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Synchrony of Marine Fish Catches and Climate and Ocean Regime Shifts in the North Pacific Ocean

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Abstract.—Catches of 19 marine fish species from the eastern and western portions of the North Pacific Ocean during 1970–2004 were examined to determine whether there was synchrony in their responses to the generally accepted climate regime shifts that occurred during that period. Catches for these species represented approximately 55% of the total fish catch in the North Pacific in the 1990s. Five distinct groups were apparent in the data, and each group exhibited a different response to the climate regime shifts of 1977, 1989, and 1998. Some species appeared to have responded only to the regime shift in 1977, others responded only to the shift in 1989, and a few species responded to both. The trends in the time series of catches for these five groups were not random, and shifts in catch generally coincided with regime shifts as identified by the Pacific Decadal Oscillation and other indices of climate change. Although this study examined the relationship of fisheries to trends in climate, there is an obvious linkage to the population dynamics of a particular species. Understanding how climate affects these linkages may help improve our ability to reliably forecast population and fishery trends in the future.

There is general acceptance and a growing body of scientific evidence that climate change affects ecosystems, including aquatic ecosystems, in complex ways (IPCC 2007; Yoo et al. 2008). Extreme events, such as an El Niño or La Niña, may cause significant temporary changes in physical and biological systems, while regime shifts typically result in more persistent ecosystem-level changes (Beamish and Bouillon 1993; Hare and Francis 1995; Mantua et al. 1997; Hare and Mantua 2000; McFarlane et al. 2000). For instance, abundance of Pacific salmon *Oncorhynchus* spp. on both sides of the Pacific Ocean appears to be strongly related to the state of the marine ecosystem as evidenced by the effect of regime shifts that result in extended periods (on a decadal scale) of either low or high salmon productivity (Hare and Francis 1995; Mantua et al. 1997; Beamish and Noakes 2002). Other aspects of population dynamics have also been affected by climate change. For example, stocks of sockeye salmon *O. nerka* and pink salmon *O. gorbuscha* returning to the Fraser River, Canada, exhibited distinct differences in the relationship between spawning stock

size and recruitment in different climate regimes; these differences have been interpreted as climate-related impacts on freshwater survival, marine survival, or both (Beamish et al. 2004b). Also, synchronous shifts in the marine survival of coho salmon *O. kisutch* stocks from southern British Columbia to Oregon also suggest that climate change is a contributing factor in coho salmon productivity and perhaps as important as the large hatchery programs or salmon enhancement programs that are in effect (Beamish et al. 2000; Beamish and Noakes 2002). Similarly, shifts in size at age or geographic distribution have also been noted for wild and hatchery Chinook salmon *O. tshawytscha* and chum salmon *O. keta* throughout the North Pacific, with one of the causes being hypothesized as linked to climate-related ecosystem changes (Helle and Hoffman 1998; Fukuwaka et al. 2007; Heard et al. 2007; Nagata et al. 2007).

There is evidence of perhaps as many as five climate regime shifts over the past century (1925, 1947, 1977, 1989, and 1998; Mantua et al. 1997; Minobe 1997), and historical information suggests that these events have occurred on a fairly regular basis over hundreds and perhaps thousands of years (Mantua et al. 1997; Beamish et al. 1999; Finney et al. 2000, 2002). Beamish et al. (1999) have shown that shifts in total Pacific salmon production roughly coincide with these regime shifts, and Klyashtorin (2001) observed similar patterns and shifts in catches for 12 key marine fish

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species from both the Pacific and the Atlantic. Klyashtorin (2001) simulated catches for these 12 marine fish species for 100 years into the future (to 2099) to determine whether reasonable forecasts (simulations) of catch could be generated for 10 to 15 years into the future (to 2010 or 2015). The resulting forecasts (simulated catches) were strongly influenced by the assumed climate trend (Klyashtorin used a 50–60-year cycle for his simulation modeling); in general, the predictions were not entirely consistent with the observed catches between 2000 and 2006. The results, however, did identify some trends in climate and fisheries (catch).

There is some evidence that Pacific sardine *Sardinops sagax* also undergo huge abundance shifts coincident with regime shifts to the extent that these fish essentially disappear from specific geographic regions for extended periods of time and then subsequently reappear in large numbers when the climate regime is more favorable (Kawasaki 1983; Beamish et al. 1999; McFarlane and Beamish 2001; McFarlane et al. 2002). Strong year-classes for several other species of marine fish, including sablefish *Anoplopoma fimbria*, Pacific cod *Gadus macrocephalus*, and various flatfish species, have also been found to coincide with significant climatic events, such as an El Niño, a La Niña, or a regime shift. These species tend to have high fecundity and rely on infrequent strong year-classes to sustain their population over the long term. Subsequent increases in recruitment for these species tend to support fisheries for a number of years after the climatic event (McFarlane et al. 2000; Beamish et al. 2004a). Clark et al. (1999) also found evidence that climate change affected the size at age and recruitment of Pacific halibut *Hippoglossus stenolepis*. Fortuitously, the decrease in size at age for Pacific halibut in the 1990s coincided with a reduction in fishing pressure so that stocks were not overfished. Tian et al. (2004) also reported that increases in abundance of the Pacific saury *Cololabis saira* appeared to be positively related to the occurrence of an El Niño.

It is clear from evidence provided in a number of studies that climate profoundly affects fish production and that these effects are not random (Finney et al. 2000; Hare and Mantua 2000; McFarlane et al. 2000; Beamish and Noakes 2004; Beamish et al. 2004b; Yatsu et al. 2005; Lehodey et al. 2006; Osgood 2008). It would be informative and useful to determine whether fisheries for major species responded to climate change in a similar fashion, as the future health of these fisheries has major economic and social impacts. To that end, we examined catches for 19 species of marine fish from both the eastern and

western North Pacific Ocean for the period 1970 to 2004. Catches for these 19 species represented approximately 55% of the catch in the North Pacific and approximately 15% of the total worldwide catches of marine fish during the 1990s. Changes (as measured by catch) in these fisheries in relation to the 1977, 1989, and 1998 regime shifts were examined for each species to determine whether there were patterns in the catch data and whether the patterns were specific to particular groups of species.

Methods

The species considered in this article represent the major fisheries in the North Pacific, and in some cases the species are common on both sides of the Pacific Ocean (Table 1). They represent a broad range of both short- and long-lived species occupying a variety of ecosystems and exhibiting different life history strategies. Although most of the species considered in this study are recruited to the fishery at a relatively young age, approximately half of the species could potentially live to more than 20 years of age (Table 1). Combined catches from all regions and areas were used to measure temporal changes for each of the 19 species. Catch information came from two main sources. For Pacific salmon, catches were obtained from the North Pacific Anadromous Fish Commission (www.npafc.org); for all other species, catches were obtained from the Food and Agriculture Organization of the United Nations (FAO; www.fao.org).

