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Pandalid Shrimp as Indicator of Ocean Climate Regime Shift

by

Paul J. Anderson

National Marine Fisheries Service, Alaska Fisheries Science Center
Kodiak Laboratory, P.O. Box 1638, Kodiak, Alaska 99615-1638 USA
Phone:(907) 481-1723 - Fax: (907) 481-1701 - Email: paul.j.anderson@noaa.gov

Abstract

Pandalid shrimp are central components of the cold-regime boreal marine ecosystem in the Gulf of Alaska. Declines in abundance of several Pandalid species occurred quickly following water column warming due to an abrupt climate change after 1977. Shrimp trawl surveys conducted from 1953 - 1999 are used to describe how shrimp composition in catches changed relative to environmental parameters. Proportion of shrimp in survey catches was found to be negatively correlated with water column temperature. Pandalid shrimp species which occupied inshore and typically shallower water declined to near functional extinction, while offshore and deep water shrimp species have maintained low population levels. Possible mechanisms responsible for the chronic decline of several taxa of Pandalid shrimp and other crustaceans and replacement by other species are discussed. Abrupt climate change has an immediate effect on lower trophic levels of boreal marine ecosystems and rapid pandalid shrimp population changes are one of the first indicators that a community regime shift is underway.

Key words: Pandalid shrimp, Gulf of Alaska, Climate change, *Pandalus borealis*, *Pandalus goniurus*

Introduction

Pandalid shrimp have undergone significant population declines in the Gulf of Alaska (GOA) since the late 1970s (Anderson, 1991, Anderson et al. 1997, Orensantz et al 1998). Pandalid shrimp of several species represent a group of megafauna that occupy a central position in the cold-regime boreal ecosystem in the Gulf of Alaska. Several species of pandalid shrimp occupy the shelf and continental slope of the GOA. Rathbun (1904) reported on the general and depth distribution of Pandalid species collected from the early survey work by the R/V Albatross (1880) and the Harriman expedition (1899) in the north east Pacific. Eight species of pandalids in two genera represent the largest segment of the near-shore shrimp biomass in the GOA, while other deep water and small cryptic species do occupy this area, they are not encountered in great numbers and are not the subject of this paper. In the GOA the family Pandalidae are represented by two genera. In the genera *Pandalus* there are seven main species; *Pandalus borealis*, *P. goniurus*, *P. hypsinotus*, *P. jordani*, *P. danae*, *P. platycerous*, and *P. tridens*. Additionally, in the genus *Pandalopsis* there is *Pandalopsis dispar* that is locally abundant in near-shore areas of the GOA. All of the above species are protandric hermaphrodites, maturing first as males and then transforming to females at variable times thereafter.

The GOA was one of the major producers for pandalid shrimp harvests in the eastern Pacific from about 1955 to the end of the 1970s (Anderson and Gaffney, 1977, Orensantz et al. 1998). Kodiak Island and the adjacent south side of the Alaska peninsula with its numerous bays was the center of shrimp fishing activity in the GOA (Figure 1). The Kodiak Island area was first fished in 1958. Catches gradually increased until 1971 and then declined (Table 1). All areas along the Alaska peninsula declined after 1977 (Table 1). All GOA shrimp fisheries declined rapidly after the late 1970's due to reduced abundance as measured by shrimp surveys. In turn, most of the area that was formerly fished was closed to fishing between 1979-85. The causes of the decline in pandalid shrimps of several species were attributed to climate induced changes in the physical regime of the GOA that affected water column temperature after 1977 (Piatt and Anderson, 1996, Anderson and Piatt, 1999). Failure of recruitment after 1975 (Anderson 1991) lead to a continual decline of the fished population until closures were instituted by the management authority, the Alaska Department of Fish and Game (ADF&G).

Methods

Shrimp and other small-mesh trawl surveys were conducted nearly continuously from 1953 to the present (1999) in the GOA. Data from several different agencies has been compiled into a signal database to represent the period of record. Small-mesh trawl surveys for shrimp were conducted by the National Marine Fisheries Service (NMFS) 1953-99 and the ADF&G from 1970-98 and comprise most of the data set.. Sampling areas were designated by early exploratory surveys that had the purpose of locating commercial quantities of shrimp. Over 90% of survey tows were conducted in May - October. Early surveys had shown that shrimp concentrate in relatively deeper locations in the inshore bays and gullies of the GOA (Ronholt 1963). Consequently, most survey tows were restricted to depths greater than 55 m. After 1971, survey strata were designed for all known major shrimp concentrations in the central and western GOA. Random tow sampling locations within each strata were selected for each survey from 1972 to present. Prior to 1972, trawls were conducted with a variety of small-mesh gear having different catch efficiencies. These data are used here to compare relative (%) catch composition from 1953 to 1997. From 1972 onward, ADF&G and NMFS standardized methods and used “high-opening” trawls with 32 mm stretched-mesh throughout (Anderson 1991). Catch per unit effort (CPUE) was calculated as kg caught per km trawled. Between 1953 and 1997, 8996 trawls covering 17,406 km were conducted. Annual effort averaged 259 trawls year $^{-1}$ (range: 22-775). To examine trends in mean catch biomass only trawls (n = 6812) conducted after 1971 were used. Overall, mean and median CPUEs were similar (r=0.94), and mean catch data were used for all calculations and to illustrate biomass trends in all species.

