SEASONAL SEA ICE, THE COLD POOL AND GADID DISTRIBUTION ON THE BERING SEA SHELF

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ABSTRACT

The variability in winter seasonal sea ice cover, its impact on the summer hydrography of the Bering Sea shelf, and the consequences to the demersal distributional patterns of walleye pollock (*Theragra chalcogramma*) and Arctic cod (*Boreogadus saida*) were investigated. Winter ice conditions acquired by remote sensing techniques were compared to the following summer's hydrographic conditions and fish distributions acquired from fisheries surveys between 1972-1993. Linkages among atmospheric, oceanic, and biological interactions occurred on two scales, an interannual mode of warm or cold conditions and multi-annual regimes of warm, cold or mixed conditions. The southernmost extent of sea ice as measured along meridian 169^{o}W (P_S) can be used to identify warm or cold conditions on the shelf. Warm conditions occurred when P_S extended southward, between 60^{o}-57^{o}30'N, bottom temperatures were 3.8^{o}-4.6^{o}C and the subsurface cold pool of water extended eastward, between meridians 170^{o}-166^{o}W. Cold conditions occurred when P_S extended southward, between 57^{o}30'-56^{o}N, bottom temperatures were 1.2^{o}-3.0^{o}C and the subsurface cold pool of water extended eastward, between meridians 163^{o}-158^{o}W. During the 20 year time series of climatic conditions, three regimes occurred: a cold regime prevailed from 1972-1977, a warm regime from 1978-1984, and a mixed regime from 1985-1991.

Age-1 and age-2 and older walleye pollock were primarily in the outer domain during cold conditions and in the middle and inner domain during warmer conditions. Arctic cod were present during cold conditions. Shifts in distribution of these species have ecosystem-wide consequences and can occur on either interannual scales or on the time-scale of regime shifts. Changes in the level of piscivorous predation on age-1 pollock, including cannibalism, occurred on the annual scale while prey species of seabirds and marine mammals fluctuated on the regime scale. Warm or cold summertime conditions were predictable from the previous winter's ice extent, which provides basic information on the level of environmental variability that affects biological systems and can be utilized in modeling this system. The results predict that older pollock will be concentrated in the outer domain following winters with extensive ice, information which could be useful to the fishing industry.

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CHAPTER ONE - Introduction - Characteristics of the Bering Sea Shelf and Two Gadids

Introduction

Fish populations have evolved over millions of years, adapting to changing environments. Their distributions are a function of each species' history, and the present and past environmental conditions. Changes in salinity, temperature, current speed and direction, and other physical conditions have resulted in changes in the areas species can, and where they do, live. Glacial and interglacial events have had an impact on the distributions of marine and terrestrial populations. Today, the Arctic Ocean is covered by multi-year sea ice and is bounded by marginal seas that are ice-covered seasonally. An understanding of species distribution must be grounded in the environmental variability of the species' genetic history. Once the boundaries of a distribution are known, further investigation can address the reasons why these boundaries exist.

With the current concern about global warming, changes in environment and populations at all levels are open to the exercise of prediction. Climate models predict that the effects of increased CO_2 will be most pronounced at high latitudes in winter. The manifestation of these changes would be in the variation of seasonally formed sea ice, that currently has significant interannual fluctuation in amount and expanse, and also varies over longer time scales. I have chosen this physical factor to evaluate and have used retrospective data to chart the timing and extent of seasonal sea ice (SSI) variability.

Consideration in the investigation of cause and effect is the linearity of the component parts. What type of analysis is appropriate when considering the interactions of a linear system, governed by the laws of physics, and a nonlinear system, subject to evolution? Physical processes, such as atmospheric pressure systems and their consequences to the flow and mixing of surface waters, often bear linear relationships to each other. Scales of biological systems are not predictable and contain a non-linear component. However, within a set of experienced environmental variation, some behaviors and responses have some level of predictability. I have used linear analytical tools in probing the relationship of fish distributions to their environment, with the caveat that variability in the response of fish to a physical situation resides within a range of possible responses. Given the range of environmental variation a population has experienced over its evolutionary history, a particular range of responses can be anticipated and is, perhaps, predictable.

The purpose of this study is to determine the variability in

SSI, its impact on the hydrography of the shelf and the consequences to the distribution of walleye pollock (*Theragra chalcogramma*) and Arctic cod (*Boreogadus saida*) on the Bering Sea shelf, annually and over decadal time scales. These two gadids were studied because they cohabit the continental shelf between Alaska and Russia. Additionally, they are key species linking lower and upper trophic levels and benthic and pelagic food webs in this subpolar ecosystem.

Sea ice introduces variability on the Bering Sea shelf that affects the system all year. Interannually, SSI cover on the shelf has varied as much as 30% (Niebauer 1983) and is responsible for fresh water import to areas unaffected by river discharge. The presence of SSI is affected by the Aleutian Low Pressure System (ALPS) (Overland and Pease 1982) and in turn affects the characteristics of a cold bottom water mass (Khen 1988). I tested the hypothesis that interannual variation in the seasonal presence of sea ice is an indicator of the distribution of walleye pollock and Arctic cod.

Study Area

The Bering Sea is a semi-enclosed sea of the North Pacific. It consists of two parts: a deep basin bounded by the Aleutian Islands to the south, and a shallow shelf to the north. The shelf gently slopes from 200 m at the shelf break, to 50 m at its northern boundary, the Bering Strait. The eastern and western boundaries are the continental land masses of Alaska and Russia. This shallow shelf, in the eastern Bering Sea, is the focus of this work (Fig. 1.1), an area covered by SSI every winter (Sancetta and Robinson 1983). SSI is defined by the seasonal range of ice limits. The boundary of multi-year ice varies each summer, as does the southernmost SSI extent.

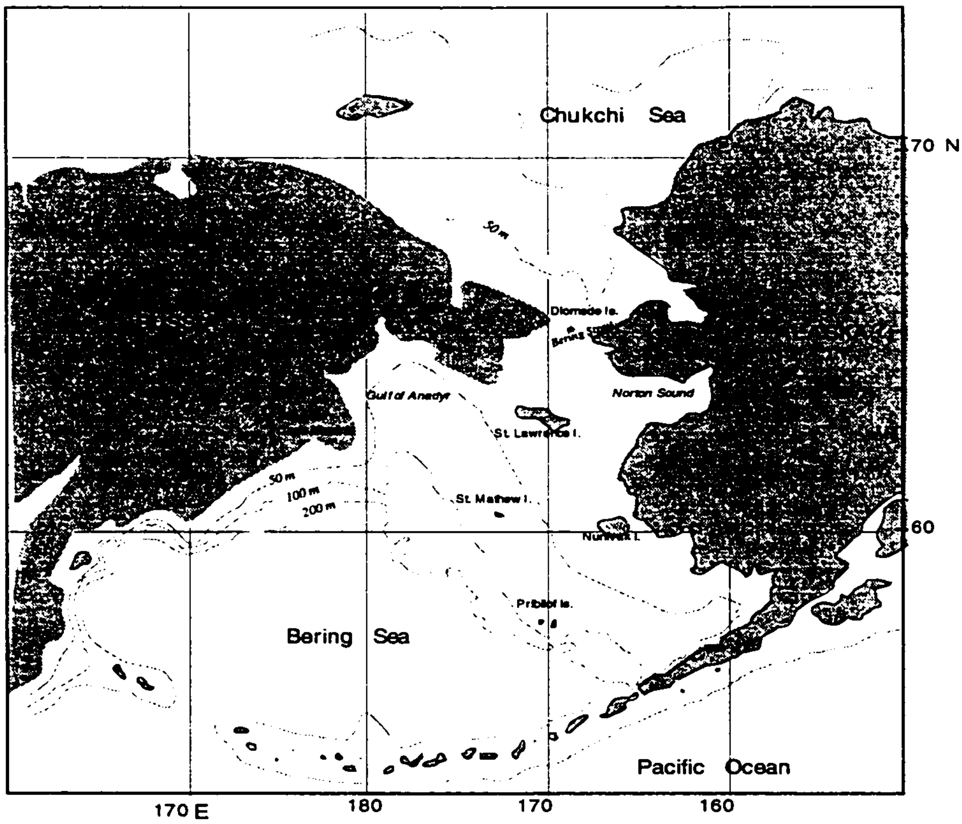


Fig. 1.1 - The study site with major geographic areas. The Bering Sea consists of two, approximately equal parts, with a shelf north of the 200 m isobath and a deep basin to the south.

Flow and Water Masses

Water enters the Bering Sea through various Aleutian passes (Stabeno and Reed 1994). Because the Pacific Ocean is approximately 0.5 m higher than the Arctic Ocean (Stigebrandt 1984), flow is toward the Arctic (Coachman and Shigaev 1992) (Fig. 1.2). Over the shelf, the direction of flow for Bering Shelf water (BSW) is northward along the western side and for Alaska Coastal water (ACW) flow is northward along the eastern side. The direction and strength of the wind, especially in summer, influence the rate of northerly flow. Wind from the north occasionally reverses the flow, driving it southward (Coachman and Shigaev 1992).

The Bering shelf consists of three hydrographic domains (Kinder and Schumacher 1982) (Fig. 1.2). The inner domain extends from shore to the inner front formed at the 50 m isobath. The middle domain extends from the 50 to 100 m isobaths and is bounded by the inner and middle shelf fronts. The outer domain extends seaward of the 100 m isobath to the shelf break.

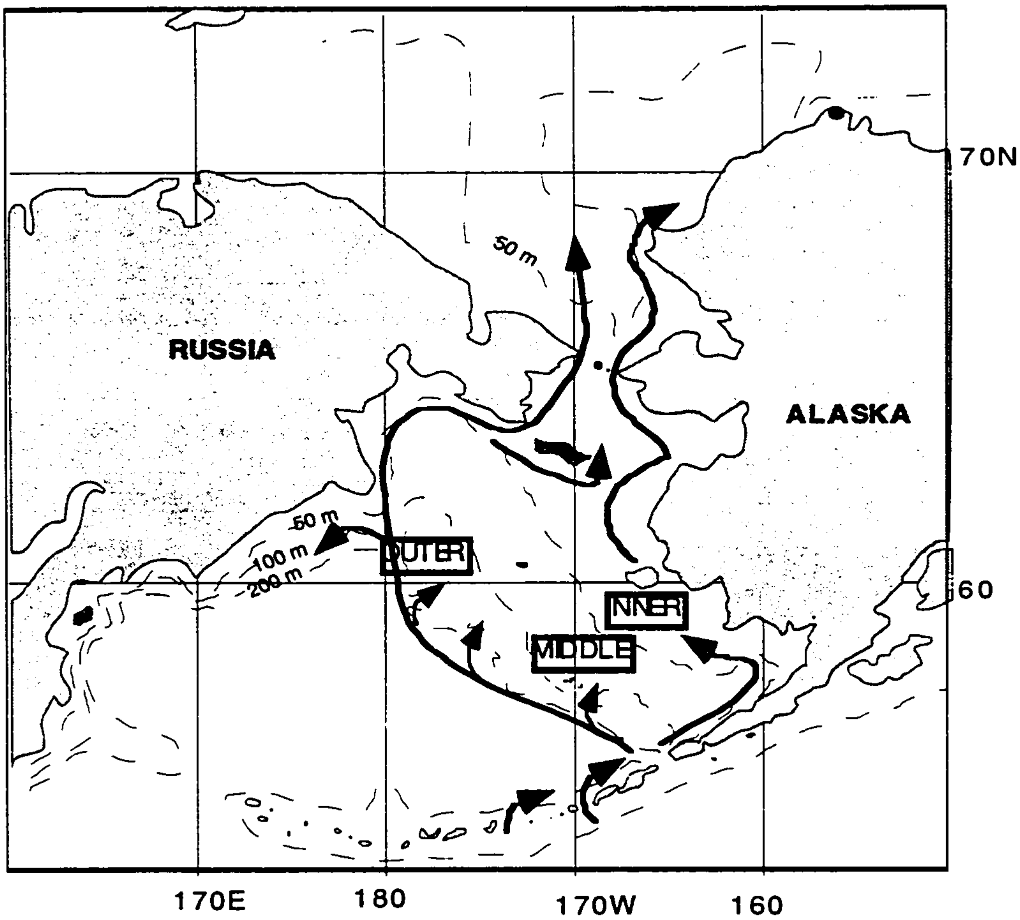


Fig. 1.2 - Bathymetry and water flow onto and over the Bering shelf. Dashes mark the 50, 100, and 200 m depth contours which roughly correspond to the inner, middle and outer shelf domains, respectively. The principal flow over the shelf is northward into the Chukchi Sea.

In summer, the outer domain is stratified in three layers. The surface layer, extending 30-50 m deep, is modified by surface heating and precipitation, which produce warm, low salinity water (Kinder and Schumacher 1982). The middle layer, Bering Shelf Water (BSW), is a finely structured layer, where lateral transport of shelf and basin water results in the interleaving of water masses with different temperatures and salinities but similar densities (Coachman and Charnell 1979). The bottom layer is Bering Slope Water (Coachman 1986). In winter, the water column of the outer domain is two-layered. The bottom layer is Bering Slope Water. Above the Bering Slope Water lies BSW formed by the mixing of Bering Slope Water and surface water (Schumacher et al. 1979). BSW flows northeastward along isobaths, with some on-shelf flow (Fig. 1.2). At Cape Navarin, a portion of BSW flows northward.

The middle domain is a layered system in summer, consisting of a warmer, more saline surface layer and a cold bottom layer below 30-50 m (Fig. 1.2). Characteristics change with varying ice conditions of the previous winter. The bottom layer is characterized by temperatures of 2.0^{o}C and salinities of <32.4 psu in the east (Maeda 1977), and <-1.0^{o}C and >33.2 psu in the west (Hufford and Husby 1972), where it is termed Anadyr Water (AW). This cold pool exists from the Gulf of Anadyr at 179^{o}W to at least 171^{o}W and may extend as far east as 158^{o}N. Flow is generally northward with BSW along the western boundary and ACW to the east (Fig. 1.2). The melting of ice in spring is important in forming a cold, low salinity surface layer, stratifying the middle shelf domain (Schumacher et al. 1979) and providing conditions suitable for primary production (Alexander and Niebauer 1981). Bottom salinities may be due to the brine produced during the freezing process over the inner shelf and in polynyas. In winter, the middle domain is vertically well mixed unless the melting at the marginal ice zone causes stratification (Schumacher et al. 1979).

The inner domain of the southeastern Bering Sea shelf is a homogeneous, tidally mixed area (salinity >31.5 psu to <32 psu), influenced by river runoff and ice formation (Kinder and Schumacher 1982). ACW flows northward along the coast of Alaska (Fig. 1.2), maintaining a well-mixed water column on the Bering shelf. A layered water column occurs only in Norton Sound where a warmer, fresher surface layer results from the inflow of the Yukon River (Muench et al. 1982). A strong meridonial front persists around 169^{o}N in the Chukchi Sea where ACW and BSW/AW meet. The warmer, less saline ACW remains on the surface with either BSW (Walsh et al. 1990) or Resident Chukchi Water (RCW) (Weingartner in press) forming the bottom layer. In some years ACW persists throughout the water column in the northeastern Chukchi Sea, to 70^{o} N (Wyllie Echeverria et al. in press). In addition, Siberian Coastal Water (SCW), flowing southeastward, joins the bottom water of the BSW or the RCW on the central and northeastern Chukchi shelf (Garrison and Becker 1975). During flow reversals, SCW may extend south of Bering Strait onto the Bering shelf. In winter, mechanical stirring, freezing and melting results in a homogeneous water column (Garrison and Becker 1975, Kinder and Schumacher 1982, Muench et al. 1982).

Aleutian Low Pressure System (ALPS)

The direction and force of air flowing over the Bering Sea has major impact on the marginal sea ice zone, literally pushing the ice along the direction of the wind (Pease 1980, Overland and Pease 1982). During winter months (September through May) the Aleutian Low Pressure System (ALPS) can have three modes. A weak pressure system (>1000 mb) transports cold air of continental and Arctic origin over the shelf from the north and east (Fig. 1.3 a,b,c,f). An intense pressure system (<1000 mb), centered over the Aleutian Islands or in the western Bering Sea, results in an influx of cold air acting to maintain ice cover (Fig. 1.3 g, h, i). A third condition occurs when warmer air circulates northward from the North Pacific onto the southeastern Bering Sea shelf, flowing counter-clockwise around an intense low pressure system (Fig. 1.3 d, e) (Emery and Hamilton 1985).

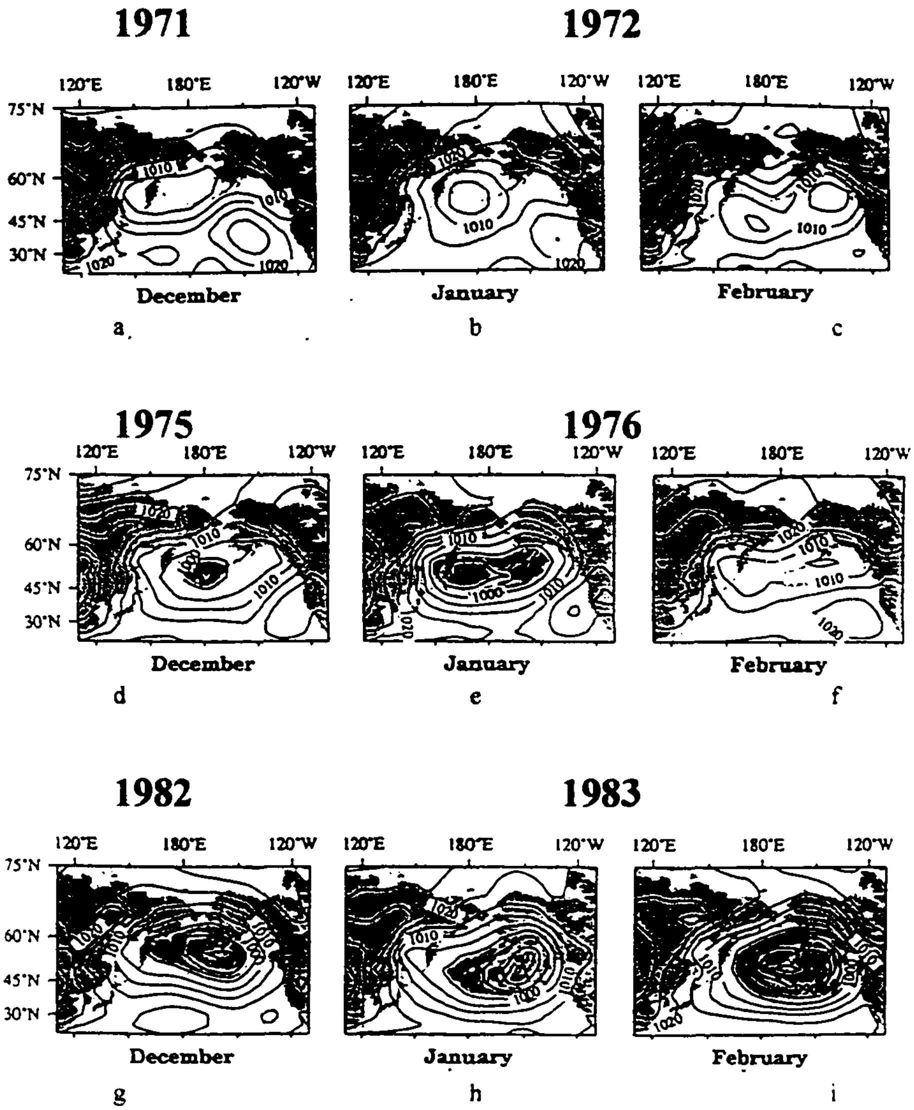


Fig. 1.3 - Representative locations of the Aleutian Low Pressure System during winter months. Shaded areas indicate intense low pressure cells of <1000 mb. Winds from the north and east push ice southward, winds from the south push ice northward.

Sea Ice Processes

Sea ice is formed throughout winter and is pushed southward by winds to its thermodynamic limit where melting occurs. Sea ice begins forming in September. Ice crystals form on the sea surface when shelf water has cooled to a depth of several meters, and snow crystals provide nuclei for growth (Weeks and Ackley 1986). Crystals, or frazil ice, are mixed by surface turbulence to depths of several meters and then aggregate on the surface as a thin layer of "grease" ice or patches of "pancake" shaped ice. Sheets of ice then form, thickening into floes and rafting as the ice is pushed southward by wind. The thickness of seasonal sea ice varies from thin grease ice, during ice production, to 2 meters thick in open water, and solid fast ice anchored to shore. The salinity of sea ice is a function of the amount of salt trapped during the freezing process and the rate of brine drainage throughout winter. Salinity in the range of 14 psu during the freezing period is reduced to about 3 psu as the ice thickens and brine is extruded throughout the season (Weeks and Ackley 1986).

The growth of SSI in the Bering Sea has been described as a conveyor belt (Pease 1980). Ice usually forms in water shallower than 30 m and in polynyas, areas of open water in ice covered seas, bounded by land and ice (Fig. 1.4). Polynyas in the Chukchi and

Bering seas are maintained by wind, pushing ice away from land, and occur to the leeward of islands (e.g. St. Lawrence, Nunivak, St. Matthew) and land masses (e.g. in Kotzebue Sound; Norton Sound; Gulf of Anadyr; Bristol Bay) (Niebauer and Schell 1993) (Fig. 1.4). A major ice production area occurs off Cape Dubrovsky in Anadyr Strait where bottom water is upwelled to the surface throughout the year (Pease 1991). In winter this upwelling (Nihoul et al. 1993) of relatively warm water (0^{o} to $+1^{o}C$) freezes upon contact at the surface, analogous to a sensible heat polynya. Wind and currents move newly formed ice away from this area which maintains this as a site of nearly continuous ice formation. The cooling of surface waters and the exclusion of salt during freezing results in a well-mixed water column during periods of ice production. As the season advances, ice thickens and is advected southward by prevailing winds out of the northeast. Ice can advance 100's of km beyond the growth region, reaching as far south as the shelf break (Pease 1980).

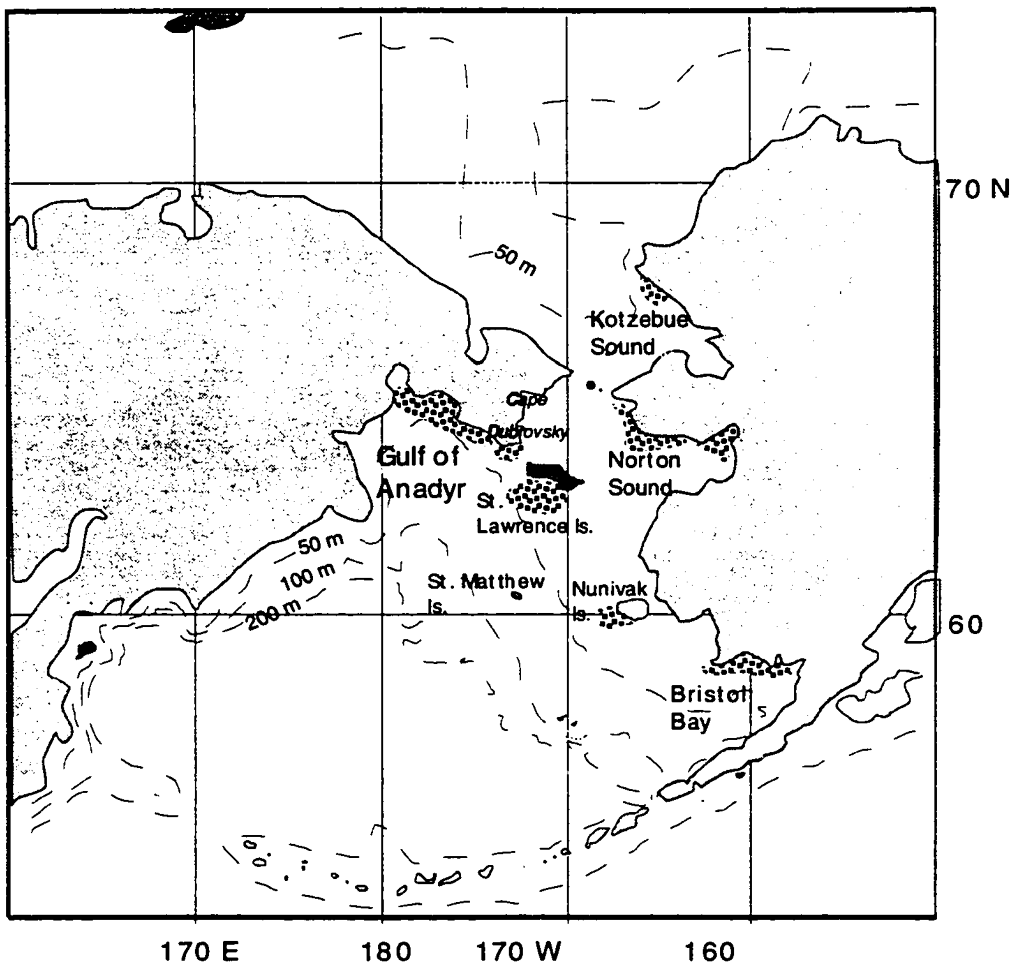


Fig. 1.4 - Map of the general sites of polynyas in the Bering and Chukchi Seas (shaded areas). Situated in the lee of islands and land masses, polynas are areas of new sea ice formation throughout winter.

SSI cover reduces the amount of light penetration in the water column and decreases the effect of wind on water circulation. Additionally, ice formation produces brine, resulting in mixing of the water column. In contrast, melting forms a fresh water layer at the surface and consequently the water column becomes stratified. In the Bering Sea, ice extent varies annually (McNutt 1981, Niebauer 1988), correlates with wind intensity and direction (Niebauer 1983; Overland and Pease 1982, Mysak and Manak 1989) and correlates to a lesser extent with sea surface and air temperatures (Skjoldal and Rey 1989). SSI affects shelf hydrography through melting, freezing and acting as an insulating cover, changing vertical stratification, and directly influencing shelf wide heat and salt budgets.

The southern extent of the ice edge, the marginal ice zone (MIZ), is usually no farther than the shelf break, where it contacts warmer oceanic water. Three ice zones exist in the MIZ and are affected by oceanic swell. The interior zone extends about 100 km and consists of floes 0.2-0.3 m thick; the transition zone extends about 5 km and consists of rectangular floes 0.3-0.6 m thick; the outermost edge zone extends 5-10 km and consists of small broken floes that are tilted and can have keel depths of 2-4 m (Martin et al. 1982). At the edge zone melting ice forms a cold, low salinity lens of water that extends 20-30 meters below the surface. Above the pycnocline, typical temperatures are less than -0.5°C and salinities less than 31.9 psu. Salinity and temperature both increase seaward of the ice edge and with depth (Pease 1980, Martin et al. 1982, Alexander and Niebauer 1981). Flow at the MIZ near the shelf break is northwestward, paralleling the ice edge. The upper layer flow provides heat adequate to melt the sea ice (Muench and Schumacher 1985).

Direction and strength of currents, water column stability, and the degree of ice cover on the Bering shelf vary with large scale weather patterns in the Pacific (Niebauer and Day 1989). The direction and strength of the winds in this area are a function of the position and intensity of the ALPS, particularly in winter. Seasonal sea ice is investigated here because it can be studied by remote sensing techniques, and has a direct impact on the salinity and temperature of associated water masses. Impacts of atmospheric forcing can, therefore, be studied more directly and in more detail. The pattern of SSI growth and retreat was studied in this work using 20 years of satellite observations of the concentration and position of sea ice (1972-1991).

The Fish

Walleye pollock occupy a semi-pelagic (or semi-demersal) habitat and are distributed on the shelf and slope in the North

Pacific, from Cape Blanco, Oregon to Japan (Allen and Smith 1988). In the Bering Sea, adults occupy the deep basin, ranging as far north as Saint Lawrence Island and occasionally the Chukchi Sea (Wyllie Echeverria 1995). Concentrations of adults have been sampled from temperatures of 0-5°C, (Efimkin and Radchenko 1991) but more often occur in waters warmer than 3°C (Bakkala and Alton 1986). Walleye pollock are a dominant species in the southern reaches of the Bering Sea shelf. Population surveys since 1972 provide an annual census of groundfish abundance and distribution. Walleye pollock have been the target of international fisheries, and more recently are the target of national fishing efforts. Pollock have been the focus of research aimed at understanding recruitment variability and population declines of pollock predators (birds and marine mammals).

Age-1 pollock (100-200 mm Fork Length [Bakkala and Alton 1986]) primarily occupy shelf regions across the Bering Sea (Radchenko and Sobolevskij 1992), ranging north into Norton Sound (Wolotira et al. 1977) and the southeastern Chukchi Sea (Wyllie Echeverria 1995). Concentrations of age-1 fish have been reported in the inner and middle domains, northwest of the Pribilof Islands (Bakkala and Alton 1986; Fadeyev 1989), and in the middle domain on the southeastern shelf, occurring primarily in bottom water warmer than 2°C in the relatively warm years of 1979 and 1981 (Bakkala and Alton 1986).

Walleye pollock have been referred to as a principal species in the Bering Sea ecosystem (Springer 1992), serving as a major prey as juveniles, and a major predator as adults. Walleye pollock are both predator and prey for a broad spectrum of animals, linking benthic and pelagic habitats. Food for pollock is not limited by habitat and can expand into either the benthic or pelagic realm as physical conditions allow.

Arctic cod are a cold-tolerant species that reproduce, feed and grow under ice, at the ice edge, and in ice free waters (Ponomarenko 1968, Quast 1972, Allen and Smith 1988). They produce "anti-freeze" glycoproteins that lower the freezing point of blood and allow them to live in sub-zero temperatures (Osuga and Feeney 1978). Arctic cod are circumpolar in distribution, with several stocks, including one in the Bering and Chukchi Seas (Ponomarenko 1968). They occur in a wide range of temperatures, from -1.8 to 13.5^{o}C (Andriyashev 1954; Alverson and Wilimovsky 1966; Craig et al. 1982). They are a generally small, commonly reaching 200 mm Fork Length, comparable in size to one year old pollock. Like age-1 walleye pollock, some of the population may have been missed from the pelagic habitat because they occupy both pelagic and benthic habitats. They are not adequately represented in demersal trawl surveys.

CHAPTER TWO - Characteristics of Seasonal Sea Ice on the Bering Sea Shelf

Introduction

Seasonal sea ice is examined in this study in order to understand the variability that occurs on time scales greater than one year. Interannual variability of SSI has been described by areal coverage either in square kilometers (Mysak and Manak 1989; Chapman and Walsh 1993), or by anomalies from the mean (Niebauer and Day 1989). Another descriptor was the distance between Norton Sound and the ice edge along the line of ice advance, perpendicular to the shelf break (Overland and Pease 1982). All of these techniques require extensive data records to calculate areal coverage and ice extent. The approach I have taken is to record the southernmost ice edge along a single line of longitude that spans the entire shelf. The data used are available weekly, allowing for synoptic updating and analysis. Furthermore, by examining the latitude of the ice edge over time, a number of characteristics of SSI can be defined that provide a quantitative method of evaluating a suite of annual conditions, such as extent and duration of ice cover.