At just over 12 million metric tons, the average annual catch for the 19 species considered in this study represented approximately 15% of the total worldwide catch of marine fish during the 1990s (Table 1). The biology of the various species has been described in publications that are in a variety of languages. References for species in the fisheries off the Pacific coast of North America are provided by Hart (1973) and Mecklenburg et al. (2002). Descriptions for species only caught in fisheries off the east coasts of Russia, China, Japan, and Korea exist in a number of publications in the native languages of those countries and in reports to the North Pacific Marine Science Organization (PICES; www.pices.org).

Five taxa (walleye pollock, Pacific sardine, anchovy [Japanese anchovy and northern anchovy combined], Pacific chub mackerel, and largehead hairtail [Pacific cutlassfish]) had average annual catches in excess of 1 million metric tons (Figure 1A). The largest fishery was for the walleye pollock, which is a semidemersal or demersal schooling fish that is distributed widely throughout the North Pacific. Walleye pollock spawn in large aggregations at depth (100–300 m), and eggs and larval fish are distributed by ocean currents as they

TABLE 1.—Maximum estimated age (years) and approximate average age at which the fish recruit to the fishery (lag). Estimated maximum ages are from the Food and Agriculture Organization of the United Nations; (www.fao.org), Beamish and Noakes (2004), and Beamish et al. (2006). The ages at recruitment to the fishery are from published stock assessment documents. Average catches for the period 1990–1999 and mean catch and standard deviation (SD) for the period 1970–2004 are in thousands of metric tons.

Species	Maximum	Average catch		Mean (SD)
	age	Lag	1990–1999	1970–2004
Pacific cod <i>Gadus macrocephalus</i>	25	2	423,400	310,226 (123,997)
Pacific hake <i>Merluccius productus</i>	23	2	260,200	209,390 (82,601)
Pacific halibut <i>Hippoglossus stenolepis</i>	55	7	35,400	31,028 (11,064)
Jack mackerel <i>Trachurus symmetricus</i>	35	1	304,500	212,692 (92,782)
Sockeye salmon <i>Oncorhynchus nerka</i>	7	2	169	124 (49)
Pink salmon <i>O. gorbuscha</i>	3	1	332	258 (94)
Chum salmon <i>O. keta</i>	7	3	309	235 (87)
Chinook salmon <i>O. tshawytscha</i>	8	3	15	20 (6.5)
Coho salmon <i>O. kisutch</i>	5	1	28	29 (7.3)
Pacific chub mackerel <i>Scomber japonicus</i>	14	1	1,056,600	1,277,310 (369,928)
Largehead hairtail (Pacific cutlassfish) <i>Trichiurus nitens</i>	15	1	1,001,800	840,119 (323,631)
Japanese anchovy <i>Engraulis japonicus</i> , northern anchovy <i>E. mordax</i>	7	1	1,144,200	804,620 (625,448)
Small yellow croaker <i>Larimichthys polyactis</i>	23	1	159,000	120,726 (93,075)
Walleye pollock <i>Theragra chalcogramma</i>	33	3	4,578,600	4,538,910 (1,151,117)
Pacific sardine <i>Sardinops sagax</i>	16	3	1,649,900	2,044,048 (1,962,849)
Pacific herring <i>Clupea pallasii</i>	15	3	287,600	338,733 (142,298)
Sablefish <i>Anoplopoma fimbria</i>	113	5	33,500	34,171 (11,594)
Pacific ocean perch <i>Sebastes alutus</i>	100	7	27,700	42,365 (37,084)
Pacific saury <i>Cololabis saira</i>	2	1	334,300	310,123 (86,654)

rise in the water column. Pacific sardine are widely distributed around the Pacific but inhabit more temperate waters than do walleye pollock. Pacific sardine are omnivores whose diet varies between regions but includes copepods, diatoms, a variety of other zooplankton, and occasionally larval fish. Pacific sardine populations have been known to respond rapidly and synchronously to changes in the ocean environment and often in an opposite manner from anchovy, which support another important fishery (Kawasaki 1983; Kawasaki and Omori 1988). The dramatic shift in catch for these two taxa (Pacific sardine and anchovy) coincided with the 1989 regime shift, and the change in catch was roughly an order of magnitude for both taxa (Figure 1A). Anchovy are small, nearshore, omnivorous fish that support significant fisheries for human usage and are also an important source of feed for a variety of marine fish and marine mammals, including Pacific chub mackerel. Pacific chub mackerel are found in temperate waters throughout the Pacific, with the largest catches occurring in Asian waters. The final species with average annual catches in excess of 1 million metric tons, the largehead hairtail, prefers warmer, shallower water and is mainly concentrated on the Asia side of the Pacific and to a lesser degree near the North American Baja Peninsula. Adult largehead hairtails primarily feed on fish and occasionally squid or crustaceans. Juvenile and adult largehead hairtails have

opposing diurnal vertical feeding migrations between the surface and about 400 m.

Of the remaining species considered in this study, four species (the Pacific saury, jack mackerel, Pacific hake, and small yellow croaker) prefer subtropical or warm temperate water (Figure 1B). The Pacific saury is a short-lived species typically found in shallow coastal water when young, whereas adults school offshore and are highly migratory by nature. Pacific sauries can grow to 40 cm in length and live for about 2 years, but 1-year-old fish dominate the catch in this large, important Asian fishery (Table 1). Jack mackerel are piscivores that also prefer subtropical waters and are found both inshore and off shore (500 nm or more) throughout the Pacific. Depending on conditions, jack mackerel will also move inshore and northward during the summer months into more temperate waters to feed. Pacific hakes feed on a variety of larval fish and shellfish and are important prey for various marine mammals and dogfish sharks (Squalidae). Except during spawning season, adult Pacific hakes live in large schools overlying the continental shelf and slope. Like jack mackerel, Pacific hakes are highly migratory and will move into more northerly waters to feed during warm periods. Finally, the small yellow croaker is a slow-growing bottom fish that inhabits warm coastal waters. Although small yellow croakers may live to the age of 20 years or more, they recruit to the fishery when they are young (age 1).