Catches were compared to four available climate indices for the GOA study area: the North Pacific pressure index (NPPI; an index of air pressure at sea level), sea surface temperatures (SST), GOA air temperatures, and GOA bottom water temperatures . The NPPI index was obtained from S. Hare, Univ. of Washington, Seattle, and is the same as that reported in Mantua et al. 1997. Anomalies from November-March were normalized, and positive values of the NPPI correspond to years with a deepened Aleutian Low (Mantua et al. 1997). The NPPI provides an index of large-scale and low frequency climate signals that are widespread and detectable in the North Pacific at interdecadal time scales. Changes in atmospheric pressure patterns in the North Pacific can create persistent blocking ridges that lead to decadal or longer shifts in pressure patterns and storm tracks (Wilson and Overland 1986). An index of sea level pressure and its concomitant effect on horizontal and vertical mixing through wind stress is probably important in understanding recruitment variability of near-shore species with critical larval phases.

Coastal SST time series for British Columbia were obtained from the Institute of Ocean Sciences in Sidney, British Columbia, Canada. No other comparable SST data sets are available for the northern Gulf of Alaska. Normalized anomalies were calculated from a composite of seven widespread coastal observing stations: Amphitrite Point, Race Rocks, Langara Island, Kains Island, McInnes Island, Entrance Island, and Pine Island. This index of near-shore SST was used in an attempt to integrate the wide variation that is typically seen in an area that has diverse topography like the GOA. This is similar to the index used by Mantua et al. 1997 in their analysis of North Pacific salmon production, but not include as many sites because of data gaps.

Coastal Gulf of Alaska air temperatures were obtained from the National Climate Data Center. Normalized anomalies shown in Fig. 2 are a composite of Kodiak, King Salmon and Cold Bay station records for November to March. An index of several widely-dispersed reporting stations was used in order to reflect historical changes seen in the winter temperatures over the entire region covered in this study. An understanding of the degree of residual winter cooling is probably critical for the understanding of the population changes of near-shore species. Gulf of Alaska water temperatures at depth (GAK1; 250 m) were obtained from the Institute of Marine Science, Univ. of Alaska, Fairbanks. These data span only 1971-1997, and normalized anomalies in Fig. 2 were calculated from data collected from May 15 to September 15 (fall/winter data were too infrequent to use for multi-year trends). This index reflects the deepest extent of the distribution of sampling undertaken in this study; only 66 tows were conducted in water deeper than 250 m. This index is also useful for contrasting with SST data, which may or may not reflect heat content of the entire water column.

For illustrative purposes, annual CPUE, percent composition, and climate anomaly data were smoothed using 3-year running averages. All statistics were calculated from unsmoothed data.

Results

The near-shore region of the GOA with its numerous bays and associated off-shore gullies was a major habitat for shrimp dating back to at least the early 1950s with significant declines of shrimp in these areas beginning towards the end of the 1970s (Fig 2). This decrease in Pandalid shrimp coincided with a significant warming trend in the GOA (Fig 2). The abundance, as measured by standard trawl surveys, declined uniformly throughout all study areas in the GOA (Table 2). Total pandalid shrimp biomass averaged 179.3 kg/km in the 1972-81 period. In contrast, abundance declined in all surveyed areas to only 10.1 kg/km in the recent 1990-97 time period (Table 2). Declines were evident in all sampled areas and all seasonal sampling periods. Declines occurred in areas that were fished heavily as well as those areas that were seldom fished mostly due to there distance from processing centers.

In addition to the rapid decline of several pandalid shrimp species several non-commercial species commonly found in survey catches also declined. These species included the longsnout prickleback (*Lumpenella longirostris*), the Pacific sandfish (*Trichodon trichodon*), and capelin (*Mallotus villosus*). These species were gradually replaced in the epibenthic biomass by pleuronectid fishes of several species and Pacific cod (*Gadus macrocephalus*) and walleye pollock (*Theragra chalcogramma*) (Anderson and Piatt, 1999). Although pandalid shrimp declined rapidly it took several years for the replacement of the crustacean dominated community structure to become dominated by groundfish Figure 3.

