ENSO EVENTS IN THE NORTHERN GULF OF ALASKA, AND EFFECTS ON SELECTED MARINE FISHERIES

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ABSTRACT

The 1991–93 El Niño–Southern Oscillation (ENSO) event first appeared in the northern Gulf of Alaska in autumn 1991 with warm sea-surface temperatures. In winter 1992, there were pulses of increased sea level and anomalous circulation. El Niño conditions persisted at least through summer 1993. The effects of this ENSO event on major groundfish species and Pacific herring in the northern Gulf of Alaska were examined and compared with the effects of previous ENSO events. There is little evidence that the 1991–93 or 1982–83 ENSO events affected landings of walleye pollock, Pacific cod, Pacific halibut, or arrowtooth flounder. Some changes in distribution of groundfish species were observed in 1993, but the effect was similar to changes observed in non-ENSO warm years. In general, warm ocean conditions have a positive effect on recruitment of northern stocks, but ENSO events appear to have an inconsistent effect on year-class strength within species and among different species. For example, strong year classes of halibut and arrowtooth flounder sometimes, but not always, coincide with ENSO events; ENSO events are associated with moderate to weak year classes of cod and pollock. However, post-ENSO warm years often are associated with strong recruitment of many groundfish species. Major changes have occurred in the Gulf of Alaska ecosystem since 1977. The influence of the 1976 ENSO event in precipitating these changes and the role of the frequency or strength of subsequent El Niño events is presently unknown. Herring and other stocks of small pelagic fishes may be more affected by ENSO events. In particular, decreased catches, recruitment, and weight-at-age of herring are sometimes associated with ENSO events. Furthermore, a variety of seabirds which feed mostly on pelagic forage fishes or the pelagic juvenile stages of groundfish suffered widespread mortalities and breeding failures in the Gulf of Alaska during the ENSO years of 1983 and 1993. These effects on seabirds were also observed over a wider geographic range, from California to the western Bering Sea.

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INTRODUCTION

El Niño–Southern Oscillation (ENSO) events along the west coast of North America are associated with oceanic conditions that can affect the distribution, growth, and abundance of fish populations (Wooster and Fluharty 1985). The poleward propagation of oceanic long waves along the coast or shelf break can result in deeper thermoclines, increased sea level, stronger poleward flow, and consequent redistribution of water properties with higher salinity and temperature (Simpson 1992). Atmospheric teleconnections that affect the northern Gulf of Alaska include the intensification of the Aleutian low-pressure system, changes in the wind field, increased storminess in the Gulf of Alaska, and relaxed coastal upwelling. Our objective in this paper is to document changes in the physical environment of the Gulf of Alaska that occurred in response to the 1991–93 ENSO event, compare them to previous events, and discuss how these changes may have affected marine fish populations.

There are many commercially important marine species in the Gulf of Alaska, as well as many ways to assess ENSO effects. Most commonly, range extensions or unusual occurrences of southerly species are documented. We focus our study on the impact of ENSO events on the most abundant or commercially important species, since variability in abundance of these key species will have repercussions throughout the ecosystem. We have chosen five key species for this analysis: walleye pollock, *Theragra chalcogramma*; Pacific cod, *Gadus macrocephalus*; arrowtooth flounder, *Atheresthes stomias*; Pacific halibut, *Hippoglossus stenolepis*; and Pacific herring, *Clupea pallasi*. For each of these species, we examine whether the 1991–93 ENSO had any observable immediate effects on fisheries through landings and distribution, or long-term effects on growth and recruitment. When data are available, comparisons are made with prior ENSO events. The results of these observations are used to challenge two hypotheses about the effects of El Niño on northern marine communities: (1) that ENSO events have a beneficial effect on recruitment of northern fish populations, and (2) that pelagic communities are more strongly affected by ENSO events than demersal communities.

ATMOSPHERIC AND OCEANIC TELECONNECTIONS

As early as December 1989 (Janowiak 1990), the region of warm equatorial water in the tropical Pacific expanded and slowly shifted eastward. During the last half of 1990 and early 1991 other tropical conditions evolved toward an ENSO warm episode; the warm event was fully developed by fall 1991, when increased atmospheric convection in the region of positive sea-surface temperature anomalies demonstrated critical atmospheric-oceanic coupling (Janowiak 1990, 1993; Mo 1993). The mature phase persisted through spring 1992. During summer 1992, tropical conditions reverted abruptly toward normal, but anomalously warm water continued to be found along the equator just west of the International Date Line and at other sites (CAC 1992a). By December 1992 it was apparent that mature warm-episode conditions were continuing in the tropical Pacific (CAC 1992b, 1993a). The cooling of sea-surface temperatures and consequent reduced atmospheric convection over the eastern tropical Pacific Ocean during May and June 1993 (CAC 1993b, c) heralded the waning of the 3-year event. The 5-month running mean of the standardized Southern Oscillation Index (SOI; figure 1) summarizes the 1991–93 ENSO event and allows comparison with other warm episodes.

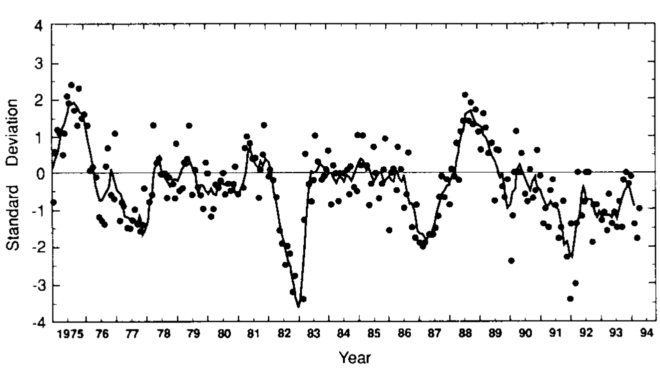

Figure 1. The Southern Oscillation Index: 5-month running mean of the difference between the standardized sea-level pressure anomalies at Tahiti and Darwin. Values are standardized by the 1951–80 mean annual standard deviation. *Circles* indicate individual monthly means. The *x-axis labels* are centered on the month of July.

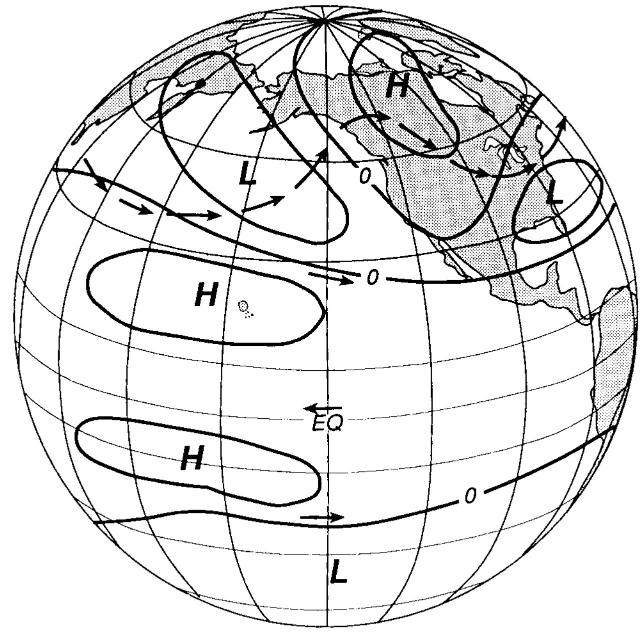

Figure 2. Schematic illustration of the hypothesized global pattern of middle- and upper-tropospheric geopotential height anomalies (*solid lines*) during a Northern Hemisphere winter that falls within an episode of warm sea-surface temperatures in the equatorial Pacific. The *single arrows* indicate strengthening of the subtropical jets in both hemispheres, along with stronger easterlies near the equator during warm episodes. The *path described by arrows* depicts a midtropospheric streamline as distorted by the anomaly pattern, with pronounced troughing over the central Pacific and ridging over western Canada (from Horel and Wallace 1981).

Teleconnections to the Northern Hemisphere

Horel and Wallace (1981) summarized theoretical studies suggesting that propagating Rossby waves provide a basis for understanding teleconnections to the Northern Hemisphere. Strong teleconnections to middle latitudes during warm episodes are possible only when westerly winds extend from the mid-latitudes into the equatorial troposphere above the region of warm water, a condition satisfied only during the Northern Hemisphere's winter. Negative midtropospheric geopotential height anomalies over the North Pacific Ocean bring about a deepening and southern displacement of the Aleutian low (figure 2). Teleconnections to the Northern Hemisphere are thought to be strongest during the second winter of a warm episode (Horel and Wallace 1981). Modified oceanic forcing due to the anomalous Aleutian low is a major reason for ENSO-related changes in the Gulf of Alaska (Emery and Hamilton 1985). Eastward-propagating equatorial oceanic Kelvin waves modify the ocean's mixed-layer characteristics and occasionally are strong enough to excite northward- and southward-propagating Kelvin waves along the west coast of the Americas (Wyrtki 1975; Enfield and Allen 1980) and Rossby waves that may rebound across the ocean (Jacobs et al. 1994).

The Pacific/North American (PNA) teleconnection index is a linear combination of normalized 500 mb geopotential height anomalies at four centers ranging from near Hawaii to the North Pacific Ocean, Alberta, and the Gulf Coast region of the United States (Wallace and Gutzler 1981). A deep Aleutian low characterizes positive values of PNA. Thus, sustained positive values of PNA during winter indicate the anomalous atmospheric pressure patterns responsible for modified forcing of the North Pacific Ocean. The Rossby wave train generated during an ENSO event is one mechanism that produces positive PNA anomalies.

The Northeastern Pacific Atmospheric Pressure Index (NEPPI) is another index of atmospheric circulation over the eastern North Pacific Ocean (Emery and Hamilton 1985). NEPPI measures the monthly mean sea-level pressure gradient between a point near Reno, Nevada, and a point in the North Pacific Ocean south of Amukta Pass in the Aleutian Islands. NEPPI tends to be strongly positive in winter, and low-valued to weakly negative in summer. Like PNA, NEPPI varies directly with the position and intensity of the Aleutian low, and positive winter excursions can result from ENSO-induced Rossby waves.

Northern Hemisphere Response

To estimate the strength and duration of the teleconnection to the North Pacific Ocean, we formed time series of PNA index anomalies (figure 3) and NEPPI anomalies (figure 4) based on 30-year and 48-year records, respectively, of indicial monthly means. In figure 3, a positive PNA trend occurred during the fall of 1991, when a distribution of negative height anomalies and above-normal height variability had developed over the eastern North Pacific. This distribution resembled the pattern associated with early stages of a developing ENSO episode (CAC 1991). The enhanced southerly winds associated with the negative height anomalies over the eastern North Pacific appeared to be related to above-normal sea-surface temperatures along the California coast during winter 1992. This pattern weakened during summer and fall of 1992. Between December 1992 and mid-January 1993, a major blocking high-pressure cell was observed over the eastern North Pacific, with persistent negative height anomalies over western North America. This anomaly pattern reflected the strong negative phase of the PNA teleconnection pattern (figure 3), and was associated with much above-normal storm activity and above-normal precipitation totals over the

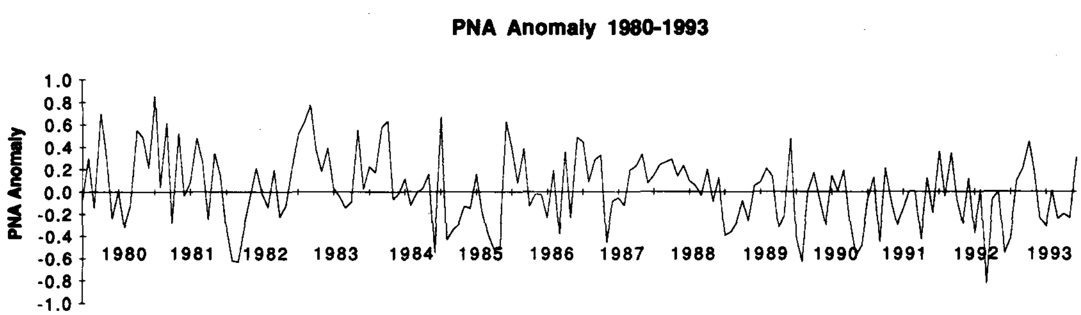

Figure 3. The Pacific/North American teleconnection index monthly anomaly, 1980–93, based on monthly means for the 30-year period from 1965 to 1994.