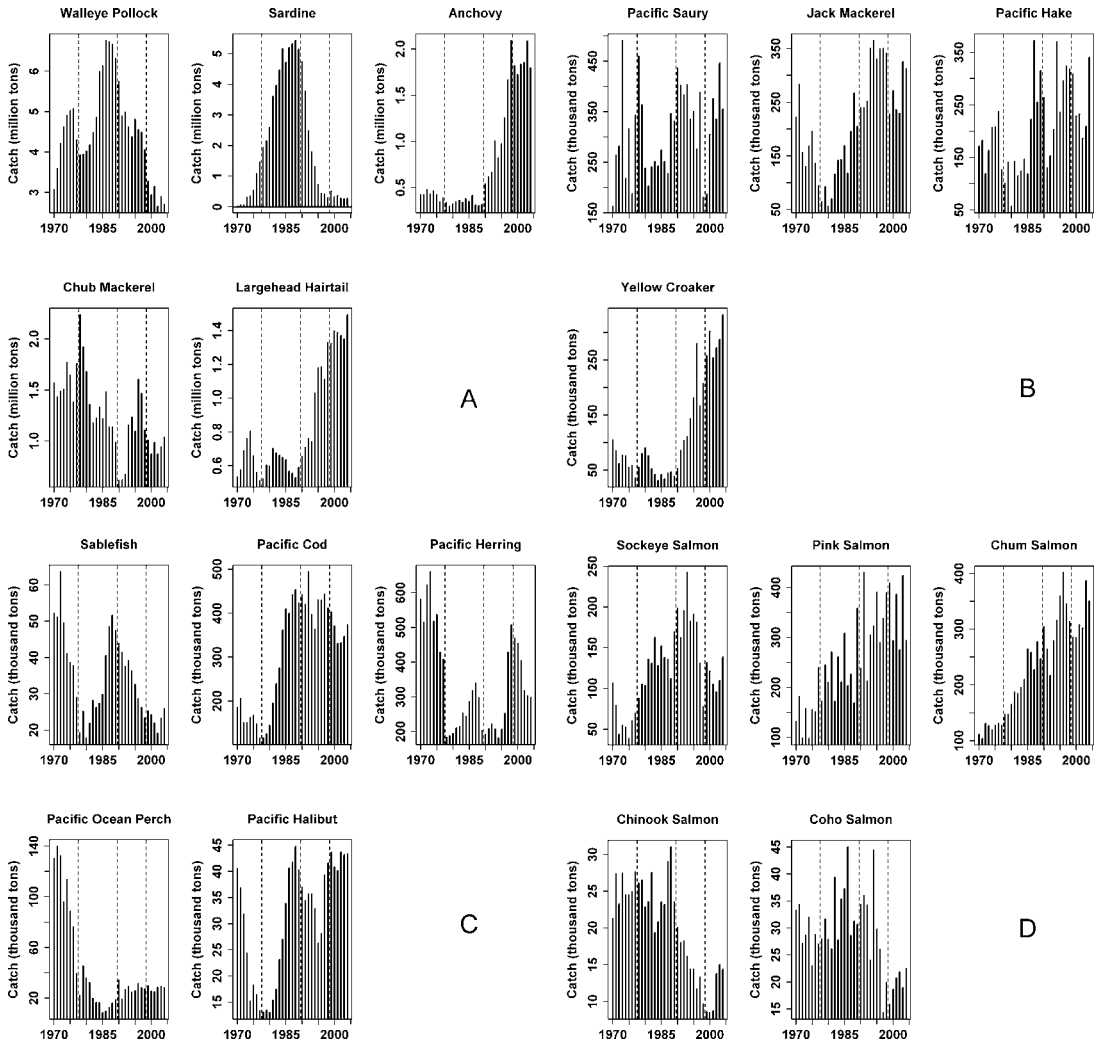


FIGURE 1.—Catches (metric tons) during 1970–2004 for (A) species with average annual landings exceeding 1 million metric tons (walleye pollock, Pacific sardine, anchovy [Japanese anchovy and northern anchovy combined], Pacific chub mackerel, and largehead hairtail [Pacific cutlassfish]); (B) species that prefer subtropical or warm temperate waters (Pacific saury, jack mackerel, Pacific hake, and small yellow croaker); (C) nonsalmonid species that prefer temperate or subarctic waters (sablefish, Pacific cod, Pacific herring, Pacific ocean perch, and Pacific halibut); and (D) five species of Pacific salmon (sockeye, pink, chum, Chinook, and coho salmon).

Eight of the other species (Pacific cod, Pacific herring, Pacific halibut, and five species of Pacific salmon) considered in this study prefer temperate or subarctic water. The Pacific cod is a coldwater, demersal fish found along the continental shelf or slope (often at depth). Adult Pacific cod feed on larval fish and crustaceans and may live for up to 25 years, although recruitment to the fishery begins at age 2. Spawning location and period appear to be dependent on bottom temperatures, with fish avoiding very cold temperatures and temperatures above 10°C (Alderdice

and Forrester 1971). The Pacific herring is another important species that prefers temperate or subarctic water temperatures and is found on both sides of the North Pacific. Although Pacific herring may reach a maximum age of 15 years, they typically start recruiting to the fishery at age 3. This pelagic species supports fisheries that harvest herring roe and fish for human consumption and that harvest fish to be used in the production of fish meal and other products. Pacific herring are also important prey for top-level predators, such as Pacific halibut. The Pacific halibut is a large,

predatory fish that is highly valued by both the commercial and recreational fishing sectors. This flatfish is found on a variety of bottom structures and spawns in deeper water. Pacific halibut eggs and larvae are pelagic and typically drift north and west into the Gulf of Alaska and Bering Sea before some of the juveniles begin their migration south to Canadian waters. The five species of Pacific salmon, with the exception of sockeye salmon, have large artificial enhancement efforts to support the rebuilding and production of salmon stocks on both sides of the Pacific. The unique life history of Pacific salmon means that there could be both marine and freshwater effects from climate change.

Two long-lived species were also considered in the study. Sablefish and Pacific ocean perch may reach 100 years of age, but typically much-younger fish are observed in the catch and the population, and there is evidence of large but infrequent recruitment events (Beamish et al. 2004a, 2006). Sablefish live near the bottom, sometimes in very deep (2,000 m or more) water, and are caught either by trap or longline. Sablefish eat a variety of marine fish and invertebrates, and sablefish juveniles are pelagic. Pacific ocean perch (one of many species of rockfish in the North Pacific) are found in cold water (preference in the 5.5–6.0°C range) at depths to 800 m but more commonly between 200 and 400 m. Pacific ocean perch are harvested along with other species of rockfish by use of trawls.

For each species considered, we estimated the standardized catch anomalies each year by subtracting the estimated mean and dividing by the estimated standard deviation of the catch time series. The anomalies for each species were then lagged by the number of years it typically takes for the species to be recruited into the fishery (Table 1). This was done so as to compare species on the basis of their first year in the marine environment, which is often assumed to be when year-class strength and productivity are determined. The standardized lagged anomalies were then used to see if particular species grouped together or exhibited similar temporal trends of positive or negative catch anomalies.