All pandalid shrimp species continued to declined after fishing was largely closed in the near-shore areas where they were once abundant (Orensantz et al 1998). There is evidence that the more shallow distributed members of pandalidae were more vulnerable to being extinguished from the near-shore ecosystem due to the 1977 climate change. Of particular note is the humpy shrimp, (*Pandalus goniurus*) that was formerly a significant part of the shrimp biomass in some bays became nearly extinct while other species primarily, northern pink shrimp, (*P. borealis*) has declined, but not to near-extinction levels. Humpy shrimp averaged 19.26 kg/km during the period 1972-81 and declined to very low levels in recent surveys 0.09 kg/km in 1990-97 (Fig.4). Humpy shrimp was not heavily targeted by commercial shrimpers, and declines after closure of commercial fisheries continued. We hypothesize that the near-extinction of *P. goniurus* was caused by sustained high winter temperature in the late 1970s (Royer 1989). This species is commonly found in relatively shallow water subject to high residual winter cooling. In contrast *P. borealis* is found at deeper depths and is buffered from extreme temperature declines in winter. These distribution traits along with abrupt changes in winter temperatures may explain part of the region-wide mechanism that was responsible for shrimp population declines.

Similarly, other pandalid shrimp species have declined. *Pandalopsis dispar*, side-stripe shrimp has declined in abundance from near-shore sampling areas. This shrimp has a more pelagic characteristic and is found at the deepest locations sampled. It is possible that the distribution of this species has shifted to deeper depth intervals, outside our sampling strata in response to GOA water column warming. *Pandalus hypsinotus*, known locally as the coonstripe shrimp, is typically identified with inshore habitats and a shallow depth range. Both of the above species have declined to near-extinction levels in our sampling areas both less than 0.002 kg/km during recent surveys from higher levels in the early 1970s ~10 kg/km for each species (Fig. 4).

Although adult populations of were relatively high in 76-79, no strong year-classes were produced by any pandalid species during this period. The mechanism that affected reproductive and larval success occurred simultaneously with the climatic forcing event in the GOA (McGowan.et. al. 1998).

Changes in the thermal regime can have a considerable impact on the abundance of pandalid species. A significant (p <0.001) relationship between GOA temperature anomaly at 250 m and CPUE (Kg/Km) for all pandalid species in shrimp survey catches was found (Fig. 5A). Similarly, there also was a significant relationship (p <0.001) found between the proportion of shrimp in survey catches and temperature anomaly at 250 m in the GOA (Fig. 5B).

Discussion

These data provide evidence of community reorganization that involved all the abundant taxa caught in shrimp stock assessment trawls driven by the 1977 climate regime shift in the GOA. Several Pandalid shrimp species are early indicators of this community-wide trophic change and declined rapidly in overall abundance. In contrast, other species, mainly groundfish, took several years to mostly replace the crustacean community structure in the inshore areas of the GOA. The transition from cold- to warm-regime community structure lagged temperature changes and required 15-20 years to complete in some areas of the Gulf of Alaska, although transition times of only 2-5 years were observed in individual bays (Anderson et al. 1997).

Linkage between the Pandalid shrimp decline and several climate indices and water temperature supports the hypothesis that the GOA ecosystem is regulated to a large degree by “bottom-up” processes (Francis et al. 1998, McGowan et al. 1998). Pandalid shrimp recruitment is highly dependant on the proper conditions during the larval phase. Pandalid shrimp in the GOA have larval stages that last for several months and dispersal distances and environmental forcing can be strong and variable over this period. Variability in the timing of zooplankton production could have a profound effect on recruitment of decapods in the GOA. The majority of shrimp and crabs in the GOA release larvae in spring or early summer (Orensanz et al.1998). Two of the strongest year classes of shrimp ever recorded were the 1971 and 1975 year classes (Anderson 1991), corresponding to the latest years of peak zooplankton biomass development in the Alaska Gyre (Mackas et al. 1998). Similarly, red king, brown king, and Tanner crabs (*Chionoecetes bairdi*) all exhibited recruitment peaks in the early 1970's (Orensanz et al.1998).

The link between physical oceanographic processes and subsequent recruitment of Pandalid shrimps is important to the understanding variability of recruitment and further is valuable in developing management strategies for these species. In order to model the climate effects as described here it will be necessary to more fully understand the mechanism by which temperature is related to the control of pandalid shrimp recruitment. The goal of developing this model will be to accurately predict the response of pandalid shrimp populations due to climate change. While the relationship of temperature to overall pandalid shrimp abundance is shown here for the GOA it is important to consider how temperature may relate to changes such as circulation, mixing, and transport. Ouellet et. Al (1995) found that secondary production in the water column influences growth and survival of *P. borealis* larvae. Models of phytoplankton and zooplankton dynamics are sensitive to upper ocean mixed layer depths and temperatures (Polovina et al. 1995). The failure of *P. borealis* recruitment after 1975 (Anderson, 1991) was most probably a result of the climate regime shift in the northeast Pacific. The fishery was largely closed by 1979 and relatively high adult populations of several species were available to produce significant larval input into the GOA (Fig 4), however no significant year classes were produced.. Climate change plays a very strong role in the recruitment success of pandalid shrimp therefore it is imperative that these mechanisms of control be better described and fully understood for successful management.