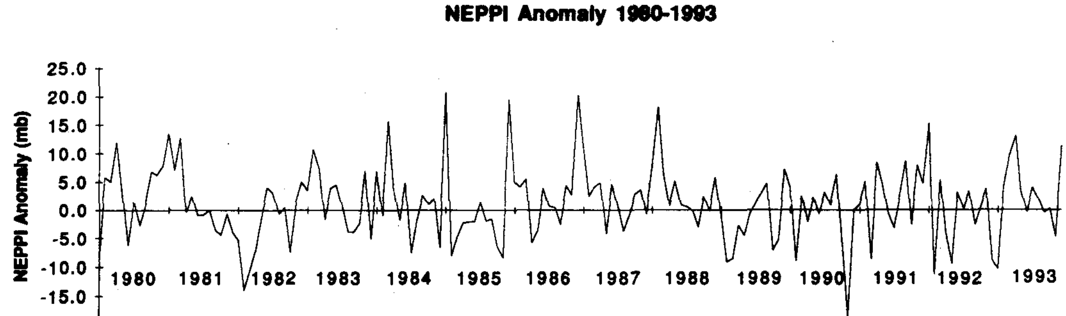

Figure 4. The Northeastern Pacific Pressure Index monthly anomaly, 1980–93, based on monthly means for the 48-year period from 1946 to 1993.

western contiguous United States (CAC 1993a). It is interesting that this well-defined PNA pattern occurred despite continued weak warm-episode conditions in the tropical central Pacific. The NEPPI anomaly series (figure 4) shows a similar relaxation of the northeastern Pacific sea-level pressure gradient during this time. In mid-January, this pattern reversed itself and persisted with well-above-normal temperatures over Alaska and the western United States until June, when a negative PNA pattern developed and lasted until December 1993.

The monthly PNA index showed positive anomalies that could be associated with an ENSO event during November 1991; January, March, and June 1992; and February, March, and April 1993 (figure 3). But only the April 1993 anomaly was larger than one standard deviation from the mean. The 1991–93 episode may be contrasted with the ENSO event of 1982–83, when PNA was anomalously positive during September and December 1982, and January through June 1983. January through April 1983 PNA anomalies were greater than one standard deviation from the long-term monthly means. The NEPPI anomaly series showed positive departures during September, November–December 1991; January, March, June, August, October–November 1992; and February–May 1993 (figure 4). Of these positive anomalies, September 1991, January and August 1992, and March–April 1993 were more than one standard deviation from their respective means. For 1982–83, NEPPI anomalies were positive during November–December 1982, January–March 1983, and May–June 1983. February, March, and June anomalies were greater than one standard deviation.

In summary, the ENSO atmospheric teleconnection to the Gulf of Alaska during 1991–93 did not appear to be as strong as during the 1982–83 warm episode, nor was the pattern as persistent. There were reversals of the PNA and NEPPI positive patterns during early 1992 and early 1993, and only the April 1993 positive anomaly was a significant departure from the 30-year PNA April mean. It is informative to note that PNA and NEPPI anomalies also occur in other years, caused by mechanisms other than ENSO events.

OCEANOGRAPHIC CONDITIONS

Sea-Level Anomalies

The upper ocean responds to climatic events in many ways, including changing sea level. One of the merits of using sea level as an index of change is that it integrates the effects of several oceanographic and atmospheric factors (e.g., local wind forcing, long-wave propagation, integrated water-column density, thermocline depth) and is often the most useful routinely measured quantity related to circulation and its variations. Sea level

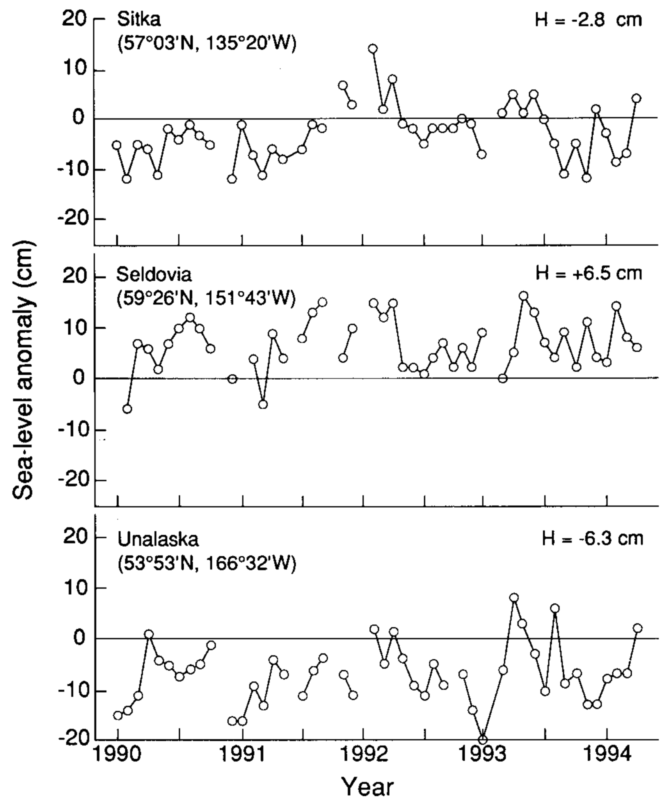

Figure 5. Sea-level anomalies from the mean monthly values (1975–86), corrected for atmospheric pressure variations, January 1990–April 1994 at Sitka, Seldovia, and Unalaska, Alaska. The mean anomalies (H) during this period are also shown. The gaps in the records resulted from missing maps in some issues of the *Climate Diagnostics Bulletin*.

has been found to be a good indicator of El Niño events and their poleward propagation (e.g., Cannon et al. 1985; Huyer and Smith 1985).

We examined sea-level anomalies from January 1990 through April 1994 at three sites (Sitka, Seldovia, and Unalaska) in the Gulf of Alaska in relation to the 1991–93 El Niño event. The data used are the monthly sea-level anomalies, corrected for atmospheric pressure variations, from the mean monthly values for the period 1975–86 as taken from maps contained in the *Climate Diagnostics Bulletin* (U.S. Department of Commerce/NOAA 1990–94). The results are shown in figure 5; for comparison, see Reed and Schumacher (1981) for the long-term mean seasonal variation at these sites and an interpretation in terms of coastal circulation.

The anomalies in figure 5 show considerable variability at the three sites. The mean anomalies for this 52-month period were approximately −3 cm for Sitka, +6 cm for Seldovia, and −6 cm for Unalaska. These differences in mean sea level are not well correlated with variations in sea-surface temperature because the temperature anomalies were predominately positive during the 52-month period at all three sites (from *Oceanographic*

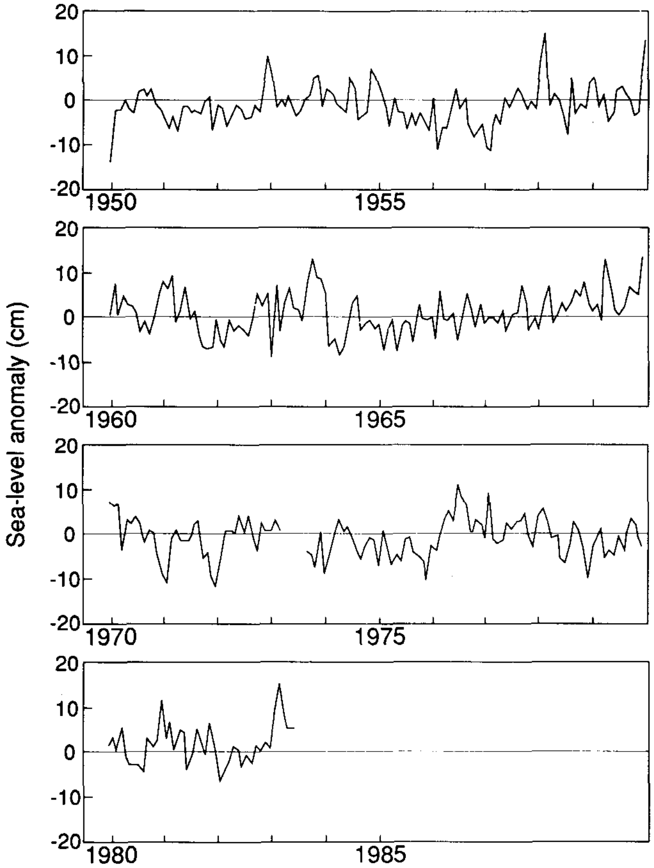

Figure 6. Sea-level anomalies from the mean monthly values (1938–83) at Sitka, Alaska, corrected for atmospheric pressure variations, 1950–83 (from data in Cannon et al. 1985).

Monthly Summary, U.S. Department of Commerce/ NOAA 1990–94). There were clear increases in sea level at all sites in winter 1992 and spring 1993 in agreement with, but perhaps 2 months later than, peak temperature and sea-level anomalies at the equator off South America. The temperature-anomaly maps cited above strongly suggest rapid poleward propagation of the ENSO signal in the eastern Pacific in two separate pulses in early 1992 and early 1993. This behavior is believed to result from long waves, and it also occurred with the 1941, 1958, and 1982 El Niño events (Cannon et al. 1985). The maximum increase in sea level in figure 5 during the two events is about 15 cm. Thus there was a significant response in much of the Gulf of Alaska to the El Niño events of 1991–93. Winds probably enhanced the oceanic long-wave propagation. The near-surface wind anomalies (from the *Climate Diagnostics Bulletin*) were strongly northward during both pulses. Coastal sea levels in Alaska are also strongly affected by freshwater runoff (T. Royer, University of Alaska, Fairbanks, pers. comm.).

A longer time series of pressure-corrected sea-level anomalies, from 1950 to 1983, is shown for Sitka in figure 6. The 1958 and 1982 (early 1983) ENSO events are prominent and had anomalies of about 15 cm. Note, however, that the 1972 event, a major El Niño in the tropics, had little effect at Sitka. The anomalies at Sitka during all events appear to be only about one-half those off Oregon and northern California (Cannon et al. 1985; Huyer and Smith 1985). There are, however, large positive and negative anomalies that are not associated with El Niño events and that are sometimes related to large variations in wind-stress forcing (Chelton and Davis 1982). In summary, the 1991–93 event at Sitka was comparable in timing and magnitude to other large events (1941, 1958, and 1982); the strong tropical event of 1972 had little effect at Sitka; but the weak tropical event of 1976 did have an effect (Cannon et al. 1985). The 1972 event had little effect north of California, at least partly as a result of strong southward winds.