Because some of the species appeared to respond to one regime shift and not others, we examined trends in the standardized lagged catch anomalies both within and across each of the regimes. Dummy variables consisting of sequences of +1 or –1 (corresponding to shifts between high and low periods of productivity, respectively) were used to simulate the following transitions: (1) from the pre-1977 regime to the 1978–1989 period and (2) from the 1978–1989 period to the post-1989 regime. There were too few post-1998 data to test the final regime shift. These dummy variables

were used to examine three scenarios: a response to the 1977 regime shift only; a response to the 1989 regime shift only; and finally, a response to both the 1977 and 1989 regime shifts. Biserial correlations have often been used to examine potential relationships between continuous and dichotomous variables, but the estimated biserial correlations can exceed 1 (or –1) in some cases, which is problematic (Ruiz 2002). Alternatively, point-biserial correlations may be used and, like Pearson's product-moment correlations, the point-biserial correlations are bounded between +1 and –1 (Glass and Hopkins 2008). Finally, Kendall's tau rank correlation coefficient (Kendall 1955) is a nonparametric measure of the strength of the relationship, with larger positive (or negative) values suggesting that the pattern of standardized lagged catch anomalies is consistent with the corresponding regime shift scenario (i.e., response to the regime shifts in 1977 only, 1989 only, or both 1977 and 1989). Both point-biserial (Pearson's) and Kendall's tau rank correlations were used to examine the relationship between the catch anomalies and the three scenarios described.

In the second analysis, the mean of the standardized lagged anomalies was estimated for each regime for each species. For example, the 1970–1977 data were used to estimate the standardized mean anomaly for each species for the first regime period in the time series. Standardized mean anomalies for each species were then similarly estimated for the other regimes (1978–1989, 1990–1998, and 1999–2004). Hierarchical clustering (based on Euclidean distances) was then used to group the estimated means of the regime anomalies for each species (Jain et al. 1999). For two long-lived species, the Pacific ocean perch and Pacific halibut, the long lag for juveniles to recruit to the fishery meant that there were no standardized catch anomalies associated with the last regime (1999–2004); therefore, these two species were not included in the clustering analysis, but their relationships to regime shifts were examined in the correlation study above.

The clustering analysis was done for combined North Pacific catch by species as well as for catches reported separately from either the eastern (FAO Fishing Area 67, roughly bounded as 175°W longitude and 40°N latitude) or western (FAO Fishing Area 61, roughly bounded as 175°W and 20°N) portions of the North Pacific.

Results

There appears to be some coherence between the lagged species catch anomalies and the regime shifts of 1977 and 1989 (Table 2). The larger positive correlations (for example, absolute values of Pearson's

TABLE 2.—Pearson’s product-moment (point-serial) correlation and Kendall’s tau rank correlation (in parentheses) coefficients between marine fish species catch anomalies and dummy variables simulating the regime shifts in 1977 and 1989. The regime shifts were from a period of lower productivity (pre-1977) to a period of higher productivity (1978–1989) and a return to a period of lower productivity (post-1989). Positive correlations indicate catch anomalies in the same direction as the regime shift. Only correlation coefficients with an absolute value greater than or equal to 0.50 are reported. Pearson’s (point-serial) correlation coefficients were typically higher than Kendall’s tau, but there was consistency in the pattern of larger estimated correlations.

Species	Positive, 1977 only	Negative, 1989 only	Positive 1977 and negative 1989
Pacific cod	0.81 (0.58)	—	—
Pacific hake	—	—	—
Pacific halibut	0.89 (0.61)	—	—
Jack mackerel	—	−0.78 (−0.63)	—
Sockeye salmon	0.71 (0.58)	—	—
Pink salmon	0.63 (0.54)	—	—
Chum salmon	0.77 (0.60)	—	—
Chinook salmon	—	0.87 (0.67)	—
Coho salmon	—	—	—
Pacific chub mackerel	—	—	—
Largehead hairtail (Pacific cutlassfish)	—	−0.84 (−0.68)	—
Anchovy ^a	—	−0.84 (−0.71)	—
Small yellow croaker	—	−0.84 (−0.71)	—
Walleye pollock	—	—	0.51 (0.52)
Pacific sardine	—	—	0.76 (0.68)
Pacific herring	—	—	—
Sablefish	—	—	0.60 (0.52)
Pacific ocean perch	—	—	—
Pacific saury	—	—	—

^a Includes Japanese anchovy and northern anchovy.

or Kendall’s coefficient > 0.5) suggest that the catch anomalies are in the same direction as the regime shift and that the shifts in both the catch anomalies and the regime index occur at about the same time. For instance, catches of Pacific cod, Pacific halibut, sockeye salmon, pink salmon, and chum salmon increased after the 1977 regime shift and did not decline substantially after the 1989 regime shift (Table 2). The negative correlations for Chinook salmon and Pacific chub mackerel suggest the opposite response to the 1977 regime shift for these two species. Two other possible groupings are suggested by this analysis, with one group consisting of the largehead hairtail, anchovy, and small yellow croaker and the other group consisting of the walleye pollock, sablefish, and Pacific sardine (Table 2). Whether or how the other species group together is not entirely obvious from this analysis.

Based on hierarchical clustering of the combined (total) catch by species, five groups were evident in the data (Figure 2A). Group 1 contained fisheries that generally were larger during periods of intense Aleutian Lows (or positive Pacific decadal oscillations). The group included the three most abundant species of Pacific salmon (sockeye salmon, pink salmon, and chum salmon) as well as the Pacific cod, Pacific hake, and jack mackerel (Figure 3). Catches for group 1 increased rapidly after the 1977 regime shift

and have generally been above the 1970–2004 average since the mid-1980s. Sockeye salmon catches declined after the 1998 regime shift to approximately the long-term (1970–2004) average catch level. That could be indicative of (1) more risk-averse management strategies for sockeye salmon fisheries or (2) a freshwater (lake) effect of climate change that has negatively influenced freshwater survival. The production of pink salmon and chum salmon is supplemented by very substantial enhancement (hatchery) programs that to a large degree would compensate for any decreased production from the freshwater phase of these species’ life cycles.