I begin this chapter with methods of identifying and quantifying seasonal sea ice characteristics. Next, those characteristics are compared with those at 178°W to determine if characteristics of the eastern and western shelf are similar. The interannual variation of SSI cover is then compared with previous studies, to determine if ice extent along meridian 169°W is representative of ice cover across the shelf. The ALPS and SSI characteristics are compared to determine the predictive value of ALPS data for SSI. If the ALPS can be used to predict ice extent on the shelf, these data can be extended back decades beyond direct observation. From these results, sea ice characteristics that are indicators of winter or spring conditions affecting summer conditions on the shelf are identified.

Methods

Sea ice conditions have been evaluated weekly by the Navy/NOAA Joint Ice Center beginning in 1963 through the present (Naval Polar Oceanography Center 1986). Their evaluation has utilized satellite imagery to create a synoptic picture of polar sea ice conditions (Barry 1986). Initially only visual band sensors were available so the images were often obscured by cloud cover (1960's-1970). With the addition of the infrared scanning radiometer in January 1971 and microwave radiometry in December 1972 accurate data of ice cover were possible. Weekly sea ice maps for the western Arctic were obtained from the

Navy/NOAA Joint Ice Center, Suitland, MD and provide information on the concentration (percent cover) of ice of varying thicknesses, stage of development, observed boundary of the ice edge, and distribution of fast ice (ice anchored to shore and the bottom) (Fig. 2.1). These data are also available in digitized format with 0.25^o latitude resolution (International Sea Ice GRID [SIGRID]) (Thompson 1981).

Digitized SIGRID data provide weekly ice concentrations (% cover) by latitude and longitude for the period 1972 to 1990. Before 1972, observations of SSI were opportunistic and data of ice concentration and position were intermittent. As data for 1991 had not yet been released in digitized format, those values were obtained from the weekly sea ice charts. The criterion used to determine the location of the ice edge was the latitude along 169^{o}W with at least 30% ice cover.

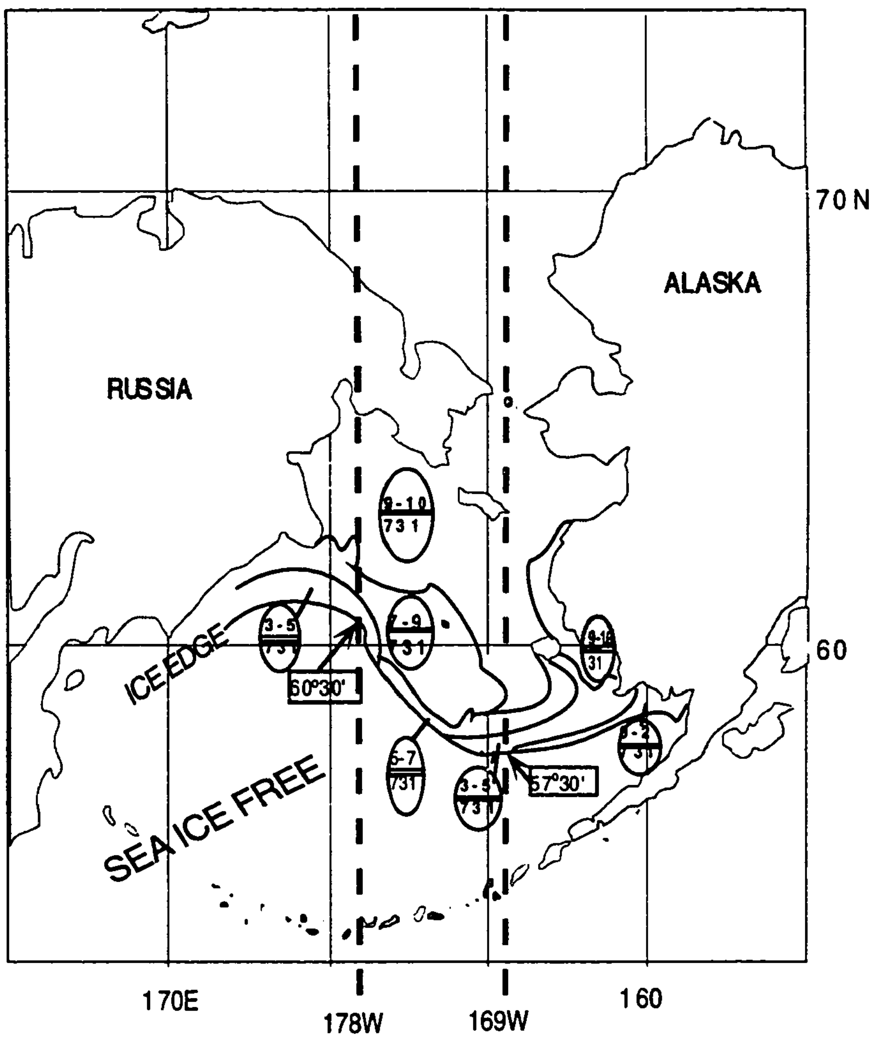


Fig. 2.1 - Representative ice chart for the Western Arctic (4 May 1982). Product of the Naval Polar Oceanography Center, Suitland, MD. Circled are various degrees of ice cover (5-7=50-70% in upper half) and the type of ice (1 [new] 3 [young ice] 7 [first year] in lower half). Longitudes 169°W, 178°W, and the latitude of southern ice extent for that date are marked.

Longitudes are presented in a decimal format in the SIGRID digitized data set and this format is also used in the present work. The availability of SSI data from the Sea Ice Charts for the Western Arctic allows for timely evaluation of sea ice characteristics without waiting for the data to be available in digitized form. All values used to characterize SSI for this study, obtained from the SIGRID data, were verified with weekly Sea Ice Charts for the Western Arctic. Updates were obtained from the weekly ice charts for 1991. Quantification of SSI characteristics is performed in the methods section, a necessary step before analysis and verification with other indicators of sea ice.

Rapid advance and retreat of the southern ice edge occurs at Bering Strait (Fig. 2.2). This is due to the narrow passage through the strait resulting in a blockage of ice moving both southward and northward. There is also an interannual variability in the northern and southern extent of the ice edge. During every year of the period studied, the ice extended over the entire inner domain (depths $\leq$ 50 m) reaching at least to the northern boundary of the middle domain (depths >50 and $\leq$100 m) (Kinder and Schumacher 1982). Variability in the time that ice remained at its southern and northern limits is evident in the shape of the curve, which is V-shaped when advance and retreat were rapid (e.g., 1979) and U-shaped when ice remained at the extreme extent (e.g., 1976 and 1982).

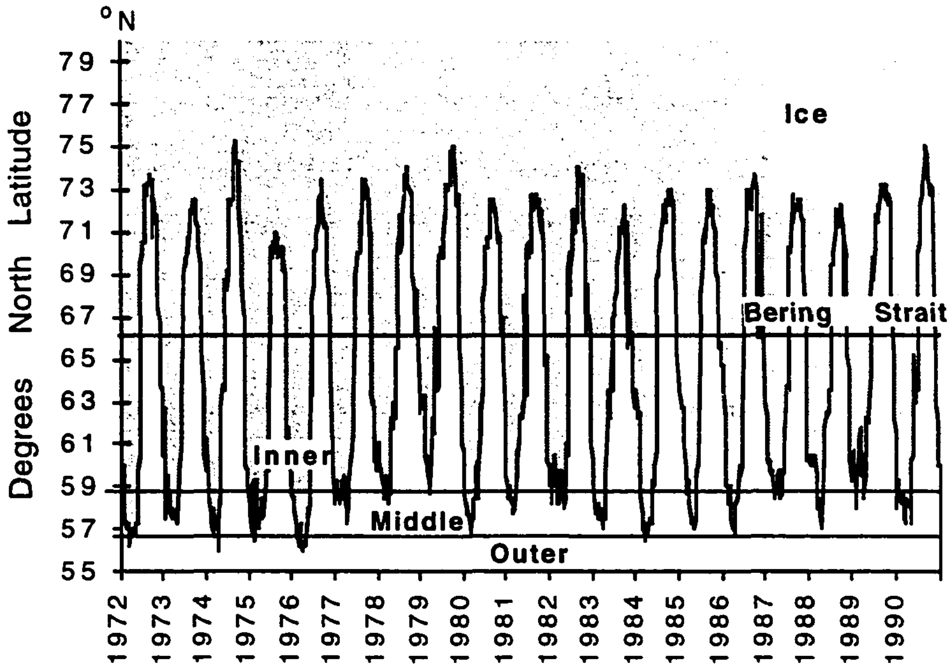


Fig. 2.2 - Southern latitude of the seasonal sea ice edge (at 30% concentration) as it advances and retreats along meridian 169°W. Data are weekly from January 1972-December 1991 and were extracted from the SIGRID data base. Latitude of boundaries for inner, middle and outer domains and Bering Strait are indicated.

The pattern of ice advance and retreat for each year between 1972-1991 provides a number of characteristics that can be quantified. These SSI characteristics consist of the latitudinal position of the ice, timing of ice movement and duration at a location. These characteristics are derived from the SIGRID data presented in Fig. 2.2 and are detailed in Fig. 2.3 with an example from 1976.

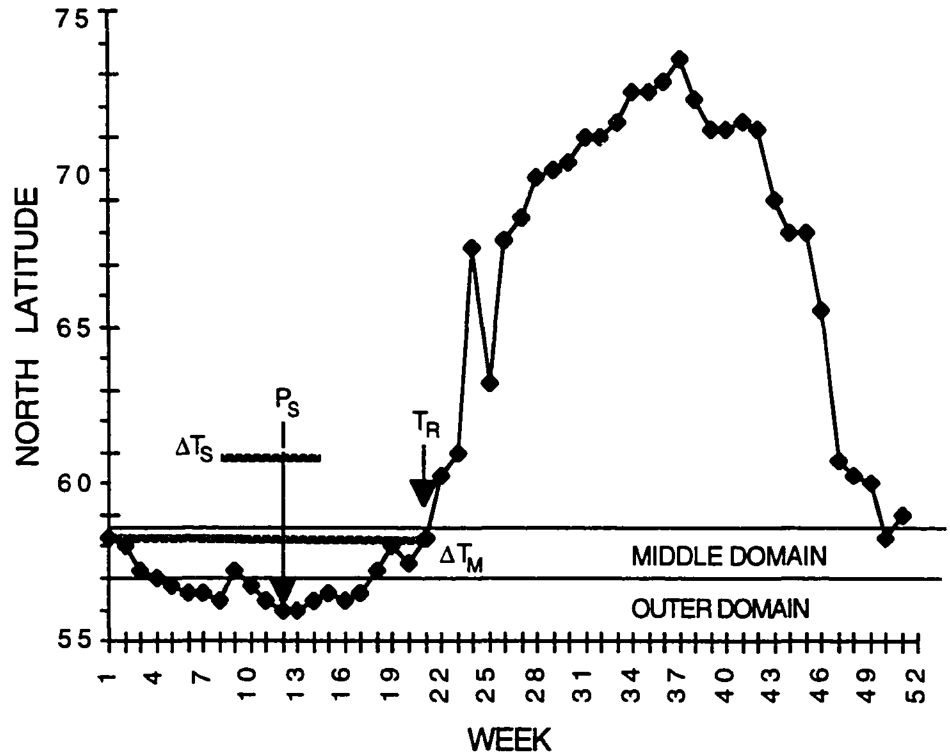


Fig. 2.3 - Weekly ice edge positions for 1976 observed along meridian 169°W. Characteristics of position and time used to describe interannual variability in seasonal sea ice are: 1) duration ice extended over the middle shelf domain (ΔT_M), 2) the position of ice edge at its southern extent (P_S), 3) duration at its southernmost extent (ΔT_S), and 4) time of the initiation of ice retreat (T_R).

The characteristics are defined as follows:

1. ΔT_M = Duration of ice cover over the middle domain (number of weeks when ice extends $\geq 58^o30'$N).

2. P_S = The furthest south advance of the ice edge (time and latitude of southernmost ice extent).

3 ΔT_S = Duration of ice at the southern extent. The ice edge advances fairly rapidly until it reaches a relatively stable southern position and fluctuates approximately $\pm$ 0.5^o between weekly measurements. Duration, then, is the number of weeks the absolute difference between the southern most ice extent and the neighboring week is $\leq 0.5^o$.

4. T_R = Timing of ice retreat (the week ice retreat begins in spring, when the change in ice extent is $>0.5^o$ of latitude).

From these definitions the SSI characteristics for 1976 are: ice reached the middle domain in the first week of January, remaining there until week 21 (ΔT_M), ice reached the southern extent of 56^oN (P_S) in week 12, and remained at its southern extreme for 7 weeks. (ΔT_S). Ice retreat began in week 21 (T_R) (Fig. 2.3).

Comparison of the behavior of sea ice in the eastern and western shelf was made with sea ice characteristics along meridian 178^oW. SSI characteristics in the western shelf were extracted from the SIGRID data base with the same parameters used for the eastern shelf (169^oW). In the Bering Sea, meridian 178°W runs northward, through the Gulf of Anadyr, terminating at the Chukotka Peninsula (65°30'N) (Fig. 2.1).

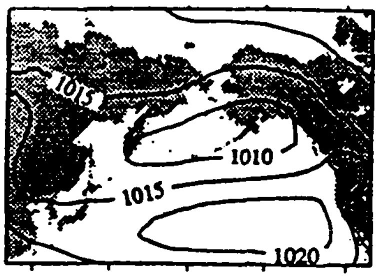
Evaluations of areal extent of seasonal sea ice on the Bering shelf were compared with extent along a single degree of longitude (169^oW). Chapman and Walsh (1993) calculated the areal coverage of seasonal ice for the Arctic between longitudes 160^oW - 180^oW using the SIGRID data base. Areal coverage is expressed in kilometers squared and calculated weekly. These data (provided by W. H. Chapman, University of Illinois) for weekly coverage were compared to the weekly southernmost extent of ice (P_S) along 169^oW. Niebauer and Day (1989) evaluate SIGRID data by the anomalies from a 40 year average. Monthly anomalies are calculated for a limited area of the Bering Sea that encompasses the central and southeastern areas. I compared monthly anomalies for November, December, January, February, March, April and May between 1972-1991 (provided by H. J. Niebauer, University of Alaska Fairbanks) with monthly values of P_S.

Overland and Pease (1982) developed a sea ice index along the direction of growth of sea ice from Norton Sound to the shelf break. The index consists of the distance from shore (km) of the ice edge in February and March. In some years the maximum ice edge is in February (lighter ice years) and in others it is in March (heavier ice years). The maximum extent (km) for each year (whether it occurred in February or March) was compared to the maximum annual extent of ice along 169°W. Values for 1972-1980 were obtained from Overland and Pease (1982) and updates for 1981-1991 by Tom Wilderbuer (NOAA/NMFS/AFSC/REFM, Seattle WA) were provided by C. Pease (NOAA/PMEL/CARD, Seattle, WA).

The Aleutian Low Pressure Index (ALPI) is a measure of the intensity of the ALPS. It is based on the area (in nautical miles) of the North Pacific with sea level pressure <1000 mb and was calculated from the monthly averaged SLP charts for winter (December-February), spring (March-May), and combined (December-May) (McFarlane and Beamish 1992) (data provided by R. J. Beamish, Department of Fisheries and Oceans, Pacific Biological

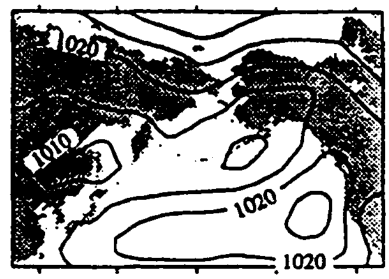
Station, Nanaimo, B.C.). The ALPI provides a region-wide index of direction and wind speed over the Bering Sea as generated by the shifting and intensity of the low pressure system. The seasonal and regional affects of the ALPS were compared to the behavior of seasonal sea ice by using the seasonal values of the ALPI and the annual values of SSI characteristics.

Detailed evaluation of the ALPS was used to determine when the Aleutian low pressure system acted on the various SSI characteristics and which ALPS characteristics affected SSI. The characteristics for the ALPS were derived from average monthly sea level pressure maps for 1972-1991 (provided by Steven Hare, University of Washington, Seattle, WA, and Phil Turet, NOAA/PMEL/CARD, Seattle, WA). For each month, characteristics of ALPS, defined by 1) the lowest pressure cell (mb), 2) the position of the low pressure cell over the Aleutian Archipelago (central, to the east or west of central), and 3) the resulting direction of wind to the southeastern Bering shelf (Maritime or Continental) were determined. Representative maps in Fig. 2.4 show an average pressure pattern in April (a), split low pressure cells causing Arctic air flow over the shelf (b), a typical pattern of a low pressure cell in its eastern position causing continental air to flow over the shelf (c) and the low pressure cell in its western position causing maritime air over the shelf (d).



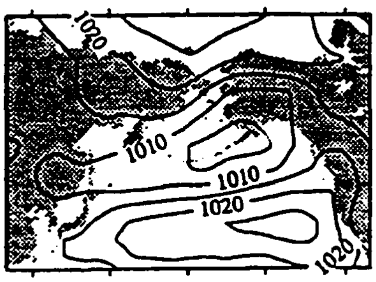
April

(a) Average



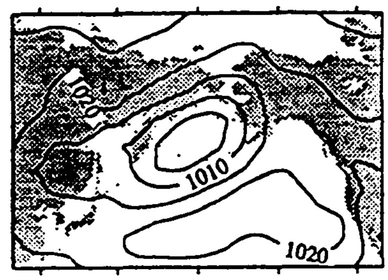
April

(b) 1973



April

(c) 1974



April

(d) 1979

Fig. 2.4 - Representative Aleutian Low Pressure Patterns for April. (a) Average pattern computed from 1953-1990, (b) Monthly pattern for 1973, when a split Aleutian low pressure system resulted in cold continental air over the shelf, (c) ALPS in an eastern position resulted in cold continental air over the shelf, (d) ALPS, centrally located, resulted in warmer air from the North Pacific over the shelf.

Correlation coefficients were calculated for comparisons between two variables and used to determine if annual values for SSI characteristics in the eastern and western shelf (along meridians 169° and 178°W) and the areal extent of sea ice (Overland and Pease 1982, Chapman and Walsh 1993) varied in a similar manner. Correlation coefficients of $r \geq 0.56$ are significant at the 99% level with n=20 (Hoel 1971).

Principal component analysis (PCA) was used to investigate relationships among multiple variables (Harris 1975). The guidelines of Jasby and Powell (1990) and Cloern and Jassby (1995), who apply PCA to identify patterns of interannual variability across a spatial and temporal grid, were followed. PCA is a multi-variate technique for exploratory analysis, used to simplify the description of a set of interrelated variables. The technique yields a set of transformed variables, the principal components, that are linear combinations of the original variables. Each principal component is orthogonal and therefore represents a unique mode of variability. The first principal component has the largest variance and is a linear combination of the original variables, the second PC is orthogonal to the first PC and has the second highest variance. The variance is the corresponding eigenvalue of the covariance matrix. The percentage of each PC to the total variance was used to determine how many PCs represent the significant proportion of the total variance. Percentages accounting for a significant portion of the variability depend upon the number of components and the size of the data set (Overland and Preisendorfer 1982). If the first principal component accounts for 30% of the variation it is significant at the level of 9 components and 20 data sets. The second component is significant at 22%, and the third at the 17% level. The table presented in Overland and Preisendorfer (1982) only presents values for data sets with a minimum of 9 components and 20 sets. For analysis with fewer components, higher percentages would be required. I rely on the combination of higher percentages and the application of Rule N (Preisendorfer and Barnett 1977) which combines high percentages and eigenvalues greater than 1.0 to identify the number of principal components that significantly represent the variability being tested. The component coefficient of each original variable measures the covariance between that variable and each PC. These component coefficients represent the underlying pattern of anomalies.

Variation over time was analyzed by summing the products of the coefficient of each variable (of each PC) by the value of each variable for each observation. In PCA this value is the amplitude or score, and is a measure of the relative strength of a particular PC for each year. It represents year-to-year fluctuation in the strength of each mode of variability. All data were normalized to minimize the affect of unequal means or variances. The mean was subtracted from each value and divided by the variance. The normalized values were used in each PCA in this work.

The data matrix for PCA consisted of annual measures of SSI characteristics along 169°W, anomalous ice cover (Niebauer and Day 1989), the Aleutian low pressure index, ALPI (McFarlane and Beamish 1993), and characteristics of the Aleutian low pressure system. The principal component analysis program in the statistical package for microcomputers, SYSTAT, was used for the analysis presented in this study.

Results

The yearly pattern of growth and retreat of SSI along 169°W is unique (Table 2.1). Variations occur in the position (latitude) and duration (weeks) of the ice. The southernmost extent of the ice edge, the duration of ice cover over the middle domain (extent south of latitude 59°N) and its southernmost extent, along with the timing of ice retreat in spring,, show both an interannual variation and longer-term patterns (Figs. 2.5-2.8).

Table 2.1 - Seasonal sea ice characteristics of duration (Δ), timing (T) and position (P) along 169°W. Subscript M = middle shelf, S = south, and R = retreat. Date corresponds with T_R (week [Month-day] ice retreat began).

YEAR	ΔT_M	P_S	ΔT_S	T_R	Date
1972	22	56.25	12	21	5-21
1973	27	57.25	10	19	5-08
1974	28	56.00	10	15	4-16
1975	28	56.50	6	19	5-06
1976	21	56.00	15	21	5-25
1977	27	57.25	13	16	4-19
1978	19	58.00	9	13	3-28
1979	3	58.75	3	12	3-20
1980	21	56.75	2	12	3-18
1981	17	57.75	4	11	3-17
1982	23	58.00	7	12	3-23
1983	20	57.00	9	11	3-15
1984	21	56.50	7	14	4-03
1985	19	57.25	7	18	4-30
1986	20	56.75	2	14	4-08
1987	20	58.50	10	16	4-21
1988	4	57.00	3	14	4-19
1989	17	58.00	5	14	4-04
1990	14	57.25	14	17	4-24
1991	14	56.75	12	19	5-08
mean	20	57	9.6	15.2	
variance	42.3	0.64	51.7	9.9	

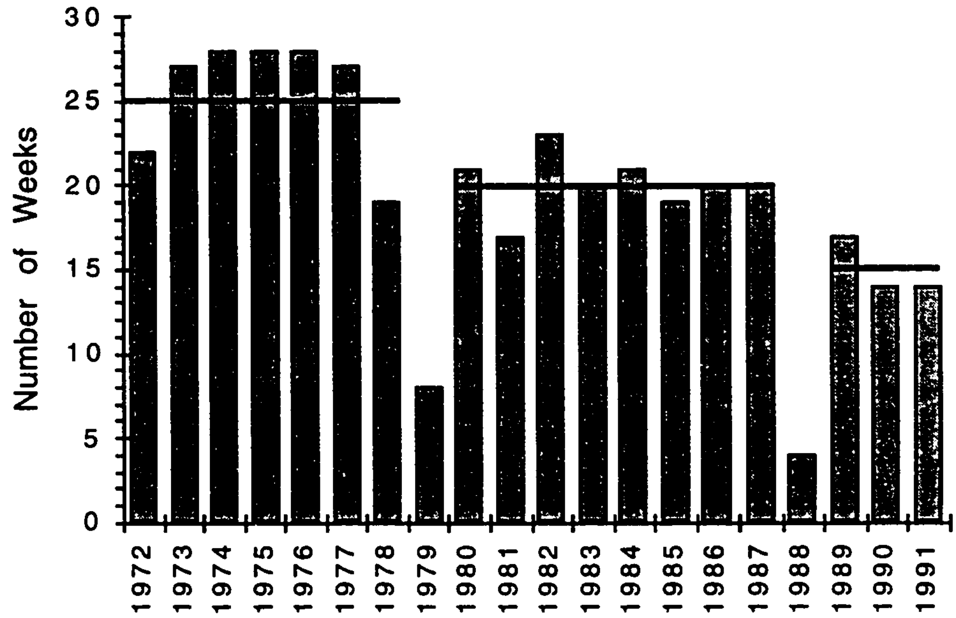


Fig. 2.5 - Number of weeks seasonal sea ice extended over the middle domain each year, represented as duration of time over the middle domain (ΔT_M). Average number of weeks for each period is indicated by a line.

The time that ice cover extended over the middle domain (ΔT_M) ranged between 3-28 weeks, with a pattern of decreasing duration over the long term (Fig. 2.5). A period averaging 26 weeks (1972-1978) was followed by a period of averaging 19 weeks (1980-1991), punctuated by years of very limited ice cover (1979, 1988).

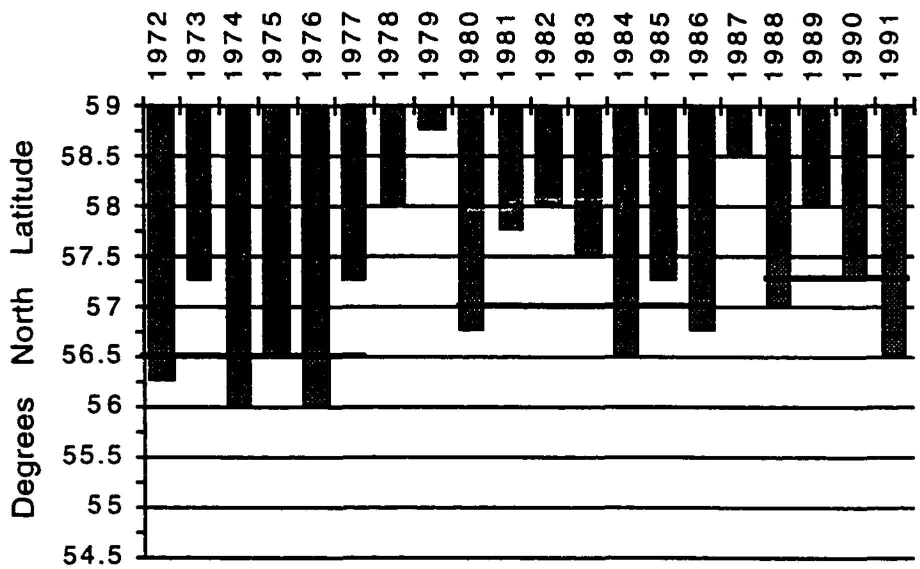


Fig. 2.6 - The southernmost latitude of seasonal sea ice extent for each year (P_S). The average number of weeks for each period is indicated by a heavy line.

The southernmost extent of the seasonal sea ice edge varied by 2.75° ranging from 56.0 - 58.75°N (Fig. 2.6). Years of extensive ice cover (averaging to 56.5°) occurred in the early 1970's (1972-1977). Reduced ice extent (averaging to 57.25°) followed, punctuated by extremely low ice extent in 1979 and 1987. Years of extensive ice cover (P_S) and duration of ice over the middle domain (ΔT_M) coincided, and 1979 marked a change in ice behavior by all indicators. Subsequently, neither pattern returned to the extremes seen between 1972-1976.

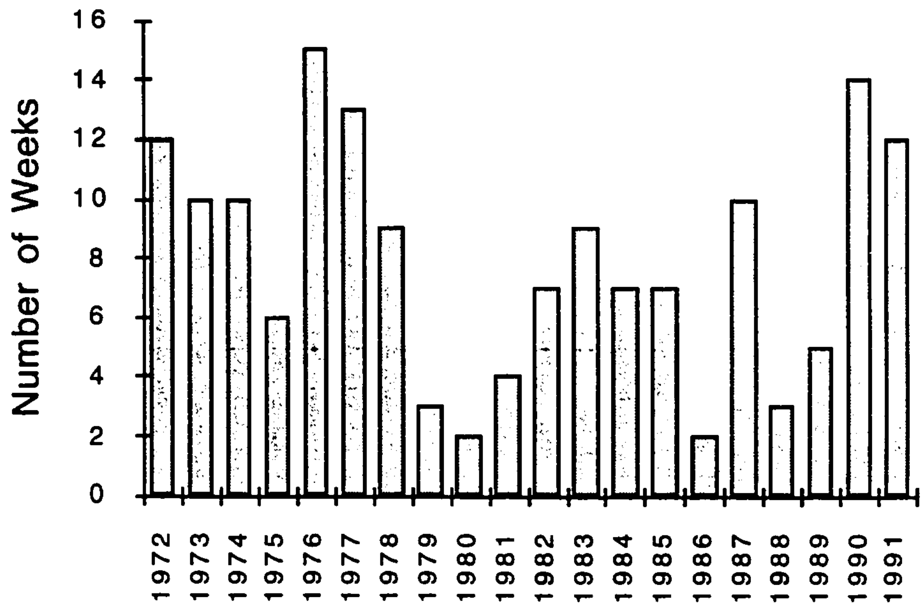


Fig. 2.7 - Number of weeks ice remained at its southern extent ±0.5° (ΔT_S).

Duration of ice at its southern extent (ΔT_S) ranged between 3-15 weeks (Fig. 2.7). The pattern of this characteristic does not fall into three different stages. Peak years, when ice remained at its southern extent for longer periods of time than in other years were 1972, 1976-77, 1983, 1987 and 1990-91.

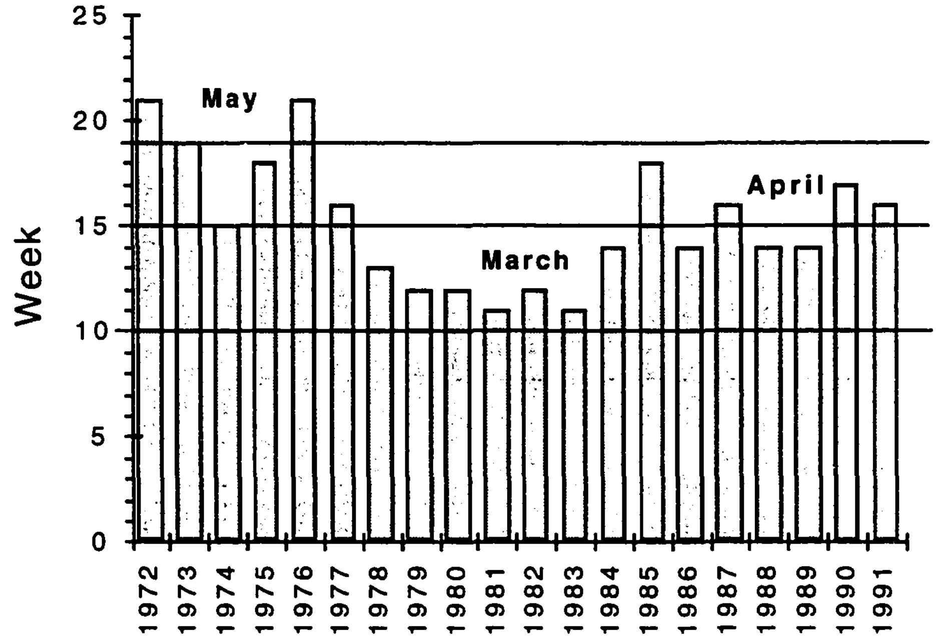


Fig. 2.8 - The week of the year when ice began retreating northward from its southernmost extent (T_R). The weeks marking the beginning of March, April and May are indicated.

Timing of retreat (T_R) varied on this section of the Bering shelf between weeks 11 and 21 (Fig. 2.8). This event occurred in three groupings, with ice retreating in late April or May between 1972-1977, in late March or April between 1985-1991 and in early to mid-March between 1978-1984. Common to P_S and ΔT_M, the behavior of SSI characteristics occurred in three stages. The early period was distinguished by extreme cold conditions followed by milder conditions after 1978.