Gulf of Alaska Temperature Series

A time series of water-column temperatures dating back to 1970 is available from waters off Seward, Alaska, at 60°N, 149°W (see figure 7). Figure 8 shows sea-surface (SST) and 250 m temperatures off Seward. The coherence between both series is high ($r = 0.60$). The 1976, 1982, 1986, and 1992 ENSO events appear in this time series as positive anomalies about one year later, most obvious at the deeper depth. Royer and Xiong (1984) noted that the 1982–83 warming appeared at depth (150–200 m) several months prior to warming at the surface, and they thus concluded that warming in the Gulf of Alaska in 1982–83 was not caused locally, but rather was an advective event. During the winter of 1992 the anomaly was about +2°C at the surface and +0.5°C at 250 m, apparently similar to the 1982 ENSO event at the surface, but weaker at depth.

A longer time series exists for air temperatures at Sitka. In general, Sitka air temperatures correspond closely to the Seward water temperatures ($r = 0.41$ for SST, and 0.42 for 250 m temperature). From the longer air-temperature time series, there appear to be cyclic low-frequency trends. Royer (1989) has proposed that these trends are related to the 18.6-year lunar nodal cycle, which explains about 17% of the variance in Sitka air temperatures, whereas the SOI explains only about 5%. At the Seward temperature station the lunar nodal cycle explains 17% and 36% of the variability in SST and 250 m temperatures, respectively, whereas SOI events explain about 14% and 13% of the variance, respectively.

Upwelling Indices

Upwelling indices are derived from large-scale geostrophic wind-stress estimates (Bakun 1973). Generally, upwelling indices at Gulf of Alaska stations are strongly negative (downwelling) in winter; weakly positive

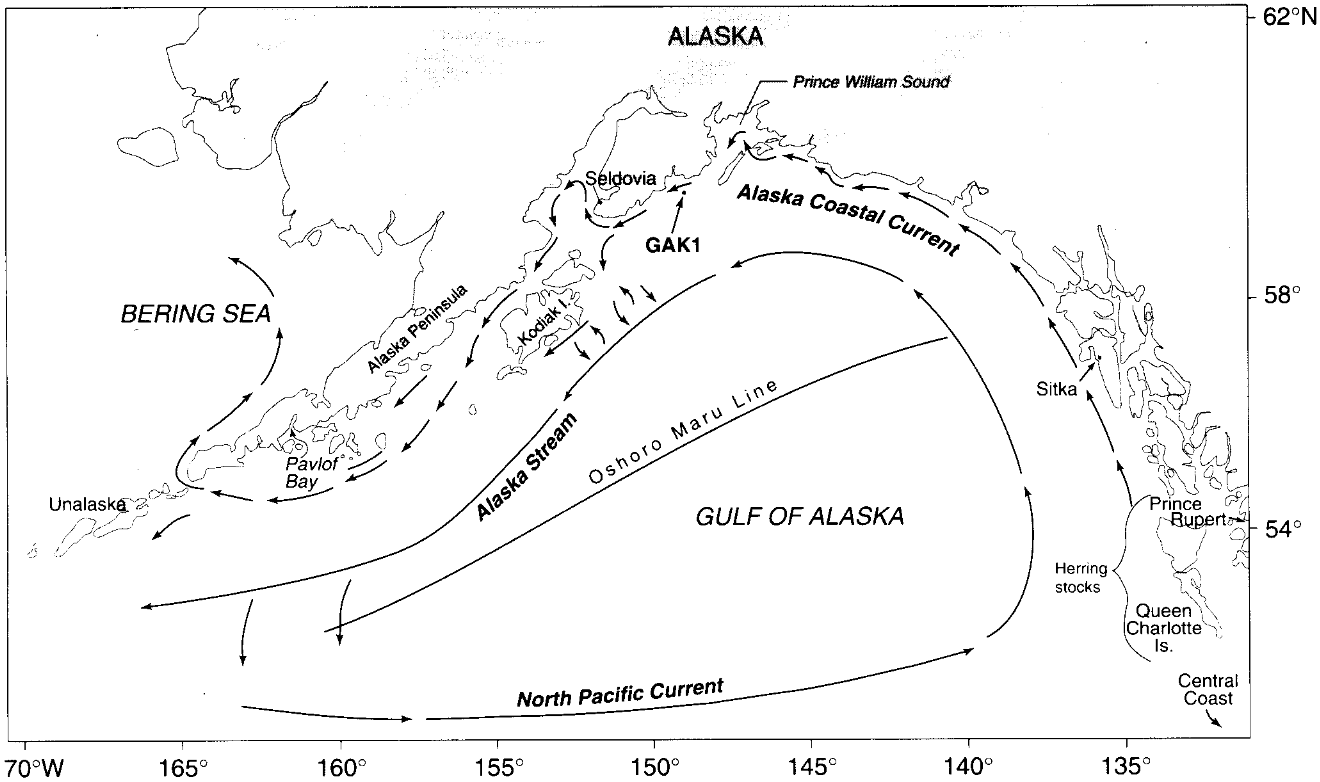

Figure 7. Gulf of Alaska, showing major current features and sites mentioned in the text. GAK1 is the water-column temperature station for Royer's (1989) series and the data shown in figure 8.

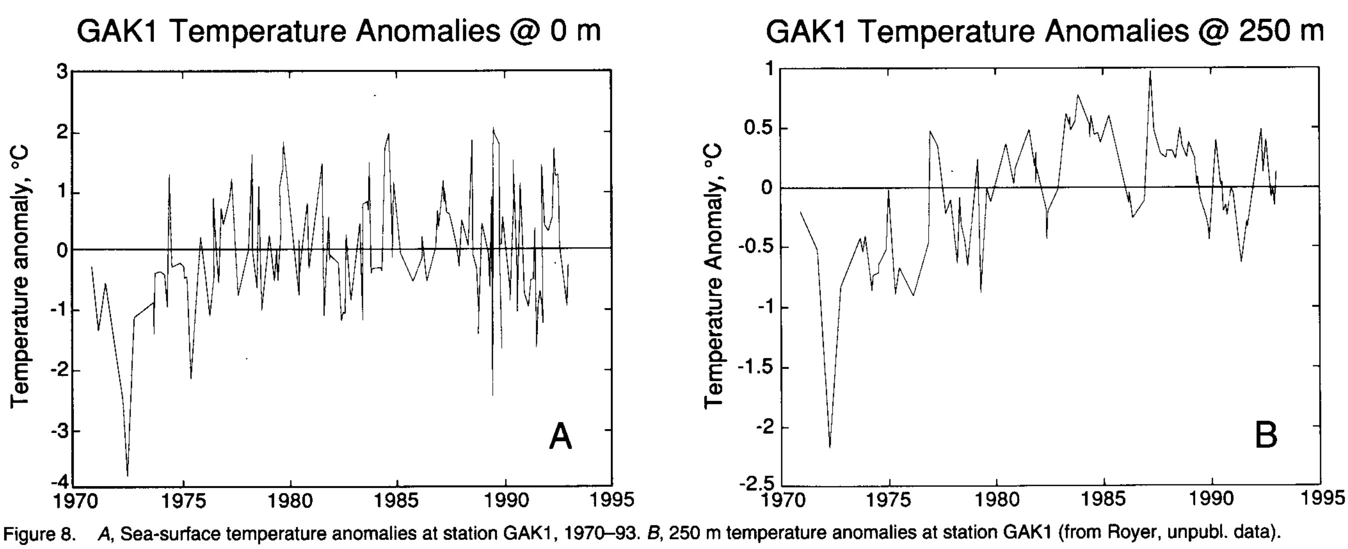

Figure 8. *A*, Sea-surface temperature anomalies at station GAK1, 1970–93. *B*, 250 m temperature anomalies at station GAK1 (from Royer, unpubl. data).

upwelling indices develop in June. Anomalies of winter (January–March) and spring (April–June) upwelling indices from 60°N, 146°W are shown in figure 9. El Niño events in the winters of 1952–53, 1957–58, 1965–66, 1982–83 were associated with strong downwelling anomalies. In some of these events, stronger downwelling anomalies appeared in the second winter, as noted above for atmospheric teleconnections. El Niño events in the winters of 1972–73, 1976–77, and 1991–93 were not associated with downwelling anomalies, and downwelling anomalies occurred in non-ENSO years such as 1950, 1974, and 1978–79. There was a springtime downwelling anomaly associated with the 1991–93 El Niño.

Circulation

Upper-ocean trajectories were simulated by the Ocean Surface Current Simulations (OSCURS; Ingraham and Miyahara 1989) model. This model combines a clima-

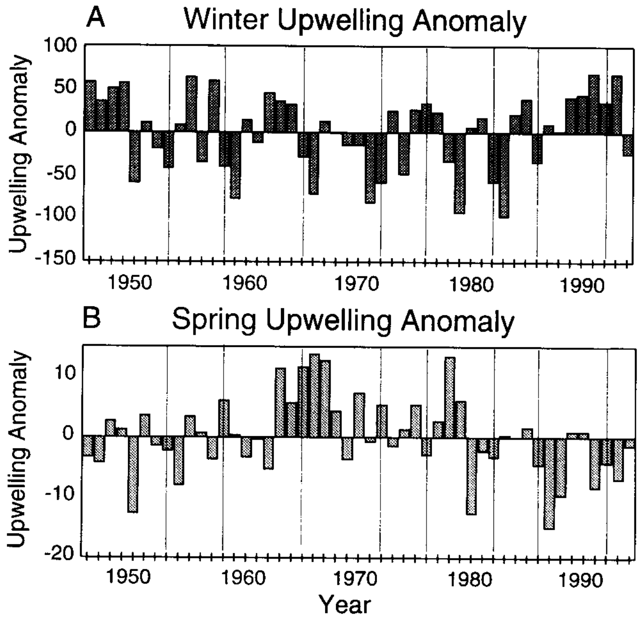

Figure 9. Upwelling index anomalies at 60°N, 146°W calculated as the deviation from the long-term mean for (*A*) winter (January–March) and (*B*) spring (April–June). Data provided by D. Husby.

tological mean density-driven (geostrophic) flow and empirically generated mixed-layer wind drift (Ingraham et al. 1991). The wind drift was derived from synoptic daily atmospheric pressure data (U.S. Navy, Fleet Numerical Oceanography Center). The wind-drift estimates were tuned to satellite-tracked drifter trajectories in the Gulf of Alaska reported by Reed (1980), and concurrent wind data. Trajectories were computed for December–March 1980–93. Most years show strong inflow toward the head of the Gulf of Alaska and southwestward outflow (as in 1989; figure 10). However, the winter of 1992–93 shows a strong anomaly, with very weak eastward flow in the central Gulf of Alaska and a strong westward flow near shore (figure 11). Flow characteristics in winter 1982–83 did not appear anomalous compared with other years.