Group 2 (largehead hairtail, anchovy, and small yellow croaker) fisheries were generally below average between 1970 and 1989 and then increased rapidly after the 1989 regime shift (Figure 4). The opposite was true of those species in group 3 fisheries (Chinook salmon and Pacific chub mackerel), which had predominantly below-average catches in the last half of the time series after the 1989 regime shift (Figure 5). Some of the decline for Chinook salmon can probably be attributed to the restrictive fishing regulations for this species beginning in the 1990s due to serious conservation concerns, but ocean survival for hatchery fish was also quite low during that period (Beamish et al. 2000). Pacific chub mackerel occupy an ecological niche similar to that of Chinook salmon, so it is

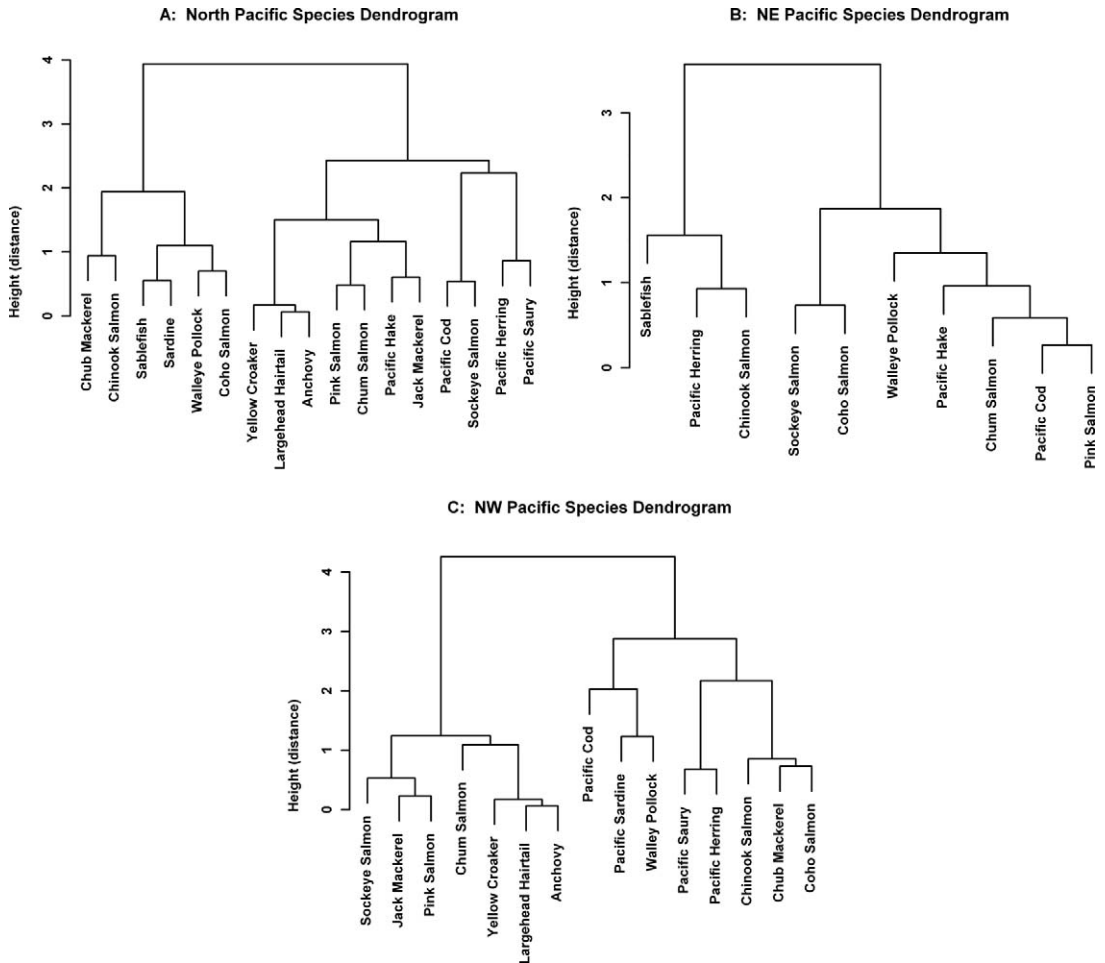


FIGURE 2.—Clusters based on mean catch anomalies for each marine fish species and each of the four climate regimes (see Methods), with clustering based on (A) combined (total) catches (metric tons) from both the eastern and western sections of the North Pacific Ocean; (B) catches from only the eastern section (FAO Fishing Area 67); and (C) catches from only the western section (FAO Fishing Area 61).

certainly conceivable that climate affected these species synchronously. The Pacific sardine, walleye pollock, sablefish, and coho salmon were included in group 4. Catches for these species tended to be below average prior to the 1977 regime shift, remained above average throughout the 1980s, and then declined after the 1989 regime shift (Figure 6). The positive catch anomalies for coho salmon in the early 1990s could also partially be attributed to aggressive fishing strategies and subsequent overfishing of this species during the fisheries dispute between Canada and the United States (Noakes et al. 2005).

The final group (group 5) included the Pacific herring and Pacific saury (Figure 7). There is evidence of runs in the catch series for both species, suggesting

that the environment (including climate change, El Niño events, and La Niña events) played a role in recruitment along with other factors (Ware 1991; Tang 1993; Williams and Quinn 2000). Tian et al. (2004) found some evidence that Pacific saury recruitment was positively related to El Niño events.

Pacific ocean perch did not appear to fit any of the groups identified previously (Figure 8). Pacific ocean perch catches were above average prior to the 1977 regime shift and have remained below average (perhaps overfished) since that time. The management for Pacific ocean perch is highly regulated, and it is possible that catch patterns are more related to management approaches than to environmental conditions including climate change. Pacific halibut catches

