacean zooplankton), higher whole body energy and lipid reserves, and reduced demands for metabolic growth that favored overwintering survival of pollock from age-0 to age-1 (Moss *et al.*, 2009; Coyle *et al.*, 2011). In 2011, Hunt *et al.* (2011) revised this hypothesis to state that warmer summer seas during the age-0 stage resulted in higher mortality of the age-0 fish due to the lack of lipid-rich prey and ultimately reduced survival to age-1. Our TC index integrates the two hypotheses and indicates that the coupled event of a cool late summer during the age-0 stage (Moss *et al.*, 2009; Hunt *et al.*, 2011) followed by a warm spring during the age-1 stage (Hunt *et al.*, 2002; Mueter *et al.*, 2011) increases the overwintering survival of pollock and cod from age-0 to age-1.

Additional mechanisms for cold summer conditions during the age-0 stage to increase groundfish YCS include reduced competition for food, reduced predation, and increased refuge for young groundfish. The distribution and diets of age-0 pollock, juvenile pink salmon, and jellyfish overlap in the middle domain shelf (50–100 m depths) of the EBS (Cieciel *et al.*, 2009). All three species consume euphausiids, amphipods, copepods, and gelatinous zooplankton (Brodeur *et al.*, 2002; Cieciel *et al.*, 2009). In comparison to an average temperature year (1999), in a cold year (1997) jellyfish (*C. melanaster*) consumed lower proportions of euphausiids and amphipods, higher proportions of gelatinous zooplankton, calanoid copepods, and crab larva, and similar proportions of age-0 pollock (Brodeur *et al.*, 2002). In contrast, age-0 pollock (30–97 mm) consumed euphausiids and large copepods during cold years (2006–2009), and primarily pollock, small copepods, and crab larvae during warm years (2003–2005) (Coyle *et al.*, 2011). Similarly, larger pollock (100–690 mm), and pink, chum, and sockeye salmon (94–910 mm) consumed primarily pollock and sand lance (*Ammodytes hexapterus*) during warm years and euphausiids during cold years (Coyle *et al.*, 2011). Prey shifting by jellyfish to higher proportions of gelatinous zooplankton and fewer euphausiids during cold years could reduce the competition for food among pollock, salmon, and jellyfish in cold years. Second, predation on age-0 pollock by other pollock and salmon was higher during warm years than cold years (Farley *et al.*, 2009; Coyle *et al.*, 2011). Third, age-0 pollock often seek refuge within the tentacles and bodies of jellyfish (Brodeur *et al.*, 2002). The two to three time higher abundances of jellyfish in recent cold years in comparison to recent warm years (Cieciel *et al.*, 2009) could increase the amount of refuge for and reduce predation risk of age-0 pollock in cold years.

SW1 and TC indices as predictors of groundfish post age-0 YCS

From a fisheries management perspective, the temperature change index and salmon growth indices show some predictive capabilities for groundfish YCS. In 2011, the TC index value of −4.23 and the cold year model predicted c. 48 000 million age-1 pollock in the EBS for 2011 and c. 20 000 million using the warm year model. Although the cold year model estimate was about twice the estimate for age-1 pollock presented in the 2011 stock assessment report to the North Pacific Management Council, the TC index was introduced as an index of environmental conditions affecting the recruitment of pollock (Ianelli *et al.*, 2011). Further development of the TC index is needed to account for spatial and temporal variation in sea temperature.

Warm and cold year comparisons of the TC and YCS relationship

Warm year (2002–2005) and cold year (2006–2010) differences in the intercepts and slopes of the regression lines of the TC and YCS models indicate that young groundfish may respond differently to the event of a cool late summer followed by a warm spring during warm and cold periods. For cod, the steeper slope of the regression line for the cold period model indicates that thermal processes related to overwintering survival were more important during the cold period. For pollock, the lower intercept of the regression in warm period model indicates that pollock were sensitive to thermal processes related to overwintering survival during warm periods.

Sources of error

An important caveat in our study is that the SW1 index time series were derived from measurements on the scales of adult salmon. Salmon endure size selective mortality during and after the juvenile life stage (Moss *et al.*, 2005). Therefore, the actual growth of the population during the juvenile stage may not be accurately represented on the scales of adult salmon. A more accurate measure of growth is to sample and measure the body size and condition of stock-specific juvenile salmon at sea or measure the growth along the edge of adult salmon scales. The trade off is between low-cost long-term monitoring of the biology of adult salmon returning to freshwater and the high-cost of monitoring juvenile salmon and age-0 groundfish at sea. The former offers a historical perspective on changes in the dynamics of marine species while the latter provides a real-time tool and possibly more accurate proxy for ocean productivity for predicting the recruitment of commercially important species.

CONCLUSIONS

The development of hypothesis-based indices of ocean productivity, such as SW1 index and the TC index, as predictors for the YCS of groundfish provides an early estimate for above or below average recruitment of groundfish to post age-0 life stages and ultimately YCS. Although these indices show promise of predictive capability, the reliability and future value of any such relationships will be based on a more detailed understanding of the underlying direct and indirect causal ecological mechanisms. Additional time series that integrate environmental conditions during multiple life stages and that index fish stock status are needed to better understand how the long-term dynamics and health of marine ecosystems will change under varying climate regimes.

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