“Top-down” processes also play a critical role in controlling Pandalid shrimp populations once the build-up of groundfish has reached high levels of abundance. Flatfish populations (several species of Pleuronectidae) gradually built up due to strong recruitment and favorable conditions inshore. A hypothesis is that predation amplified declines of shrimp. Cod, pollock, arrowtooth flounder (*Atheresthes stomias*), and halibut all prey on shrimp, and other forage species (Albers & Anderson 1985 , Livingston 1993, Yang 1993), and may have accelerated their decline. It is noteworthy that in several bays in the GOA, shrimp and capelin populations collapsed rapidly as groundfish increased inshore (Albers & Anderson 1985, Anderson et al. 1997). The spatial distribution of arrowtooth flounder showed an influx into shallow areas and inshore bays around Kodiak Island after the climate regime shift. Arrowtooth flounder (mostly those <40 cm) are heavy predators of pandalid shrimp (Yang 1993). Walleye pollock also generally increased after the change to warmer water column temperature in bays where shrimp were formerly abundant. Walleye pollock is not only the main prey for arrowtooth flounder (>40 cm)(Yang, 1993) but is a competitor for shrimp of available prey in the water column. The negative correlation observed here between predator and prey taxa, and diet trends of groundfish reported elsewhere, support the hypothesis that the GOA ecosystem is also regulated to some degree by “top-down” processes (Francis et al. 1998, McGowan et al. 1998).

The results reported in this paper suggest that shrimp react very quickly to warming climate changes and are a useful indicator of impending changes in the ecosystem that require longer time periods to fully manifest themselves. When the climate reverts to a colder regime the low population of shrimp now present may not react so quickly due to low potential larval input. In the extreme case of *P. goniurus* it may take a great deal of time for this species to rebuild in areas where it has ben extirpated from the near-shore regions of the GOA. Further, the high present biomass of fish probably precludes rapid re-building of shrimp stocks until dominant year-classes of fish die off or migrate out of inshore habitat. The GOA and the northeast Pacific are predicted to soon revert to the cold regime, in fact the coldest winter in over 100 years was recorded in Kodiak during the winter of 1998-99. If this climate trend continues it may take some time for pandalid stocks to rebuild to fishable levels due to low parent populations. Therefore pandalid shrimp are most useful as an indicator when going from cold to warm regime. The relation of pandalid shrimp abundance to temperature may not be as robust while populations are in a rebuilding mode.

Finally, there appear to be some parallels with events in the North Atlantic, where shrimp (*Pandalus* spp.), capelin (*Mallotus villosus*) and cod (*Gadus morhua*) are dominant members of that marine ecosystem. A widespread “gadoid outburst” of the 1960s was associated with warming temperatures and a shift in the timing and composition of zooplankton biomass (Cushing 1995). The more recent collapse of northwest Atlantic cod fisheries in the 1980s has been attributed to overfishing but also to recruitment and production failure associated with ocean climate change (deYoung & Rose 1993). In contrast, as groundfish stocks collapsed, the commercial catches of pandalid shrimp, capelin and crabs increased dramatically in the Northwest Atlantic and in West Greenland waters (P.A. Koeller & K. Drinkwater, Bedford Inst. Oceanogr., Dartmouth, NS, Canada, Personal communication; Pederson 1998, Frank & Carscadden 1996, Hvingel & Savard 1997).. While it can be argued that the situation in the Atlantic is complicated by long-term human influences and abundance changes in major species may not only be a result of climate change. In any case, it does appear that pandalid shrimp may be useful indicators of decadal-scale changes in northern marine ecosystems because of their short life spans and low trophic level.

Acknowledgement

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Table 1. Gulf of Alaska (GOA) Pandalid shrimp trawl landings 1958-98 in metric tons. Kodiak Island and Alaska peninsula areas are given separately. * Denotes confidential landing statistics by ADF&G.