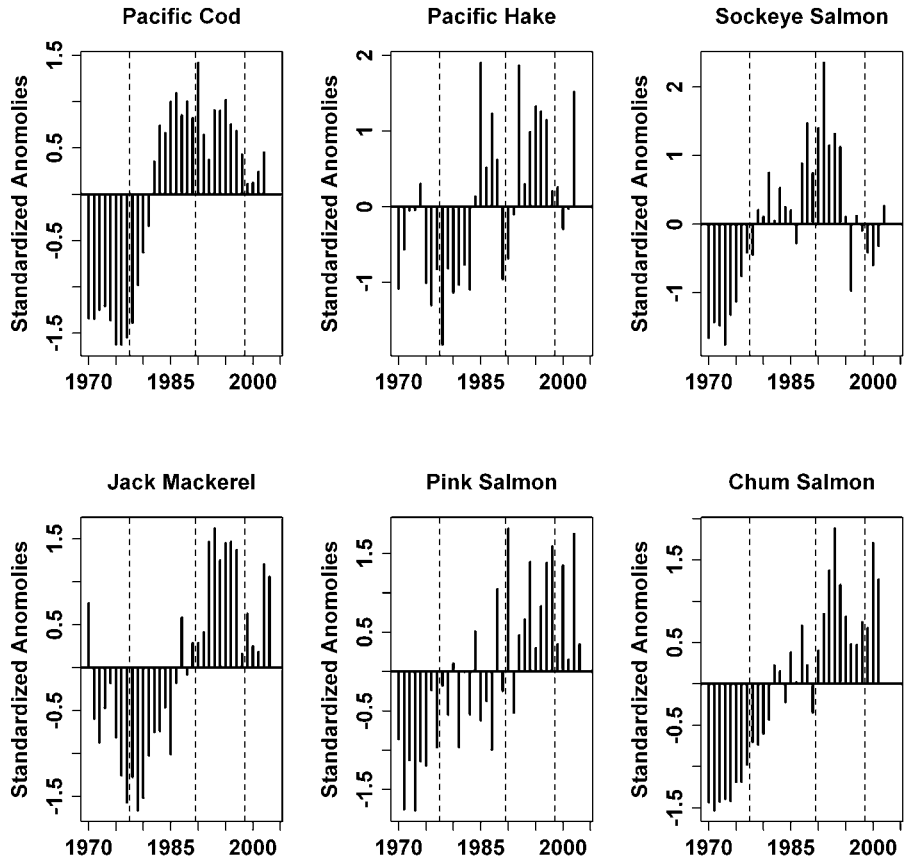


FIGURE 3.—Standardized catch anomalies for the Pacific cod, Pacific hake, jack mackerel, sockeye salmon, pink salmon, and chum salmon (group 1). The vertical lines represent the approximate time of regime shifts since 1970.

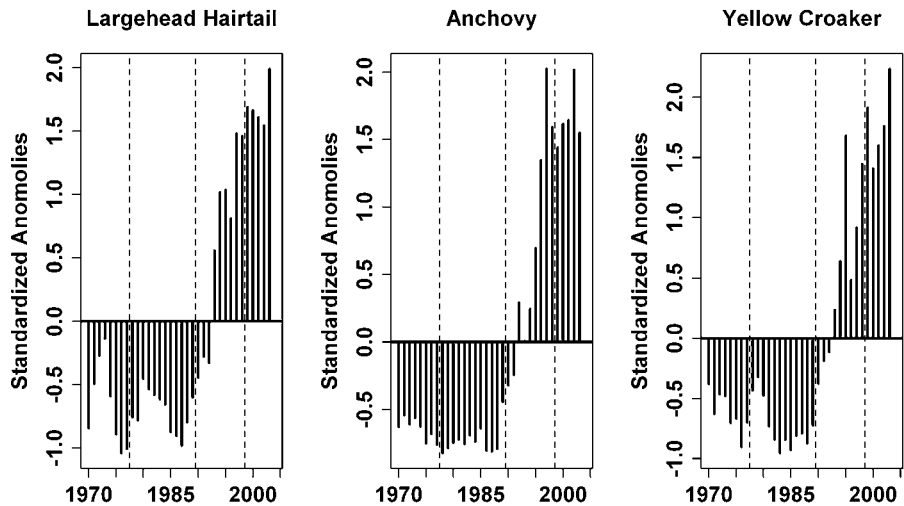


FIGURE 4.—Standardized catch anomalies for the largehead hairtail (Pacific cutlassfish), anchovy (Japanese anchovy and northern anchovy combined), and small yellow croaker (group 2). The vertical lines represent the approximate time of regime shifts.

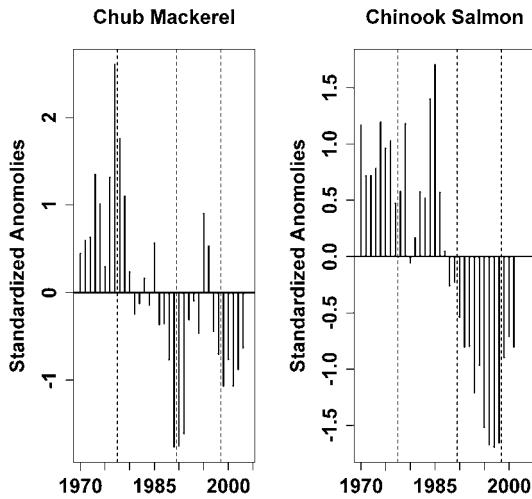


FIGURE 5.—Standardized catch anomalies for Chinook salmon and Pacific chub mackerel (group 3). The vertical lines represent the approximate time of regime shifts.

were below average until the 1977 regime shift and have been above average since that time (Figure 8). This pattern of catches is similar to the pattern for group 1. There is certainly some evidence that climate change affects both the recruitment and growth of Pacific halibut (Clark et al. 1999).

Slightly different groupings were observed when catches from the eastern and western portions of the North Pacific were considered separately. In part, this is because not all species are found on both sides of the Pacific and for species that are common to both areas, such as walleye pollock, the distribution of catch is often not equal between east and west. Two main (or perhaps more) groups were evident in the eastern North Pacific (Figure 2B). The sablefish, which has a highly regulated fishery, was somewhat different from the other species, although it was associated with Chinook salmon and an important prey fish for Chinook salmon, the Pacific herring. Sockeye salmon and coho salmon were grouped together, perhaps indicative of their depressed status (and much-reduced fisheries) in the southern part of their freshwater distribution in recent years. Pink salmon and chum salmon were grouped with the Pacific hake and Pacific cod as well as with the walleye pollock.

The groupings in the western Pacific are quite similar to those found by using combined catches, although without the sablefish and Pacific hake since these two species are primarily caught in the eastern Pacific (Figure 2C). The small yellow croaker, large-head hairtail, and anchovy were grouped together, and the Pacific herring and Pacific saury formed another

group. Sockeye salmon, pink salmon, and chum salmon were clustered with jack mackerel; three predatory species, the Pacific chub mackerel, Chinook salmon, and coho salmon, were also grouped together. The walleye pollock, Pacific sardine, and Pacific cod tended to group together in contrast to the previous case.

Discussion

There is evidence in this study and other studies to support the case that climate change affects the production and population dynamics of species that support the major fisheries of the North Pacific Ocean. The group anomalies (the sum of the individual anomalies for each species belonging to the group) have distinct temporal patterns that appear to change sign coincident with the observed regime shifts (Figure 9). There are clear differences in how individual species (and consequently groups of species) respond to climate change, and there is some evidence of compensatory shifts in production between and among the species, resulting in some stability in total catch (FAO Fishery Information Data and Statistical Unit 2006). Not every regime shift resulted in a corresponding change in production for each species. For long-lived species (such as Pacific ocean perch) or those with fisheries that are highly regulated at low levels of exploitation, it may be difficult to identify and quantify a climate signal. That does not mean that these species are not affected by climate change; it only means that a signal is difficult to detect. The same may be true for short-lived species in which the annual variation in catch or abundance is large enough to mask any relationship. The type of climate change that affects a particular species is likely to depend on the life history characteristics of that species as well as the state of the ecosystem when the climate changes. Species have by necessity evolved to adapt to environmental pressures, so it should be expected that different types of climate change will be important for each species.