EFFECTS ON MARINE FISHERIES

Landings

It is well recognized that landings reflect the influence of a number of factors, including fish distribution,

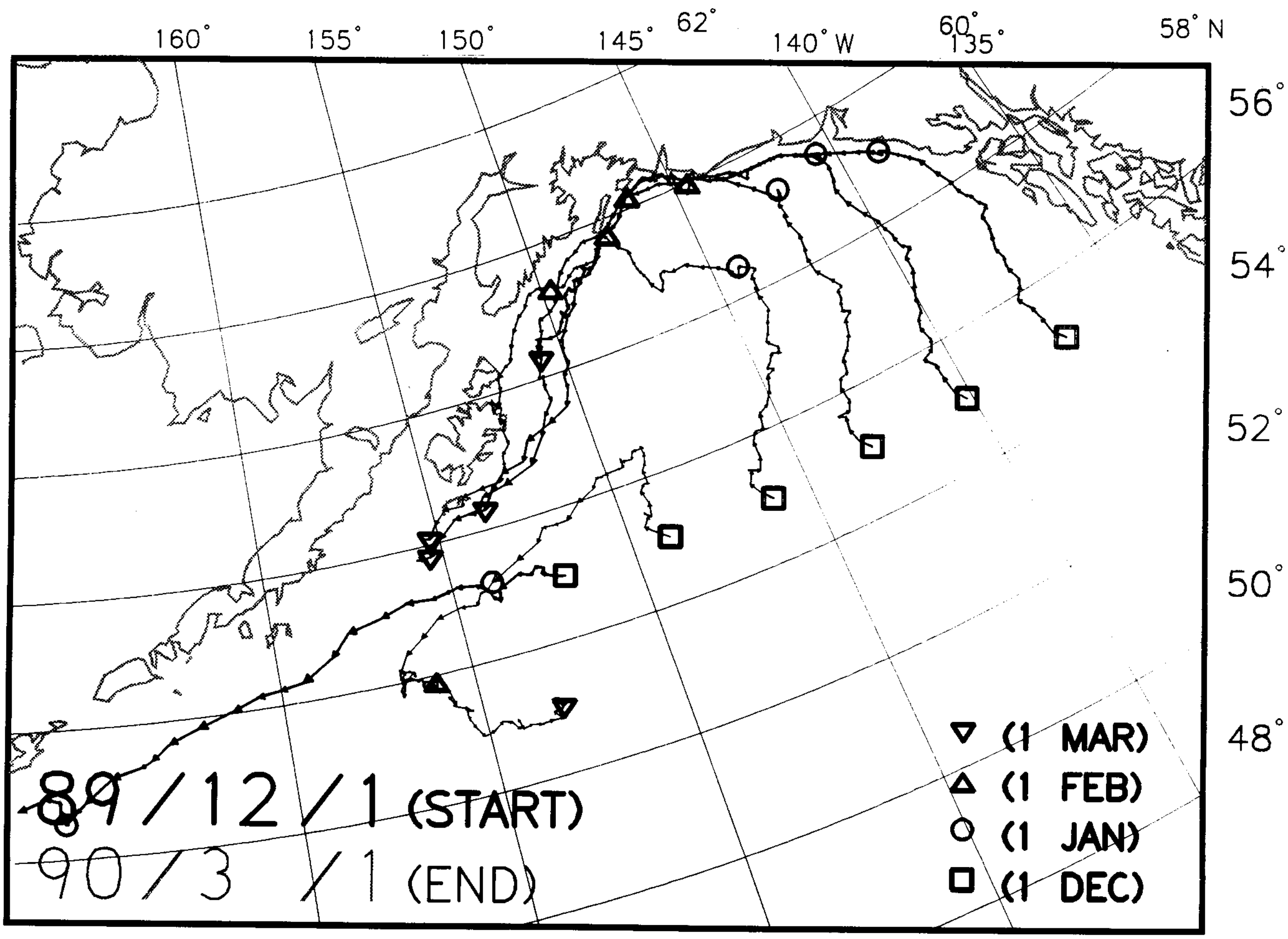

Figure 10. Computed trajectories of the upper ocean during a normal year (winter 1989–90). The symbols indicate positions on the first of the month for December, January, February, and March.

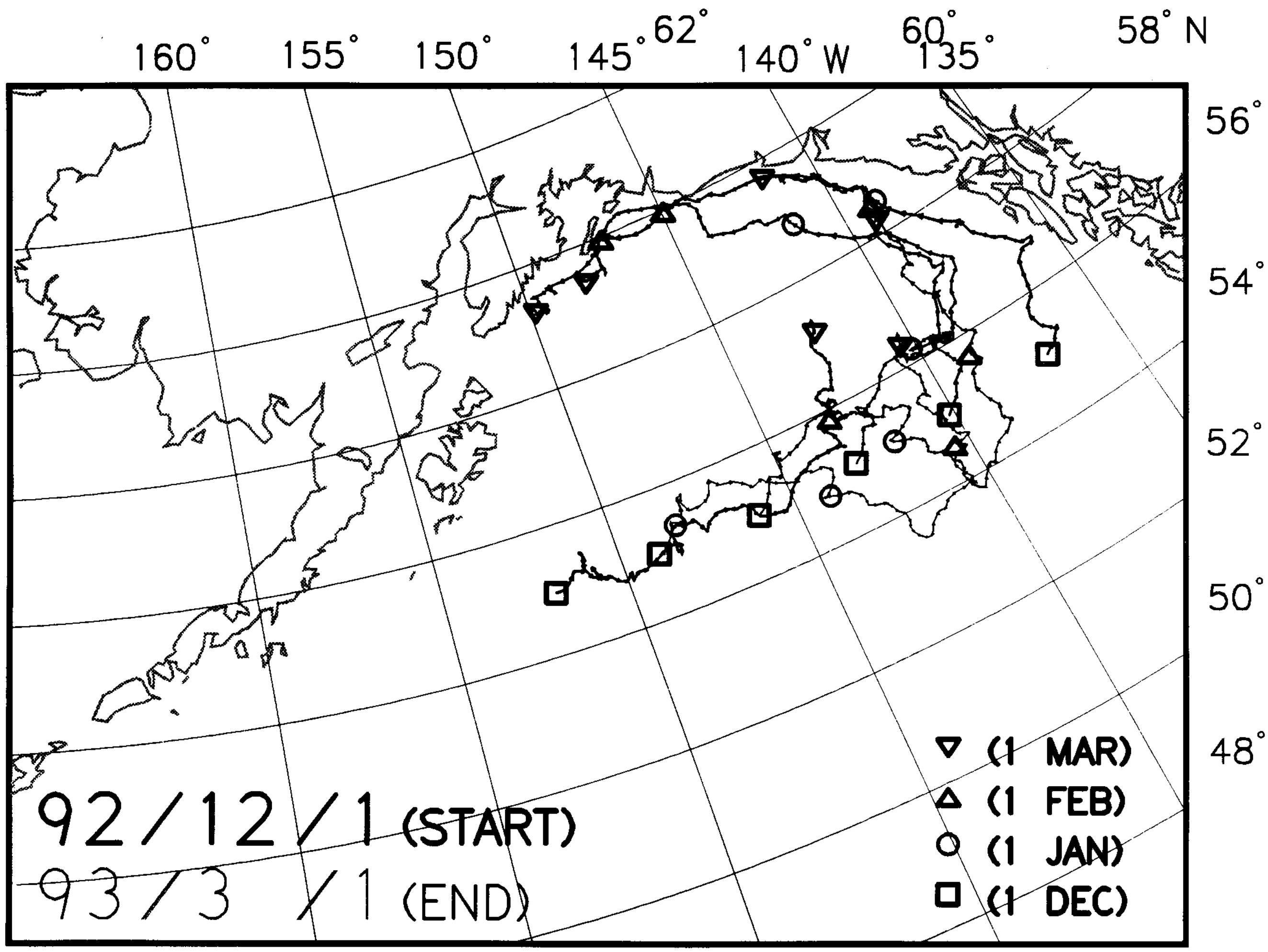

Figure 11. Computed trajectories of the upper ocean during the winter 1992–93 ENSO event. The symbols indicate positions on the first of the month for December, January, and February.

abundance, weather, economics, and management policies; but dramatic environmental events like ENSO are expected to affect catches. Landings of pollock, cod, arrowtooth flounder, halibut, and herring show marked changes over decadal time scales. However, the major ENSO events of 1957–58, 1982–83, and 1991–93 have no consistent obvious effect on landings above the longer-term trends, as reflected by the detrended time series (figures 12 and 13). Negative anomalies occurred in landings of cod and halibut in 1993, but similar decreases did not occur during much stronger El Niño events in 1958 and 1983 (the principal years when landings would have been affected). For herring, landings for three of four stocks (the three southernmost stocks) decreased in 1958. In 1983 the two northernmost stocks showed decreases in landings. However, herring landings were not anomalous in 1992–93, except in Prince William Sound, where a significant drop in landings in 1993 may have been due to a viral disease (F. Funk, Alaska Dept. Fish and Game, pers. comm.). These time series reveal little, if any, consistent short-term effect of ENSO events on fish landings.

Distribution

Distribution of fishes is one parameter expected to vary because of environmental changes. Our approach was to examine the distribution of groundfish in the Gulf of Alaska during summer 1993 and to compare the distribution with other non-El Niño warm years and with cooler years. The results are not presented in detail here, but are summarized. Data were available from the triennial National Marine Fisheries Service summer groundfish surveys in the Gulf of Alaska from 1984, 1987, 1990, and 1993. These surveys represented extensive coverage of the Gulf of Alaska. In general, the gear used was consistent for between-year comparisons (modified poly nor'eastern nets). Examination of surface-temperature maps from the triennial survey years of 1984 and 1993 showed anomalous warm surface temperatures in the northern gulf during the summer, whereas 1987 and

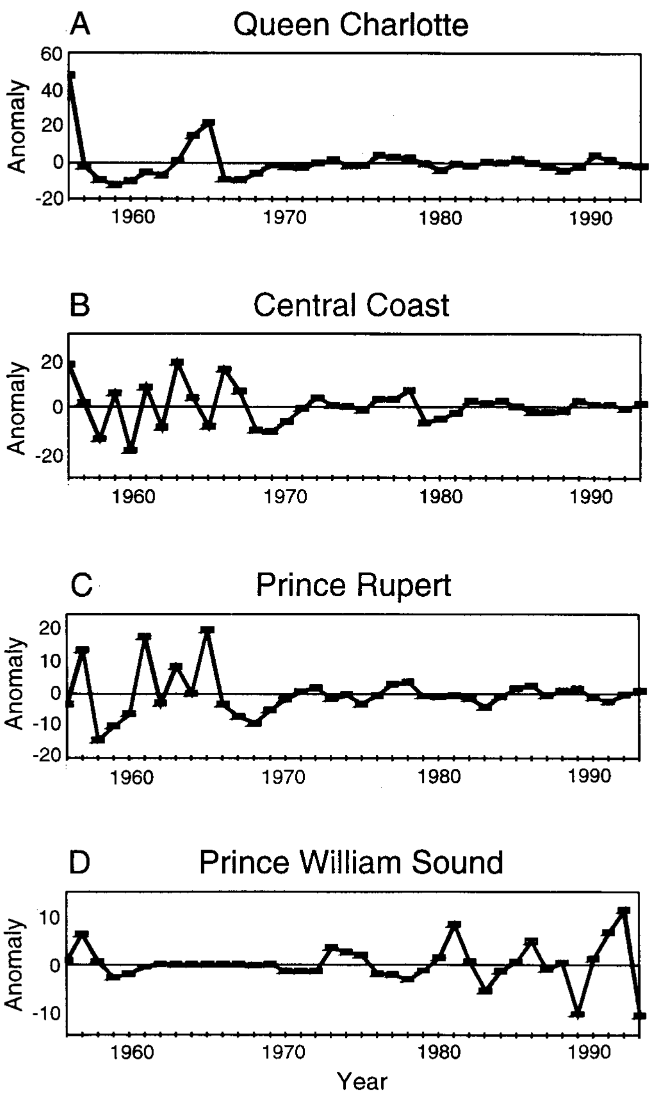

Figure 12. Anomalies of herring landings. Landings trend has been removed with a 6-year running mean.