Comparisons among SSI Characteristics

Characteristics of SSI are indicative of conditions in the Bering Sea and are inter-related (Table 2.2). The coefficients of PC1 are large for all characteristics: ΔT_M (0.667), T_R (0.837), P_S (0.715), and ΔT_S (0.769). The component coefficients show that PC1, with SSI characteristics of ΔT_M, $T_{R,}$ $P_{S.}$ and ΔT_S, behave in a similar manner and covaries over time. The same mechanism(s) may be acting upon these charact eristics in a similar way.

Table 2.2 - Component coefficients of the first principal component (PC1) of SSI characteristics on the Bering Sea shelf.

	PC1
ΔT_M	0.667
P_S	0.715
ΔT_S	0.769
T_R	0.837

The four principal components represent 56%, 20%, 16% and 8% of the variance with corresponding eigenvalues of 2.24, 0.81, 0.63 and 0.32. Due to the small number of variables, a combination of eigenvalues greater than 1 and high percentages were used to determine level of significance. PC1, with high coefficients represents the mode of variation for SSI characteristics on the Bering shelf.

Interannual behavior of PC1 is expressed as the amplitude for each year (Fig. 2.9). The values for amplitude were normalized by the mean so the scale reflects the relationship of each year to the mean for all years and shows how different or similar annual values were from each other. Extensive ice conditions are indicated by low amplitudes, when all SSI characteristics had high values (1973-1977; 1982-1983). High amplitudes reflect large variations between characteristics as occurred in 1979 and 1988 when ΔT_M and ΔT_S were both very low (Table 2.1). Average to reduced conditions are indicated near the mean, when the variation between the characteristics was low.

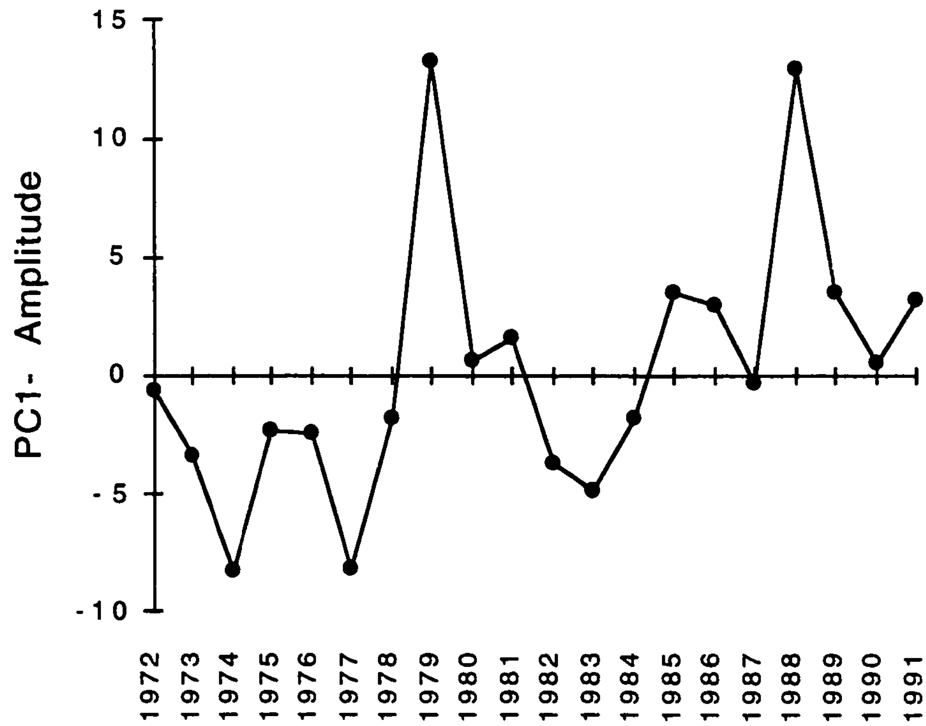


Fig. 2.9 - Annual amplitude of PC1 of seasonal sea ice characteristics on the Bering Sea shelf.

Comparison of SSI Characteristics with the Western Shelf

Longitude 178°W on the western shelf was used to compare the behavior of ice between the eastern and western regions of the Bering Sea shelf. The ice-covered portion of 178°W extends from the Arctic Ocean to the Chukotka Peninsula, Russia, commencing again in the Gulf of Anadyr and continuing to the shelf break (Fig

2.1). The narrow inner shelf along 178°W and the different hydrographic conditions (Fig. 1.3) could affect sea ice differently than conditions on the eastern shelf, nevertheless, the pattern of ice growth and retreat appears similar (Fig. 2.10).

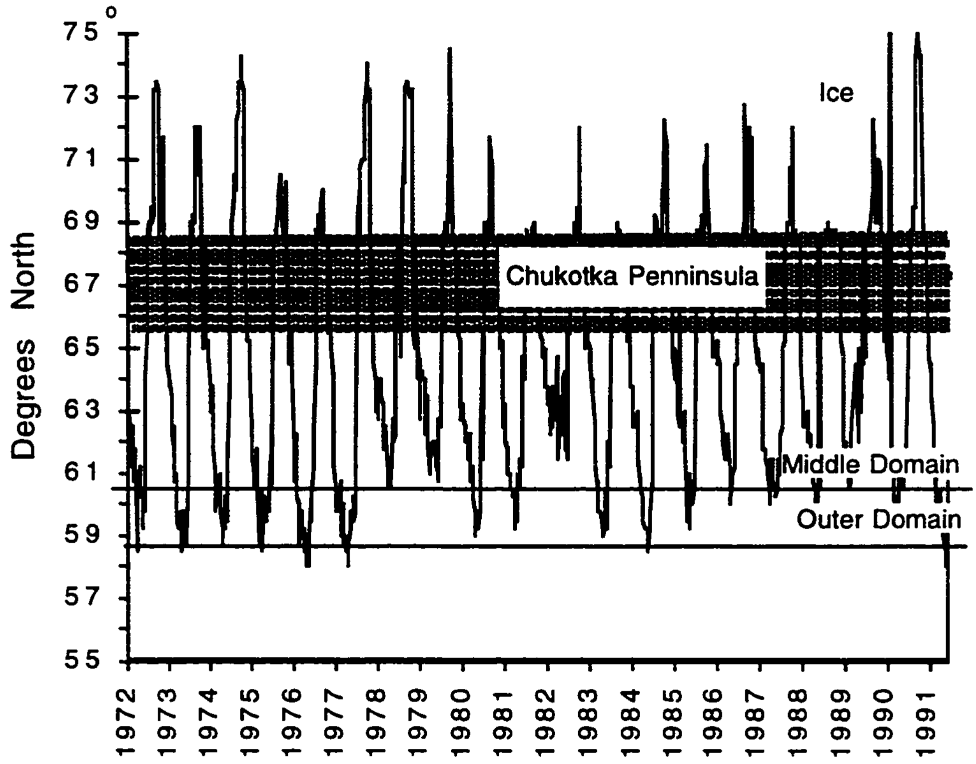


Fig. 2.10 - Southern latitude of the seasonal sea ice edge (at 30% concentration) as it advances and retreats along meridian 178°W. Data are weekly (January 1972 to December 1991) and were extracted from the SIGRID data base. The positions of the middle and outer domains are noted. This meridian crosses the Chukotka Peninsula between latitudes 65°30' and 68°30'N.

SSI characteristics of T_R and P_S were compared for the eastern and western shelf (Figs. 2.11 and 2.12). Although the shelf does not extend as far south in the west as in the east, the patterns of ice extent, P_S, were significantly correlated (r=0.75;p=0.01), as was the timing of ice retreat, T_R (r=0.50;p=0.05). The bathymetry of the middle domain (between 50 and 100 m) of the eastern and western shelf are very different so a comparison of the related characteristic (ΔT_M) was not made. Additionally, the western shelf is more oceanic and warmer, with stronger currents at the shelf break, so a comparison with ΔT_S was not made. At a given time there is generally less ice on the western shelf that on the eastern shelf.

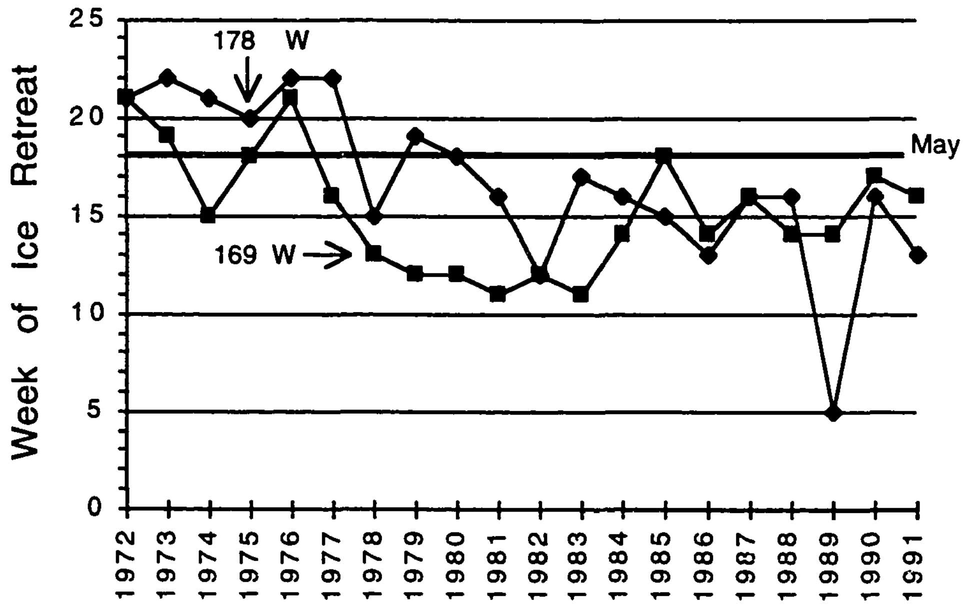


Fig. 2.11 - Comparison of the time of ice retreat (T_R) along meridians 178°W and 169°W on the Bering Sea shelf. The relationship was significant (r=0.50;p=0.05), confirming the later ice retreat in the early 1970's (May = week 18) observed along 169°W.

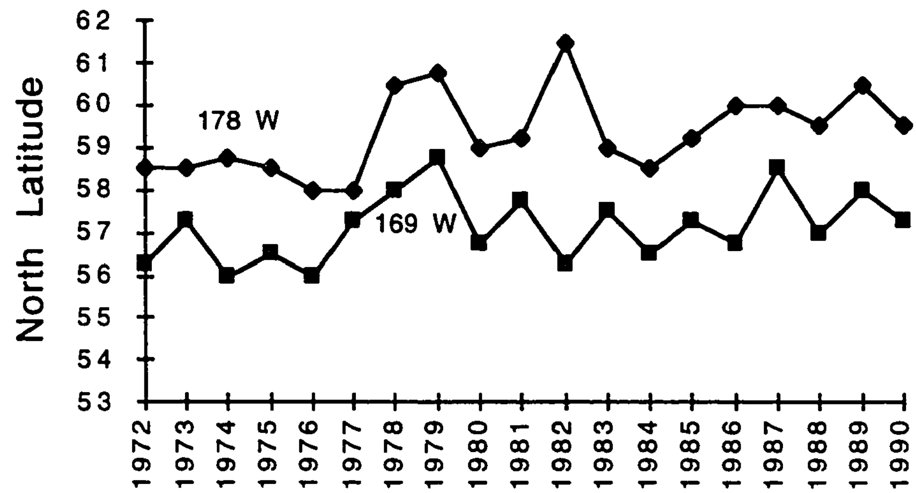


Fig. 2.12 - The southernmost extent of the ice edge (P_S) along meridians 178°W (narrower shelf) and 169°W (wider shelf) in the Bering Sea.

Comparison with Areal and Extent Indices

The areal ice cover in the Bering shelf for 1972-1991 (Chapman and Walsh 1993) is significantly correlated with the weekly ice extent, P_S ($r=0.91$; $p<0.01$)) (Fig. 2.13). The measure of southern ice extent along 169°W (P_S) reflects the general shelf-wide conditions of ice cover across the Bering and Chukchi seas. The values in the upper left corner of the graph represent summer conditions when the ice is at its farthest north position and smallest areal coverage. Conversely, the lower right corner reflects winter conditions. Both extremes of the graph show a close correspondence between areal ice cover and extent as measured along 169°W. The greatest variability was seen when ice was blocked by Bering Strait (latitude 66°N) as it advanced and retreated at those latitudes (60-70°N). Once ice clears this constriction, rapid ice advance or retreat results in rapid changes in areal cover and extent and areal differences would be most obvious from a point measurement.

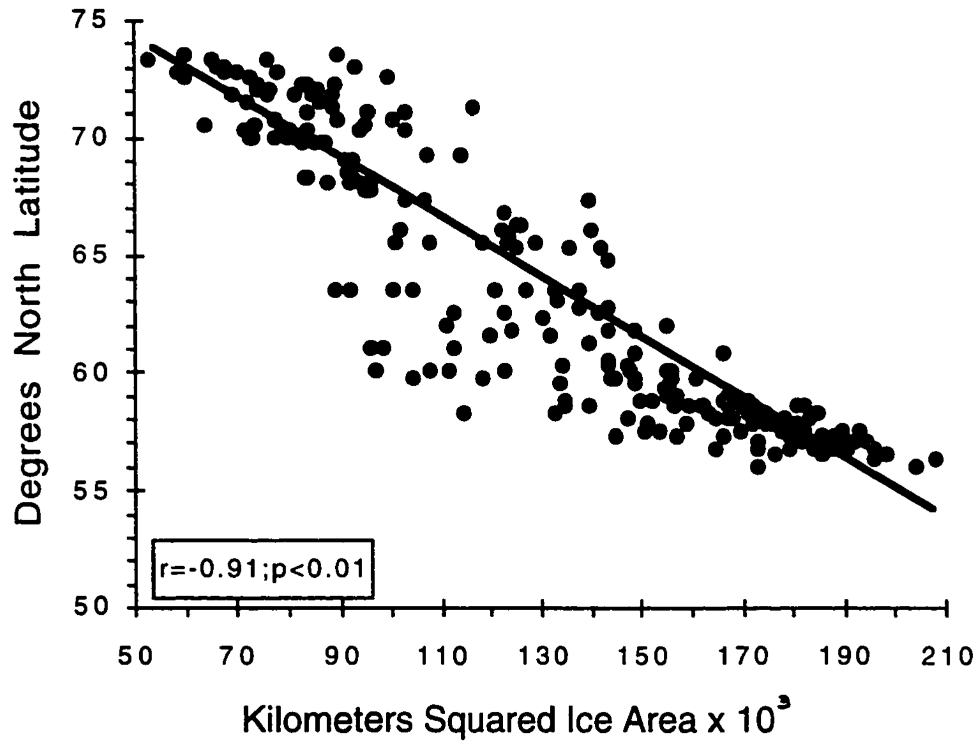


Fig. 2.13 - The relationship of the southernmost latitude of ice (P_S) with the areal coverage of ice over the entire Bering and Chukchi shelf (r=0.91;p<0.01).

SSI characteristics and the monthly anomalies of areal ice cover in the Bering Sea (Niebauer and Day 1989) were tested with PCA to detect modes of variation (Table 2.3). Three principal components represent 70% of the total variance with 44%, 14%, and

12% and eigenvalues of 4.3, 1.4, and 1.2 respectively. The first component is presented as an example, with, P_S and T_R covarying with ice anomalies in February, March, and April. The variables with the highest coefficients were P_S (0.862) and anomalous ice cover in April (0.872). PC2 is dominated by the variance in January ice cover and does not covary with any SSI characteristics.

Table 2.3 - Component coefficients of the first three principal components of SSI characteristics and monthly sea ice areal anomalies.

	PC1	PC2	PC3
ΔT_M	0.592	0.029	0.038
P_S	0.862	0.028	-0.371
ΔT_S	0.511	0.218	0.531
T_R	0.759	-0.066	0.415
Anomaly-Dec	0.350	0.479	0.467
Anomaly-Jan	-0.167	0.835	0.022
Anomaly-Feb	0.763	0.282	-0.450
Anomaly-Mar	0.787	0.208	-0.377
Anomaly-Apr	0.872	-0.270	0.080
Anomaly-May	0.597	-0.461	0.204

The relative range of interannual variability for PC1 around the mean is shown in Fig. 2.14. Minimum amplitudes between years represent similar ice conditions, dominated by ice extent and timing of retreat and ice anomalies in February, March and April. Negative amplitudes indicate extreme ice conditions and positive anomalies indicate reduced ice conditions punctuated by 1979, 1981, 1985, and 1988-89. The extreme ice years of 1976 (maximum ice cover) and 1979 (minimum ice cover), for the period of time considered, are indicated by the magnitude of their amplitudes from each other. SSI characteristics vary in concert with anomalous ice cover in spring showing a relationship between ice characteristics along 1^{o} of longitude and area-wide anomalous conditions.

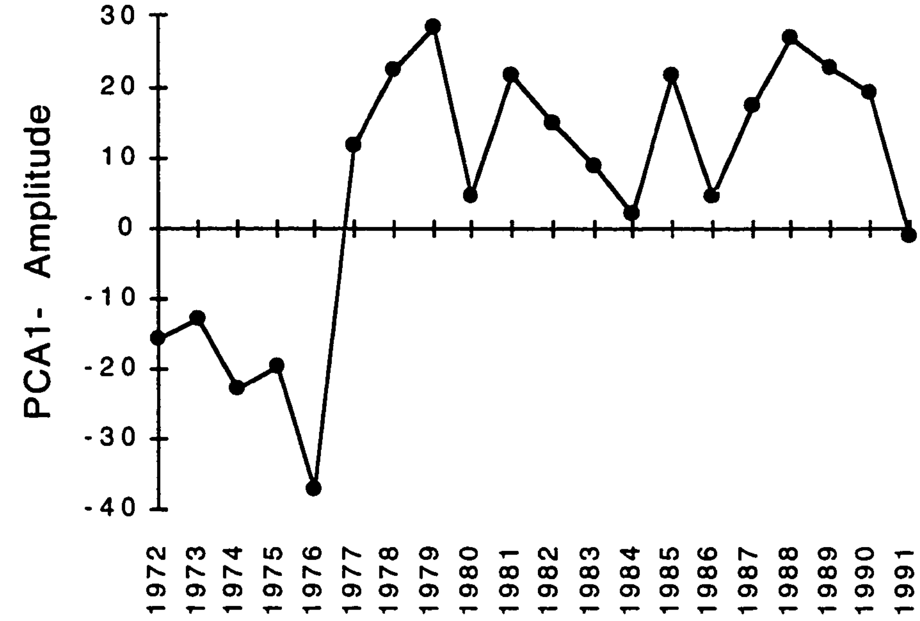


Fig. 2.14 - Time series of annual amplitude of PC1 of seasonal sea ice characteristics and anomalous ice cover on the Bering Sea shelf.

The sea ice index developed by Overland and Pease (1982), which is the maximum extent of sea ice along its axis of growth from Norton Sound toward the shelf break, and the index used in this work, the southernmost extent of the ice edge along 169°W, were compared. The two measures of ice extent were significantly correlated ($r=-0.61; p<0.01$) (Fig. 2.15). The negative correlation value is because the values for the Overland and Pease sea ice index increase with more ice, while P_S decreases with latitude for greater ice extent.

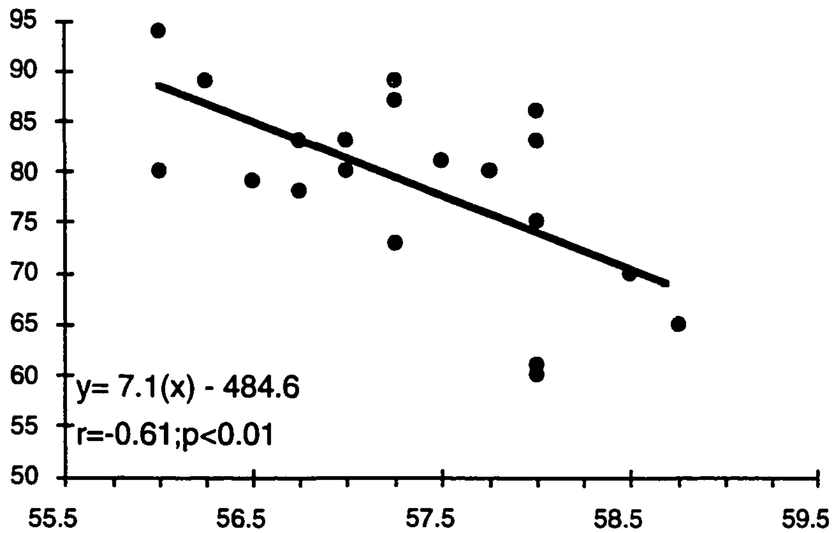


Fig. 2.15 - Position of maximum ice extent (km) from Norton Sound as it relates to maximum latitudinal extent of ice along 169°W (P_S).

The Aleutian Low Pressure Index (ALPI) and Seasonal Sea Ice (SSI)

The first three principal components contain 42%, 25%, and 15% of the variance with corresponding eigenvalues of 3.0, 1.7, and 1.1. PC1 has large coefficients for the ALPI variables and the timing of ice retreat T_R (Table 2.4). The ALPI represents the area of the low pressure cell <1000 mb, so that smaller low pressure cells, in winter and spring (and averaged for the six months), covary with ΔT_S and T_R. PC2 has high coefficients for duration of ice over the middle domain (ΔT_M) and southernmost extent of ice (P_S) and the ALPI in winter. Larger low pressure cells in winter correlate with longer durations of ice over the middle domain and greater ice extent to the south.

Table 2.4 - Covariance coefficients from PCA of sea ice characteristics; of duration of ice over the middle domain (ΔT_M), southernmost latitude of extent (P_S), duration ice remained at southern extent (ΔT_S), and time of ice retreat (T_R),with the Aleutian Low Pressure Index for winter (December-February), spring (March-May), and combined (December-May).

VARIABLE	PC1	PC2	PC3
ΔT_M	0.490	0.613	0.306
P_S	0.373	0.598	-0.606
ΔT_S	0.692	0.321	0.032
T_R	0.836	0.178	-0.252
ALPI-winter	-0.671	0.690	0.166
ALPI-spring	-0.616	-0.061	-0.714
ALPI-combined	-0.756	0.621	0.083

SSI characteristics do not all vary in the same way with the ALPI. Both winter and spring components of the index vary more closely with some SSI characteristics than others. Since extent of seasonal sea ice cover in other studies ice has been shown to be directly affected by the ALPS (Overland and Pease 1982, Niebauer and Day 1989), further investigation was indicated. The relationship between the ALPS and characteristics of SSI was evaluated using several components of the ALPS. I hoped to determine which conditions most affected the characteristics of SSI. Sea level pressure of the low pressure cell, its relative position across the North Pacific, and the resulting direction of wind to the shelf were itemized for February through April, between 1972-1991.

PCA for variability in SSI characteristics and those of the ALPS yielded a PC1 with an eigenvalue of 3.6, accounting for 28% of the total variance, dominated by the variation in SSI characteristics and sea level pressure in March and April, and wind direction to the shelf in April. The second PC is dominated by the variance in position of the low pressure cell and the direction of wind to the shelf in February. PC2 accounts for 15% of the variance with and eigenvalue of 1.9. The first component describes a significant portion of the variability and is used as an example to understand the relationship of these variables (Overland and Preiendorfer 1982). There is a strong relationship between extensive ice conditions, deeper low pressure cells in March, and a predominance of continental air sweeping the shelf in April (Table 2.5).

Table 2.5 - Covariance coefficients of SSI characteristics with the ALPS variables of sea level pressure, wind direction to the shelf, and position of the low pressure cell in the Bering Sea for February March and April between 1972-1991.

VARIABLE	PC1	PC2
ΔT_M	0.598	0.282
P_S	0.664	0.098
ΔT_S	0.673	-0.187
T_R	0.774	0.108
February-SLP	0.370	0.092
March-SLP	0.682	-0.130
April-SLP	0.574	0.049
February-Wind	0.486	-0.720
March-Wind	0.429	-0.054
April-wind	0.676	0.194
February-Position	0.124	-0.505
March-Position	0.103	0.468
April-Position	.109	.842

Sea ice characteristics covary with the intensity of the ALPS (March and April SLP) and direction of wind to the shelf (April). If significant correlations correspond with the relationships indicated by high coefficients then linear regressions can be used to predict the behavior of ice from either SLP or April winds. P_S is linearly related to the direction of wind to the shelf in April (r=-0.78) so more extensive ice occurs with winds of continental origin. The relationship between the direction of wind to the shelf with P_S has two modes. Cold air, with continental or Arctic origin blows southwestward and is associated with extensive ice years, when P_S is between 57°30' and 56°00'N. In the other mode, warm maritime air originates in the North Pacific and is associated with reduced ice years, with P_S between 58°45' and 57°30'N (Fig. 2.16).

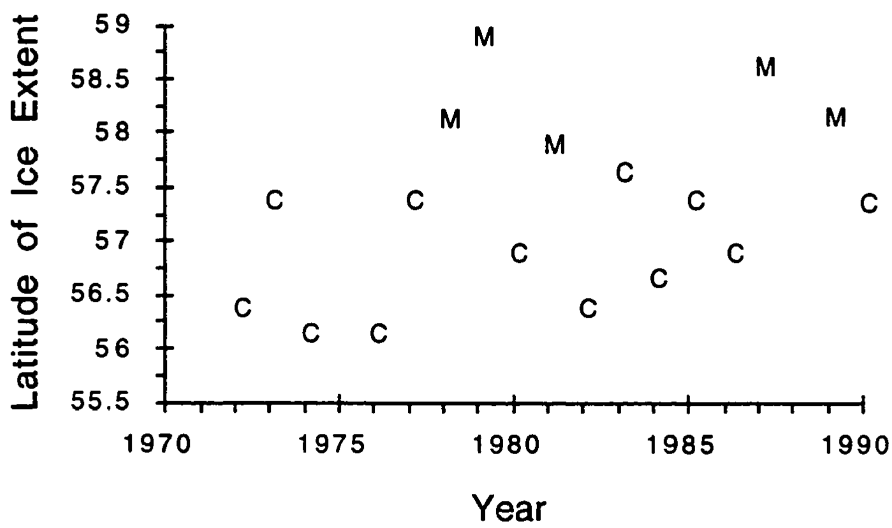


Fig. 2.16 - Comparison between continental (C) and maritime (M) air to the shelf, during April, and the latitudinal extent of ice (P_S)

Discussion

SSI characteristics provide a number of ways to view the interannual behavior of sea ice. The tendency is for heavy or light ice years to be reflected in the four SSI characteristics defined. SSI characteristics can be viewed as a unit, to describe trends in sea ice variability over time, or individually, to describe a particular behavior of seasonal sea ice. From the analysis presented here a number of indices emerge.

Characteristics of SSI, T_R, ΔT_M, ΔT_S, and P_S, are useful indicators of winter or spring conditions on the Bering shelf. The coefficients of variation for all three SSI characteristics are useful indicators of trends in sea ice behavior. In this paper, SSI characteristics were defined along 1° of longitude that spanned the open water of the Bering shelf, from the Chukchi Sea, through Bering Strait and south to the Pribilof Islands. However, any meridian could be used to derive sea ice characteristics that represent ice behavior in a localized area or a different region. The availability of digitized data allows for ease of determining sea ice characteristics in any seasonally ice-covered sea worldwide.

Evaluating sea ice conditions by using ice position along one degree of longitude (169°W) is representative of conditions on the

Bering Sea shelf. Some variation in the pattern of SSI growth is not coherent between eastern and western shelf areas in the Bering Sea, particularly when the ALPS is in its normal position, and the eastern and western sections of the shelf are affected by winds from opposite directions (Fig 1.3). The patterns of T_R and P_S are significantly correlated ($p<0.01$) in the eastern and western sections, but discrepancies occur, probably due to the strength and direction of winds to the respective areas. The areas of ice cover calculated by Niebauer (1983) and Chapman and Walsh (1993) are good indicators of interannual, shelf-wide variability. Significant correlations occurred between (P_S) and measures of areal cover and anomalies. SSI characteristics reflect the general pattern of seasonal sea ice across the Bering Sea shelf.

Scales of climatic events that have similar time scales of variability with sea ice in the Bering Sea, ranging from hemispheric conditions of El Niño-Southern Oscillation (ENSO) (Niebauer 1988, Gloersen 1995), to regional events of the Aleutian low pressure system and resulting storm tracks (Overland and Pease 1982). Sea ice extent shows a strong periodicity on scales of 2 and 4 years (Gloersen 1995) and 4-6 years (Mysak and Manak 1989), which correspond to time scales of day length changes and ENSO events, respectively (Niebauer and Day 1989, Gloersen 1995). Interannual fluctuations are seen in the SSI characteristic of P_S (Fig. 2.6). A scale of 6-7 years occurred in the covariance of P_S, ΔT_M, ΔT_S, and T_R

combined (Fig. 2.9). The general effects of hemispheric variability can be tracked in the behavior of areal sea ice cover (Niebauer and Day 1989, Gloersen 1995) and in individual characteristics of sea ice behavior. Additionally local events in atmospheric conditions during specific months can be detected in the various SSI characteristics. For instance, T_R, timing of ice retreat is related to the intensity of the Aleutian low pressure cell in March, while P_S, the southernmost latitude of ice extent is significantly correlated with the direction of wind to the shelf in April.

Characterizing the behavior of seasonal sea ice over a single meridian can be used to identify interannual variations in ice cover and extent across the shelf. Indices are useful tools that provide a relative range of conditions against which to evaluate other phenomena and can be used to model conditions and predict future states (Inhaber 1976). An upwelling index (Bakun 1975) has been used to assess upwelling in the Northeastern Pacific. It is an expression of the Ekman transport as calculated from local barometric pressure gradients. Even without a direct measurement of upwelling, distribution and abundance of populations can be evaluated against the occurrence and strength of local upwelling events. Two sea ice indices have been developed for the Bering Sea shelf. Overland and Pease used distance of ice edge from shore (Overland and Pease 1982) and Somerton (1982) used maximum extent of ice in Bristol Bay. Overland and Pease use their index to rank relatively heavy and light ice conditions, while Somerton relates the amount of ice cover in Bristol Bay to reproductive success of tanner crab (*Chionoecetes opilio* and *C. barderii*).

Sea ice extent along meridian 169^{o} W correlates significantly with other measures of ice extent and areal coverage across this region (Overland and Pease 1982, Niebauer and Day 1989, Chapman and Walsh 1993). An added advantage of quantifying SSI along a single meridian is the additional data available when quantifying the annual shape of the growth and retreat curve (ΔT_M, P_S, ΔT_S, T_R). The relationship among a variety of indicators of a physical feature can then be examined in the context of variability in other aspects of the system, either physical or biological.