There were also some differences when catches from the eastern and western portions of the North Pacific were considered separately. The largest fisheries are in the western North Pacific partly because it represents a larger area and because of the nature of the species being exploited. Thus, it is not surprising that species groupings for the western North Pacific were similar to the groupings identified using the combined (total) catches. Groupings in the eastern North Pacific may reflect some of the recent regional issues, such as the decline of southern sockeye salmon and coho salmon stocks in recent years, as well as important predator-prey relationships, such as links between Chinook salmon and Pacific herring.

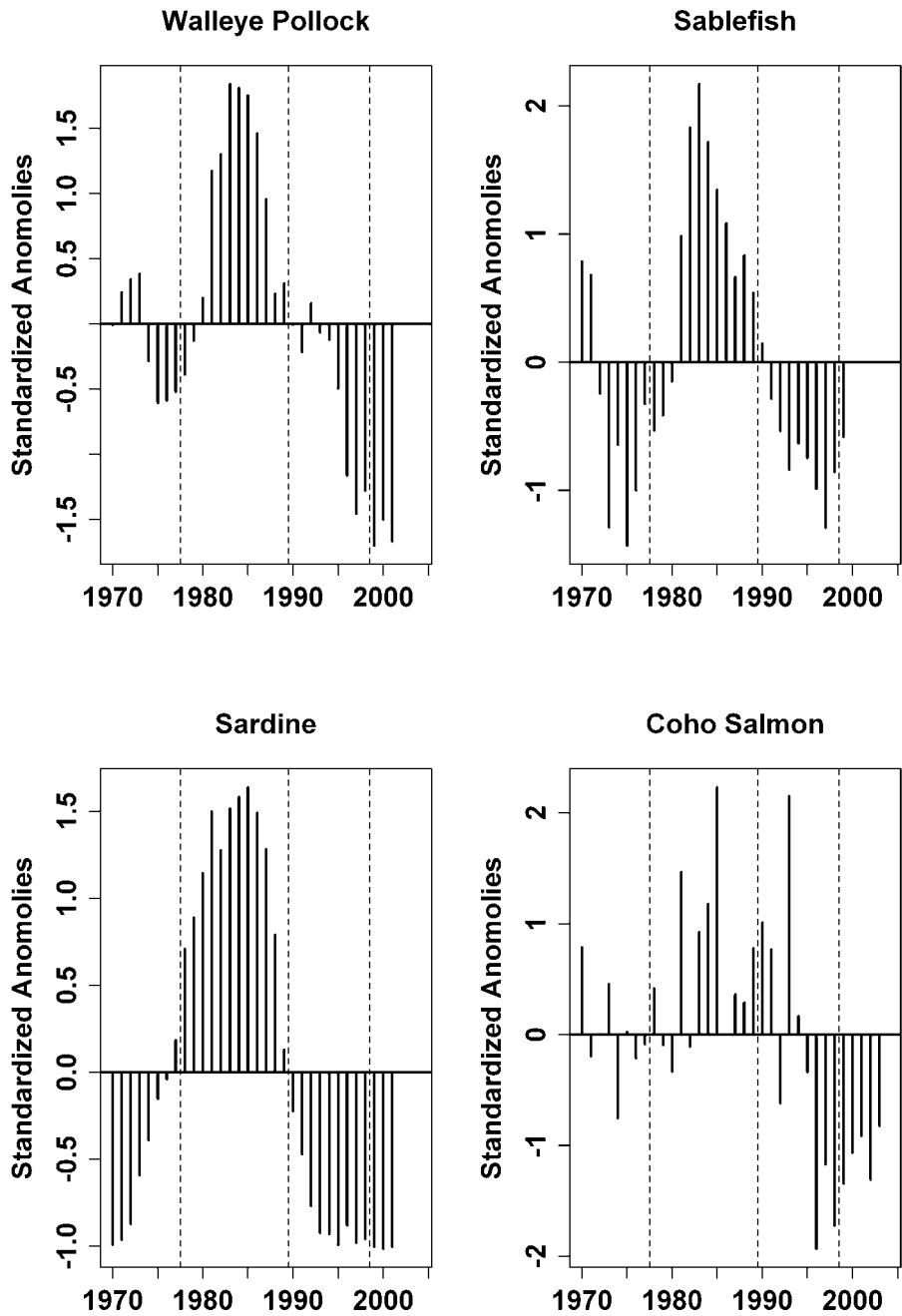


FIGURE 6.—Standardized catch anomalies for Pacific sardine, walleye pollock, sablefish, and coho salmon (group 4). The vertical lines represent the approximate time of regime shifts.

The 19 species considered exhibit a diverse range of life history strategies, and it is not immediately obvious why particular species were grouped together (Figure 2). There is some evidence of competitive interaction among ocean-entry juvenile chum salmon, pink

salmon, and sockeye salmon, so it is not entirely surprising that these species were grouped together since they also probably respond similarly to changes in their environment (Groot and Margolis 1991; Quinn 2004). Pacific hakes and jack mackerel are predators

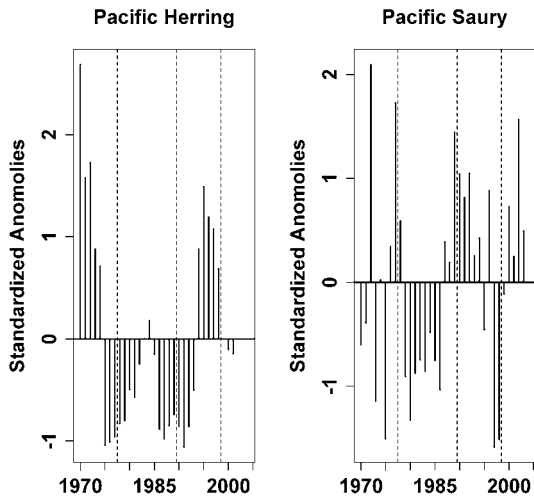


FIGURE 7.—Standardized catch anomalies for the Pacific herring and Pacific saury (group 5). The vertical lines represent the approximate time of regime shifts.