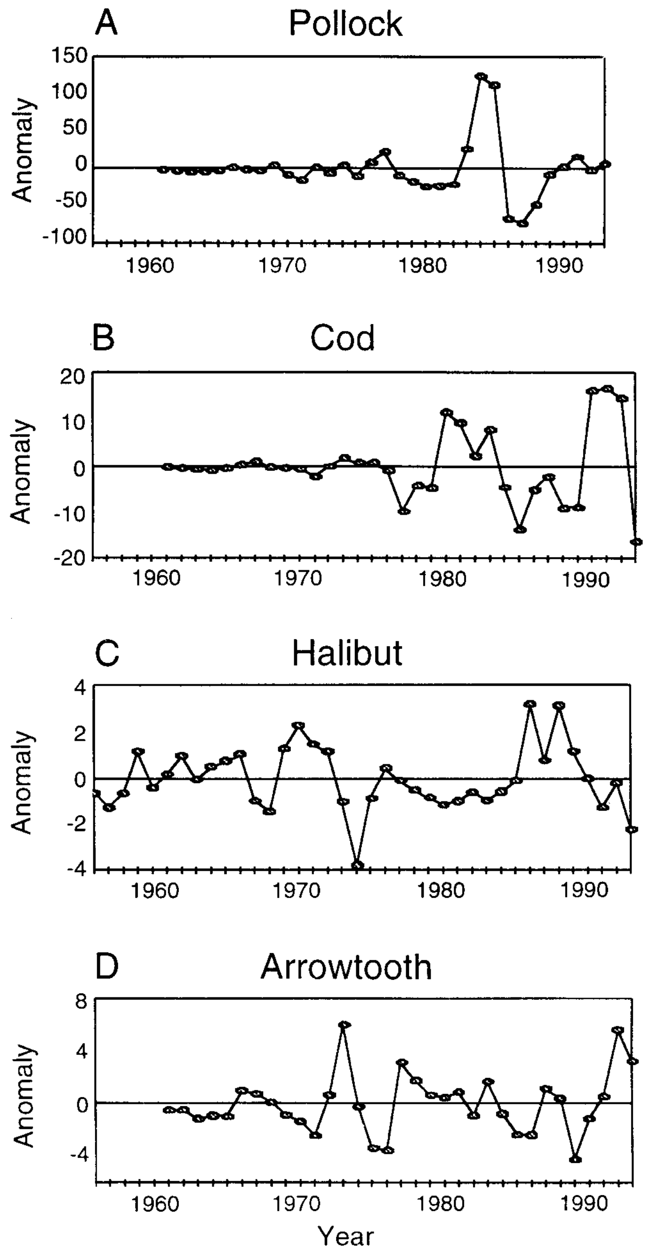

Figure 13. Anomalies of pollock, cod, halibut, and arrowtooth flounder landings. Landings trend has been removed with a 6-year running mean.

1990 showed a mix of cool and warm surface waters. The Seward 250 m temperature series confirms that 1984 was anomalously warm and that 1990 was cooler than the other years, but 1987 and 1993 (by summer, the ENSO event may have passed) are not as clear. Examination of temperature records at gear depth from the bottom-trawl surveys confirmed that 1993 was warm and 1987 was cooler.

Several types of analysis were used to examine changes in the distribution of pollock, arrowtooth flounder, Pacific cod, and Pacific halibut. First, we visually compared maps of the distribution of catches for each species and year. The second analysis method tested the hypothesis that there was no difference in groundfish distribution between all possible pairs of years. We used a statistical hypothesis test based on the Cramér–von Mises nonparametric test for a difference between two univariate probability distribution functions, developed by S. Syrjala (pers. comm., National Marine Fisheries Service). The response variable was catch-per-unit-effort (CPUE) of the individual species at each sampling location. When significant differences did exist between years, we examined the areas of difference in more detail by drawing a line roughly through the middle of the sampling area from the southwest corner (near the Islands of Four Mountains) to the northeast corner (near Cape St. Elias). All station locations were projected onto the line, and the cumulative sum of the relative CPUEs was plotted against the projected longitude. The third method we

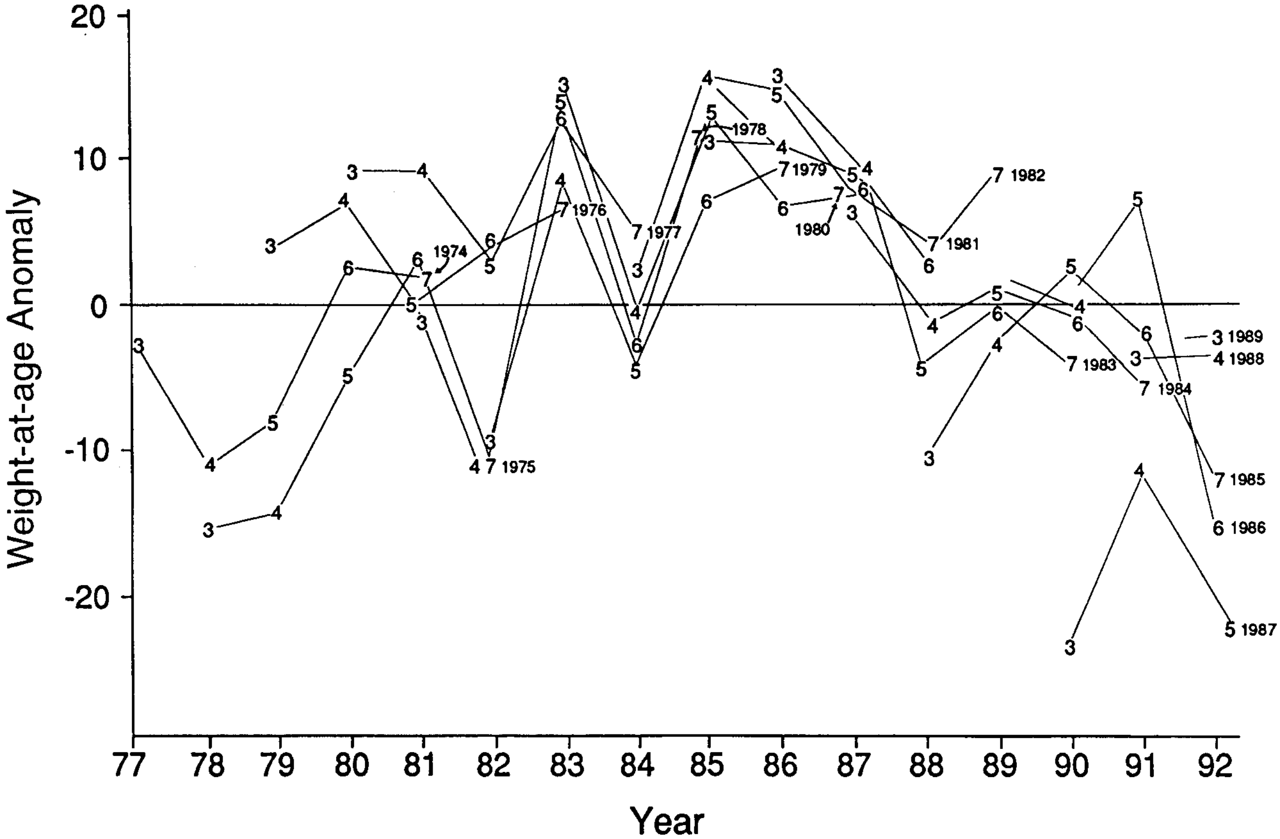

Figure 14. Anomalies of weight-at-age tracked by cohort-at-age in each year for Prince William Sound herring. Anomalies for each age grouping for each year were obtained by subtracting weight-at-age from the 1977–92 mean value for that age group. The year class is marked at the end age (usually age 7) for each cohort (data from Funk 1993).

used was a tree regression analysis on the survey data. We used the CPUE and presence/absence as the response variables, with depth and area strata as predictor variables. The Gulf of Alaska was divided into five depth strata (from 0 to 500 m) and four area strata (Shumagin, Chirikof, Kodiak, and Yakutat INPFC areas).

Visual comparison of the distribution maps did not reveal marked ENSO effects in 1993 for any of the four groundfish species. In the pairwise comparison, the distribution of pollock in 1993 was significantly different from both cool years (1987 and 1990), being more widespread, but was not different from the other warm year (1984). Arrowtooth flounder, Pacific halibut, and Pacific cod distributions did not show any differences that conformed consistently or unequivocally to ENSO, warm, or cool years. Likewise, the tree regression analysis produced no results consistent with an ENSO effect.

Distribution of groundfish species varies from year to year, and changes are difficult to detect, much less attribute to environmental factors. There may be year-class, age-class, and density effects. Furthermore, vertical distribution and activity levels may be influenced by environmental variability, thus affecting accessibility to trawl gear. Our data eventually should be subject to a thorough and stratified analysis, but the bulk approaches used here revealed no remarkable effects of the 1991–93 ENSO event on distribution of these groundfish species.

Weight-at-Age

Weight-at-age data for herring sampled from the fishery by the Alaska Department of Fish and Game are available from Prince William Sound. The weight-at-age anomalies of each cohort, calculated as the residual from the mean weight-at-age for each age group, were plotted by year (figure 14). A trend for a period of higher weight-at-age from 1980 to 1988 is observed, approximately corresponding to a warm ocean era (Hollowed and Wooster 1992). The 1982–83 ENSO event did not appear to have an effect on herring weight-at-age. Weight-at-age of herring caught in 1992 was anomalously low. Whether this was due to the viral infection mentioned above or ENSO conditions is unknown. In Kamishak Bay, near Kodiak Island, the results are somewhat different, with average to above-average mean weight-at-age in 1992, but below-average weight-at-age in 1993 (from data in Yuen et al. 1994). Trends can be removed from these data (and those following) by first-

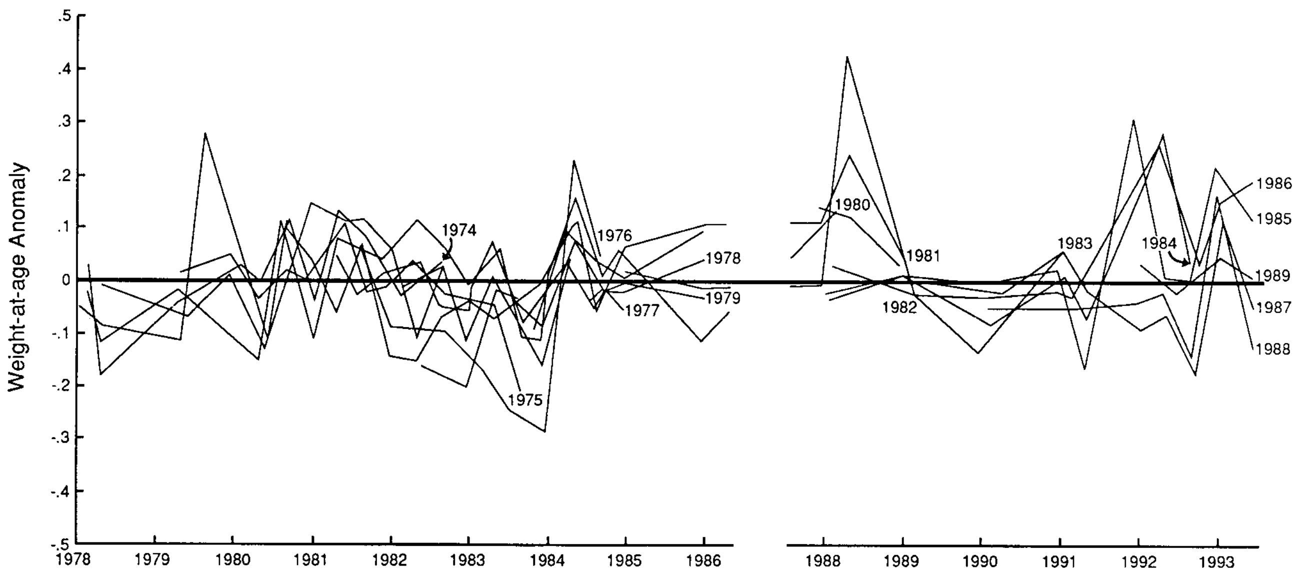

Figure 15. Anomalies of weight-at-age tracked by cohort-at-age in each year for Chirikof Island region male walleye pollock. Anomalies for each age grouping for each year were obtained by subtracting weight-at-age from the 1978–93 mean value for that age group. The year class is marked at the end age (usually age 8) for each cohort (Hollowed, unpubl. data).

order differencing, which is equivalent to analyzing growth increments; this result is easily visualized from the data presented and does not substantially influence our conclusions.