Year	Kodiak Island	Alaska Peninsula	GOA
1958	14.46	0	14.46
1959	1298.15	0	1298.15
1960	1450.60	0	1450.60
1961	5027.44	0	5027.44
1962	5739.83	0	5739.83
1963	4589.71	0	4589.71
1964	1968.21	0	1968.21
1965	6270.10	0	6270.10
1966	10930.39	0	10930.39
1967	17358.19	0	17358.19
1968	15634.91	2108.50	17743.41
1969	18757.81	1395.68	20153.48
1970	28205.21	2396.54	30601.75
1971	37264.68	2866.67	40131.35
1972	26468.44	8483.69	34952.13
1973	31983.80	18416.04	50399.84
1974	25493.96	21681.94	47175.90
1975	26415.67	20048.99	46464.66
1976	1853.67	28282.63	30136.30
1977	21188.46	32485.07	53673.53
1978	11979.21	14821.79	26801.00
1979	9301.47	12182.12	21483.59
1980	5834.86	5825.67	11660.53
1981	12293.03	32.18	12325.21
1982	8669.31	0	8669.31
1983	4713.42	0	4713.42
1984	1260.56	0	1260.56
1985	1334.90	0	1334.90
1986	519.81	0	519.81
1987	*	0	?
1988	*	0	?
1989	0	0	0
1990	0	0	0
1991	0	0	0
1992	0	0	0
1993	0.77	0	0.77
1994	0	0	0
1995	0	0	0
1996	0	0	0
1997	0	0	0
1998	5.40	0	5.40

Table 2. Catch per unit effort (CPUE) of all Pandalid shrimp species combined in Gulf of Alaska (GOA) shrimp survey areas 1972-97. All data reflects standard surveys with the same sampling gear for all years.

Year	Number of Trawls	CPUE
1972	161	188.69
1973	194	217.54
1974	217	277.24
1975	557	242.16
1976	628	207.25
1977	428	182.64
1978	419	115.11
1979	414	165.03
1980	548	108.00
1981	775	89.15
1982	395	56.92
1983	194	42.38
1984	334	40.00
1985	284	19.32
1986	248	8.98
1987	228	19.56
1988	103	0.61
1989	208	12.85
1990	158	1.01
1991	22	12.32
1992	101	35.28
1993	22	2.07
1994	22	0.59
1995	108	20.05
1996	22	7.47
1997	22	2.11
Total	6,812	