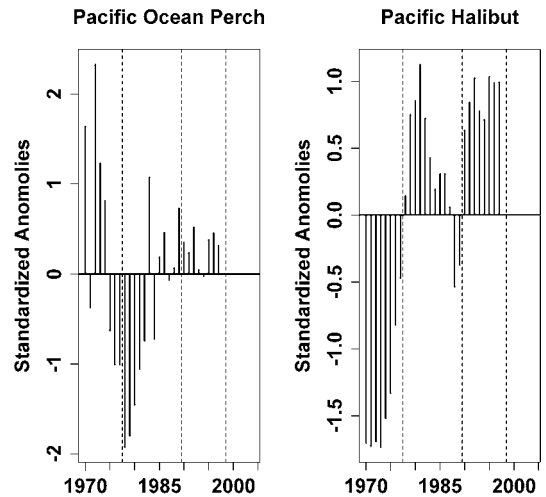


FIGURE 8.—Standardized catch anomalies for Pacific ocean perch and Pacific halibut. The vertical lines represent the approximate time of regime shifts.

that prefer similar habitat and both adjust their movements and distributions in response to changes in their environment and prey availability, so it is again not surprising that they would be grouped together. Other predatory species, such as the Pacific chub mackerel and Chinook salmon as well as the walleye pollock and coho salmon, were also grouped together, although the precise reasons for these particular clusters are unclear other than that they are predators with potentially some overlap in distribution and prey preference. Some pelagic species, such as the Pacific saury and Pacific herring, were clustered together, whereas others (e.g., Pacific sardine and anchovy) were grouped with species that prefer deepwater or bottom habitat. However, some of these deepwater species, such as the sablefish and the small yellow croaker, either spawn in shallow water or have a pelagic larval stage, which might explain the association with certain pelagic species. However, it is clear that much more work is required if we are to understand the linkages between the various species.

This study does not address the sustainability of the particular fisheries, and for some species a diversity of management approaches and strategies is employed throughout their range. These practices have resulted in declines in some stocks, and management practices have also tended to moderate catches from year to year. In some cases, significant declines in abundance took place before this study (e.g., small yellow croaker; Jin 1996) and the catches employed in this study reflect how climate has influenced these populations at a lower state of abundance. However, for some stocks or

species, there have also been dramatic increases in catch (or abundance) that cannot be easily attributed to changes in the management of these fisheries, and such increases may be related to climate change (Figure 1). There appears to be compelling evidence of a species-specific response to climate change (Spencer and Collie 1997; McFarlane et al. 2000; Lehodey et al. 2006; Mueter et al. 2007; Osgood 2008), and this study provides a broader perspective of this important issue. In addition to the various socioeconomic effects, biological changes at the population level may well influence genetic diversity, interactions with other species, and a species' ability to adapt to future environmental stresses.

Equally unfortunate is our inability to forecast precisely how global warming will affect the dynamics of key climate indicators. Hindsight shows us that major fluctuations in the abundances of key species and their fisheries will occur in the future. These fluctuations might be better anticipated today than 30 years ago, but we still lack an ability to forecast changes in climate or production trends in a way that is useful to management. It is difficult to have a clear understanding of the impacts of global warming on these major fisheries until more is understood about the linkages between climate and production of the various species. Important ecosystem changes have also occurred through human interventions. For instance, large-scale salmon enhancement projects have altered freshwater survival for salmon stocks and in doing so may have negatively affected wild salmon stocks and other species (Hilborn and Eggers 2001). Regime shifts

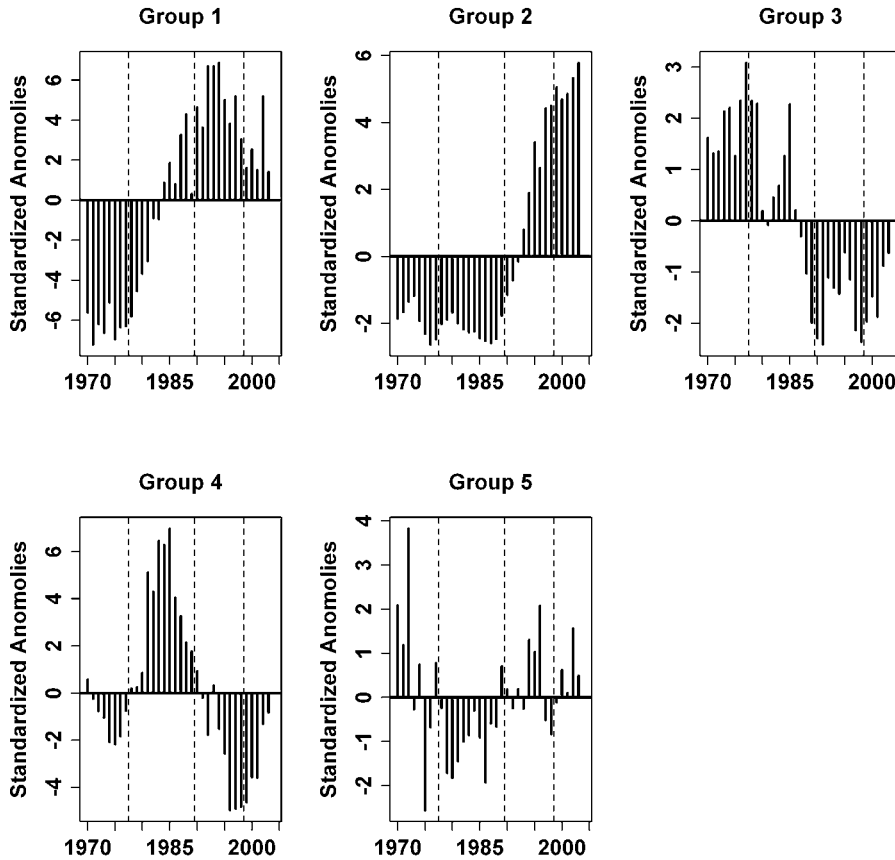


FIGURE 9.—Standardized summed catch anomalies for the species within the five groups identified in this study (see Figures 3–7 for a list of species belonging to each group). The anomaly for each species was lagged by the number of years it typically takes for the species to be recruited into the fishery.

may also mask problems that only become apparent in the future, so management strategies need to be robust and adaptive (Schindler et al. 2008). Fishing has also affected the age structure in numerous fish populations and fisheries, with many of the older fish being removed from the population. This can affect future recruitment and genetic diversity and represents a form of overfishing (Berkeley et al. 2004; Beamish et al. 2006). There is evidence that top predators in the ocean have been removed through overfishing, resulting in ecosystem changes and loss of biodiversity (Pauly et al. 1998).

There is also evidence that conditions in the spawning and rearing areas, which affect the amount of prey available to first-feeding young, are important for survival and recruitment (Beamish and Mahnken 2001). Climate change can affect these processes and subsequent recruitment to the fishery and catch. Because certain species respond to climate change similarly to other species, it may be possible to use

what we learn studying one species to predict, in general terms, the dynamics of a species from the same group. At the least, it should provide guidance for designing research projects for species of interest, which will help generate insight and advice for fisheries managers and interested stakeholders.

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