The mean weight-at-age of pollock sampled from the fishery is available from 1978 to 1993 (Hollowed, unpubl. data). For Hollowed's data, we plotted male pollock sampled from the Chirikof Island region. There are notable trends for every age group to show negative anomalies in the third trimester (autumn–winter) of 1983, and for every age group to show positive anomalies in the second trimester (summer) of 1984 and first trimester of 1993 (figure 15).

Recruitment

One problem in making quantitative observations about the 1991–93 ENSO effects on fishes is that many data are not presently available. For example, we will not know much about recruitment of most marine fish populations spawned during the last ENSO until 1996–97. Thus, we use data from earlier ENSO periods, such as 1957–59 and 1982–83, where year-class success and catches of marine fisheries are part of the historical record. The year classes of 1982–83 were relatively poor or unremarkable for herring stocks all over the Gulf of Alaska (figure 16). The post-ENSO years of either 1984 or 1985 were strong for all herring stocks examined. The 1958 ENSO had a positive effect on recruitment for the Prince Rupert stock, while recruitment was relatively poor for all other stocks. All herring stocks had strong year classes during one or more of the post-ENSO years from 1959 to 1961. Preliminary information indicates that herring stocks from the west coast of Vancouver Island will have a below-average to poor 1992 year class (Dan Ware, Pacific Biological Station, Nanaimo, B.C., pers. comm.).

Because halibut recruit to the fishery at age 8, data on recent ENSO effects are limited. Recruitment from the ENSO years 1941–42 and 1958 was relatively weak compared with surrounding years (unpubl. data for these early years). The 1983 year class of halibut in the northern gulf appears to be relatively strong compared with surrounding years (figure 17). This is similar to the situation for arrowtooth flounder. In fact, halibut and flounder both had relatively strong year classes in 1977 (1976–77 ENSO) and 1987 (1986–87 was a moderate ENSO). Given these similarities, it is interesting that the two species share early life-history characteristics of outer shelf/slope distributions, wintertime spawning, and relatively large larvae.

For pollock and cod—both mostly shelf-dwelling species—the 1983 year classes were relatively weak (figure 17). The 1976–77 year classes were strong for pollock, and other strong year classes appeared in the post-ENSO years 1978, 1984, and 1988. Cod showed strong year classes in 1977 and 1984. Preliminary data indicate that recruitment of the 1992–93 year classes of pollock will be average to below average (Anne Hollowed, pers. comm.), and there is some very preliminary information that the 1994 year class is strong (C. Wilson, pers. comm.). At this writing, no recent information was available for cod.

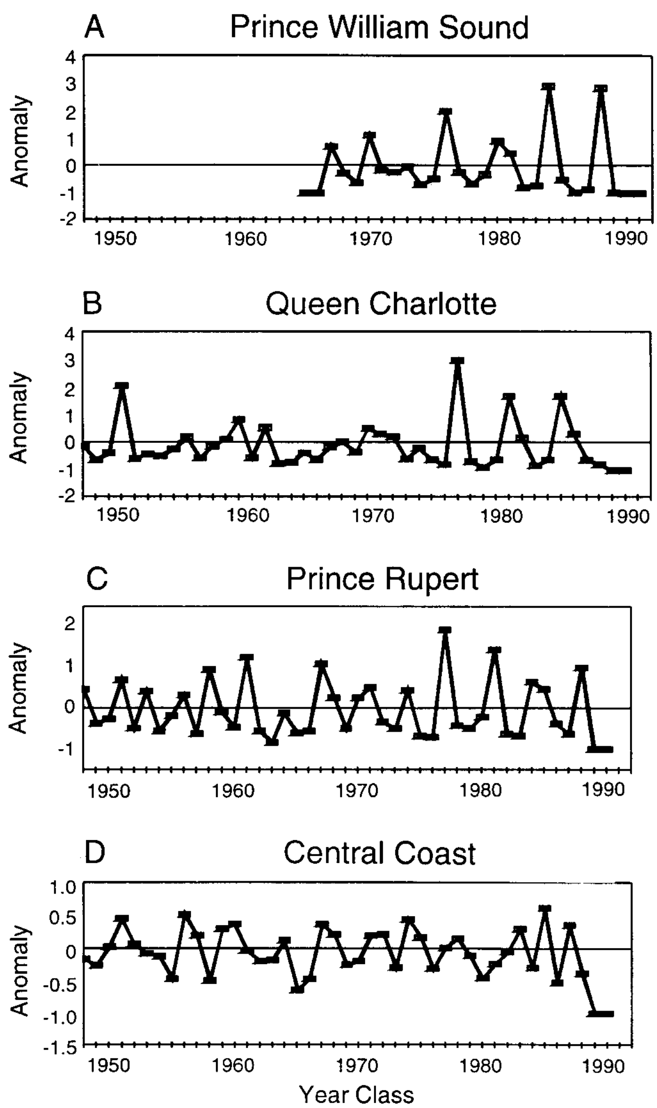

Figure 16. Recruitment anomalies for herring stocks, 1948–88, calculated as the deviation of recruitment from the 5-year running mean for each year class (data from Funk 1993; Schwiegert and Fort 1994).

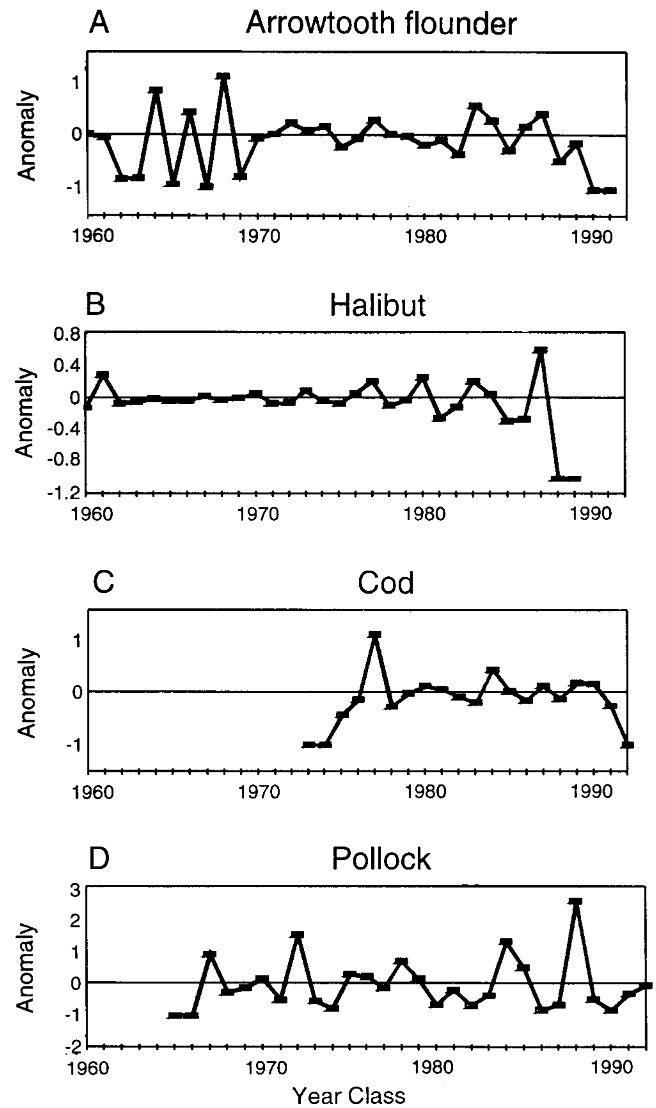

Figure 17. Recruitment anomalies for pollock, arrowtooth flounder, and cod, 1960–91, calculated as the deviation of recruitment from the 5-year running mean for each year class (data from A. Hollowed and T. Wilderbuer, Alaska Fisheries Science Center, pers. comm.). Recruitment anomalies for halibut were calculated from data provided by A. Parma (International Pacific Halibut Commission, pers. comm.) and from IPHC (1994). No single time series covering the historical and updated halibut data existed, therefore two time series of halibut recruit biomass were blended by means of regression where the two series overlapped; $R^2 = 0.88$, $P < 0.001$.

ECOSYSTEM EFFECTS

Pavlof Bay Community Time Series

A time series of trawl data from Pavlof Bay is available from Anderson (unpubl. data) and Piatt and Anderson (in press). Pavlof Bay is at the western part of the Gulf of Alaska (see figure 7) and has been sampled with shrimp bottom trawls every summer since 1972. Although Pavlof Bay is just one location on a very long coast, its long time series is the best available; there is consistency in the gear used and time of sampling; and the trends observed are long-lasting, apparently not just the result of short-term local variability. Where gulfwide data are available for comparison, the trends observed in Pavlof Bay are consistent. Most evident in the time series is a dramatic drop in the composition of shrimp and small pelagics beginning in 1977 (figure 18; these same trends appear when CPUE is plotted). This change was followed by increases in pleuronectids (mostly juveniles), including flathead sole, yellowfin sole, and arrowtooth flounder. However, pertinent to our analysis, there are no remarkable changes directly associated with the strong 1982–83 and 1991–93 ENSO events.

Zooplankton

Little detailed information on the dynamics of zooplankton species in the Gulf of Alaska during ENSO

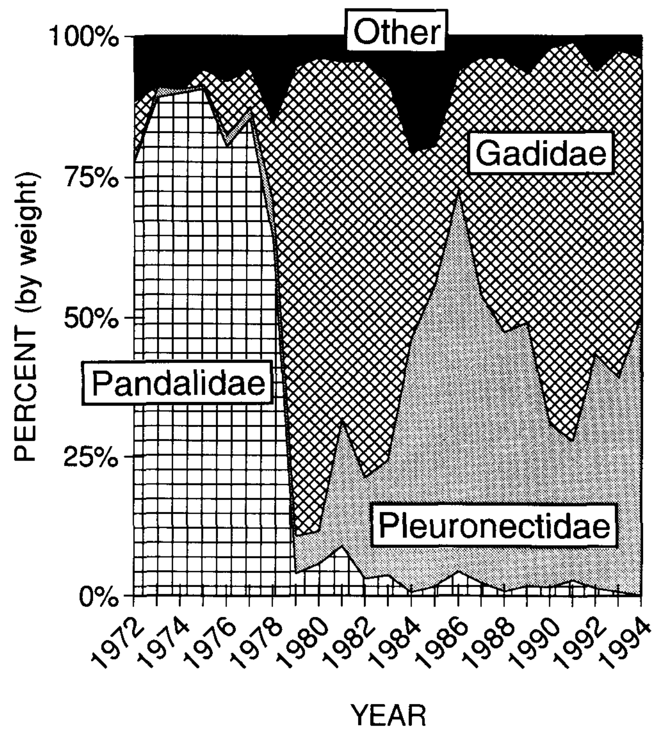

Figure 18. Change in the species composition by weight in "shrimp-trawl" catches in Pavlof Bay, Alaska, 1972–92 (P. Anderson, unpubl. data).