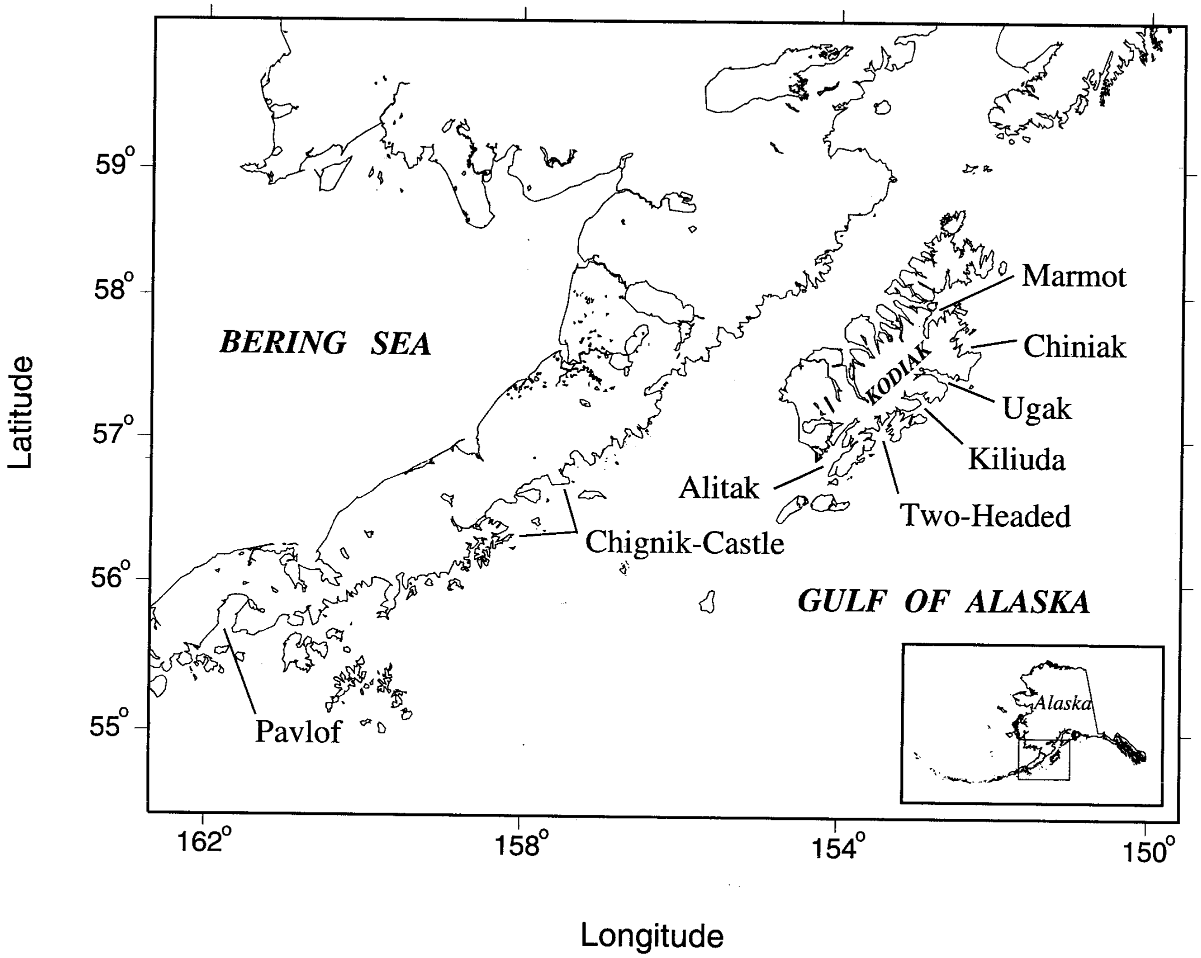

Figure 1. Major pandalid shrimp fishing and survey areas in the Gulf of Alaska.

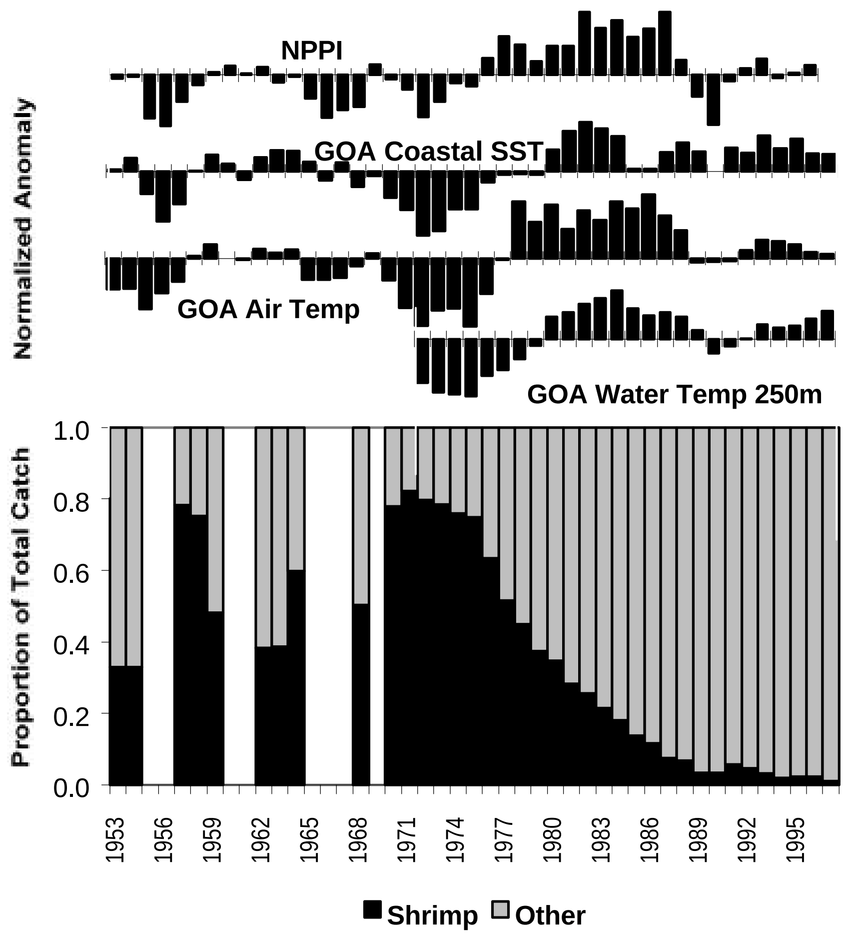

Figure 2. Changes in % composition of shrimp to other species in 1953-97 small-mesh trawl survey catches (3 year running average) in comparison to available climate indices (November through March normalized) for the Gulf of Alaska .