CHAPTER THREE - Effects of Sea Ice on the Cold Pool

The cold layer of bottom water is a persistent feature in the middle domain of the Bering Sea shelf (Takenouti and Ohtani 1974, Ohtani 1973). The hydrography of the middle domain in the summer is two-layered, with a thermocline at 20-30 m separating the surface and bottom water masses. Temperature and salinity characteristics of the bottom layer change every year. However, once the thermocline is established in spring the character of the middle domain remains fairly stable throughout the summer. Low northward summertime flows of 1-5 cm sec^{-1} have led to this area's nickname, "the cold pool" which implies a stagnant body of water(Kinder and Schumacher 1982). Barnes and Thompson (1938) first observed that subsurface water on the middle shelf is primarily affected by seasonal sea ice conditions of the preceding winter. During a multi-year study they noted that reduced ice cover corresponded to warmer bottom temperatures on the southeastern shelf. The possible relationship between sea ice extent and the areal extent of the cold pool has also been discussed by Maeda et al. (1967, 1968), Takenouti and Ohtani (1974) and Laevastu (1993), but the specifics of the relationship have yet to be determined.

The cold pool of the middle domain extends from the Gulf of Anadyr in the west, with temperatures of <-1.0^{o}C and salinities >33.2 (Hufford and Husby 1972), to a variable eastern boundary over the southeastern shelf, with temperatures and salinities of 2^{o}C and 32.0, respectively (Maeda et al. 1967; 1968). It is an extensive body of water with temperatures that range outside those of the preferred habitat of many sub-Arctic species and may affect their distribution and that of their prey (Kihara and Shimada 1988). Even though most of the conditions on the Bering shelf are within the limits of a sub-Arctic system, the cold pool of the middle domain more closely fits the parameters of an Arctic system. This "Arctic island" of water on the Bering Sea shelf may limit the distribution of sub-Arctic species or provide a southern refuge for Arctic species.

The hypothesis tested here is that the amount of seasonal sea ice covering the Bering Sea shelf in winter is related to the characteristics of the cold pool on the middle domain the following summer. That relationship is explored and a model proposed to allow the prediction of the behavior of the cold pool in summer from sea ice the previous winter. Since sea ice conditions are monitored by satellites and the data are received and processed daily, a database exists that may allow forecasting of hydrographic conditions on the Bering shelf.

Methods

Data reports of summer benthic trawl surveys for bottomfish, conducted by the Alaska Fisheries Science Center, Seattle, WA, contain maps of the bottom temperatures recorded by expendable bathythermographs (XBT) at each station on the eastern Bering Sea shelf between 1972-1993. The maps provide coverage from 158°W in the southeastern Bering shelf eastward to 179°W (Fig 3.1). The size of the area covered varies each year with the minimum eastward boundary of 160°W. As data from only the eastern shelf was routinely collected, areal analysis of the cold pool was not possible. The characteristic of the cold pool available for systematic evaluation was the easternmost extent. The 2°C isotherm was considered the boundary of the cold pool on the southeastern shelf (Maeda et al. 1967, 1968) and used as the boundary in this study. Additional bottom isotherm maps of the southeastern Bering Sea were consulted for data extending back to 1955 (Maeda 1977).

Seasonal sea ice (SSI) characteristics of the ice edge's southernmost extent (P_S), the duration ice remaining over the middle domain (ΔT_M), duration at southern extent (ΔT_S), and the timing of ice retreat in spring (T_R) were evaluated from satellite data (Navy/NOAA-Joint Ice Center, Suitland, MD) along a line of longitude (169°W) (Chapter 2). These characteristics of SSI covary over time with interannual variability and change over longer time frames. The characteristics covaried and had three distinct conditions: 1972-1977 (extreme ice), 1978-1983 (reduced ice), and 1984-1991 (mixed).

Principal component analysis was used to investigate variance among normalized variables of SSI characteristics and the cold pool (Jassby and Powell 1990). Linear regressions were used to estimate the extent of cold bottom water in the middle domain from significantly correlated SSI characteristics.

Results

Characteristics of the Cold Pool

The minimum and maximum extent of the cold pool between 1957-1993 varied by 12° longitude (556 km) (Fig. 3.1). Between 1956-1969 the cold pool extended between 167°W, eastward to 162°W (Table 3.1). In 1960, and for the period 1970-1977, the cold pool extended farther eastward into Bristol Bay than it did during the 1960's. Between 1979-1982 the widest fluctuations occurred in the extent of the cold pool, with the minimum and maximum boundaries reached in alternating years.

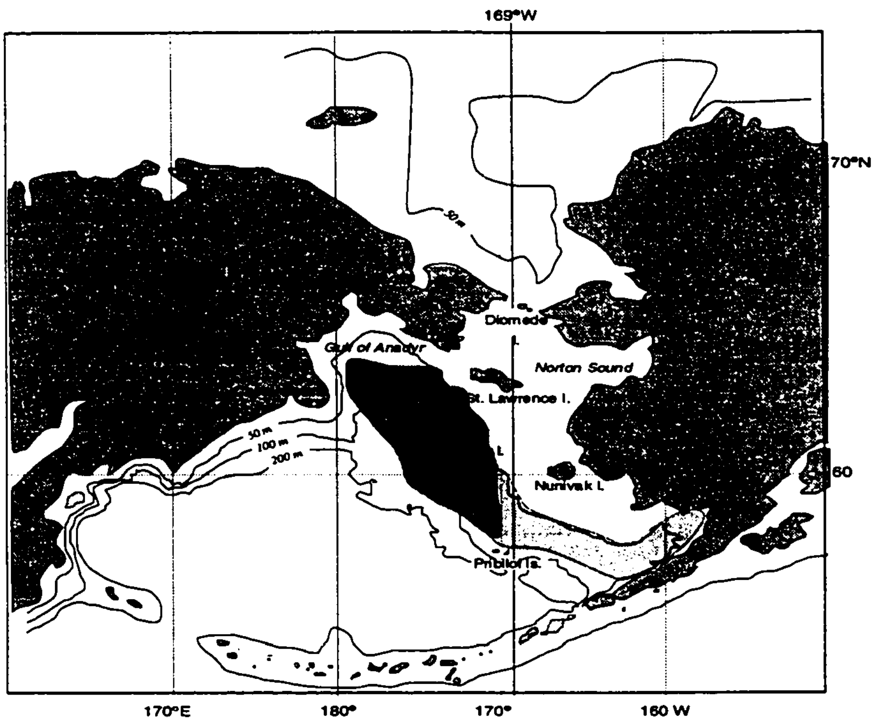


Fig. 3.1 - Representative minimum (170°W) and maximum (158°W) annual extent of cold bottom water (<2.0°C) between 1963-1990. Light shading indicates maximum extent in 1982, dark shading indicates minimum extent in 1979.

A distinct pattern in the extent of cold water is evident (Table 3.1). Longitude 163°W is the most common eastern boundary (30% of the time) during a 37 year period (1956-1993). This may be related to the bathymetry of the region. The bottom contour in the region becomes more complex eastward of 163°W. Shoaling and steeper bottom topography may serve as a boundary except in years of extreme ice cover.

Table 3.1 - Eastern boundary (west longitude) of 2^{o}C isotherm (the cold pool) in the middle shelf domain of the eastern Bering Sea for each year between 1956-1993.

Pribilof Is. Bristol Bay

Degrees West Longitude

170	169	168	167	166	165	164	163	162	161	160	159
from Takenouti and Ohtani (1974)											
			56		61	63	59	60			
			58		67	65	62				
							64				
							66				
from Hokkaido University (1968-1970)											
				69			68	70			
from Maeda (1977)											
								73		71	72
								74			75
											76
from the data base at NOAA/NMFS/RACE, Seattle WA											
81	79	78		83			85	92	77		80
89	87			90			86		84		82
	93						91		88		

Relationship between Seasonal Sea Ice and the Cold Pool

SSI characteristics covaried with the extent of the cold pool and the average bottom temperatures over the southeastern Bering sea shelf (Table 3.2). The components covary such that longer duration of ice over the middle domain and at its southern extent, later timing of ice retreat, more southerly extent of sea ice, more easterly extent of the cold pool, and colder bottom temperatures correspond. The negative loadings are due to the values for ΔT_M, ΔT_S, and T_R increasing as values for P_S, CP, and BT are decreasing. Negative values result when ice moves farther south (lower latitudes), when the cold pool extends farther eastward (lower longitudes), and when bottom temperatures drop.

Table 3.2 - Component coefficients of the first principal component (PC1) of SSI characteristics and the cold pool (CP) and average bottom temperatures (BT) on the Bering Sea shelf.

	PC1
Eigenvalue	3.2
Percent	53%
ΔT_M	0.613
P_S	-0.817
ΔT_S	0.540
T_R	0.773
CP	-0.820
BT	-0.767

The amplitude for each year shows the relative variation around the mean (Fig. 3.2). Interannual variation was small between 1972-1977, and then the amplitude increases annually until a peak is reached in 1979. The wide variation between 1976 and 1979 shows the extreme conditions that existed in these two years and is reflected in sea ice conditions and the cold pool, as well. When sea ice conditions are extreme or reduced, a corresponding increase or decrease occurs in the extent of the cold pool.

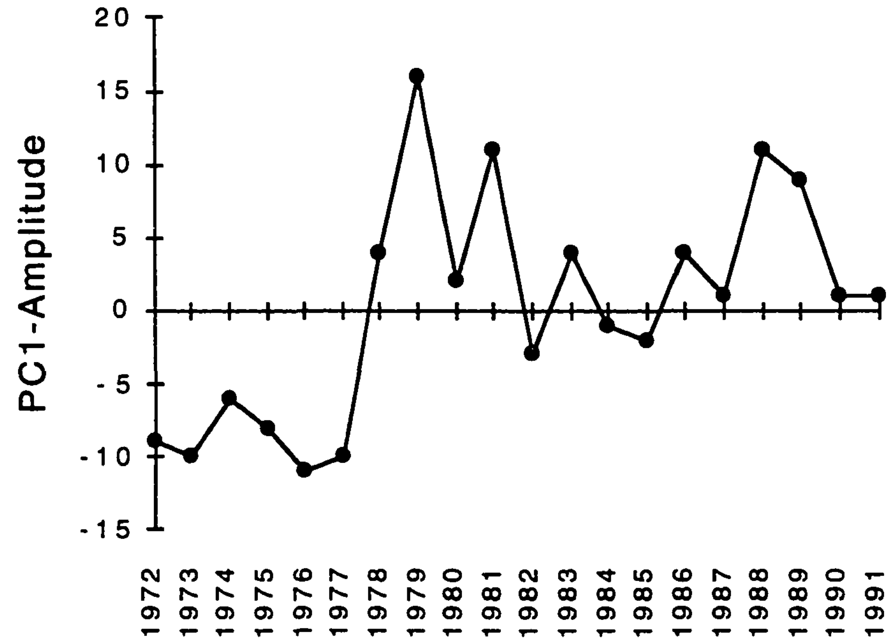


Fig. 3.2 - Annual amplitude of the first principal component of seasonal sea ice characteristics and the cold pool on the Bering Sea shelf. Variance is around the mean for 1972-1991.

The highest coefficients were between P_S and the CP, and these characteristics were used to develop a model to predict the extent of the cold pool in summer from ice extent the previous winter.

The linear model:

$$\text{eastern extent of cold pool } (^{o}W) = -21.468 + 3.241\, P_S$$

(latitude [^{o}N] of southernmost ice extent)

$r=0.68$; $p<0.01$

was developed using data from 1972 to 1990. The predicted extent of the cold bottom layer versus the measured extent shows that the extent of SSI during winter affects the expansion or contraction of the underlying bottom water mass. In order to test this relationship, data for 1991-1993 were included and compared to the estimate (Fig. 3.3). The relationship of heavy ice cover and eastern extent of the ice edge shows that when P_S is 57^{o}30', or more northerly, the cold pool extends into Bristol Bay, east of 163^{o}.

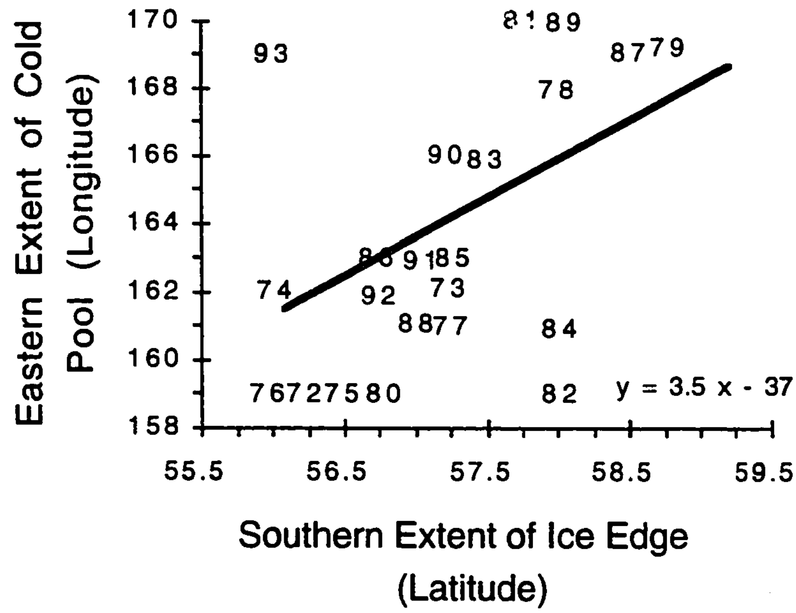


Fig. 3.3 - Regression of the eastern extent of the cold pool versus the southernmost latitude of ice extent between 1972-1991 ($r=0.68$; $p<0.01$). Predicted values for 1991-1993 fall on the line, measured values are denoted by year.

Comparison with Average Bottom Temperatures

Average summertime bottom temperatures found on the southeastern Bering shelf (Goddard and Zimmermann 1993) covaried with SSI characteristics on a similar scale to the cold pool. Average temperatures recorded by XBT's during the annual surveys to the eastern Bering Sea by NOAA/NMFS/AFSC/RACE were significantly correlated with P_S (Fig. 3.4).

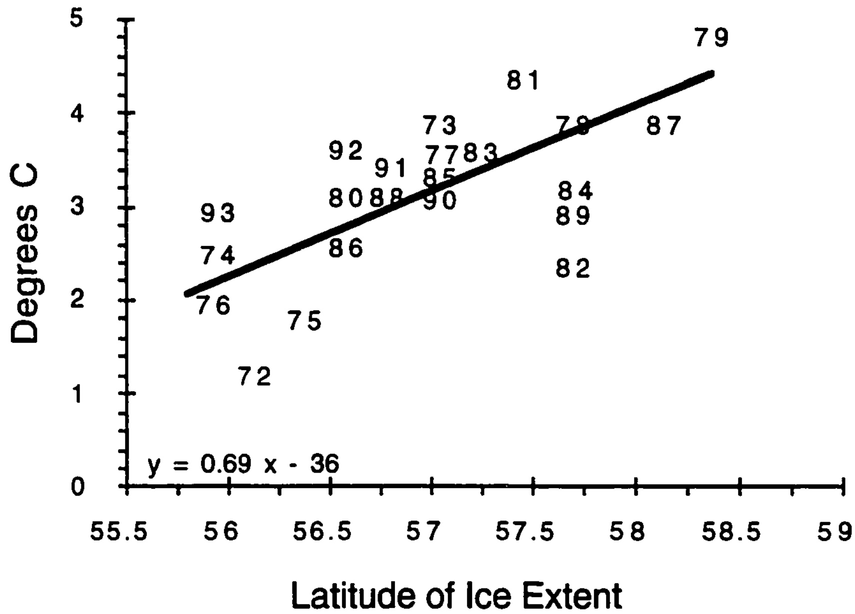


Fig. 3.4 - Regression of the average bottom temperatures in the eastern Bering Sea versus the southernmost latitude of ice extent between 1972-1993 ($r = 0.66$; $p<0.01$).

Discussion

The dynamics of the cold pool of subsurface water that dominates the middle domain have been discussed since the first scientific voyages documented bottom temperatures of the Bering Sea shelf (Barnes and Thompson 1938). Variability in extent occurs in the east, where the shelf is wide and rises gently toward the inner shelf. The minimum size of the cold pool ranges between the Gulf of Anadyr eastward, to St. Matthew Island (Fig. 3.1). The cold pool can extend all the way into Bristol Bay, and has an average extent to meridian 163°W (Ingraham 1981, Reed 1995).

The extent of the 2° isotherm on the Bering Sea shelf in summer is related to the extent of seasonal sea ice the preceding winter. The southernmost latitude of seasonal sea ice extent along longitude 169°W is significantly correlated with the eastern extent of the cold pool. A linear model based on P_S predicts the relative position of the cold pool the following summer (and by inference, its size). The extreme extent of the cold pool ranged over 12° of longitude, between 171° and 159°W, and P_S ranged 2.75°, between 56° and 58°45'N, for the period 1972-1993. Years with extensive ice cover and large cold pools correspond, so that when ice extends southward between 57°30' and 56°N, the cold pool extends eastward between 164° and 159°W. The model is based on data between 1972 and 1990, a time period when variability in the cold pool was the same as variability observed over the longer period between 1956-1990 (Table 3.1).

Khen (1988) compared the variable of "sea icing" with the location of the 2°C isotherm on the Bering shelf, based on Russian cruises between 1956-1987. Although he did not define his measure of "sea icing", the correlation between ice and the cold pool was significant ($r=0.76$), as was the relationship in this study. Additionally, the relationship he reported for icing and water temperature ($r=0.68$ for offshore Pribilof transect and $r=0.76$ for onshelf transect) was similar to the value calculated for 1972-1990 ($r=0.66$). The variability in cold pool conditions is very consistent, and the relationship with seasonal sea ice conditions is clear.

The average summertime bottom temperatures on the whole southeastern shelf, recorded between 1972-1993, also reflect the amount of ice cover on the shelf the previous winter (Fig. 3.4). The relationship corresponds to colder summer bottom temperatures with more extensive ice cover (P_S) and supports the hypothesis that summertime bottom temperatures on the Bering Sea shelf are related to the amount of ice cover the previous winter (Barnes and Thompson 1938, Takenouti and Ohtani 1974, Maeda et al. 1967, 1968, Laevastu 1993).

Populations of fish and invertebrates residing in the middle domain, that are sensitive to water colder than 2°C, will be affected by the amount and extent of the cold water. The cold pool of water that persists throughout summer can affect growth rates and distributions of organisms with temperature preferences bordering 2°C. Walleye pollock is a sub-Arctic species with a reproductive strategy and behavior that indicates water colder than 2°C is not preferred (Sakuri 1989), while Arctic cod, an Arctic species that can live under the cover of ice, prefers temperatures cooler than 3°C (Rass 1968). When the boundary of the temperature that populations prefer changes location annually, their habitat may expand or contract accordingly.

CHAPTER FOUR - Walleye Pollock and Arctic Cod

Introduction

Abiotic conditions have been shown to affect abundance and distribution of various fish (Cushing 1982) and shellfish species (Somerton 1982). In particular, much work has been performed on gadids in the Atlantic Ocean and their changes in distribution and abundance in relation to changes in climatic conditions (Rose et al. 1994, Malmberg and Blindheim 1994, Heessen and Daan 1994). On the Bering Sea shelf, survival of larval tanner crab (*C. opilio*) may be affected by sea ice through the timing of the phytoplankton bloom (Somerton 1982), and walleye pollock (*Theragra chalcogramma*) abundance may be dependent on both fecundity and winter conditions at age-1 (Ohtani and Azumaya 1995). In this chapter I analyze the distributional patterns of pollock and Arctic cod. Distribution of pollock has been reported to be positively related to bottom water temperature greater than 3^{o}C (Bakkala and Alton 1986), and that of Arctic cod (*Boreogadus saida*) to water temperatures of 3^{o} and colder (Ponomarenko 1968). Given the affect of sea ice on shelf hydrography, the potential for changes in walleye pollock and Arctic cod distributions predictable from winter ice cover exists.

As walleye pollock age, their principal area of distribution changes between pelagic and benthic habitats with interannual variations within life history stages (Karp and Walters 1994). Young-of-the-year larvae are planktonic and age-0 occur in mid-water. Pollock, age-1 and older, were reported from mid-water and benthic surveys in 1979, 1982, 1985, and 1988 (Karp and Walters 1994). Larger proportions of age-1 pollock occurred in benthic trawls in 1982, 1985 and 1988. Only in 1979 were large numbers of age-1 reported in mid-water, probably a reflection of the large 1978 year class (Karp and Walters 1994). For pollock older than one year, a higher proportion of two- to five-year-old fish were found in mid-water in 1979, 1982, 1985, and 1988, and fish older than 5 were primarily found near the bottom (Karp and Walters 1994).

Walleye pollock and Arctic cod are used in this study to test the effects of environmental variation on the distribution of fish species in the western Arctic. Both species are gadids, overlap in the range of distribution, with pollock, a sub-Arctic species reported as far north as the Chukchi Sea (Wolotira et al. 1977, Wyllie Echeverria 1995), and Arctic cod, an Arctic species occurring as far south as the Bering shelf (Allen and Smith 1988). They are key species in food webs of the North Pacific and marginal seas of the Arctic Ocean respectively. The Bering Sea shelf is the area where the boundaries of both species occur and where environmental parameters could change the boundaries of a species distribution.

Interannual variations in the distribution of walleye pollock and Arctic cod need to be quantified, after which investigations into the pattern of distribution can be made. Pollock and Arctic cod are investigated for three reasons: 1) they are key species in food webs of fish, birds and marine mammals in the subarctic and Arctic, 2) patterns of distribution may be related to environmental conditions and 3) it may be possible to predict their distributions from environmental indices, particularly of sea ice.

Methods

The Resource Assessment and Conservation Engineering Division (RACE) of the National Marine Fisheries Service, Seattle, Washington has conducted annual surveys of the Bering Sea shelf since 1965 (Wakabayashi et al. 1985; RACE 1992; Bakkala 1993). The survey area has expanded over time, from the southeastern shelf in 1972-74 to include the central shelf in 1975 (Fig. 4.1). Bottom trawls were used to sample shellfish and groundfish for resource assessment in this area (Wakabayashi et al. 1985, RACE 1992). Surveys were conducted annually during June and July, and into August and September during years of expanded coverage (Appendix 1). These surveys provide the basic data needed to investigate changes in a biological community over decadal time periods.

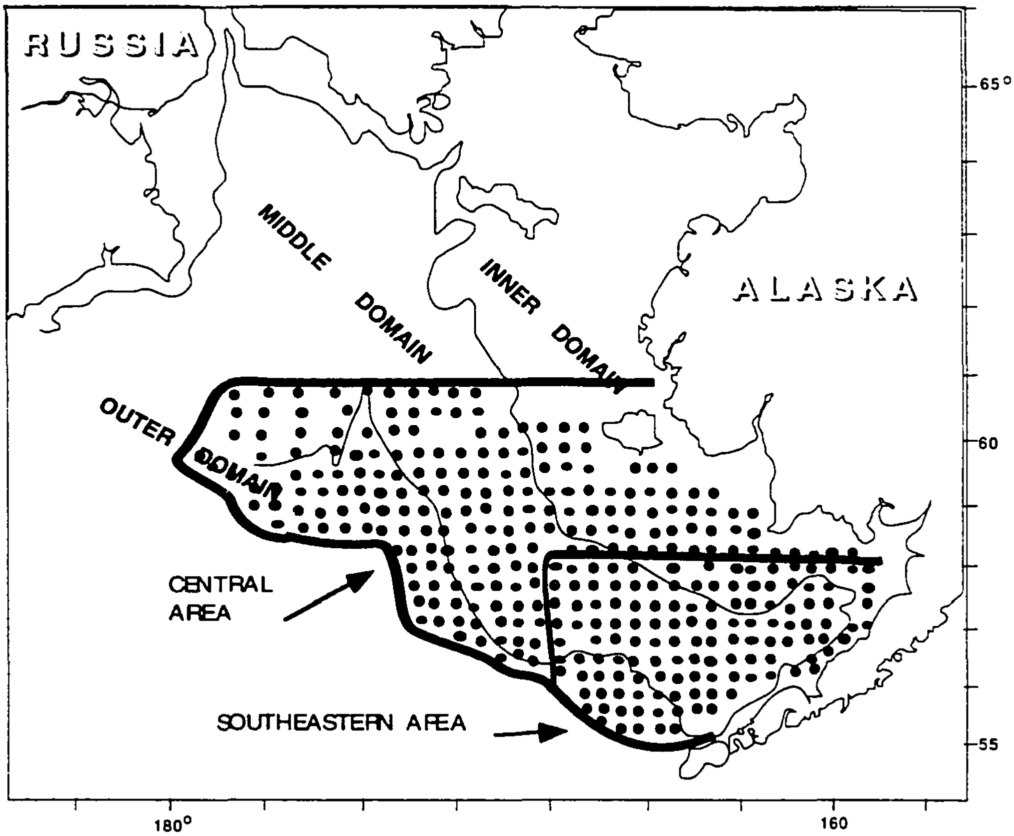


Fig. 4.1 - Map of the study area showing general station locations used to calculate percentage of stations with pollock or Arctic cod over total stations in each area and in each domain.

Position, depth and bottom temperature at stations, along with fish size and abundance, were selected from the RACE data base and used in this study. Annual maps were constructed, showing abundance of pollock and Arctic cod at each station. All stations sampled (+), and those where pollock or Arctic cod were caught (**o**) are represented (Appendices 2, 3 and 4).

The distributions of walleye pollock and Arctic cod were analyzed by selecting the same stations, method of calculating areal distribution, and statistical techniques. Pollock captured in bottom trawls were divided into two size classes. Age-1 fish are $\leq$ 20 cm Fork Length and age-2 and older are fish > 20 cm Fork Length. A separate set of maps was constructed for each age grouping (Appendices 2 and 3, respectively). Arctic cod >10 cm FL are caught with bottom trawls and separate maps representing their distribution were constructed (Appendix 4).

Abundance estimates for the stations analyzed in this work were calculated from abundance data at each station divided by the area swept by the trawl (CPUE in numbers/hectare) (Mintel and Smith 1981). Net openings were calibrated beginning in 1982, enabling an additional adjustment of the area swept related to the actual dimensions of the net opening. Prior to 1982 the net was considered to have a standard opening and area swept was only an estimation (Rose and Walters 1990). Limitations arise from the variety of ships and gear employed when using abundance data for 1972-1992. As a consequence, CPUE can be a function of gear rather than a real change in abundance (Walters and McPhail 1982, Hoff 1989). Although CPUE is represented on the distributional maps (Appendices 2, 3 and 4), presence or absence of pollock at a station and not the abundance estimates were used in this study to evaluate distributions.

The Bering Sea shelf was divided into two areas, southeast and central, for analysis of inter- and intra-annual variability (Fig 4.1). Each area was further divided by the three hydrographic domains found on the shelf (Chapter 1). The southeastern shelf has been consistently sampled since 1972 and was the most extensively sampled area evaluated in this study. The southeastern area, lying between 55° and 58°N latitude and 160° and 169°W longitude, was sampled over a time period that includes the years preceding the climate shift in the North Pacific that occurred in 1976-77 (Trenberth 1990; Trenberth and Hurrell 1994; Miller et al. 1994). In most years (1974-1993), the southeastern shelf was sampled with a minimum number of stations; 28, 70, and 27 for the inner, middle and outer domains, respectively (Fig. 4.1). The central shelf area, lying between 58° and 61° N and west from 169° to 178° W, was sampled routinely after 1979, with 55, 80, and 61 stations sampled from the inner, middle and outer domains, respectively (Fig. 4.1).

Presence/absence data were evaluated separately for age-1 pollock, age-2 and older pollock, and Arctic cod at each station. The number of stations in each domain and area with each species was divided by the total number of stations sampled, yielding percentage of stations occupied by each species. The number of stations used to calculate the percentages remained as consistent as possible among years. Not all stations were sampled in all years, and in some years more stations were sampled than in earlier years (Appendix 1). The percentage of stations sampled was used to analyze the relationships between areas and domains, and distribution and year-class strength.

The effect of year-class strength on the distributional patterns of age-1 pollock was investigated by comparing the year-class strengths estimated by virtual population analysis (VPA) with the concentrations of age-1 pollock. Large year classes may affect population distribution on the shelf. Wespestad and Dawson (1993) provided year-class strength estimates from a calculation to age-0 based on the abundance of 3 year old pollock landed by the commercial fishing effort (Fig. 4.2).

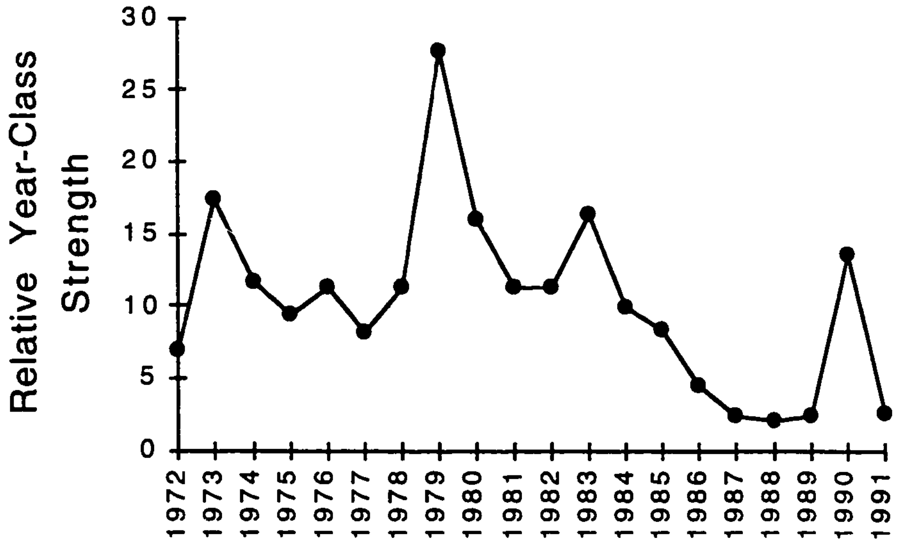


Fig. 4.2 - Relative ranking of year-class strength based on virtual population analysis (Wespestad and Dawson 1993).

Distributional patterns were investigated by assigning the domain with the highest percentage each year as the domain of primary distribution. When two or more domains were within 10% of each other, the distribution was ranked evenly between domains. A fixed percentage was not used to assign a principal area of distribution because in some years a low percentage of age-1 pollock was sampled from all areas and domains. When the pattern of distribution appeared to switch between domains, analysis of variance was used to determine if the percentages were significantly different for each time period in the inner, middle or outer domains. The average percentage of stations with pollock or Arctic cod was taken for each time frame and domain, and an analysis of variance for two factors without replication program (Microsoft EXCEL) was used.

Principal component analysis (PCA) was used to determine relationships of age-1, age-2 and older pollock, and Arctic cod for each domain of the central and southeastern areas. I used the percentages of stations with the target fish from each year, area and domain to determine modes of variation.

Results

Age-1 Pollock on the Southeastern Shelf

Interannual variation in the percentage of stations at which age-1 pollock were present on the southeastern shelf fluctuated from 0% to 86% in the inner domain, 14% to 82% in the middle domain, and 0% to 85% in the outer domain (Table 4.1).

Table 4.1 - Distribution of age-1 pollock on the southeastern Bering Sea shelf, with percentage of stations with pollock (number of stations sampled) in the inner, middle and outer domains.