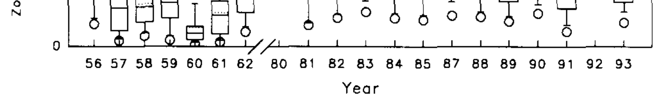

Figure 19. Box plot of annual zooplankton biomass across the *Oshoro Maru* line of stations, June 1956–93. Shown are means (*horizontal dotted lines*); 50% value (*horizontal solid lines*); 10% and 90% values (*vertical capped lines*); range (*circles*); and 25% and 75% values (*boxes*).

events was available for this synthesis. Instead, several bulk parameters on zooplankton standing stocks were available. These may reflect changes in distribution, production, species composition, or predation mortality.

A long-term time series of zooplankton biomass (settled volumes) for the central Gulf of Alaska was available from data collected by scientists from Hokkaido University, sampling from the *Oshoro Maru*. Vertical hauls from 150 m to the surface were made with fine-mesh 330 μm mesh nets. These data were first summarized up to 1989 by Brodeur and Ware (1992), and the time series was extended for this analysis. Although a smaller number of stations were occupied since 1989 than previously, virtually identical transects were sampled during these later years (figure 7). In the central gulf, 1983 was unremarkable in zooplankton biomass compared with previous years. Zooplankton biomass was relatively high for 1992 and very low for 1993 (figure 19).

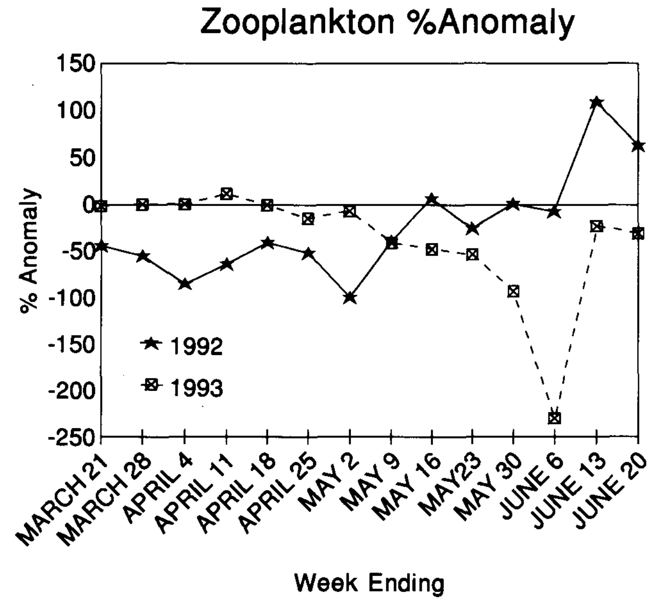

Figure 20. Weekly zooplankton volume anomalies in 1992 and 1993, calculated as the deviation from the long-term, 1986–93 mean value at Erlington Passage, Prince William Sound (data from Prince William Sound Aquaculture Institute).

A coastal zooplankton-volume time series from 1986 to 1993 was available for Erlington Passage at the entrance to Prince William Sound (Prince William Sound Aquaculture Corp., unpubl. data). We examined anomalies by comparing the weekly zooplankton volume to the long-term weekly mean. Both 1992 and 1993 had long periods of anomalously low zooplankton abundance compared with the mean (figure 20).

Marine Bird Indicators

Seabirds may be more sensitive to ENSO events, or at least their response is more visible than that of large predatory fish. Aspects of seabird biology (e.g., reproductive success, diet, foraging effort) provide direct and indirect information on the availability of forage fish species. Abundant seabirds, such as common murres (*Uria aalge*), black-legged kittiwakes (*Rissa tridactyla*), and tufted puffins (*Fratercula cirrhata*) feed on a variety of pelagic fishes.

Evidence for exclusive effects of short-term ENSO events on seabird reproductive success in the gulf is equivocal because of high annual and geographic variability in breeding success of some species (Hatch 1987), a lack of time-series data on most seabird species, and the background effects of concurrent changes in forage-fish

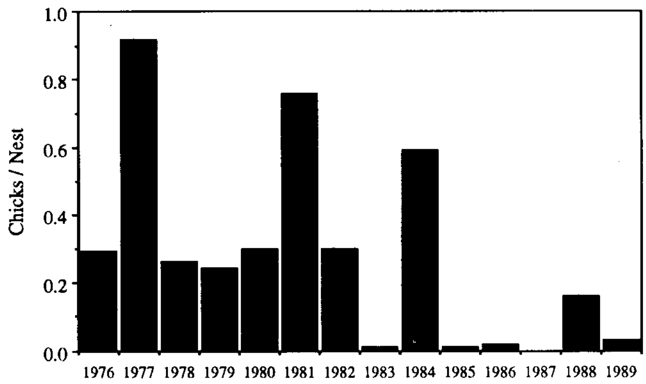

Figure 21. Productivity (number of chicks fledged per nest) of black-legged kittiwakes at selected colonies in the Gulf of Alaska from 1976 to 1989. Averaged data from Middleton, Barren, and Semidi Islands, and Chiniak Bay (data from Hatch et al. 1991).

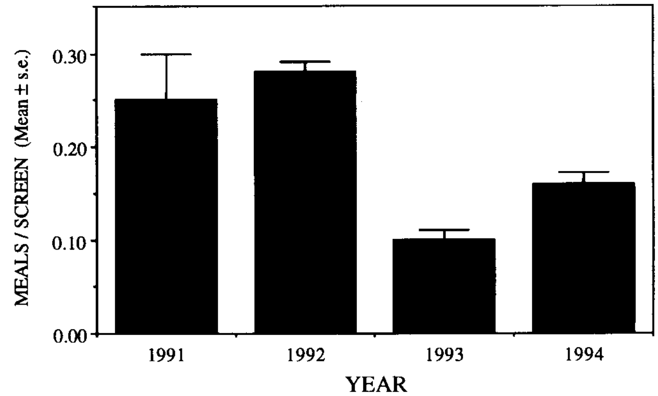

Figure 22. Foraging success of tufted puffins in 1991–94 at 16 colonies in the northwestern Gulf of Alaska as measured by the number of chick meal deliveries recovered per burrow entrance screened (analogous to CPUE, see text). From Piatt, unpubl. data.

populations and the marine environment (Piatt and Anderson, in press). For example, kittiwake breeding success in the Gulf of Alaska (figure 21) was extremely low in 1983 compared with previous years, but it was also low in subsequent years—perhaps in response to long-term changes in forage-fish populations. Some species (e.g., murres) are able to buffer against wide fluctuations in prey abundance by increasing the time spent foraging, thereby maintaining a relatively constant level of breeding success (Burger and Piatt 1990). Seabirds mature late (at 3–8 years) and are long-lived (average 8–15 years), so changes in population size generally reflect long-term processes. Short-term effects of ENSO events or other factors on recruitment or adult survival in any one year are difficult to detect from population surveys alone.

Large-scale mortality ("wrecks") of seabirds from starvation provides evidence for extreme changes in prey availability in response to ENSO events. Seabird wrecks occur periodically in Alaskan waters, and the largest wrecks in recent decades occurred during ENSO years. Following the 1982–83 ENSO event, widespread mortality and breeding failure of seabirds was observed from California to Japan and Russia (Lobkov 1986; Oka 1986; Hatch 1987; Ainley and Boekelheide 1990). In the Gulf of Alaska and western Bering Sea, thousands of dead, emaciated seabirds—mostly surface-feeding species such as kittiwakes and shearwaters—washed up on beaches. The 1992–93 ENSO event had similar far-reaching effects on seabirds. Breeding success and phenology of seabirds on the Farallon Islands in California was reduced, and unusual numbers of starved Cassin's auklets (*Ptychoramphus aleuticus*) were found on beach surveys in central California. In British Columbia, dead murres and rhinoceros auklets (*Cerorhinca monocerata*) were found in numbers 3–4 times higher than usual for winter beach surveys on Vancouver Island (Burger 1993). From Sitka to Kodiak in the northern Gulf of Alaska, an estimated 100,000 murres died of starvation in February–April 1993 (Piatt and van Pelt 1993). Breeding success of murres and kittiwakes at several locations in the gulf was also much reduced in summer 1993 (Piatt, unpubl. data; D. Roseneau, pers. comm.).

Detailed studies of tufted puffin feeding ecology in the northwestern Gulf of Alaska in 1991–94 (Piatt, unpubl. data) also suggest that forage fish were relatively unavailable to puffins in summer 1993. Preliminary analysis of these data suggest that "normal" puffin chick meal delivery rates observed in 1991 and 1992 declined by about one-half in 1993, and recovered somewhat in 1994 (figure 22). All-day observations of marked puffin burrows at three intensive study sites also revealed that maximum feeding rates declined from an average of about 6 meal deliveries per chick per day in 1992 to only about 2–3 meals/chick/day in 1993; the average returned to about 3–5 meals/chick/day in 1994. Puffin productivity was diminished in 1993, and large numbers of dead or emaciated puffin chicks were found in 1993. Juvenile pollock and cod, sand lance, and capelin made up most of the prey consumed in all years. Other than the fact that the proportion of pollock in diets peaked in 1992 at all sites, there were no consistent trends in diet composition between years and sites. This suggests that diminished puffin foraging success in 1993 was not due to problems in obtaining any one prey species, but rather to reduced availability of all forage-fish species.

DISCUSSION

How atmospheric and oceanic forcing affects the structure and dynamics of large marine ecosystems of the northeast Pacific over different time and space scales is a challenging problem facing fisheries oceanographers. Even with severe natural perturbations like El Niño, the

TABLE 1
Physical Characteristics of ENSO Events in the Gulf of Alaska

ENSO event	Subtropical classification	250 m Temperature anomaly	Winter SST	Sea-level peaks	SOI	PNA	NEPPI
1957–58	Strong		Very warm 1958–64	Strong winter 1958 1959 autumn	Moderate	Strong autumn 1957, winter–spring 1958	Moderate
1963	Weak		Very warm	1964 autumn	Weak	Moderate autumn 1963	Strong winter 1963–64
1965	Moderate		Moderate	None significant	Moderate	Weak	Weak
1969	Weak		Warm–1970	1969 winter 1970 winter	Weak	Strong spring/ autumn 1969, winter 1970	Strong winter 1969–70
1972–73	Strong	Cold	Cold 1971–76	None significant	Moderate but prolonged	Moderate	Weak
1976	Moderate	Warm winter/ spring 1977	Very warm 1977	1976 summer 1977 winter	Weak	Strong autumn 1976, winter 1977	Strong autumn autumn 1976, winter 1977
1982–83	Strong	Warm autumn 1982–spring 1985	Warm 1980–88	1983 strong winter	Strong	Strong winter 1983	Moderate winter 1983
1986		Warm autumn 1986–autumn 1988	Warm	1987 moderate winter	Moderate	Moderate winter 1986, 1987	Strong winter 1986, 1987
1991–92		Warm begins spring 1992	Warm 1992–94	1992 winter 1993 moderate winter/spring	Moderate but prolonged	Moderate winter 1992, winter/spring 1993	Moderate autumn/ winter 1992, winter/spring 1993

effects on high-latitude biological communities are hard to ascertain, partially because of the high degree of natural variability, complex interrelationships, poorly understood mechanisms controlling community structure, short time series, and statistical difficulties (Paine 1986). Furthermore, most fisheries information is collected for purposes of stock assessment and monitoring the fishery, not for studying environmental effects. Thus the space and time scales of data coverage are not always appropriate for alternate uses.