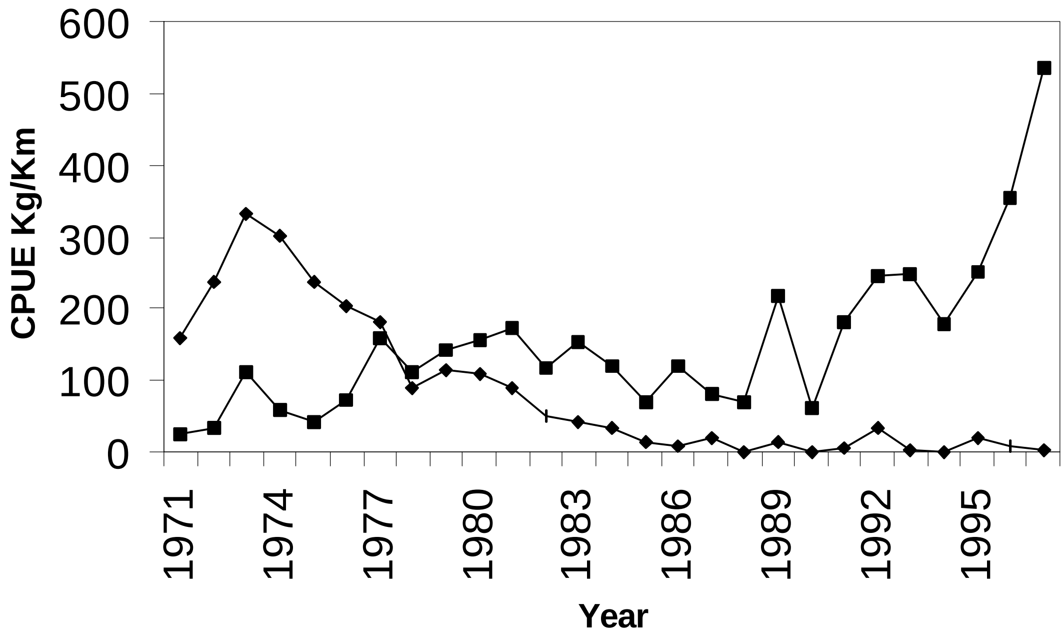

Figure 3. Relative change in CPUE (Kg/Km) of total pandalid shrimp and groundfish (Pleuronectidae, Pacific cod, and Walleye pollock) 1971-1997 in shrimp survey catches.