	Domains of the Southeastern Shelf		
Year	Inner	Middle	Outer
1972	43% (21)	82% (56)	75% (16)
1973	4% (24)	14% (49)	70% (23)
1974	21% (28)	31% (70)	41% (27)
1975	57% (28)	73% (70)	67% (27)
1976	21% (28)	41% (70)	44% (27)
1977	0% (28)	25% (61)	0% (27)
1978	11% (28)	41% (70)	19% (27)
1979	82% (28)	73% (70)	85% (27)
1980	61% (28)	49% (70)	13% (23)
1981	29% (28)	63% (70)	15% (27)
1982	29% (28)	66% (70)	56% (27)
1983	36% (28)	69% (70)	22% (27)
1984	46% (28)	61% (70)	19% (27)
1985	75% (28)	59% (70)	11% (27)
1986	43% (28)	46% (70)	19% (27)
1987	29% (28)	29% (70)	0% (27)
1988	43% (28)	54% (70)	19% (27)
1989	18% (28)	56% (70)	7% (27)
1990	75% (28)	77% (70)	41% (27)
1991	86% (28)	69% (70)	26% (27)
1992	29% (28)	53% (70)	0 % (27)
1993	64% (28)	64% (70)	7% (27)
MEAN	39.9	53.9	31.4
VARIANCE	628	341	663

Population distribution of age-1 pollock is the most variable in the middle domain. As occurrences decrease in the middle and outer domains, they increase in the inner domain. The middle domain had the highest coefficient (0.902) covarying with the population in the outer domain (0.505), and inner domain (0.870). The three principal components account for 61%, 29% and 10% of the variance with eigenvalues of 1.8, 0.9 and 0.3, respectively.

The interannual variability of the stations with pollock was highest in years when pollock were predominately in the middle and outer domains, as was the case in 1973-74, and from 1976-78 (Table 4.1; Fig. 4.3). The lowest amplitudes occurred in 1979-80, 1983-84, 1985 and 1990-91, when the population was low in the outer domain. Amplitudes around the mean occurred in years when the population was predominately in the middle domain.

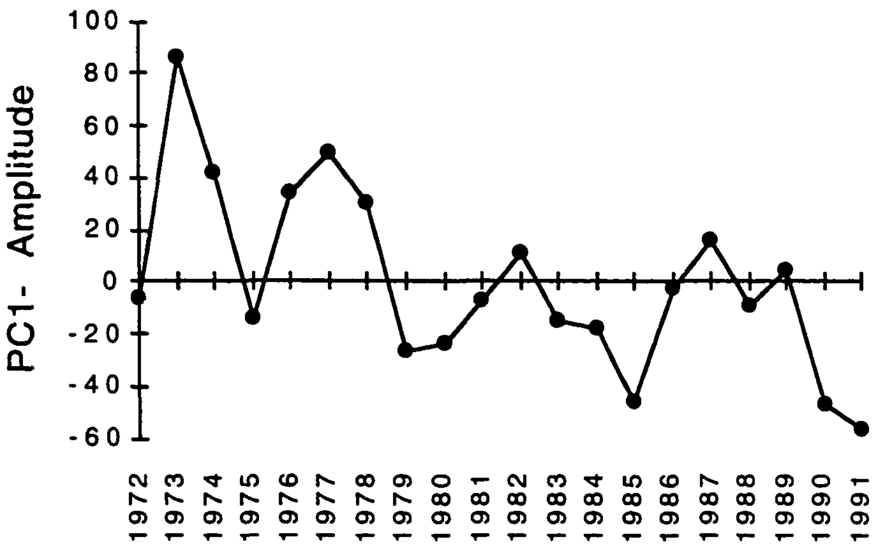


Fig. 4.3 - Annual amplitude of the first principal component for age-1 pollock in the southeastern area of the Bering shelf from 1972-1993.

Age-1 Pollock on the Central Shelf

The percentage of age-1 pollock on the central shelf fluctuated from 0% to 85% in the inner domain, 14% to 94% in the middle domain, and 18% to 98% in the outer domain (Table 4.2). Analysis from the inner domain began in 1979 due to missing values (Table 4.2).

Table 4.2 - Distribution of age-1 pollock on the central Bering Sea shelf with percentage of stations with pollock (number of stations sampled) in the inner, middle and outer domains.

	Domains of the Central Bering Sea Shelf		
YEAR	Inner	Middle	Outer
1972	not sampled	not sampled	66% (3)
1973	not sampled	64% (11)	71% (7)
1974	0% (9)	33% (18)	70% (10)
1975	46% (54)	14% (71)	18% (61)
1976	14% (21)	41% (34)	68% (28)
1977	not sampled	73% (26)	95% (20)
1978	not sampled	64% (53)	98% (51)
1979	37% (54)	94% (80)	98% (61)
1980	55% (53)	79% (71)	79% 48)
1981	45% (20)	77% (66)	69% (55)
1982	60% (55)	78% (80)	75% (61)
1983	69% (55)	84% (80)	76% (58)
1984	64% (55)	84% (80)	64% (61)
1985	64% (55)	38% (80)	15% (61)
1986	42% (55)	36% (80)	8% (61)
1987	11% (55)	43% (80)	10% (61)
1988	43% (55)	78% (80)	51% (61)
1989	35% (55)	88% (80)	48% (61)
1990	85% (54)	94% (80)	61% (61)
1991	82% (55)	83% (80)	72% (61)
1992	36% (39)	52% (75)	23% (60)
1993	45% (55)	91% (80)	74% (61)
MEAN	51.5	66.2	58.8
VARIANCE	383	583	804

The distribution of age-1 pollock in the middle and outer domains had the highest coefficients (0.935 and 0.935, respectively) and covaried with the distribution in the inner (0.658) domain. The three principal components accounted for 73%, 24% and 4% of the variability, with corresponding eigenvalues of 2.2, 0.7 and 0.1. The largest amplitudes occurred in 1979, 1984 and 1991 corresponding to the highest population distributions in the outer and middle domains relative to the inner domain (Table 4.2) (Fig. 4.4).

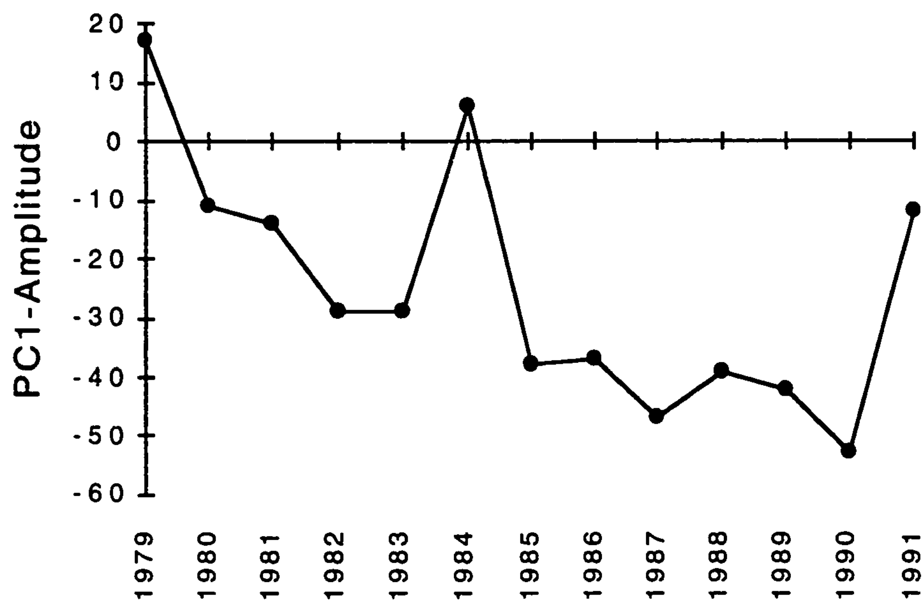


Fig. 4.4 - Annual amplitude of the first principal component for age-1 pollock in the central area of the Bering shelf from 1979-1993.

Variation of Age-1 Pollock due to Abundance

The annual values of year-class strength (Wespestad and Dawson1993), and age-1 pollock in the southeastern and central shelf areas were compared with correlation analysis (Table 4.3). Variations in the percentages of stations in the inner and middle domains where age-1 pollock were caught were not related to year-class strength. However, year-class strength was correlated with populations in the outer domain. Strong year classes resulted in an increased distribution in the outer domain of both the southeastern and central areas (r=0.62 and 0.56 respectively).

Table 4.3 - Correlation coefficients between year-class strength of age-1 pollock and percentage of stations with pollock by area and domain on the Bering shelf. * Level of significance r=0.56; p<0.01 for n=20.

	Year-Class Strength
Southeastern Shelf	
Inner domain	0.24
Middle domain	0.32
Outer domain	*0.62
Central Shelf	
Middle domain	0.15
Outer domain	*0.56

Patterns of Distribution in Age-1 Pollock

The middle domain is the principal area occupied by age-1 pollock across the shelf. Pollock occurred in the middle domain 82% of the time in the southeastern area (18 out of 22 years) (Fig. 4.5) and 71% of the time in the central area (15 out of 22 years) (Fig. 4.6). Analysis of variance was used to test the hypothesis that the populations changed principal distribution between domains. In the southeastern shelf the distribution pattern changed in 1977 to the middle shelf (or away from the outer shelf), and in 1984 the population increased in the inner domain (Fig. 4.5). The distribution pattern based on the percent pollock in each domain for the years 1972-1976, 1977-1984 and 1985-1993 were significantly different ($F=0.09$; $p=0.05$) for these time frames of 5-9 years ($F=1.0$;$p=0.05$). On the central shelf shifts in the pattern of distribution occurred in 1979 and 1983 (Fig. 4.6). Percentages were significantly different between domains ($F=1.6$;$p=0.05$) and for each time frame ($F=2.7$; $p=0.05$). The outer domain was occupied early in the study period and the inner domain later (Figs. 4.7 and 4.8).

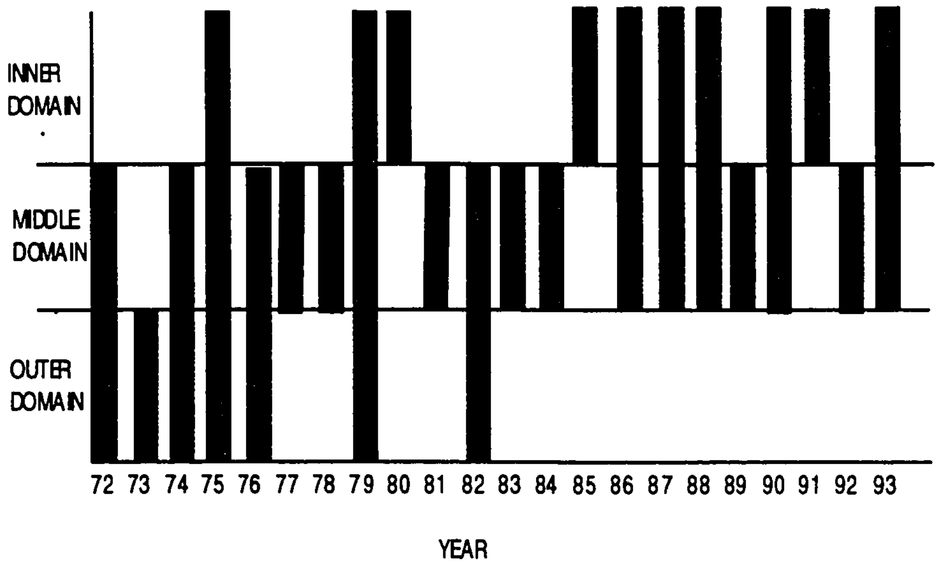


Fig. 4.5 - Relative distribution of age-1 pollock on the southeastern Bering Sea shelf. Domains with the highest percentage of stations with age-1 pollock are designated the primary domain of distribution. In 1972 percentages in the middle and outer domains were within 10% of each other and distributions are considered equal between both domains. All years and domains were sampled.

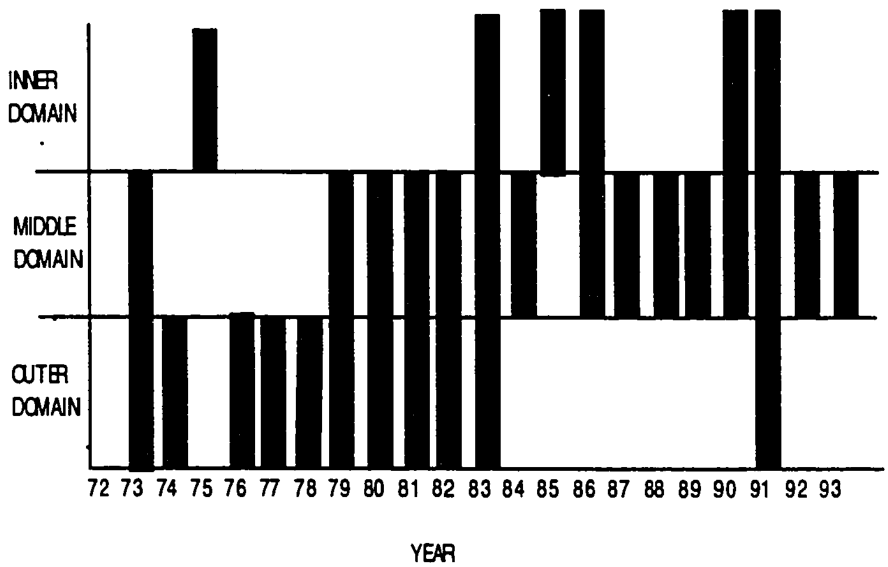


Fig. 4.6 - Relative distribution of age-1 pollock on the central Bering Sea shelf. Domains with the highest percentage of stations with age-1 pollock are designated the primary domain of distribution. The inner domain was routinely sampled after 1978.

Age-2 and Older Pollock on the Southeastern Shelf

Interannual variation in the percentage of age-2 and older pollock on the southeastern shelf fluctuated from 50% to 100% in the inner domain, 64% to 100% in the middle domain, and 92% to 100% in the outer domain (Table 4.4). Higher percentages of stations with age-2 and older pollock occurred in the outer domain than in the other two domains.

Table 4.4 - Distribution of age-2 and older pollock on the southeastern Bering Sea Shelf with percentage of stations with pollock (number of stations sampled) in the inner, middle and outer domains.

	Domains on the Southeastern Bering shelf		
Year	Inner	Middle	Outer
1972	85% (21)	84% (56)	100% (16)
1973	59% (24)	65% (49)	100% (23)
1974	61% (28)	64% (70)	100% (27)
1975	18% (28)	62% (70)	85% (27)
1976	40% (28)	70% (70)	100% (27)
1977	50% (28)	82% (70)	96% (27)
1978	56% (28)	98% (70)	100% (27)
1979	84% (28)	99% (70)	100% (27)
1980	72% (28)	100% (70)	96% (27)
1981	96% (28)	97% (70)	100% (27)
1982	39% (28)	71% (70)	74% (27)
1983	96% (28)	100% (70)	100% (27)
1984	96% (28)	100% (70)	100% (27)
1985	89% (28)	99% (70)	100% (27)
1986	100% (28)	100% (70)	100% (27)
1987	100% (28)	99% (70)	24% (27)
1988	86% (28)	100% (70)	96% (27)
1989	97% (28)	100% (70)	100% (27)
1990	97% (28)	94% (70)	96% (27)
1991	100% (28)	100% (70)	100% (27)
1992	100% (28)	100% (70)	100% (27)
1993	100% (28)	100% (70)	96% (27)
MEAN	93.8	90	78
VARIANCE	281	201	614

The principal mode of variance for age-2 and older pollock on the southeastern shelf is high for the middle (0.954) and inner (0.954) domains. The population in the outer domain had a very small coefficient of variation (0.052) reflecting the small variation in the percent of the population in the outer domain which remained greater then 90% except in 1975, 1982 and 1987 (Table 4.4). The three principal components accounted for 61%, 33% and 6% of the variance with corresponding eigenvalues of 1.8, 1.0 and 0.2. Low interannual variations indicate that there are years with small variations in distribution between the inner, middle and outer domains as occurred in 1972-1974, 1982-1986, and 1988-1993 (Fig. 4.7). The large change in amplitude seen in 1975, 1978, and 1982 reflects a low population in the inner domain.

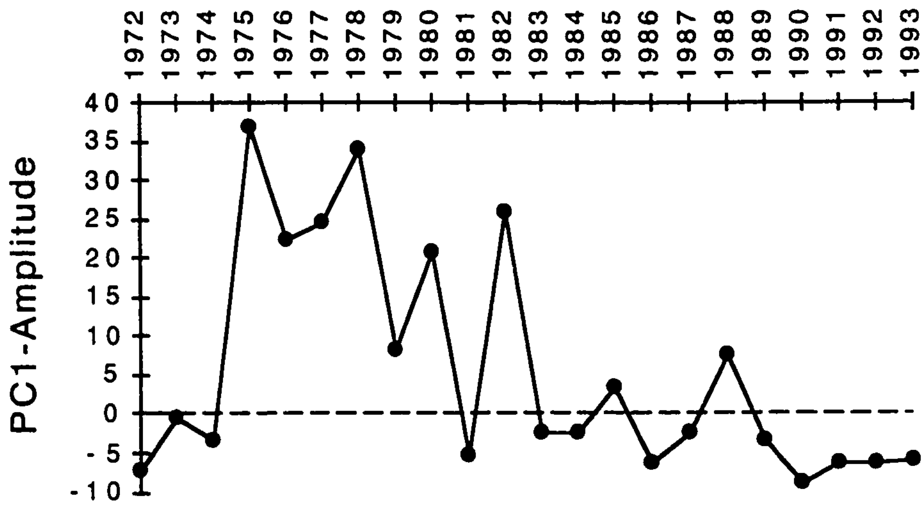


Fig. 4.7 - Annual amplitude of PC1 for age-2 and older pollock in the southeastern area of the Bering shelf from 1972-1993.

Age-2 and Older Pollock on the Central Shelf

Interannual variation in the percentage of stations at which age-2 and older pollock were present on the central shelf fluctuated from 33% to 100% in the inner domain, 11% to 100% in the middle domain, and 31% to 100% in the outer domain (Table 4.5). Higher overall percentages of stations with adult pollock occurred in the outer domain (x =93) than in the inner (x=78) or middle domains (x=88).

Table 4.5 - Distribution of demersal age-2 and older pollock on the central Bering shelf with percentage stations with pollock (number of stations sampled) in the inner, middle and outer domains.

	Domains in the Central Bering Sea Shelf		
Year	Inner	Middle	Outer
1972	not sampled	not sampled	not sampled
1973	not sampled	100% (11)	100% (7)
1974	not sampled	86% (18)	100% (10)
1975	33% (54)	11% (71)	46% (61)
1976	42% (21)	78% (34)	100% (28)
1977	not sampled	84% (26)	100% (20)
1978	not sampled	100% (53)	98% (51)
1979	68% (54)	97% (80)	100% (61)
1980	76% (53)	100% (71)	100% (48)
1981	70% (20)	100% (66)	100% (55)
1982	62% (55)	88% (80)	90% (61)
1983	100% (55)	100% (80)	100% (58)
1984	90% (55)	95% (80)	96% (61)
1985	87% (55)	89% (80)	98% (61)
1986	96% (55)	100% (80)	100% (61)
1987	45% (55)	51% (80)	31% (61)
1988	84% (55)	98% (80)	98% (61)
1989	74% (55)	98% (80)	100% (61)
1990	90% (54)	88% (80)	94% (61)
1991	80% (54)	93% (80)	100% (61)
1992	74% (54)	88% (80)	100% (61)
1993	80% (54)	100% (80)	97% (61)
MEAN	78.4	87.8	92.8
VARIANCE	14	439	338

The principal mode of variance for age-2 and older pollock on the central shelf is high for the middle (0.957), outer (0.959), and inner (0.835) domains. The three principal components accounted for 84%, 14% and 2% of the variance, with corresponding eigenvalues of 2.5, 0.4 and 0.1. Population on the central shelf covaried during this time period.

The scale of the interannual variability of stations with pollock was similar for 1972-1978 when pollock occurred primarily in the outer domain (corresponding to a lack of sampling in the inner domain). In 1978 through 1982 the population was high in both in middle and outer domains, with another change beginning in 1983 and continuing through the study period, when pollock were distributed all across the central area (Table 4.5; Fig. 4.8).

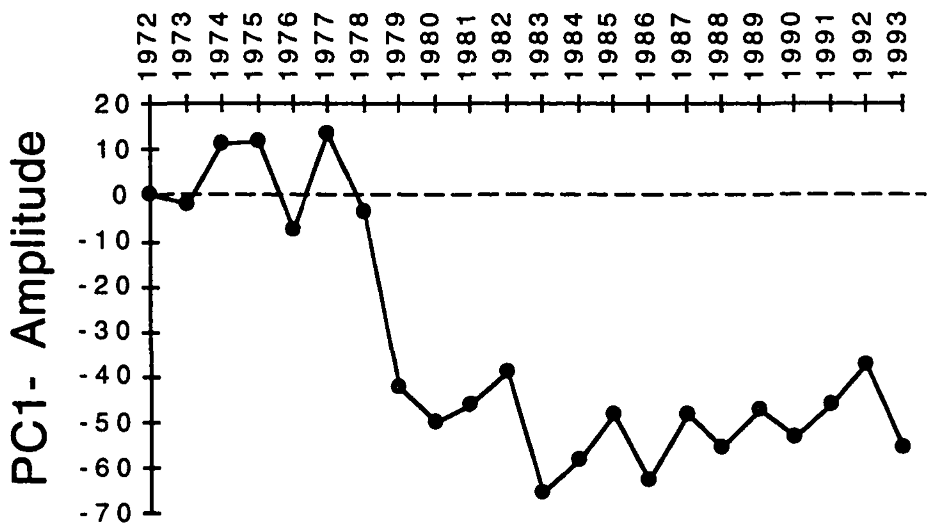


Fig. 4.8 - Annual amplitude of the first principal component of variation for age-2 and older pollock on the central area of the Bering shelf from 1972-1993.

Patterns of Distribution for Age-2 and Older Pollock

The outer domain is the most consistent area occupied by age-2 and older pollock on the southeastern and central shelf areas. Pollock occurred in the outer domain in 95% (21/22) of the years sampled in the southeastern area and 95% (20/21) of the years sampled in the central area. The domain with the highest concentration of pollock for each year shows an increasing importance of middle domain after 1977 and the inner domain after 1982, with a loss of importance for the inner domain on the central shelf after 1987 (Figs. 4.9 and 4.10). Analysis of variance was used to test the apparent differences in population distributions between 1972-1977, 1978-1982, 1983-1993 (Fig. 4.9). The distributions were significantly different between each time frame (F=2.2; p=0.05).

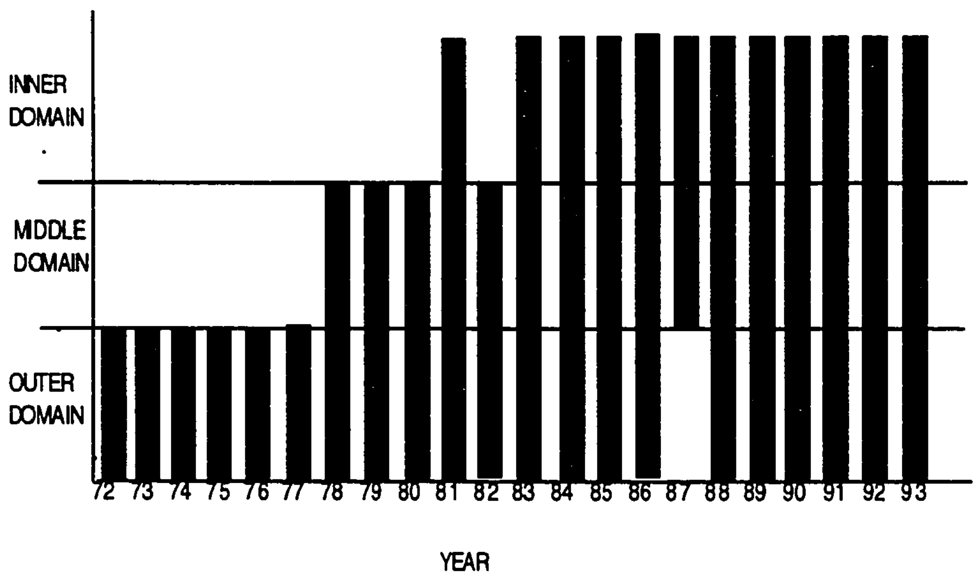


Fig. 4.9 - Relative distribution of age-2 and older pollock on the southeastern Bering Sea shelf. Domains with the highest percentage of stations with age-2 and older pollock are designated the primary domain of distribution. In 1972 percentages were high only in the outer domain. All years and domains were sampled.

Analysis of variance was used to test the hypothesis that distributions changed between domains on the central shelf, for the time period 1973-1977; 1978-1982, 1983-1987, and 1988-1993. The time periods of 5-6 years were significantly different from each other ($F=3.1; p=0.05$), but the percentage of stations with pollock was high and the population was often distributed in all three domains, particularly between 1983-1987. In the early 1970's populations were primarily in the outer domain, with increasing percentages in the middle domain after 1978 and the inner domain after 1982. The population decreased in the inner domain after 1987 (Fig. 4.10).

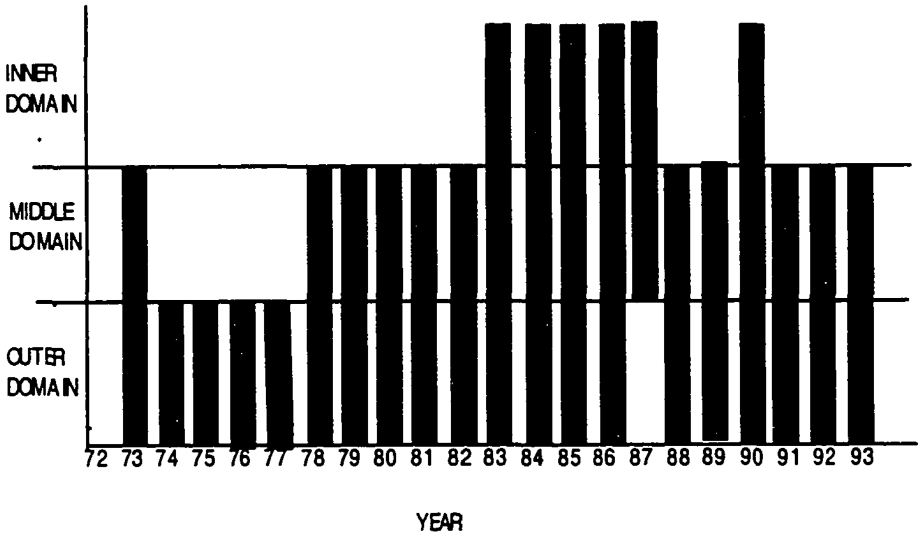


Fig. 4.10 - Relative distribution of age-2 and older pollock on the central Bering Sea shelf. Domains with the highest percentage of stations with age-2 and older pollock are designated the primary domain of distribution. In 1973 percentages in the middle and outer domains were within 10% of each other and distributions are considered equal in both domains. The inner domain was routinely sampled after 1978.

Arctic Cod on the Southeastern Shelf

Arctic cod were rarely caught in the southeastern Bering shelf (Table 4.6). Low percentages occurred in the inner domain in 1985 and 1986, and in the middle domain in 1975, 1976, and 1986. Arctic cod were absent from the outer domain in all years. The southeastern Bering shelf was the most consistently sampled area but lies at the very edge of the range of Arctic cod (Allen and Smith 1988). Overall, the occurrence of Arctic cod on the southeastern shelf was occasional (Fig. 4.11). Further analysis of this area for changes in distribution between domains is not justified.

Table 4.6 - Distribution of Arctic cod on the southeastern Bering Sea shelf with percentage of stations with Arctic cod (number of stations sampled) in the inner, middle and outer domains. ns=not sampled.

year	Inner	Middle	Outer
1972	0% (28)	0% (70)	0% (61)
1973	0% (28)	0% (70)	0% (61)
1974	0% (28)	0% (70)	0% (61)
1975	0% (28)	1% (70)	0% (61)
1976	0% (28)	10% (70)	0% (61)
1977	0% (28)	0% (70)	0% (61)
1978	0% (28)	0% (70)	0% (61)
1979	0% (28)	0% (70)	0% (61)
1980	0% (28)	0% (70)	0% (61)
1981	0% (28)	0% (70)	0% (61)
1982	0% (28)	1% (70)	0% (61)
1983	0% (28)	0% (70)	0% (61)
1984	0% (28)	0% (70)	0% (61)
1985	4% (28)	0% (70)	0% (61)
1986	4% (28)	3% (70)	0% (61)
1987	0% (28)	0% (70)	0% (61)
1988	0% (28)	0% (70)	0% (61)
1989	0% (28)	0% (70)	0% (61)
1990	0% (28)	0% (70)	0% (61)
1991	0% (28)	0% (70)	0% (61)
1992	0% (28)	0% (70)	0% (61)
1993	0% (28)	0% (70)	0% (61)

Arctic Cod on the Central Shelf

Interannual variation in the percentage of Arctic cod on the central shelf fluctuated from 0% to 16% in the inner domain, 0% to 40% in the middle domain, and 0% to 5% in the outer domain (Table 4.7). Higher overall percentages of stations with Arctic cod occurred in the middle domain than in the other two domains. Arctic cod occurred in the inner domain 50% of the years sampled, in the middle domain 81% of the years sampled and in the outer domain 12% of the years sampled. When percentages are 5% or less (2 stations out of 60 or 4 stations out of 80) the presence of Arctic cod is not considered representative of the species occupying an area.

Table 4.7 - Percentage stations with Arctic cod in the central Bering shelf (number of stations), ns=not sampled.

year	Inner	Middle	Outer
1972	ns	ns	ns
1973	ns	ns	ns
1974	ns	ns	ns
1975	2% (55)	24% (80)	0% (61)
1976	16% (55)	22% (80)	0% (61)
1977	0% (2)	0% (80)	0% (61)
1978	ns	0% (80)	0% (61)
1979	2% (55)	0% (80)	0% (61)
1980	5% (55)	24% (80)	5% (61)
1981	0% (55)	3% (80)	0% (61)
1982	0% (55)	0% (80)	0% (61)
1983	0% (55)	5% (80)	2% (61)
1984	7% (55)	31% (80)	0% (61)
1985	2% (55)	9% (80)	0% (61)
1986	5% (55)	40% (80)	0% (61)
1987	0% (55)	5% (80)	0% (61)
1988	5% (55)	31% (80)	0% (61)
1989	0% (55)	1% (80)	0% (61)
1990	0% (60)	0% (80)	0% (61)
1991	0% (60)	0% (80)	0% (61)
1992	0% (60)	4% (80)	0% (61)
1993	0% (60)	1% (80)	0% (61)
MEAN	2.3	10.5	
VARIANCE	16	178	

The principal mode of variance for Arctic cod on the central shelf is high for the middle (0.906) and inner (0.882) domains. The population in the outer domain has a smaller coefficient (0.361) due to the low occurrence in the outer domain (Table 4.7). The three components account for 58%, 32% and 10% of the variance with corresponding eigenvalues of 1.7, 1.1 and 0.4.

The interannual variability was highest in 1986, followed by 1988, 1984 and 1975 (Fig. 4.11). The high variations reflect the high percentages of Arctic cod found in the middle domain compared to the inner domain in those years (Table 4.7). The occurrence of Arctic cod in the outer domain was occasional and a minor part of the observed variance.