Although the 1991–93 ENSO event was a moderate one, in retrospect it manifested itself in the Gulf of Alaska as a clear signal in the physical environment, with anomalous atmospheric conditions, altered circulation patterns, increased sea level, and increased temperature. These conditions are compared with other ENSO events in table 1. Similar conditions, however, also occur in non-ENSO years in the Gulf of Alaska. Whether ENSO conditions in the northern Gulf of Alaska are due to local effects, remote forcing, or atmospheric teleconnections is not completely understood. Certainly anomalous warming and cooling patterns in the North Pacific result from complex interactions between atmospheric and oceanic processes in the tropics and extratropics. Norton and McClain (1994) conclude that warming episodes associated with equatorial forcing events are more likely to be detected at depth (>100 m), because of oceanic long waves, whereas warming associated with local forcing is more likely to be detected at the surface, and the most pervasive regional ocean warming effects during the fall–winter cooling season are associated with the equatorial atmosphere. Maximum warming (in the northern coastal California Current) occurs in the fall–winter season following the tropical El Niño initiated in the previous December through July. Trenberth and Hurrell (1994) point out the connection between tropical SST variations and atmospheric and SST variations in the North Pacific via the ENSO process and teleconnections through the North Pacific Oscillation (NPO, the oscillation from the winter Aleutian low pattern to summer North Pacific high pattern). Hamilton (1988) and Murphree et al. (1992) suggest that the teleconnection between the tropical and extratropical North Pacific may be more related to enhanced atmospheric heating in the far western equatorial Pacific due to high SST in the Western Pacific Warm Pool than to enhanced heating in the eastern or central equatorial Pacific. These studies point out that remote forcing, in terms of its sources and consequences, is complex. Indeed, a recent paper (Jacobs et al. 1994) suggests that ENSO events have long-term effects on the ocean and continental climate, lasting up to a decade or longer.

There are many documentations of ENSO effects on biota at lower latitudes, particularly within the California Current system, where the ENSO signal is more dramatic (e.g., see papers in Wooster and Fluharty 1985; also, Mysak 1986; Arntz et al. 1991). Mearns (1988) summarized unusual sightings and range extensions of fish species associated with historical ENSO events along the west coast of North America. However, Mearns noted that some years with many unusual fish observations could not be attributed to ENSO events or other obvious environmental anomalies.

For the Gulf of Alaska, there are also records of unusual sightings and range extensions of southern fishes during the 1982–83 ENSO (Karinen et al. 1985; Pearcy and Schoener 1987), but there is little knowledge of El Niño effects on groundfish production of key species. We use the data presented here to challenge two hypotheses about ENSO and biological communities: first, that El Niño events initiate strong year classes at the northern end of a species range through the beneficial effect of warming, and poor year classes at the southern end of a species range (Bailey and Incze 1985); second, that pelagic fish are more sensitive to ENSO events than demersal fish (adapted from Paine [1986], who proposed that pelagic communities were more sensitive than benthic communities).

Data presented here are not entirely consistent with the hypothesis that recruitment of northern stocks is favored by ENSO events (Arntz et al. 1991 and further data presented here for 1982–83 and 1991–93). In retrospect, it is overly simplistic to represent complex ecosystem interactions by a simple proxy like temperature (Wooster and Bailey 1989). The ENSO years 1958, 1983, and preliminary data for 1992–93 indicate that ENSO events do not have a consistent effect on recruitment for any species. The fact that 1983 was warm, but resulted in poor to average recruitment for many coastal species (cod, pollock, herring) in the Gulf of Alaska indicates that something other than warm temperatures was determining recruitment success in these circumstances. ENSO events may be unfavorable for recruitment because of decreased coastal upwelling (less nutrient input) and lessened zooplankton production (although possibly heightened upwelling in the central gulf gyre; Brodeur and Ware 1992); anomalous circulation patterns affecting distribution of organisms; or changes in food-web structure (Brodeur and Pearcy 1992). Strong year classes for many species occurred in the warm years of 1959–61, 1978, and 1984, all 1–3 years after ENSO events. If history repeats itself, one could speculate on strong recruitment years for many coastal species for the 1993–95 year classes.

However, for some of the outer shelf and slope species—arrowtooth flounder, Pacific halibut, and sablefish (off Canada; McFarlane and Beamish 1992)—strong year classes often coincide with ENSO events (winters of 1958–59, 1976–77, and 1986–87). Some aspects of this association are worth investigating further, including similarities in the life histories of these species, the effect of longwave propagation up the slope during strong ENSO events, the tendency for equatorial forcing to be felt more strongly at depth (Norton and McClain 1994), and transport of abundant large oceanic copepods shoreward (McFarlane and Beamish 1992).

Are pelagic species more affected by ENSO events than demersal species? The results presented here, and summaries of effects on salmonids (Mysak 1986; Pearcy and Schoener 1987; Arntz et al. 1991) are generally supportive. Since many pelagic species are active swimmers with high metabolic rates, one would expect that a 2° SST increase, coupled with decreased upwelling and consequent low zooplankton production (as observed in the coastal areas) would have a high cost. For demersal species that are often more sedentary, a 0.5° elevation in bottom temperatures would not appear significant. At more northern latitudes such as the Bering Sea, these species experience a higher degree of thermal variability (−2° to 3°) due to surface ice effects on bottom-water formation. Furthermore, since these species are higher-trophic-level predators, the complexity of the food web and time lags buffer these demersal species from variability in pelagic secondary production.

Although all the species examined here show long-term trends in abundance and landings, none of the groundfish species examined show obvious short-term perturbations directly attributable to ENSO events. The same conclusion holds for the distribution patterns of the major groundfish species; although some change in distribution is observed during ENSO events, the effect is similar to non-ENSO warm years. Many of the flatfish species appear to maintain their distributions independent of temperature variation; however, the roundfish species, like cod, are expected to vary their distribution in response to temperature (Perry et al. 1994). It may be that the distribution changes we observed were small relative to the large scale over which the groundfish data were examined, or that bottom-water temperature variations are relatively minor. The 1983 ENSO event appeared to be related to an anomalous low weight-at-age for pollock in the autumn, perhaps due to decreased upwelling and zooplankton production earlier in the year. However, pollock weight-at-age recovered for positive anomalies in the summer of 1984. In the moderate ENSO event of 1993, positive weight anomalies were noted for pollock in the winter season. These data point out the inconsistent and equivocal effect of different ENSO events on groundfish production.

Small pelagic fishes may be most vulnerable to ENSO-related changes in the environment. The weight-at-age of herring in Prince William Sound showed strong negative anomalies for most age classes in 1992, and in Kamishak Bay in 1993. However, strong positive anomalies were observed in Prince William Sound in 1983. Similar negative anomalies in weight were observed for herring in San Francisco Bay during the 1982 ENSO (Arntz et al. 1991). Although one would expect that this reflects poor condition and should result in poor reproductive success, the 1982 year class of herring in San Francisco Bay was relatively strong (Arntz et al. 1991).

The decreased seabird feeding levels, high mortalities, and reproductive failures observed in the gulf in 1983 and 1993 probably reflect changes in the abundance or distribution of small pelagic fish prey. Small fishes may have been distributed deeper or farther offshore, thus affecting their availability to seabirds and influencing foraging energetics. The mechanisms by which ENSO events can influence forage-fish availability are not well understood. The availability of forage-fish species near the sea surface may be strongly influenced by temperature and depth of the thermocline (Methven and Piatt 1991). Water temperatures may also affect spawning and schooling behavior of forage fish, thereby influencing the size and density of schools available to seabirds. The density of prey aggregations, rather than abundance, may be the most important factor influencing foraging success for diving species such as murres and puffins (Piatt 1990). Recruitment of pelagic fishes can also be influenced by ENSO events; recruitment of herring stocks has, for the most part, been below average or unremarkable during most major ENSO events.

Major changes have occurred in the Gulf of Alaska ecosystem beginning in the late 1970s. Hollowed and Wooster (1992) suggest that a climatic shift beginning in 1977 was initiated by the 1976 ENSO event. The shift in climate and oceanographic conditions occurring in 1977 is well documented (Royer 1989; Trenberth 1990; Trenberth and Hurrell 1994; Miller et al. 1994), as is its effect on marine production (Venrick et al. 1988; Brodeur and Ware 1992; Hollowed and Wooster 1992; Piatt and Anderson, in press). Although the 1976 ENSO event was described as moderate, the intensity of the Aleutian low was the strongest in 36 years, and warming of the West Coast was extensive in winter of 1977 (Mysak 1986).

Decadal changes in fish communities in the Gulf of Alaska observed by Piatt and Anderson (in press; figure 18) have apparently caused some notable changes in seabird ecology. While capelin populations crashed and pollock populations exploded in the late 1970s, the diets of five common seabirds in the Gulf of Alaska changed accordingly, as pollock and sand lance replaced capelin as the dominant prey. Breeding success and population size of several seabird species (murres, kittiwakes, murrelets) in some areas of the gulf have declined through the 1980s and remained low in the early 1990s (Hatch et al. 1991; Hatch and Piatt 1994; Piatt and Anderson, in press).

To summarize, the structure and dynamics of the Gulf of Alaska marine ecosystem are significantly affected by a complex series of atmosphere/ocean interactions occurring both remotely and locally, and at varying time scales. However, neither the linkage between oceanographic changes and the marine biota in terms of mechanisms, nor causes of the rapid and coherent shifts in this ecosystem are well understood. The phasing of atmospheric, ENSO, and tidal forcing may be important to the long-term physical and biological conditions in the Gulf of Alaska. An ENSO event during the nadir of the lunar tidal cycle might have a much different effect than if it arrived at the peak of the cycle. For example, the 1958 and 1976 ENSO events occurring as the tidal cycle produced warming appeared to trigger persistently warm climatic periods (1958–64 and 1977–84; see Hollowed and Wooster 1992).

The major ecosystem changes in the Gulf of Alaska are probably related to decadal-scale changes in the physical environment such as the warming episode commencing in 1977. Margalef (1986) speculated that the principal cause of biological fluctuations in marine ecosystems is change in the input of physical energy (sun, winds, currents). These inputs, or "kicks," are discontinuous and disrupt established ecological relationships within an ecosystem. It has been noted that for some fish species, strong recruitment years occur at the beginning of these ecosystem kicks (Saetersdal and Loeng 1984; McFarlane and Beamish 1992), perhaps because of disrupted community structure and an ecological release from predation and competition. For example, if pelagic fish populations are disrupted by an ENSO event, their effectiveness as competitors or predators on pelagic larvae of groundfishes may be diminished, allowing opportunistic recruitment success.

We conclude that ENSO events do appear to affect production processes of the major commercial groundfish fisheries in the Gulf of Alaska, but these effects are equivocal, sometimes minor, and inconsistent among different El Niño events. ENSO effects on the physical environment are diminished in the Gulf of Alaska compared with lower latitudes, and reverberations in the biological realm are also lessened. Relative to the major changes in the gulf ecosystem that occur over longer, decadal time scales, ENSO events are of relatively short duration. However, ENSO events, either by their frequency, atmospheric teleconnections, or phasing with other environmental factors, may be linked with these ecosystem shifts. ENSO effects on small pelagic fishes (including ichthyoplankton) are more likely to be consequential. In turn, fish-eating seabird populations can be strongly affected by ENSO events.

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