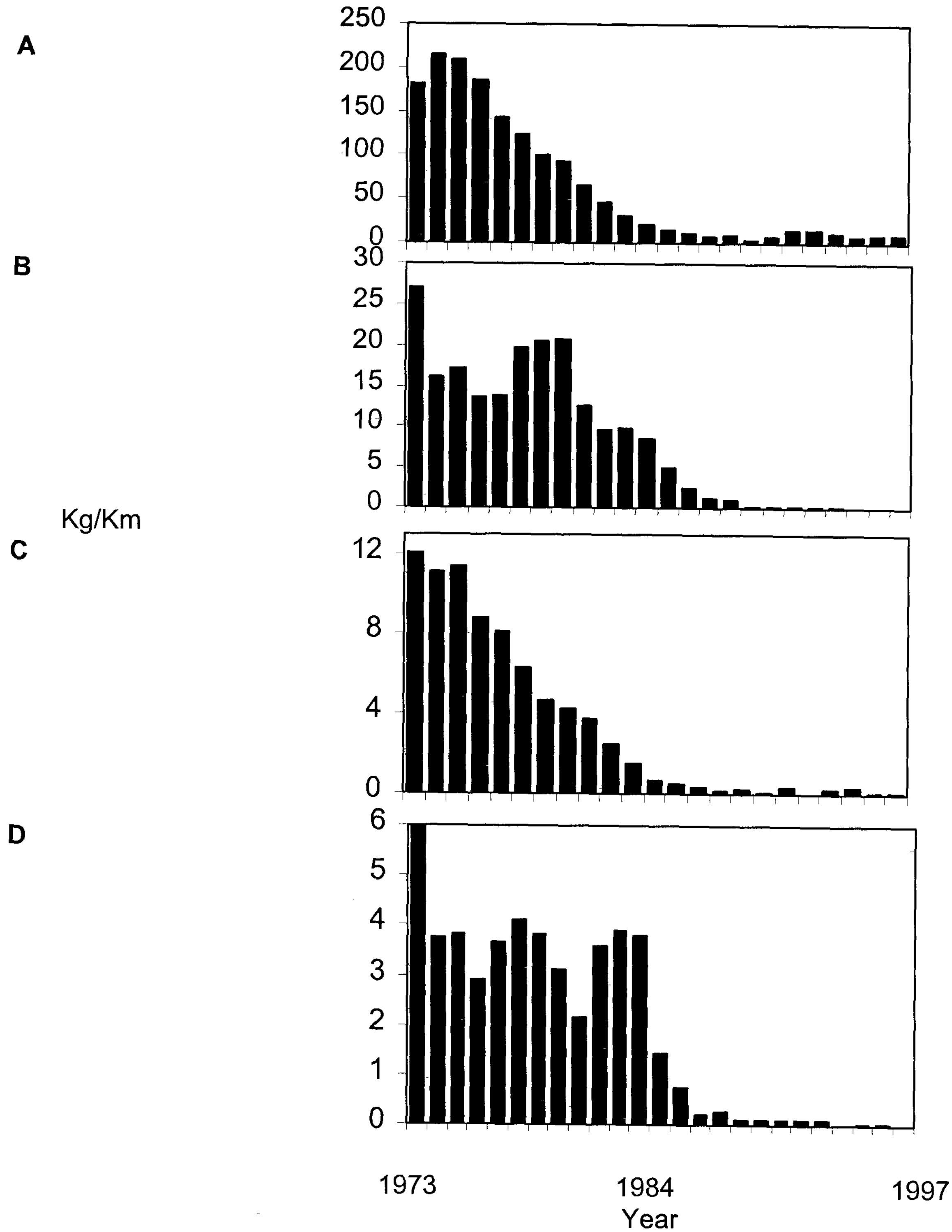

Figure 4. Relative abundance (kilograms per kilometer towed) of four species of Pandalid shrimp in the Gulf of Alaska 1973 - 1997 (3 year running average) from shrimp trawl surveys (A) *Pandalus borealis*, (B) *P. goniurus*, (C) *Pandalopsis dispar*, and (D) *Pandalus hypsinotus*.

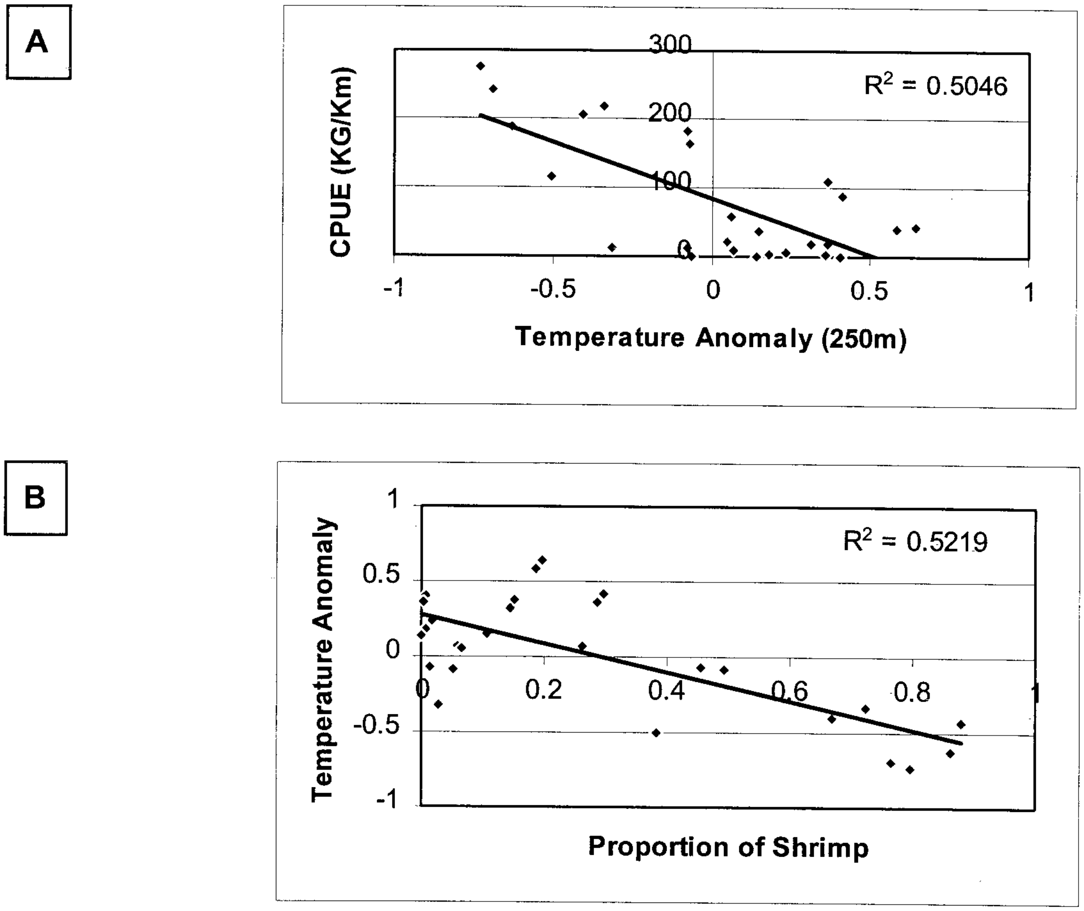

Figure 5. Comparison of shrimp abundance in survey catches to Gulf of Alaska water column temperature anomaly (250 m) 1971-97 (A) Annual average CPUE of Pandalid shrimp in relation to Gulf of Alaska water column temperature; (B) Annual proportion of shrimp in survey catches compared to Gulf of Alaska water column temperature.