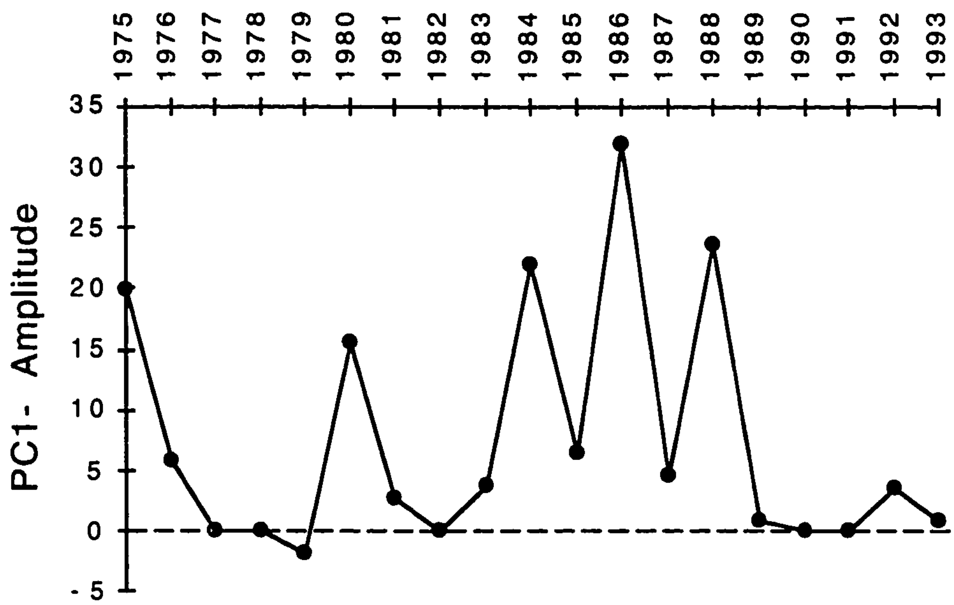


Fig. 4.11 - Annual amplitude of the first principal component of variation for Arctic cod on the central area of the Bering shelf from 1975-1993.

Patterns of Distribution for Arctic Cod

Arctic cod occur primarily in the middle domain, and to a lesser extent in the inner domain of the central shelf. They never predominated in the outer domain (Fig. 4.12).

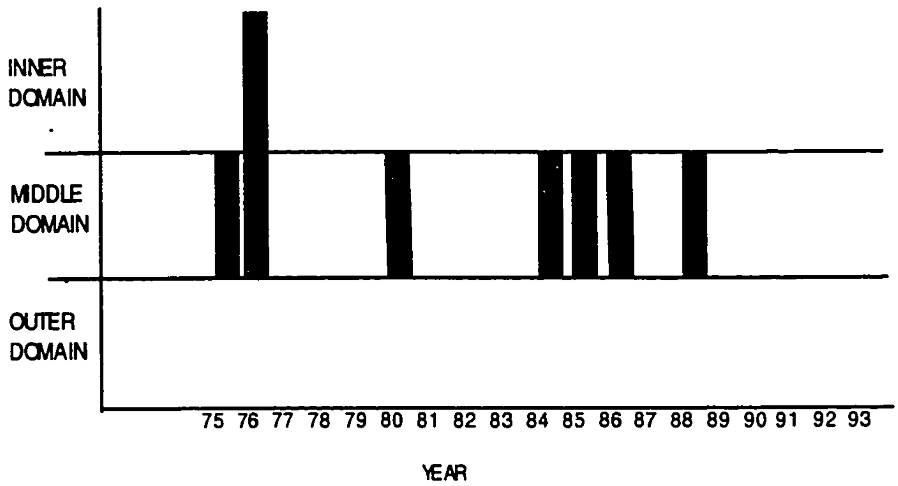


Fig. 4.12 - Relative distribution of Arctic cod on the central Bering Sea shelf. Domains with the highest percentage of stations with Arctic cod are designated the primary domain of distribution. Occurrences are ignored if percentages were below 5%. In 1976 percentages in the middle and outer domains were within 10% of each other and distributions are considered equal between both domains. Sampling began in 1975 and few or no cod were found in 1977-79, 1981-83, 1987, or 1990-93.

Discussion

Shifts in the distribution of fish populations on annual and seasonal bases are well documented (Harden Jones 1968; McKeown 1984; Rankin 1985). Gadids of the Pacific, Arctic, and Atlantic Oceans have ontogenetic (Godoe et al. 1989), reproductive (Brander

1994), feeding (Ponomarenko 1994; Vdovin et al. 1994), and wintering migrations (Shimada and Kimura 1994). In the Pacific, both walleye pollock and Arctic cod migrate annually. Age-2 and older walleye pollock migrate to shallow areas in spring in order to reproduce and remain to feed throughout summer (Radchenko and Sobolevskij 1992), but then over-winter in the deep basin of the Bering Sea (Radchenko and Sobolevskij 1992). Less is known about the behavior of age-1 pollock. They may remain on the shelf in winter or may move to the slope region. Arctic cod migrate seasonally on the Bering and Chukchi shelves with the advance and retreat of sea ice (Ponomarenko 1968), remaining in relatively cold water of -1.8 to 3°C throughout the year.

Ontogenetic differences in the distribution of age-1 and age-2 and older pollock on the Bering shelf occur not only among pelagic and demersal habitats (Karp and Walters 1994) but between shelf domains as well. A principal area of distribution is demersal and in the middle domain for age-1 pollock, and both pelagic and demersal and in the outer domain for fish two and older. Arctic cod are primarily distributed in the middle domain of the central area when they occur on the Bering shelf.

Low percentages of age-1 pollock occurred in 1976, 1986, and 1987, while the percentage was high in 1979 (Tables 4.1 and 4.2). The percentages in the inner and middle domains are not correlated to year-class strength. However, the percentage in the outer domain is related to year-class strength. These results indicate that when high percentages occur in the inner or middle domains, it is not always due to year-class strength, but when large year classes do occur, age-1 fish will occupy the outer domain. It appears that the outer domain is occupied when the middle domain becomes crowded and may be considered a secondary habitat for age-1 fish.

Age-2 and older pollock are distributed across the shelf in relatively high percentages (Tables 4.4 and 4.5). They tend to be concentrated in the outer domain, spreading into the middle and inner domains occasionally. The concentrations are usually very high, with the exceptions of 1975, 1982, and 1987 (central area). Low percentages do not correspond with shifts in distribution between areas, but tend to occur across the whole area. This may indicate that fewer fish migrate to the shelf, possibly as a response to less desirable conditions. Arctic cod occur on the shelf in 7 of the 20 years studied. The pattern of variability, if there is one, is not apparent.

Shifts in seasonal habitats between years may occur in response to changing environmental conditions which, in turn, change migration patterns. Shifts in distribution are particularly evident near the environmental boundaries for a species. For example, Maeda (1977) regressed abundant year classes against the eastern extent of 2°C isobath for yellowfin sole. A cold pool extent between 167°-165°W correlated with high year classes, while low year classes were correlated with eastern extent to 164°W or less.

The distribution of age-1 and age-2 and older pollock has shifted between and across domains twice during the two decades spanned by my study. The outer domain was the principal area occupied by age-1 and age-2 and older pollock during the early 1970's. An increase in pollock in the middle domain occurred in the late-70's and persisted to the end of the study period. High percentages expanded into the inner domain occurred in the mid-1980's. These shifts of population are probably related to large scale changes in environmental conditions. For instance, a North Pacific-wide shift in regime appears to have occurred in 1977, from a cold period to a warm period (Trenberth and Hurrell 1995). This regime shift was so dramatic that changes have been documented for 40 variables of environmental and biological systems (Ebbesmeyer et al. 1990), including changes in the year-class strengths of 7 stocks of groundfish (Hollowed and Wooster 1995) and in the reproductive success of some seabird species (Decker et al. 1995). Pollock moved farther up on the shelf after 1977. Another shift in environmental conditions in this region occurred with the strongest El Niño of the century, that occurred in 1982-1983 (Wooster and Hollowed 1995; Decker et al. 1995). As a result, general environmental conditions may have changed significantly in the mid-1980's, and resulted in occasional expansion of pollock into the inner domain.

A boundary between Arctic/sub-Arctic ecosystems occurs on the Bering Sea shelf, and it is there that shifts in seasonal habitats and migration patterns may be more readily apparent. In this study, shifts were observed over two decades, for the sub-Arctic species, walleye pollock, and the Arctic species, Arctic cod. Changes in the pattern of distribution were not predominantly interannual but occurred over a longer time frame. The behavior of changing the principal domain of distribution, on the scale of 6-8 years for age-1 pollock and 5-6 years for age-2 and older, is probably due to regional environmental variability rather than local variations. Understanding the changing distributions of pollock and Arctic cod on the Bering shelf requires understanding changes in environmental conditions over long time periods.

Variation in migration patterns and in areas of summertime distribution of age-1 pollock and Arctic cod affects predator-prey interactions. The availability of pollock to marine mammals and birds will be dictated by whether the pollock distribution overlapstheir foraging areas (Springer 1992, Sinclair et al. 1994). Age-1 pollock and Arctic cod are of similar size and habitat but have distinct temperature tolerances, and, therefore, Arctic cod will move into some areas where fewer age-1 pollock are found. High percentages of Arctic cod were in the middle domain of the central shelf in 1975, 1976, 1984, 1986 and 1988 (Table 4.7). Arctic cod, however, do not occur as frequently as age-1 pollock in the middle domain of the Bering shelf and cannot be expected to replace age-1 pollock as a prey species. They would be available as prey if low percentages of age-1 pollock occurred, as they did in 1975 and 1986.

Such shifting distributions of different age classes will change the dynamics of cannibalism of age-0 and age-1 by pollock age-3 and older (Livingston 1988, Livingston et al. 1993). Shifts in the concentrations of age-1 pollock from the outer to the middle and inner domains, seen after 1976, change the area of overlap with age 2+ pollock, which were concentrated in the outer domain.

Shifting distributions of fish populations, and the effects on them of environmental conditions, have ecosystem-wide consequences. Every feature of the ecosystem, from the timing, intensity, and species composition of the production cycle to the abundance of apex predators, such as marine mammals and seabirds, is affected by environmental conditions. The consequences of interannual variability in the environment have been recognized, but understanding the response of individual species to a given range of variability is fundamental in building a model of system-wide responses to changing climatic conditions. The indication from the shift of population distributions for age-1 pollock and age-2 and older pollock is that populations are responding to longer term climatic changes than previously considered. With the availability of decadal time series these trends could be investigated and placed in an ecosystem context.

CHAPTER FIVE - Walleye Pollock, Arctic Cod and their Relationship to Seasonal Sea Ice on the Bering Shelf

Introduction

Proxy data, such as the deposition of fish scales in sediments, have afforded a peek into time scales of population variation in the oceans (Baumgartner et al. 1992). Bottom sediment cores that span a 2000 year period reveal a 60 year cycle of abundance for anchovy (*Engraulis mordax*) and sardine (*Sardinop sagax caeruleus*) off California. Few data sets exist that span millennial time scales for oceanic populations, but they provide an indication of the time scales of interactions between species and their environment. The analysis of historic data sets, along with new data acquisition, is essential in understanding interactions among the atmosphere, ocean and biota occurring on decadal time scales (Francis and Hare 1994). Response of a species to interannual variation and variation over longer time periods is imbedded within its evolutionary history. Annual and decadal time scales are relevant to our understanding of population dynamics and the effects of human interactions, and it is these time scales that are within the grasp of our data acquisition and analysis.

Changes in water mass characteristics can be generated by distant physical phenomena and by the relationship of the earth to the sun or moon (Royer 1986, Wyatt et al. 1994). For example, changes in the direction and intensity of wind, generated by changes in atmospheric pressure, directly affect the movement of water masses, with consequences to the distribution of planktonic species, species dependent upon the planktonic food web, and in general, fish distribution (Jakobsson 1969, Sinclair 1987, Taggart and Leggett 1987, Norcross and Austin 1988; Wyllie Echeverria et al. in press). The variability in winds is a result of change in the high and low atmospheric pressure systems that envelop the earth and change in response to variations in heat. The Aleutian low pressure system in the North Pacific affects biological systems at least as far south as central California (Ainley et al. 1995). Changes in water temperature in the North Pacific have been observed from warming and cooling related to El Niños or La Niñas with subsequent distributions of mobile species expanding or retreating along with the changing temperature of the water (see El Niño North 1984, Wooster and Fluharty, editors). The Niño events propagate from the equatorial Pacific eastward and then northward resulting in changes in water temperature and depth of the thermocline across the northeastern Pacific (Norton and McLain 1994).

Analysis of the relationship between the atmosphere and oceans and marine populations began in the North Atlantic. Marine fish populations have been sampled on a routine basis since the turn of the century. The founding of the International Council for the Exploration of the Seas in 1902 has provided an international organization to coordinate marine studies of the populations in the North Atlantic. As a result, much information has been generated on the variation in marine populations and their relationship to the environment (see Cod and Climate Change, ICES 1994). At least in the North Atlantic, comparisons of populations and environmental parameters that span decadal time scales are now possible.

In the Pacific, physical and biological data sets are much shorter, spanning only the past three to four decades. The California Cooperative Oceanic Fisheries Investigations (CalCOFI) have concentrated on hydrography and plankton along the coast of upper and lower California since 1949. In the North Pacific, biological sampling of commercially important fishery resources has been conducted since the 1960's by Japan (Hokkaido University) and the National Marine Fisheries Service. Annual surveys of benthic species of invertebrates and finfish began on the Bering Sea shelf in 1972 (Mintel and Smith 1981, Wakabayashi et al. 1985). The data collected during these benthic surveys were used in Chapter 4 to analyze the distributional patterns of select species. Variations from year to year and on a scale of 4-6 years were observed when data from 20 years were analyzed (Chapter 4). At least for age-1 pollock (*Theragra chalcogramma*), age 2+ pollock and adult Arctic cod (*Boreogadus saida*), shifts in distribution between the inner, middle and outer domains of the Bering Sea shelf (Kinder and Schumacher 1982) occur over longer time spans than interannually (Chapter 4). These data, which span 23 years, include a suite of demersal species whose population characteristics of distribution and abundance can be related to environmental variables.

A dominant physical factor for the Bering Sea is the presence of the Aleutian low pressure system. The position and intensity of the low pressure cell dictates the direction and strength of the winds. During winter, at this high latitude, light and temperature decrease. The winds, have substantial effects on winter conditions, with cold winds blowing from the Arctic and warmer winds from the Pacific. The effects are observed in the extent and degree of seasonal sea ice that extends across the waters of the Bering shelf (Overland and Pease 1982, Niebauer and Day 1989, Chapman and Walsh 1993).

In this study, the relationships between seasonal sea ice (SSI) and fish distributions are explored in order to anticipate distribution of species in summer from ice conditions the previous winter. Although the presence of seasonal sea ice precedes the measures of fish distribution, a possible effect is through changes in temperature and buoyancy of shelf waters from the melting of SSI. A surface feature, monitored by satellite, that is related to the behavior of various populations on the shelf, would be a useful tool in evaluating and anticipating changes in the structure of populations on the shelf.

Three characteristics of SSI have been described and illustrate variations in the extent, duration and timing of sea ice on the shelf (Chapter 2). The southernmost extent of SSI along longitude 169°W (P_S), varies interannually and over longer time frames (Chapter 2). P_S is a characteristic of SSI that is readily monitored, is indicative of the extent of SSI on the shelf, and anticipates the extent of cold bottom water on the middle domain (Chapter 3). The amount of ice extending and remaining over the middle domain (ΔT_M) provides a measure of how much fresh water will be introduced into the middle and outer domains from the melting of sea ice. The timing of ice retreat (T_R) heralds the advent of spring, when the sea surface is once again exposed to heat and light and the production cycle commences. The timing of spring can be inferred from the retreat of the ice edge defined by T_R. Interannual variation in the retreat of ice spans 2.5 months, from mid-March to the end of May.

The objectives of this study are 1) to compare the distributions of a sub-Arctic species, walleye pollock, and an Arctic species, Arctic cod, to the behavior of SSI in order to establish SSI as a proxy measure of future patterns of fish distribution, and 2) to compare fish distributions to the environment affected directly by sea ice (water temperature) and the climatic conditions that directly affect SSI (Aleutian low pressure system).

Methods

Principal component analysis (PCA) was used to determine relationships of the distribution of age-1 pollock, age-2 and older pollock, and adult Arctic cod with the physical conditions of SSI, and ocean temperatures. Data sets for age-1 (10-20 cm Fork Length) and age-2 and older pollock (>20 cm Fork Length) include the inner, middle and outer domains of the southeastern shelf area and the middle and outer domains of the central area for 1972-1993 (Fig. 4.1). The data set for adult Arctic cod (10-30 cm FL) included the inner and middle domains of the central shelf area between 1975-1993. SSI characteristics of southernmost extent (P_S), duration ice remained over the shelf (ΔT_M), duration at southern extent (ΔT_S), and the timing of ice retreat from the shelf (T_R) were used as measures that describe the behavior of sea ice interannually between 1972-1993. Average bottom temperatures for the southeastern Bering Sea shelf (1972-1990 from Goddard and Zimmermann 1993, and 1991-1993 from G. Walters, pers. comm. NMFS/AFSC-Seattle, WA), and the eastern extent of the 2°C isotherm were used to represent water temperature conditions. All variables were normalized by subtracting the mean and dividing by the variance.

Variation over time was analyzed with the amplitude of the chosen principal components. The data for 1972 and all the data for the inner domain of the central shelf were omitted from this analysis due to missing data. The data matrix consisted of 21 values for stations sampled with walleye pollock for the years 1973-1993. The data matrix for Arctic cod consisted of 19 values for the years 1975-1993.

Variation over time for the significant principal components of each population was tested for correlations with measures of sea ice variability. Correlation coefficients of $r \geq 0.56$ are significant at the 99% level (n=20) (Hoel 1971).

Linear regressions were used to estimate the distribution of fish populations from significantly correlated SSI characteristics. Log+1, of the percent stations with fish, was used to compare population relationships with physical parameters. Data sets for physical characteristics of the Bering Sea shelf spanned 22 years. The data set for walleye pollock spanned 22 years, and for Arctic cod 19 years, between 1975-1993.

Results

Seasonal Sea Ice Characteristics

The distribution of age-1 pollock is influenced by ice conditions on the shelf (Table 5.1). Age-1 pollock on the middle domain of the southeastern and central shelf areas inversely varied with sea ice conditions particularly with ΔT_M and T_R. The first mode of variability (PC1) was for increasing age-1 populations in the middle domain with reduced ice extent, shorter duration of ice over the middle domain, shorter duration of ice cover at its southern extent, and earlier timing of ice retreat (Table 5.1). PC1 is sufficient to show the relationship between SSI characteristics and the distribution of age-1 pollock on the Bering Sea shelf. The second and third components are dominated by population distributions on the southeastern shelf and distributions in the outer domain, respectively and do not covary with measures of SSI.

Age-2 and older pollock on the central shelf area and in the inner and middle domains of the southeastern area inversely varied with ΔT_M and T_R (Table 5.1). Percent of stations sampled with age-2 and older pollock increased in the middle domains, the southeastern shelf inner domain and the central shelf outer domain with reduced ice extent, shorter duration of ice over the middle domain and earlier timing of ice retreat, as was the case with age-1 pollock. PC2 was dominated by populations in the outer domain covarying, out of phase with variation in PC1, and did not vary with SSI characteristics.

Table 5.1 - Principal component analysis of distributions for pollock and Arctic cod and characteristics of SSI.

	Age-1 PC1	Age-2 and older PC1	Arctic Cod PC1
Eigenvalue	3.1	3.7	2.9
% Total Variance	35%	41%	49%
Components			
SE-inner domain	0.535	0.742	-
SE-middle domain	0.687	0.827	-
SE-outer domain	0.050	0.343	-
Central-inner domain	-	-	0.848
Central-middle domain	0.741	0.790	0.586
Central-outer domain	0.302	0.560	-
ΔT_M	-0.793	-0.716	0.529
P_S	-0.534	-0.382	0.864
ΔT_S	-0.519	-0.521	0.503
T_R	-0.724	-0.696	0.452

The highest coefficients of variation were between duration of ice over the middle domain, and age-1 pollock and age-2 and older pollock in the middle domain (Table 5.1). Correlations were calculated to determine the significance of this relationship. Variability of age-1 pollock in the central area (Fig. 4.6) correlated with ΔT_M ($r=-0.53$; $p<0.02$), as did age-2 and older pollock ($r=-0.70$; $p<0.01$). Thus, the duration of ice cover over the middle domain varies in the same way as pollock distributions and can be used to predict the principal area where age-1 and age-2 and older pollock will reside on the Bering Sea shelf the following summer. A linear model, useful in predicting the behavior of pollock in summer, was developed from these relationships (Fig. 5.1).

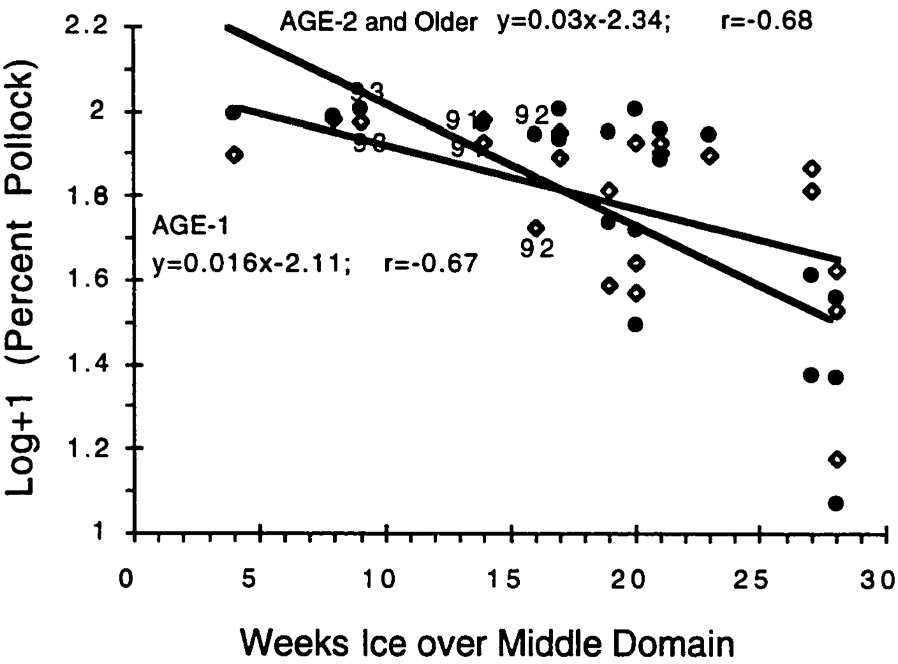


Fig. 5.1 - Relationship between the number of weeks ice remained over the middle domain (ΔT_M) of the central shelf and the percent stations with pollock for the period 1973-1993. Diamonds denote age-1 and circles age 2+. Years indicate measured values for 1991, 1992, and 1993; predicted values are on the line.

The equations are:

a) $\log(\%\ \text{age-1 pollock}) = 0.016\,(\Delta T_M) - 2.11$

b) $\log(\%\ \text{age 2+ pollock}) = 0.03\,(\Delta T_M) - 2.34$

where:

% = percentage stations with pollock in the middle domain
ΔT_M = number of weeks ice remains over middle domain

with significant correlation coefficients of $r = -0.67$ with $F = 6.2$ ($p=0.02$) for age-1 pollock and $r=-0.68$ with $F=15$ ($p=0.001$) for age 2 and older pollock.

The equations were derived from data between 1973-1990, and tested with data from 1991, 1992 and 1993 (Fig. 5.1). The trend of higher percentages of age-1 and age 2+ pollock in the middle domain with shorter duration of ice cover over the middle domain was found for both the southeastern and central areas of the Bering Sea shelf.

Arctic cod distributions on the central Bering shelf and SSI characteristics covaried (Table 5.1). Percent stations sampled with Arctic cod increased with more extensive ice cover, longer duration of ice over the middle domain and at its southern extreme, and a later timing of ice retreat. Arctic cod occur in the middle and inner domains in summers following winters when SSI characteristics had values indicative of cold conditions

The inner and middle domains and the southernmost extent of ice vary in the same way (Table 5.1). Correlation coefficients were significant for P_S and the distribution of Arctic cod in the middle ($r=0.66$; $p<0.01$) and inner ($r=0.67$; $p<0.01$) domains. Since Arctic cod occurred in the middle domain more often than in the inner domain, the regression for the middle domain is presented here (Fig. 5.2).

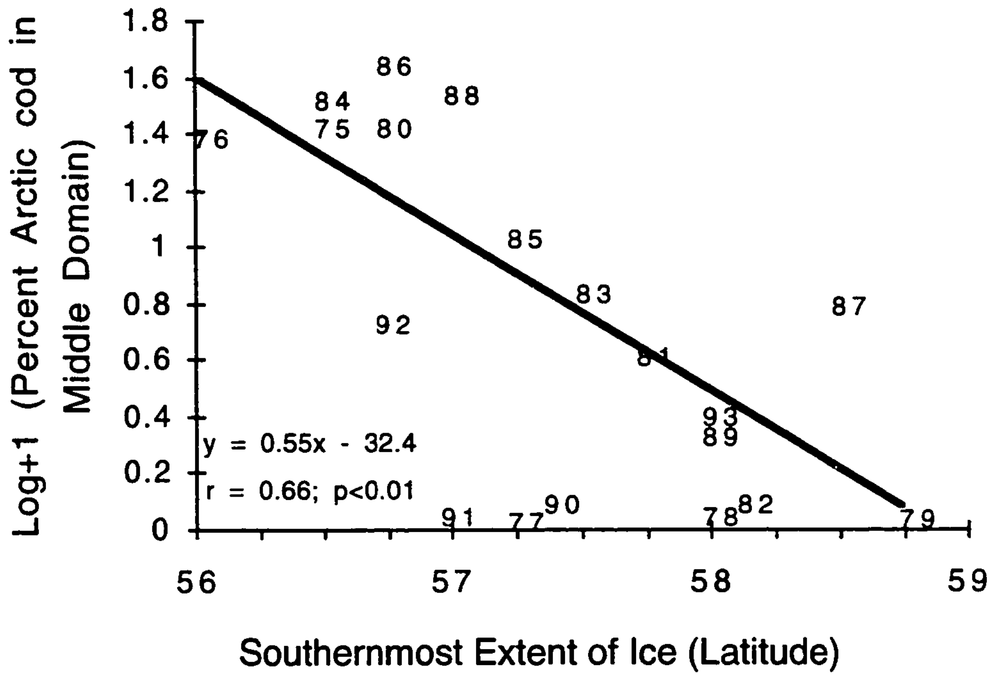


Fig. 5.2 - Relationship between the southernmost extent of sea ice and log of the percent stations with Arctic cod for the period 1975-1993. Observed values are marked with year; predicted values fall on the line.

The linear equation is:

$$\log(\%\ \text{Arctic cod in middle domain}) = 10.3\ (P_S) - 602$$

where:

% is the percentage of Arctic cod in the middle domain and

P_S is the southernmost extent of sea ice in degrees north latitude.

This equation was derived from data collected between 1975-1990, and tested with data from 1991, 1992 and 1993. Although the relationship is linear, with higher percentages of Arctic cod in the middle domain occurring when seasonal sea ice extends farther south, distinctly more Arctic cod (>10%) occur in the Bering Sea when ice extends between latitudes 57^o and 56^oN (Fig. 5.3).

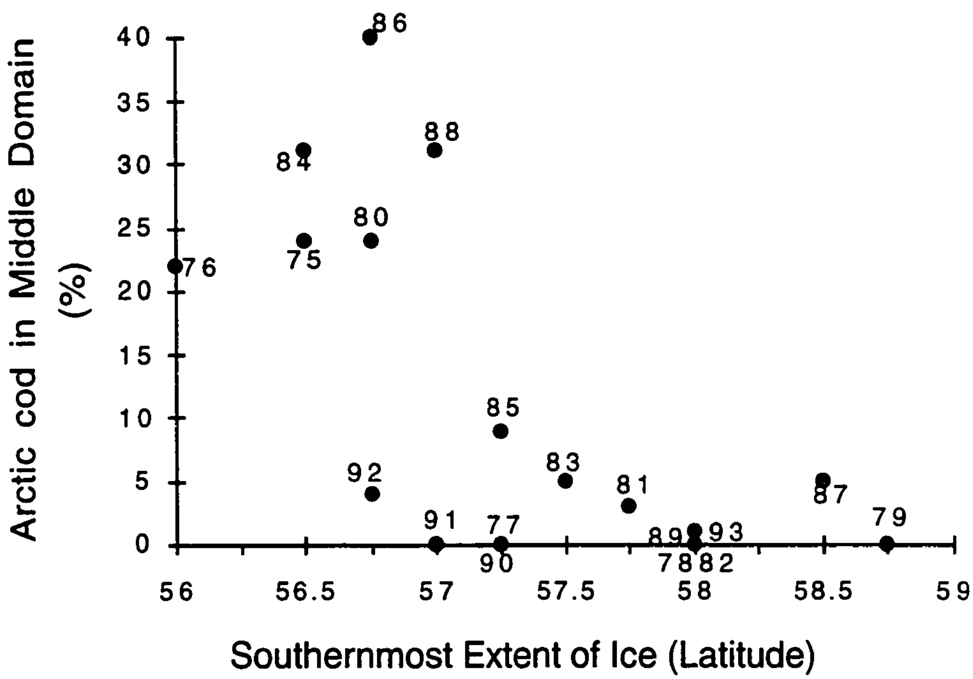


Fig. 5.3 - The southernmost extent of sea ice versus the percent stations with Arctic cod in the middle domain of the central shelf for the period 1975-1993. Higher percentages occurred when sea ice was more extensive.

Water Characteristics

Population distributions of age-1, age-2 and older pollock and Arctic cod in the inner and middle domains covary with the easternmost extent of the cold pool and the overall average bottom temperatures on the southeastern Bering Sea shelf (Table 5.2). PC1 contained a significant portion of the variability between populations and water temperature. Percent total variance was 30% for age-1, 42% for age 2+ pollock and 67% for Arctic cod. Therefore, the first principal component accounted for a significant portion of the variability among these three populations and water conditions of bottom temperature and the extent of the cold pool. Coefficients of variation for each component indicate which components covary (high positive values), contrast (high negative values, unless the values get smaller as the variable increases as is the case with the cold pool extent) or do not covary (low numbers). Age-1 pollock increased in the middle domain (SE and Central) with increasing bottom temperatures and a less extensive cold pool. Age 2+ covaried across the shelf with increases in populations, with warmer bottom temperatures and a less extensive cold pool (Table 5.2). Populations of age-1 pollock in the outer domain did not covary with measures of bottom temperature.

Table 5.2 - The first principal component for pollock and Arctic cod distributions, by area and domain, and characteristics of water temperature on the Bering Sea shelf. Cold pool is a measure of the easternmost longitude of the 2°C bottom isotherm and the bottom temperature is the average bottom temperature in the southeastern shelf area (Goddard and Zimmermann 1993). No comparisons are indicated with a -.

	Age-1 PC1	Age-2 and older PC1	Arctic cod PC1
Eigenvalue	2.3	3.4	2.6
% Total Variance	34%	48%	66%
Components			
SE-inner domain	0.332	0.809	-
SE-middle domain	0.434	0.802	-
SE-outer domain	0.065	0.371	-
Central-inner domain	-	-	0.765
Central-middle domain	0.850	0.815	0.794
Central-outer domain	0.557	0.590	-
Cold Pool	-0.655	-0.614	0.831
Bottom Temps	-0.768	-0.728	0.848

The population of Arctic cod increases in the central shelf when bottom temperatures drop, indicated by either a larger cold pool or lower average bottom temperatures (Fig. 5.4). This trend holds true for populations in both the inner and middle domains (Table 4.2), and although Arctic cod have been found in warmer temperatures, occurrence on the Bering shelf is greaatest when water temperatures are ≤ 3.0°C (Fig. 5.4).

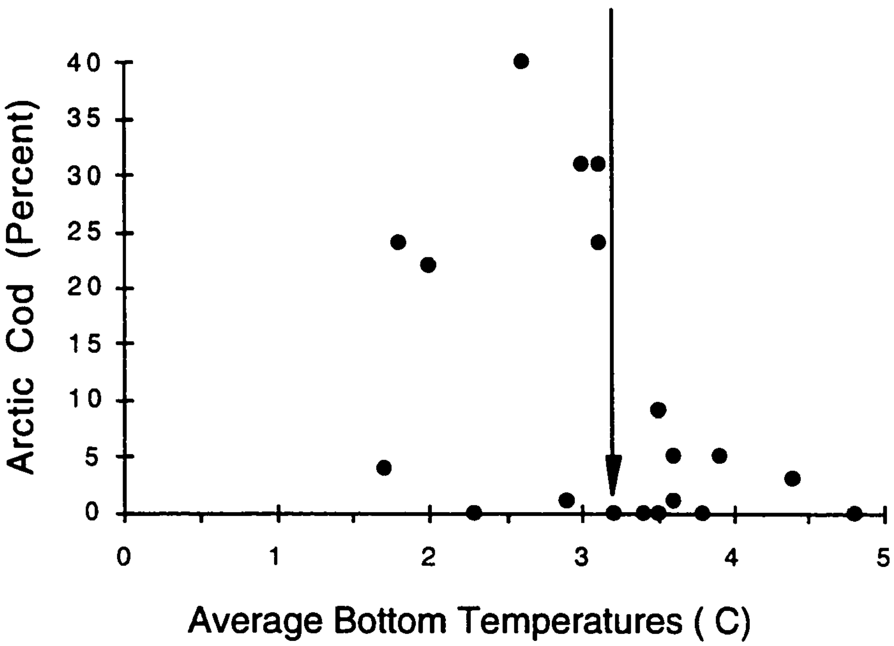


Fig. 5.4 - Presence of Arctic cod, measured by the percent of stations sampled in the middle domain of the central shelf area that contained cod, and the average bottom temperatures on the Bering Sea shelf.

Discussion

Seasonal sea ice, particularly in spring, is an indicator of water mass characteristics and patterns of distribution of pollock and Arctic cod on the Bering Sea shelf the following summer. The association of pollock and Arctic cod populations with the middle domain habitat are apparent and coincident with affects of seasonal sea ice. Fluctuations of both populations around the middle domain are the dominant characteristic of the behavior of pollock distributions during summer.

The variation of conditions in the habitat of the middle domain, particularly water temperature, is a result of variation in seasonal sea ice. As we have seen in Chapter 2 the extent and amount of cold bottom water is related to the extent of seasonal sea ice. More cold bottom water occurs in years of extreme ice conditions, when ice extends farther south and remains over the middle domain for a longer period, than in years when ice conditions are reduced.

Distributions of walleye pollock are related to water temperature. In results of the bottom trawl surveys to the eastern Bering Sea shelf in 1975 and 1979-1982, Bakkala and Alton (1986) report the distribution of the pollock population to be positively correlated with average bottom temperatures. They found a high proportion of the pollock population inside the 100 m isobath (i.e., the inner and middle domains) when average bottom temperatures were above 3°C. During the 5 years of their study, the cold pool expanded to its farthest eastern extent and retreated to its farthest western extent twice (Table 3.6). During these extreme conditions of more (1975, 1980, 1982), or less (1979, 1981) cold water, the pollock population was observed to occupy areas during warm years that they did not occupy during cold years. Over a 20 year period the population of age-1 and age-2 and older pollock continued to covary with bottom temperature conditions. When average bottom temperatures were colder than 3°C, and the cold pool extended into Bristol Bay, there were lower percentages of the pollock population in the inner and middle domains.

Arctic cod range farther south when the presence of SSI results in a more extensive cold pool, and colder average bottom temperatures, than in years with reduced ice cover, smaller cold pool and warmer average bottom temperatures. These findings support Gillispie's et al. (in press) conclusion that Arctic cod will occupy waters warmer (2-3°C) than previously thought. The summertime conditions in the middle domain affect the distribution of both walleye pollock and Arctic cod. When conditions are favorable for walleye pollock they are unfavorable for Arctic cod.

Population distributions of age-1 pollock changed in 1977 and 1985 and those of age-2 and older in 1977, 1982, and 1987 (Chapter 4), corresponding to a change in the climate of the North Pacific. Characteristics of atmospheric pressure systems affect the oceanic environment on the Bering Sea shelf in three ways: 1) surface layer mixing with stronger pressure cells; 2) warming of SST from El Niño events and/or southern water masses transported northward; and 3) more or less ice cover. A reduction in sea level pressure across the North Pacific from a mean of 1010 mb between 1946-1975 was followed by lower pressure averaging 1007 between 1976-1988 with the anomalous low pressures occurring in winter months (Trenberth and Hurrell 1994). Intensified low pressure in winter and the accompanying shift in the Aleutian low eastward, results in winds from the south, water from the south and reduced ice cover. Winter sea surface temperatures on the Bering Sea shelf were anomalously cooler between 1966-1976 and anomalously warmer between 1977-1987, then cooled again between 1988-1991 (Wooster and Hollowed 1995). The warm period was punctuated by anomalies greater than 1 standard deviation in 1977, 1979, 1981 and 1985. The transition years of 1977 and 1988 were consistent across the eastern North Pacific (Hollowed and Wooster 1992). Another phenomenon that affects SST is the El Niño events that occur on a time scale of 2-5 years, with more intense El Niños on a decadal time scale (Wooster and Hollowed 1995). The strongest El Niño of this century occurred in

1982/83 (Wallace 1983) during an already warm period, with the result of increased SST across the eastern North Pacific and into the Bering Sea. Sea ice conditions in the Bering Sea (Mysak and Manak 1989, Chapman and Walsh 1993, Salmon 1992) show a change from a cold period to a warm period around 1977. Shifts in the pollock distributions correspond with the timing of various environmental changes. A redistribution of age-1 pollock from the outer to the middle domain occurred after 1977, during the generally warmer period, and an increased distribution in the inner domain after an extreme El Niño event (1983). The distribution of both age-1 and age 2+ pollock follows similar patterns. This implies that age-1 and older fish are responding to environmental changes in a similar way.

The distribution of Arctic cod changes in concert with environmental conditions but opposite to the response of walleye pollock. Arctic cod extends southward, onto the Bering Sea shelf from their principal area of distribution to the north. The range of Arctic cod extends to lower latitudes during periods of colder conditions in the North Pacific. Anecdotal information by P. M. Hansen and R. W. Blacker at the end of Rass's paper (1968) indicates that the abundance and distribution of Arctic cod have changed dramatically off northern Greenland. Arctic cod were abundant between latitudes 69^{o} and 72^{o} N, in the 1920's, and all but disappeared by the mid-1930's. It was hypothesized that this decline was related to changes in climate. A period of warming in the North Atlantic has been documented for 1930's-1960's when large increases in more southerly stocks of Atlantic cod (*Gadus morhua*), herring (*Clupea harengus harengus*), redfish (*Sebastes marinus*) and Atlantic salmon (*Salar salar*) were noted (see Cushing 1982). Arctic cod populations were apparently displaced to the north during this long warming period in the Atlantic; a similar response is seen in the Pacific where Arctic cod were found farther south when the climate was cooler.

Changes in climatic conditions of the North Pacific are correlated with the shifting patterns of distribution of fish species. The atmosphere affects the ocean and ice conditions which in turn affect the habitat of fishes. Seasonal sea ice characteristics of P_S, ΔT_M or T_R are indicators of distribution of populations on the shelf and have higher coefficients of variation than other indices. They provide a window, through which we can glimpse future conditions.

CHAPTER SIX - Variation in Sea Ice and the Cold Pool of the Bering Shelf - Consequences to the Ecosystem

Introduction

Environmental variability affects the distribution of species and that, in turn, affects species interactions. Conditions of the demersal habitat of the Bering Sea shelf (Fig. 6.1), and species interactions related to it, were evaluated in this study. Throughout this work the emphasis has been on the demersal age-1 pollock (10-20 cm Fork Length) (*Theragra chalcogramma*), ages-2 and older pollock (>20 cm Fork Length), and Arctic cod (*Boreogadus saida*) (10-25 cm Fork Length). The benthic habitat on the Bering Sea shelf is dominated by a pool of relatively stationary, subsurface water with temperatures at, or below the physiological limit of many sub-Arctic species. However, surrounding this submerged island of Arctic water is a subarctic habitat available to mobile fish species such as pollock.

The capacity to live under the sea ice has enabled Arctic cod to populate an environment not available to walleye pollock, a sub-Arctic species lacking the "anti-freeze" glycoproteins of Arctic cod. Age-1 pollock and Arctic cod are nearly indistinguishable in external appearance, both serving as a forage fish linking benthic and pelagic food webs (Sameoto 1984) and upper and lower trophic levels. As two forage fishes with different habitat requirements, they provide a means for the comparison of behavior of a sub-

Arctic and Arctic species in a habitat with both components. Age-2 and older pollock were investigated separately from age-1, because they are caught by the commercial fishery and are linked to age-0 and age-1 fish, not only genetically, but also as predators. The distribution of Arctic cod extends to the Bering Sea during cold years. The distribution of age-1 walleye pollock changes on a scale of every 6-7 years, as does the distribution pattern for age-2 and older walleye pollock (Chapter 4).

Age-1 walleye pollock are a transition stage in the size-specific vertical distribution of this species and are vulnerable to factors that determine year-class strength. Recruitment is related to several factors, including environmental variables of air temperature, bottom temperature and ice conditions at ages-0 and 1 (Quinn and Niebauer 1995). Ohtani and Azumaya (1995) report that abundance of walleye pollock is related to a combination of fecundity and winter conditions at age-1. Winter conditions play an important role in determining the year-class strength of walleye pollock and on their distribution (Wyllie Echeverria in press). As age-1 fish are reported to winter on the shelf (Radchenko and Sobolevskij 1992), heavy ice conditions during winter may act to concentrate age-1 fish, their predators, and their prey in the narrow range of ice-free water near the shelf break. This shrinking habitat increases species interactions and could result in poor recruitment at age-2.

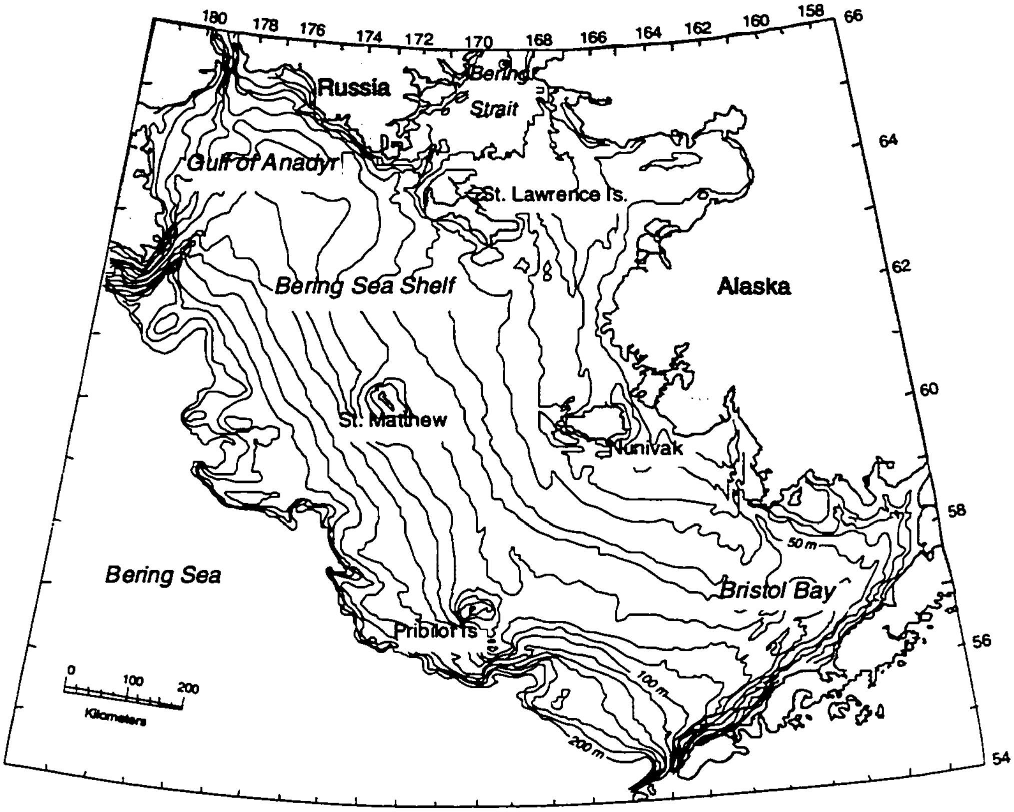


Fig. 6.1 - The Bering Sea shelf showing the inner domain (landward of the 50 m isobath), the middle domain (between the 50-100 m isobaths) and the outer domain (seaward of the 100 m isobath to the shelf break at the 200 m isobath). The bathymetry is shown in 10 m increments between 0-100 m and 20 m increments between 100-200 m isobaths.

The interannual distribution of a species has ecosystem-wide consequences. Availability of age-1 pollock, a fish utilized as prey by a number of seabirds and marine mammals with limited foraging areas, and by fish predators with temperature limitations, will be enhanced or diminished depending on their pattern of distribution. Predictable patterns of distribution for age-2 and older pollock can be provided to the commercial fishing fleet. Following winters of extensive ice cover, fish will be concentrated in the outer domain, providing the fleet with a more limited fishing area and higher concentrations of their target species, as opposed to conditions following a winter with reduced ice cover. The fluctuation of fish distributions and their relationship to environmental variables can be used to understand and predict ecosystem wide changes on the Bering Sea shelf.

In this chapter I evaluate the biological repercussions of the cold and warm modes that delineate the interannual physical conditions on the shelf (Chapters 2 and 3) with regard to distribution of prey species (age-1 pollock and Arctic cod) and their predators (piscivorous fishes, seabirds and marine mammals). The extent of seasonal sea ice along longitude 169°W (as described in Chapter 2) can be used to define climatic modes and detects regime shifts between cold and warm phases. Insights into conditions of the demersal habitat and species interactions can be derived from a single variable based on the extent of sea ice cover along meridian 169°W.

The Bering Sea Shelf

Hydrographic conditions on the Bering Sea shelf result from a combination of atmospheric forcing and the oceanic state (Peixoto and Oort 1992, Trenberth and Hurrell 1995). Winds affect the water over the shelf through surface mixing and by affecting seasonal sea ice extent (Overland and Pease 1982, Niebauer and Day 1989). The oceanic state affects sea surface temperatures and reacts over a longer time scale than synoptic atmospheric forcing (Trenberth 1990, Royer 1993). Winter and summer conditions differ drastically on the shelf and the transition between the two determine the shelf's physical state the following summer (Chapters 2 and 3).

Winter on the shelf is a turbulent time when sea and ice meet. Winds from the north push ice southward, from its origin in the Chukchi Sea and polynyas in the Bering Sea, to the southernmost edge, where warmer air and water temperatures halt ice advance through melting. Winds whip the Bering shelf periodically throughout winter and the direction and strength of these storms affects the limit of ice advance (Overland and Pease 1982). In the recent past, ice has covered the inner domain each winter, with variability in the extent of ice ranging across the middle and into outer domains (Chapter 2). Under the ice, water continues its northward flow toward the Arctic Ocean. The water column is isolated from surface storms and is generally homogeneous due to the continued extrusion of brine from both polynyas and seasonal ice throughout winter. The amount of fresh water introduced onto the shelf system from the melting of sea ice is directly related to the hydrographic conditions the following summer (Chapter 3).

During summer three frontal features divide the shelf into different environments or domains (Kinder and Schumacher 1982). The inner shelf front coincides with the 50 m isobath and separates a shallower mixed water column from a two-layered water column in waters deeper than 50 m. The middle front approximately coincides with the 100 m isobath and separates the middle domain from the three-layered, outer domain. The shelf break front marks the hydrographic outer boundary of the shelf. Situated in the middle domain of this sub-Arctic shelf is a semi-isolated body of subsurface water, called the cold pool, with temperatures characteristic of an Arctic system, of -1.8° to 2.0°C (Takenouti and Ohtani 1974).

It is difficult to image the presence and dynamics of this cold pool of water without a terrestrial or atmospheric analog. The cold pool is a large body of water about 220 km wide and a variable extent of 556 km to 1334 km in length. On average, the cold pool extends from the Gulf of Anadyr (Khen 1988) to 163°W in the east (Ingraham 1981, Reed 1995) (Fig 6.2). This massive volume of water changes character each fall, as a result of mixing, and is reestablished each spring due to stratification. Its significance lies in its size, persistence, and the species assemblages associated with it. The middle domain is deep enough to stratify into two layers when surface waters are warmed in spring. This stratification, in combination with low flow rates, "traps" the residual water formed by winter conditions below the mixed-layer depth. The annual influx of cold, low-salinity water is essential in maintaining the cold pool as a recurring summertime feature. It extends from the bottom (which is 50-100 m deep) to the thermocline (10-15 m from the surface), and varies in thickness from 35 to 90 m. Its presence is dependent upon four factors: 1) bottom topography, 2) sea ice, 3) depth, and 4) currents. The gently sloping bottom topography between 50 and 100 meters characterizes the middle domain, and the shelf only becomes steep and convoluted east of 163°W in Bristol Bay and in the western Gulf of Anadyr, as the shelf meets its terrestrial boundaries at 180°W (Fig. 6.1). The minimal extent, to 171°W, coincides with a change in the bathymetric contours from a northwest-southeast direction to an east-west direction. The long-term (1902-1990) average extent is 163°W (Ingraham 1982, Reed 1995), where the bathymetry changes again, but this time to a northeast-southwest direction.

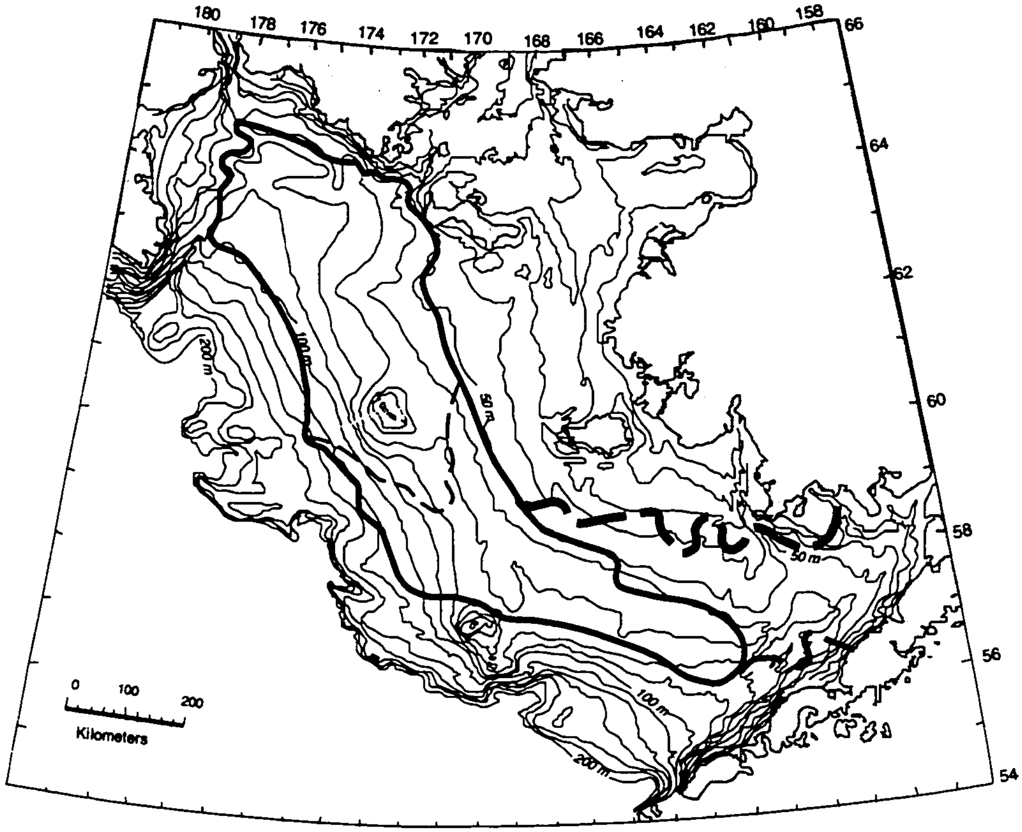


Fig. 6.2 - The areal coverage of the subsurface cold pool in the middle domain. The solid line marks its long term average extent (Ingraham 1981; Reed 1995). Small dashes mark the minimum extent and large dashes maximum extent.

The cold pool on the western shelf has very different characteristics than its eastern component. At its minimal size, the cold pool on the western shelf is colder and more saline than to the east, with water temperatures <-1.0°C and salinities <33.2 psu (Hufford and Husby 1972). This water is more saline due to brine extrusion that occurs with the formation of sea ice in the St. Lawrence Is. and Cape Dubrovsky polynyas. The formation of cold, saline water in the middle domain is a dense water type and persists as the cold pool in the western shelf. As long as sea ice formation occurs at these polynyas, a cold pool should exist in the western shelf of the middle domain. The eastern edge of the cold pool varies annually and is related to the extent of ice the preceding winter (Chapter 3). This eastern cold pool is characterized by temperatures ≤2.0°C and salinities of 32.4 psu (Maeda 1977). The maximum southeastward extent of the cold pool is limited by the continental land mass of Alaska and the Alaskan Peninsula.

Scales of Variability

At least two scales of environmental variability exist on the Bering Sea shelf, interannual fluctuations between warm and cold modes and regime shifts on the scale of multiple years. For the interannual scale of variability, two modes can be defined from the southernmost extent of ice (P_S) (Table 6.1). When ice extends

Table 6.1 - The characteristics of cold or warm conditions can be made from the southernmost extent of sea ice along meridian 169°W. Additionally, conditions can be characterized by the direction of wind (in April) to the shelf, the extent of the cold pool in the middle domain, and the average summertime bottom temperature of the southeastern shelf. An intermediate (mezzo) state occurs occasionally, when neither warm nor cold conditions dominate.

Mode	Wind direction	Seasonal ice (latitude)	Cold pool (longitude)	Bottom temperature
COLD	continental	57°30'-56°	163-158°W	1.2-3.0°C
Mezzo	continental	57°30'-57°	166-163°W	3.0-3.8°C
WARM	maritime	60°-57°30'	170-166°W	3.8-4.6°C

between 57°30' and 56°N conditions are cold, continental or Arctic air sweeps the shelf from the northeast, causing the cold pool to strengthen and extend eastward of meridian 163°W (Fig. 6.1), and average bottom temperatures are 1.2-3°C (Chapter 3). Arctic cod occur on the Bering Sea shelf in the inner and middle domains when conditions are cold (Chapter 4). A warm mode occurs when ice remains north of 57°30'N. The cold pool is weakened, lying west of

St. Matthew Is. (170°W) and meridian 166°W, and average bottom temperatures on the southeastern shelf range between 3.8-4.6°C (Table 6.1). Arctic cod are not found on the Bering Sea shelf under these conditions (Chapter 4). Occasionally an ambiguous situation arises when continental air sweeps the shelf, and the limits of sea ice and the cold pool border the two modes. This intermediate condition does not represent average conditions and is termed the mezzo, or middle, mode. From charting the maximum extent of ice along meridian 169°W, the maximum extent can be determined for a particular year. From this single measure of ice extent the subsurface conditions on the middle domain 3-4 months later can be predicted.

Why a boundary condition of ice extent appears at 57°30'N can only be speculated upon. The number of conditions, for example, the size of cold pool, average bottom temperatures, and species distributions, that relate to this boundary are too numerous to be coincidental. A combination of hydrographic conditions, depth, and the slope of the bottom may act to limit the influence of ice melt. At 57°30' the slope of the bottom in the middle domain changes direction from southeast to eastward. When ice extends beyond 57°30'N, the melting edge of the ice is physically located over the part of the shelf where the cold pool will extend to in summer.

The second scale of variability is multi-annual, warm and cold regimes (Fig. 6.3) of 6-7 years duration. Regimes composed of the years 1972-1977, 1978-1983 and 1984-1990 in the Bering Sea resembled the sea surface temperature patterns of predominantly cold, warm, and mixed conditions that are described by Wooster and Hollowed (1995) for the Northeastern Pacific of 1971-1976, 1977-1984 and 1985-at least 1990. The condition since 1984, while cooler than the preceding period, did not return to the steady cold conditions of 1972-1977. Wooster and Hollowed (1995) attribute this pattern to the teleconnection of the El Niño-Southern Oscillation (ENSO) that controls the atmospheric conditions of the eastern Pacific (Trenberth 1990). El Niño events of 1976-1977 and1982-1983 are the boundary years between the cold, warm and mixed regimes on the Bering Sea shelf. The mixed regime is punctuated by the warm years of 1987 (El Niño of 1986-1987) and 1989 (weak El Niño following a strong anti-El Niño). The teleconnection between ENSO events in the tropical Pacific and the warming and cooling observed in the Bering Sea appears to be via the atmosphere, in particular the ALPS (Niebauer and Day 1989). The interannual and regime scale climatic shifts between warm and cool conditions are a result of the annual ENSO pattern and the frequency of occurrence of El Niños and La Niñas.

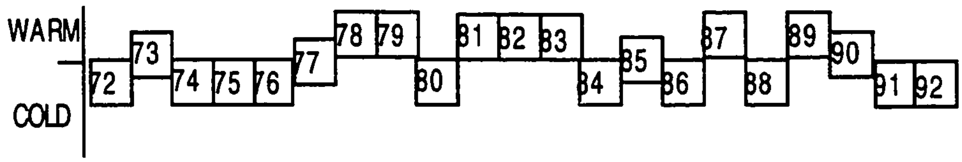


Fig. 6.3 - Timeline of two climatic modes reveals regime scale variability on the Bering Sea shelf. Intermediate conditions are on the line, midway between warm or cold modes. A cold regime occurred between 1972-1977, a warm regime between 1978-1983, and a mixed regime between 1984-1990

Predator-Prey Interactions

Species distributions may vary on either the interannual or regime scale with consequences to their predators. Shifts in the distribution of walleye pollock occur on the regime scale. Age-1 pollock generally were distributed in the middle and outer domains during the cold regime, and in the middle and inner domains during the warm and mixed regimes (Chapter 4). Age-2 and older pollock were distributed primarily in the outer domain during the cold regime (1972-1977), expanding into the middle domain during the warm regime (1978-1982). They extended their distribution further into the inner domain in the mixed regime after 1983 (Chapter 4). Changes in the distribution of age-2 and older walleye pollock will affect fishing efforts by humans. Warm and mixed regimes, with their concomitant reduced ice conditions, open up fishing areas on the Bering Sea shelf earlier than during a cold regime. In this case, pollock would be distributed over a wider area, increasing the effort needed to capture them, with walleye pollock spread across the middle, as well as, the outer domain.

The distribution of Arctic cod varied on the interannual scale, occurring on the shelf only during cold years. Cold bottom temperatures influence the positioning and movements of walleye pollock and Arctic cod on the Bering Sea shelf (Chapter 4). Even with only two species as examples, the affects of changing environmental conditions on the distribution of species are apparent. The influence of the cold pool on species distributions and interactions is a key factor in understanding the dynamics between predator and prey. Walleye pollock are the principal prey of many marine mammals, seabirds, and fish on the shelf (Kihara and Shimada 1988; Livingston 1991; 1993; Springer 1992; Sinclair et al. 1994) and shifts in the distribution of walleye pollock impact the entire food-web.

Interactions between predators of age-1 walleye pollock may vary on the scale of interannual availability or on the longer-term, complex regime scale. The scale of variability of each predator, as well as the distributional patterns, must be evaluated when considering the interactions between predator and prey. Shifts in the distribution of age-2 and older walleye pollock will change the area, or encounter rate, for cannibalism on age-0 and age-1 walleye pollock, as well as change the area of the commercial fishery on pollock. Predation by seabirds and marine mammals that are limited in their foraging areas because of nesting and pupping requirements, is another consideration (Springer 1992, Sinclair et al. 1994). As we have seen, species and environmental conditions vary on at least two scales. An understanding of the scales of variability and the resultant responses of both predator and prey species is the level needed when investigating ecosystem scale interactions.

Walleye pollock, arrowtooth flounder, (*Atheresthes stomias*), and Pacific cod, (*Gadus macrocephalus*) (Shuntov and Dulepova in press, Livingston et al. 1993) are the principal fish predators on age-1 walleye pollock, from the Sea of Okhotsk to the Bering Sea. Predation levels for the years 1984-1992 (Livingston 1991, 1993, pers. comm., National Marine Fisheries Service, Alaska Fisheries Science Center, Seattle WA) ranged between 100-15,000 million fish per year for cannibalism, between 100-1,400 million fish per year by arrowtooth flounder, and between 60-1,600 million fish per year by Pacific cod. These data were divided into three categories to evaluate relative predation pressure from each predator on age-1 pollock, and demonstrates that predation by cannibalism is much higher than either of the other major piscine predators (Table 6.2). Additionally, relative ranking of predation shows interannual variability that corresponds to warm or cold/intermediate climatic modes, particularly by older pollock and arrowtooth flounder (Table 6.2). Predation pressure during this time period, which was dominated by mixed regime conditions, is related to the interannual condition or warm of cold rather than on a regime scale.

Table 6.2 - Relative (low, medium, high) level of predation by age-2 and older walleye pollock, arrowtooth flounder and Pacific cod on age-1 walleye pollock for the years 1984-1992. Cold (C), warm (W) (in bold type) or mezzo (M) modes of environmental conditions are identified.

YEAR	MODE	CANNIBALISM	ARROWTOOTH FLOUNDER	PACIFIC COD
1984	C	no data	HIGH	LOW
1985	M	HIGH	MED	MED
1986	C	MED	HIGH	HIGH
1987	**W**	**LOW**	**LOW**	**MED**
1988	C	HIGH	MED	LOW
1989	**W**	**LOW**	**LOW**	**LOW**
1990	M	HIGH	HIGH	MED
1991	C	MED	MED	MED
1992	C	HIGH	LOW	LOW

Predation by fish is linked to water temperature and to the distribution of age-1 pollock (Kihara and Shimada 1988, Livingston et al. 1991, 1993). The occurrence of juvenile walleye pollock within and inshore of cold water masses has led to the hypothesis that juvenile walleye pollock can occupy different habitats than age-2 and older pollock, thus reducing cannibalism (Francis and

Bailey 1983). Predation on age-1 walleye pollock was positively correlated with overlapping distributions of Greenland turbot (*Reinhardtius hippoglossoides*), yellow Irish lord (*Hemilepidotus jordani*), and thorny sculpin (*Icelus spiniger*) and warmer bottom temperatures (Kihara and Shimada 1988). Predation pressure on age-1 walleye pollock is heavy from their major piscine predators (age-2 and older walleye pollock, arrowtooth flounder and Pacific cod) (Table 6.3), and lighter for other predators (Greenland turbot, yellow Irish lord, and thorny sculpin) during the cold mode (Kihara and Shimada 1988). Predation pressure was highly variable from Pacific cod and a clear pattern was not seen for the period 1984-1992 (Table 6.2). Conditions which increase predation from one suite of predators may reduce predation from another suite.

Table 6.3 - Distribution of age-1 and age-2 and older walleye pollock during cold and warm modes on the Bering Sea shelf and the corresponding predation pressure (heavy, medium, light) on age-1 pollock, by cannibalism, arrowtooth flounder and Pacific cod between 1984-1992.

Mode	AGE-1	AGE-2 AND OLDER POL-LOCK	CANNI-BALISM ON POLLOCK	ARROW-TOOTH FLOUNDER	PACIFIC COD
Cold	middle outer	outer	heavy	heavy medium	heavy medium light
Warm	inner middle	inner middle outer	light	light	medium light

A dominant prey of lactating Northern fur seals (*Callorhinus ursinus*) near the Pribilof Islands is walleye pollock (National Marine Fisheries Service 1992, Perez and Bigg 1986, Sinclair et al. 1994). In addition to pollock, capelin (*Mallotus villosus*) and Pacific herring (*Clupea harengus*) were important items for 1958-1974 (Kajimura 1984), with sandlance (*Ammodytes hexapterus*) but not herring or capelin eaten by seals collected in 1981, 1982 and 1985

(Sinclair et al. 1994). The distribution and abundance of each principal prey species could be significant in the feeding success and nutritional benefit to these seals during lactation and the success of pups when they begin feeding. Although the data do not exist for every year (1972-1991) a shift appears to have occurred in the diet of seals sometime between 1974 and 1981, during the transition between a cold regime and a warm regime (Table 6.4). Demersal trawls adequately represent the age-2 and older walleye pollock population on the shelf. However, age-1 walleye pollock and Arctic cod also inhabit the pelagic environment (Rose and Walters 1990) and must be taken into account when evaluating food availability. Concentrations of Arctic cod also occurred northwest of the Pribilof Islands in 1975, 1976, 1980, 1984, 1986 and 1988 (Chapter 4), and could be utilized by northern fur seals when they are concentrated within the feeding range of seals, as occurred in 1975, 1976 and 1986 (Chapter 4).

Table 6.4 - Reproductive success and food habits of thick-billed murres and northern fur seals in the Bering Sea vary on the time scales of regime shifts shown in Fig. 6.3.

Years	Regime	Age-2 and older Pollock	Northern Fur Seal		Thick-billed Murres	
		Predominant Domain	Repro-duction	Food	Repro-duction	Food
1972-1977	Cold	Outer	good	capelin pollock	good	capelin
1978-1984	Warm	Middle	poor	pollock sand-lance	poor	pollock
1985-1991	Mixed	Middle and Inner	poor	pollock sand-lance	poor	pollock

Reproductive success of thick-billed murres (*Uria lomvia*) on the Pribilof Islands between 1974-1991 (Decker et al. 1995) was not correlated with interannual measures of sea ice condition, age-1 or age-0 pollock abundance or sea surface temperature (Hunt et al. in press). Decker et al. (1995) propose that an ecosystem-wide change occurred on the Bering Sea shelf, with the regime shift of 1976-77, and that a shift back has not yet happened. Cold, warm and mixed regimes (Table 6.4), defined using P_S, are in agreement with their conclusions. While a regime shift to cooler conditions did occur in 1985, it was not on the scale of multiple years of cold conditions that occurred in the cold regime (Fig. 6.3). A return to pre-1978 conditions has not occurred as yet, and consequently reproductive and feeding behavior in thick-billed murres and northern fur seals have not returned to their pre-1978 levels. Possibly the colder conditions that affect the distribution of age-1 pollock are acting on the capelin and herring to change their distribution, decreasing their availability to thick-billed murres and northern fur seals. The modeling efforts of Pascal and Adkison (1994) testing the effects of sea lion harvest, short-term environmental fluctuations and transient effects of age-class structure, conclude that Steller sea lion declines were not related to short-term environmental fluctuations but to significant long-term environmental degradation, perhaps on the scale of the regime shifts of 6-7 years duration. The reproductive success and prey species of Steller sea lions (NMFS 1992), black-legged kittiwakes and thick-billed murres (Decker et al. 1995, Hunt et al. in press) is not related to interannual shifts in the distribution of age-1 pollock but rather to shifts on the scale of regimes.

Summary

The physical environment of the Bering Sea shelf is complex, with daily variability in the position and intensity of the Aleutian Low Pressure System (ALPS), resultant storm tracks, the marginal ice zone, air temperature, water temperature and water column mixing. By averaging conditions of the ALPS into monthly means, trends in the behavior of the ALPS were investigated and the long-term (monthly, annual) affects on the Bering Sea system determined. In particular, the affects of the ALPS on the marginal ice zone were investigated as a recurring physical phenomenon with a remotely acquired record. From satellite data, the southernmost position of the sea ice edge was determined and used to predict both physical and biological conditions that occurred on the shelf the following summer. This key piece of information provides a large-scale indication of either warm or cold conditions.

Insights into the relationship among atmospheric, oceanic and biotic conditions on the Bering Sea shelf will aid in the understanding of this system and provide baseline data useful in projecting future conditions through modeling efforts. The extent of sea ice is an abiotic indicator that signals future conditions in the system. Two principal modes, cold and warm, can be measured with the benefit that the parts of the system (bottom temperature, cold pool, distribution of species) that vary on an annual basis can be determined from winter conditions. This extends to the distribution of harvestable stocks with the result that the location of some species, such as walleye pollock, could be predicted. With the availability of the scale of physical conditions that affect biological systems, information for atmosphere-ocean modeling as well as ecosystem modeling efforts can be tested with numbers that represent real conditions.

The correspondence of regime-scale variability spanning the North Pacific system are suggestive of a single cause, across the area for the physical state of the ocean. The regimes defined for the Bering Sea, based on the amount of seasonal sea ice and controlled by the position and strength of the Aleutian low pressure system, have timing and duration similar to those of the regimes defined by sea surface temperatures in the Northeastern Pacific (Wooster and Hollowed 1995). Additionally, the behavior and interactions of species, while having an interannual component, also respond on the scale of the observed regimes. Year-class strength of walleye pollock in the Bering Sea is higher during warmer regimes (Hollowed and Wooster 1995). Also, during the warm regimes predicted by ice extent, age-2 and older walleye pollock are distributed more widely over the outer, middle and inner domains of the Bering Sea shelf. This increase in available habitat and generally warmer conditions appears to be conducive to larval survival in this sub-Arctic species. Evidence of the links between the physical and biological systems enables us to predict events in the biological system from the physical system. Sorting out the scale of variability for each portion of the ecosystem is fundamental to our understanding of the system, enabling us to predict the types of ecosystem responses that will occur under varying climatic scenarios.

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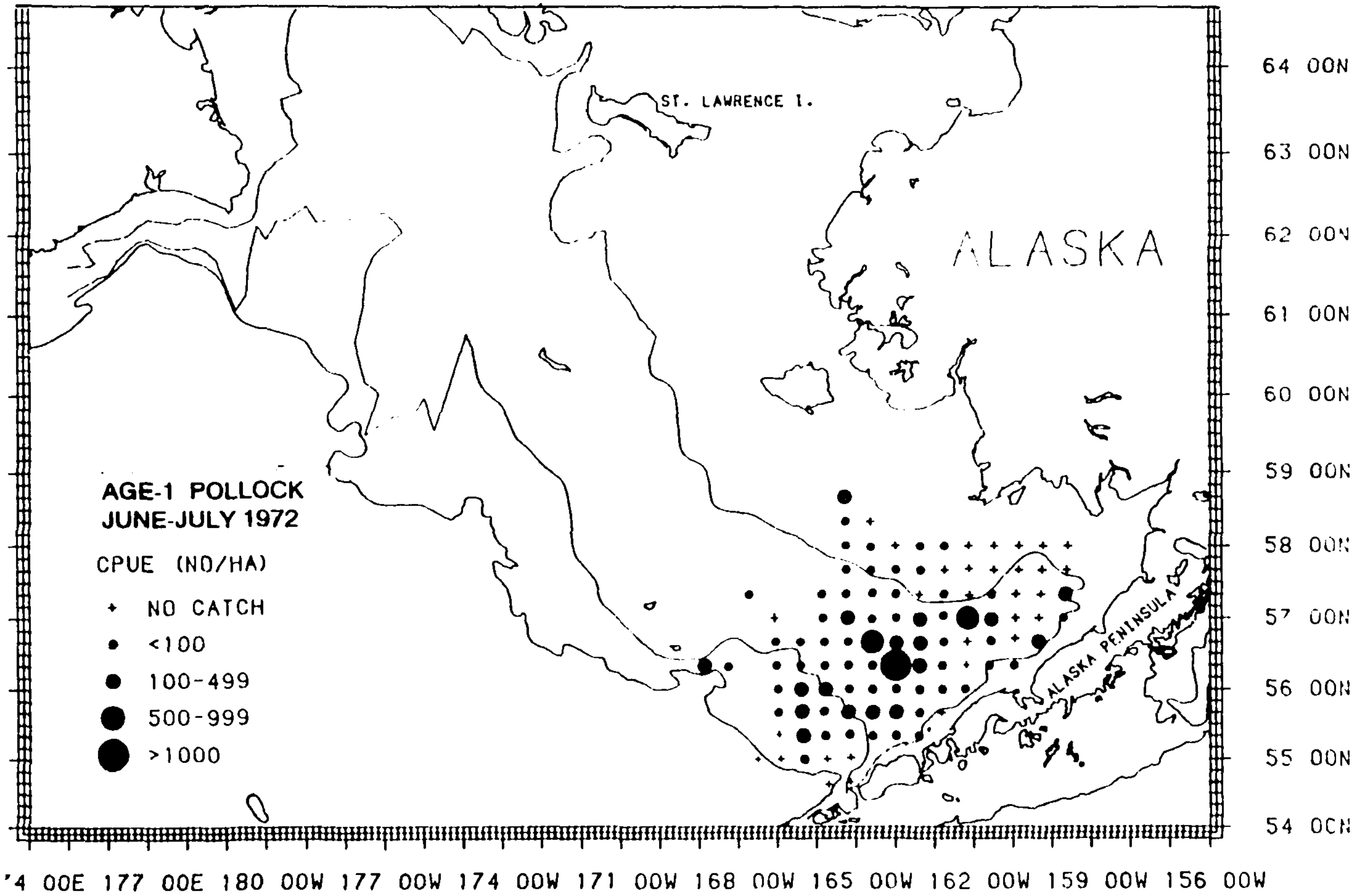
APPENDIX 1 - Dates, Vessels and Stations used to Describe Walleye Pollock and Arctic Cod Distribution on the Bering Sea.

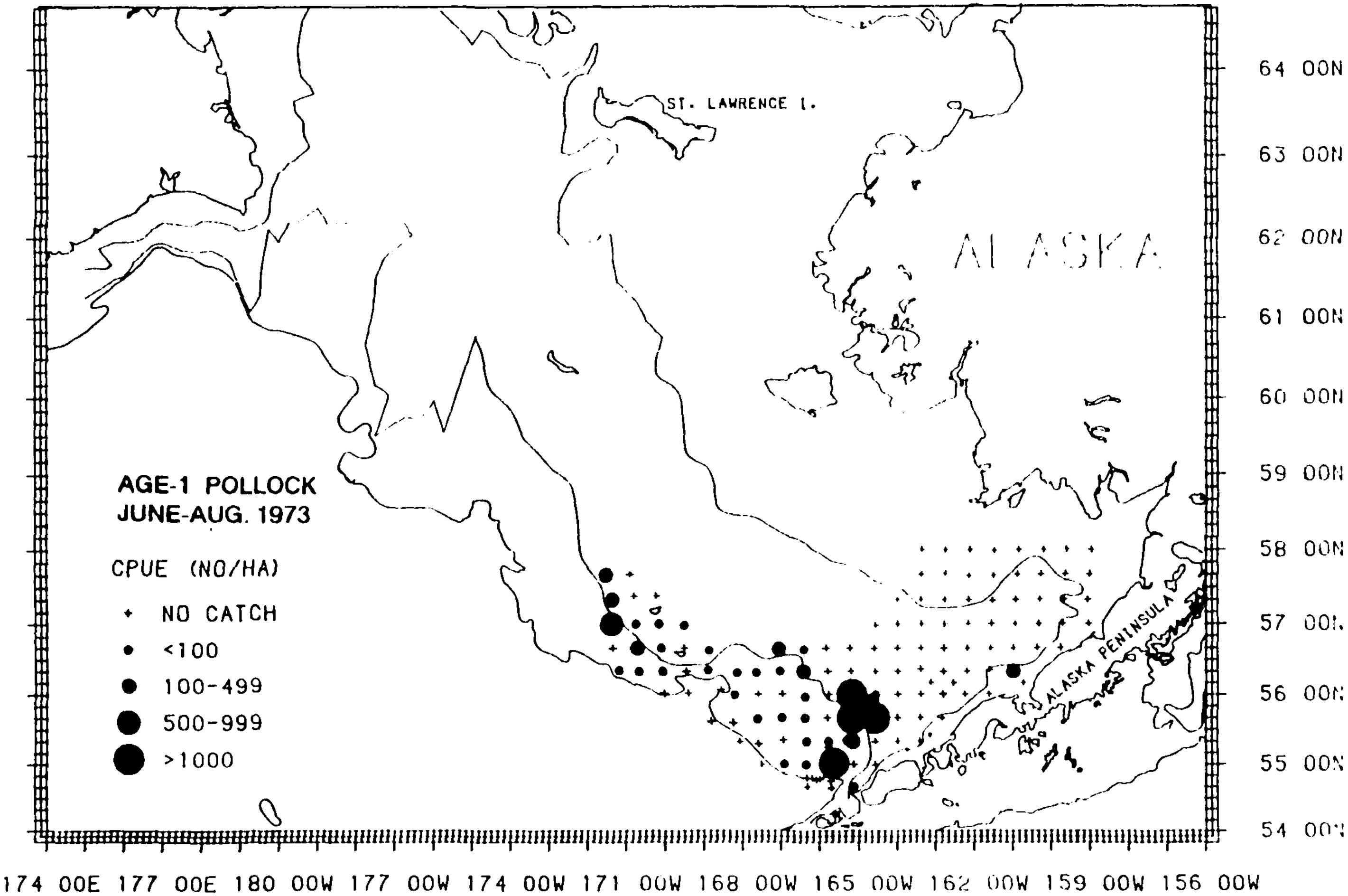
Year	Dates	Vessel	Stations
1972	28May-24Jul	R/V Oregon	103
1972	6Jun-27Jun	M/V Ocean Star	67
1973	18Jun-29Jun	M/V Tordenskjold	8
1973	26Jun-18Jul	M/V Mark I	58
1973	9Jul-12Aug	R/V Oregon	92
1974	2Jun-10Jun	M/V Tordenskjold	43
1974	14Jun-1Aug	R/V Oregon	97
1974	23Jun-24Jul	M/V Anna Marie	95
1975	1Jun-10Aug	R/V Oregon	149
1975	7Aug-30Sep	M/V Pat San Marie	207
1975	18Aug-20Oct	R/V Miller Freeman	213
1976	2Sep-9Oct	R/V Oregon	106
1976	21Apr-13Jun	M/V Anna Marie	159
1976	21Apr-20Jun	M/V Pat San Marie	214
1977	4Jun-5Aug	R/V Oregon	172
1977	10Jul-8Aug	M/V Smarag	205
1978	20May-7Jul	R/V Oregon	113
1978	18Jun-16Aug	M/V Paragon II	196
1979	22May-19Aug	M/V Paragon II	332
1979	25May-24Aug	R/V Miller Freeman	115
1979	26Jul-5Aug	Ryoan Maru No. 31	155

1979*	26Jul-5Aug	21	118
1980	12May-30Jul	M/V Ocean Harvester	258
1980	22May-9Jul	R/V Oregon	120
1981	22May-20Jul	R/V Alaska	175
1981	22May-3Aug	R/V Chapman	217
1982	29May-11Jul	1	149
1982	31May-1Aug	M/V Pat San Marie	211
1982*	1Sep-15Sep	R/V Oregon	99
1983	7Jun-27Aug	SRTM 8459	203
1983	7Jun-6Aug	R/V Alaska	188
1983	8Jun-6Aug	R/V Chapman	186
1983	15Jun-19Aug	Milogradova	347
1984	9Jun-26Aug	R/V Chapman	251
1984	10Jun-10Aug	R/V Alaska	207
1984	28Aug-7Sep	R/V Miller Freeman	80
1985	24May-7Sep	Daikichi Maru No32	354
1985	3Jul-6Oct	Argosy	293
1985	8Jun-7Aug	R/V Alaska	207
1986	3Jun-6Aug	Morning Star	241
1986	4Jun-11Jul	R/V Alaska	142
1987	3Jun-7Aug	M/V Pat San Marie	176
1987	27May-30Jul	R/V Alaska	207
1988	3Jun-6Aug	Ocean Hope 3	187
1988	4Jun-6Aug	R/V Alaska	187
1989	4Jun-14Aug	Ocean Hope 3	175

1989	6Jun-14Aug	R/V Alaska	179
1990	22May-12Jul	R/V Alaska	176
1990	4Jun-6Aug	Novokotovsk	276
1990	16Aug-16Sep	Ocean Hope 3	271
1991	7Jun-30Aug	Ocean Hope 3	263
1991	20Jun-13Aug	Alaska	214
1992	5Jun-3Aug	Ocean Hope 3	174
1992	6Jun-3Aug	Alaska	187
1993	4Jun-26Jul	Arcturus	205
1993	6Jun-26Jul	Aldebaran	191

APPENDIX 2 - Distribution and abundance maps of age-1 walleye pollock for 1972-1993.


ST. LAWRENCE I.
ALASKA
ALASKA PENINSULA
AGE-1 POLLOCK
JUNE-JULY 1972
CPUE (NO/HA)
+ NO CATCH
<100
100-499
500-999
>1000
64 00N
63 00N
62 00N
61 00N
60 00N
59 00N
58 00N
57 00N
56 00N
55 00N
54 00N
'4 00E 177 00E 180 00W 177 00W 174 00W 171 00W 168 00W 165 00W 162 00W 159 00W 156 00W


AGE-1 POLLOCK
JUNE-AUG. 1973
CPUE (NO/HA)
+ NO CATCH
<100
100-499
500-999
>1000
ST. LAWRENCE I.
ALASKA
ALASKA PENINSULA
64 00N
63 00N
62 00N
61 00N
60 00N
59 00N
58 00N
57 00N
56 00N
55 00N
54 00N
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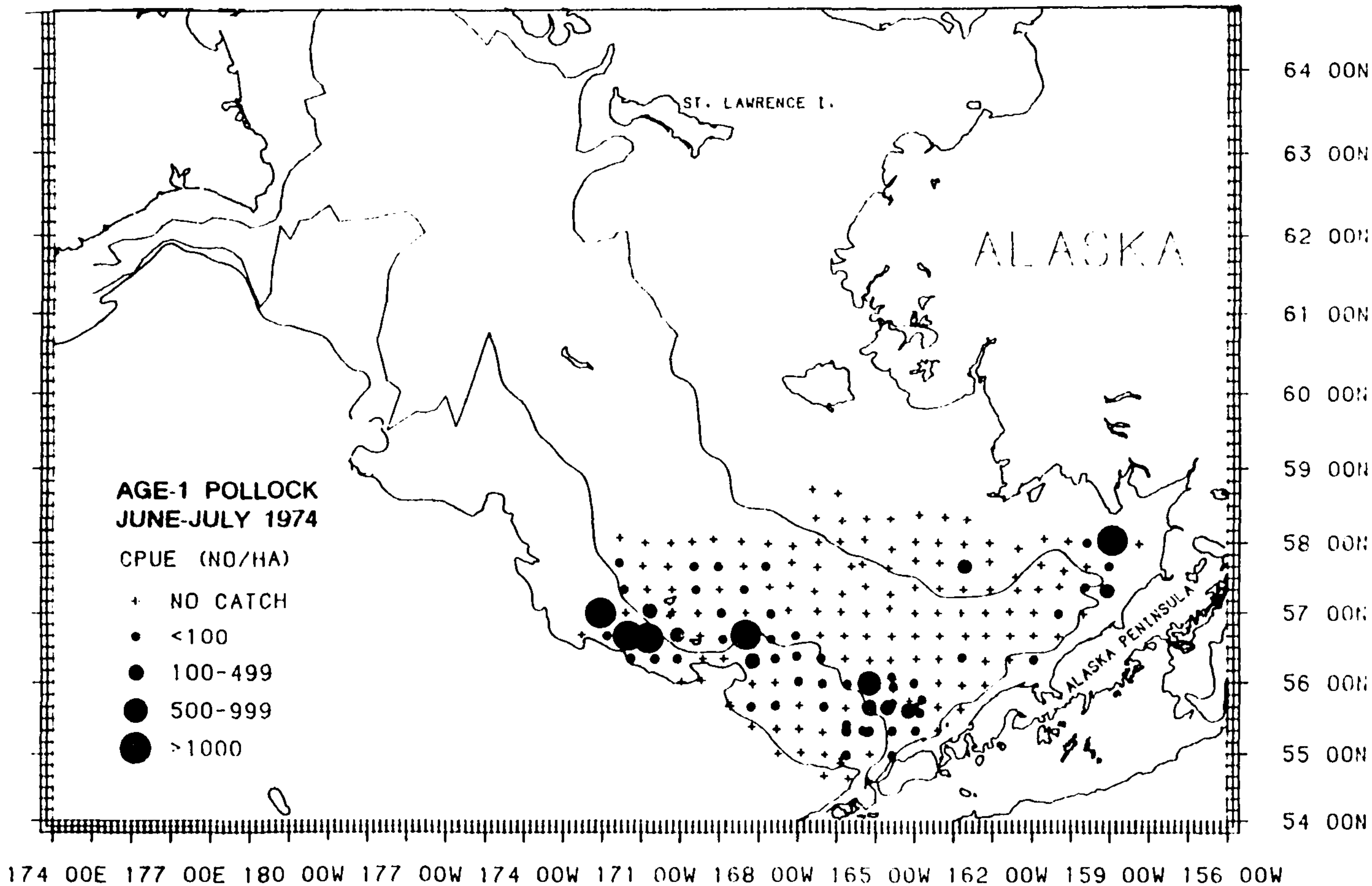
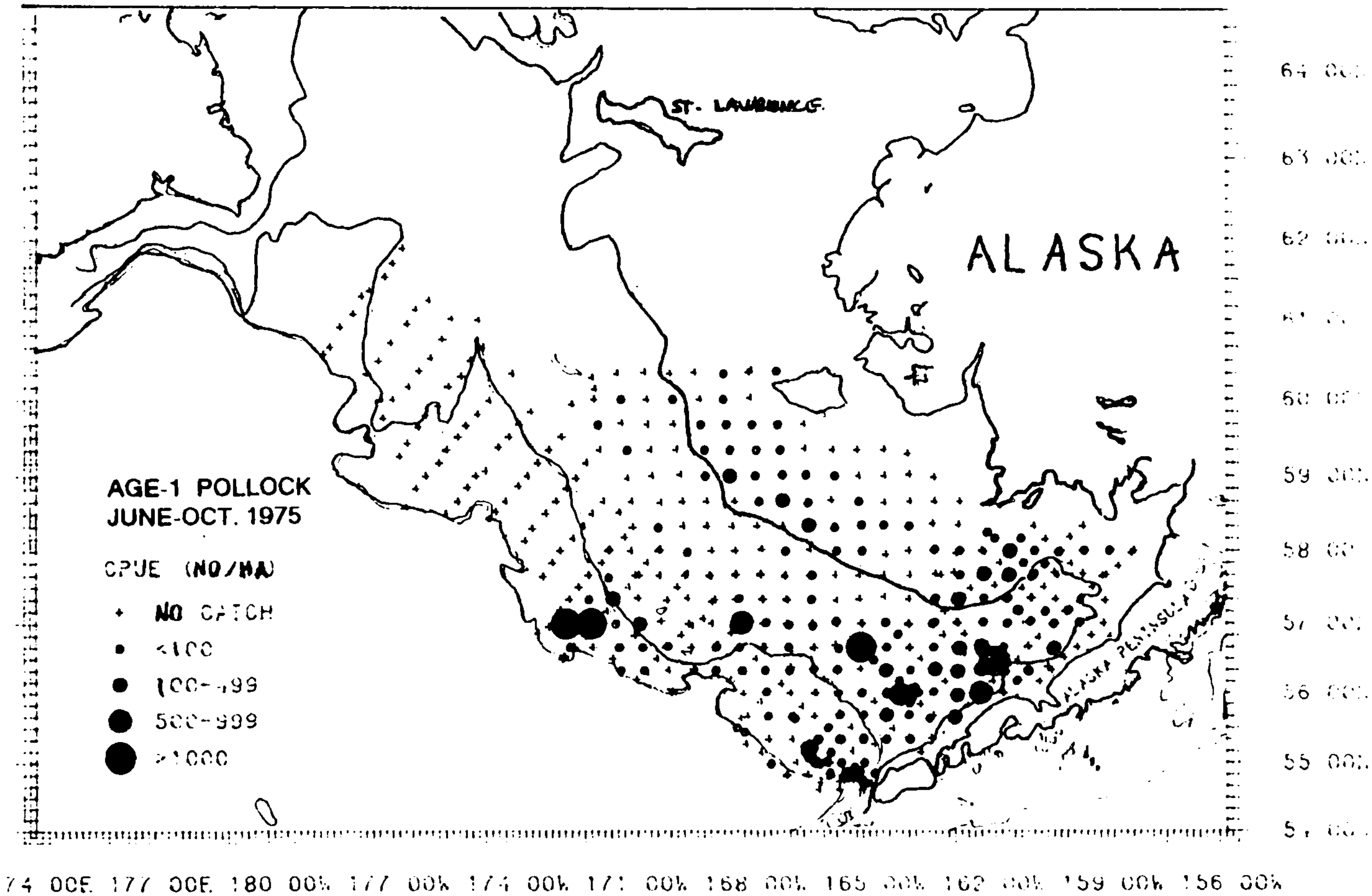

ST. LAWRENCE I.
ALASKA
ALASKA PENINSULA
AGE-1 POLLOCK
JUNE-JULY 1974
CPUE (NO/HA)
NO CATCH
<100
100-499
500-999
>1000
64 00N
63 00N
62 00N
61 00N
60 00N
59 00N
58 00N
57 00N
56 00N
55 00N
54 00N
174 00E 177 00E 180 00W 177 00W 174 00W 171 00W 168 00W 165 00W 162 00W 159 00W 156 00W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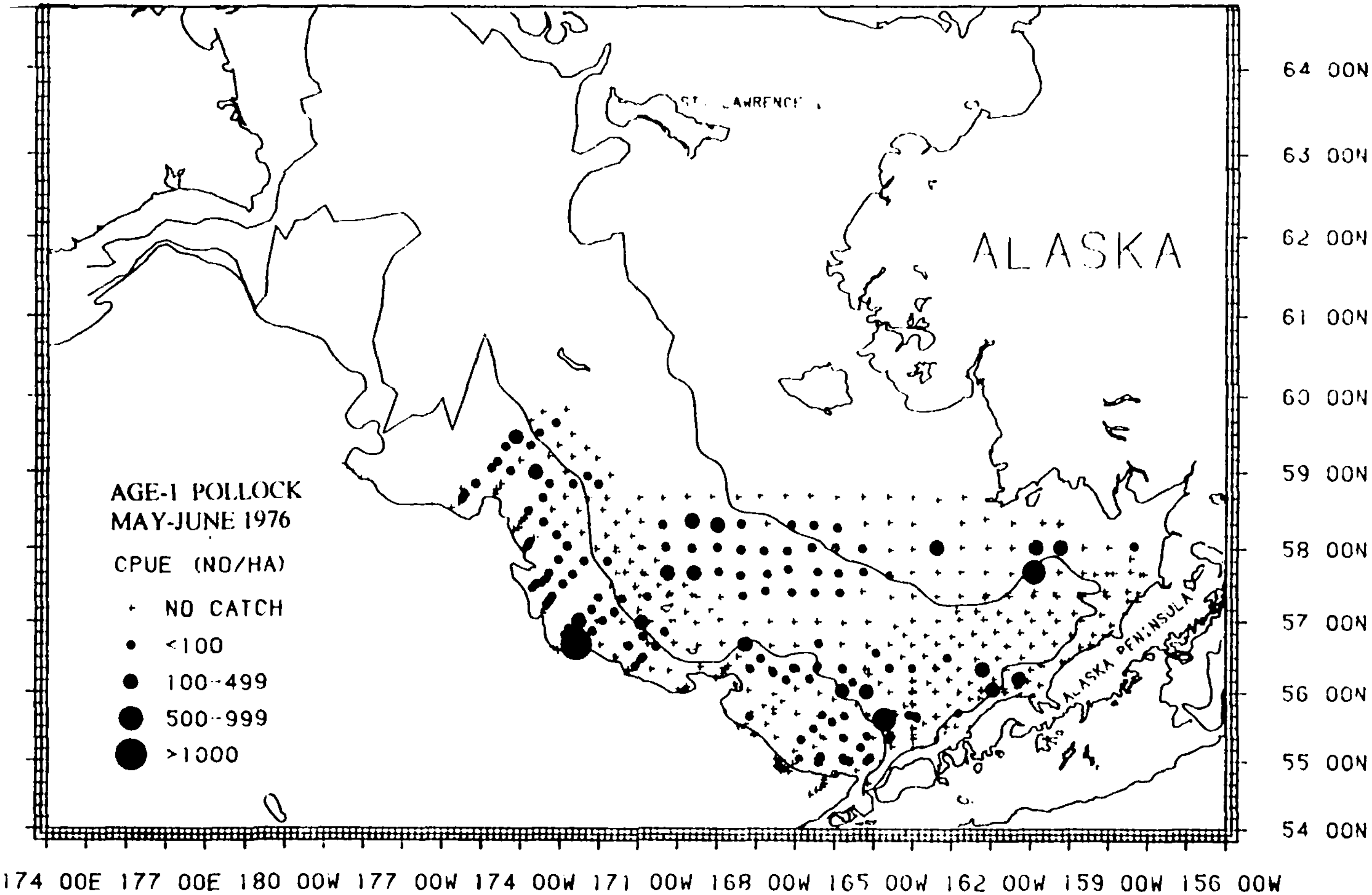
JUNE-OCT. 1975
CPUE (NO/HA)
NO CATCH
<100
100-499
500-999
>1000
ALASKA


AGE-1 POLLOCK
MAY-JUNE 1976
CPUE (NO/HA)
NO CATCH
<100
100-499
500-999
>1000
ALASKA
ALASKA PENINSULA
64 00N
63 00N
62 00N
61 00N
60 00N
59 00N
58 00N
57 00N
56 00N
55 00N
54 00N
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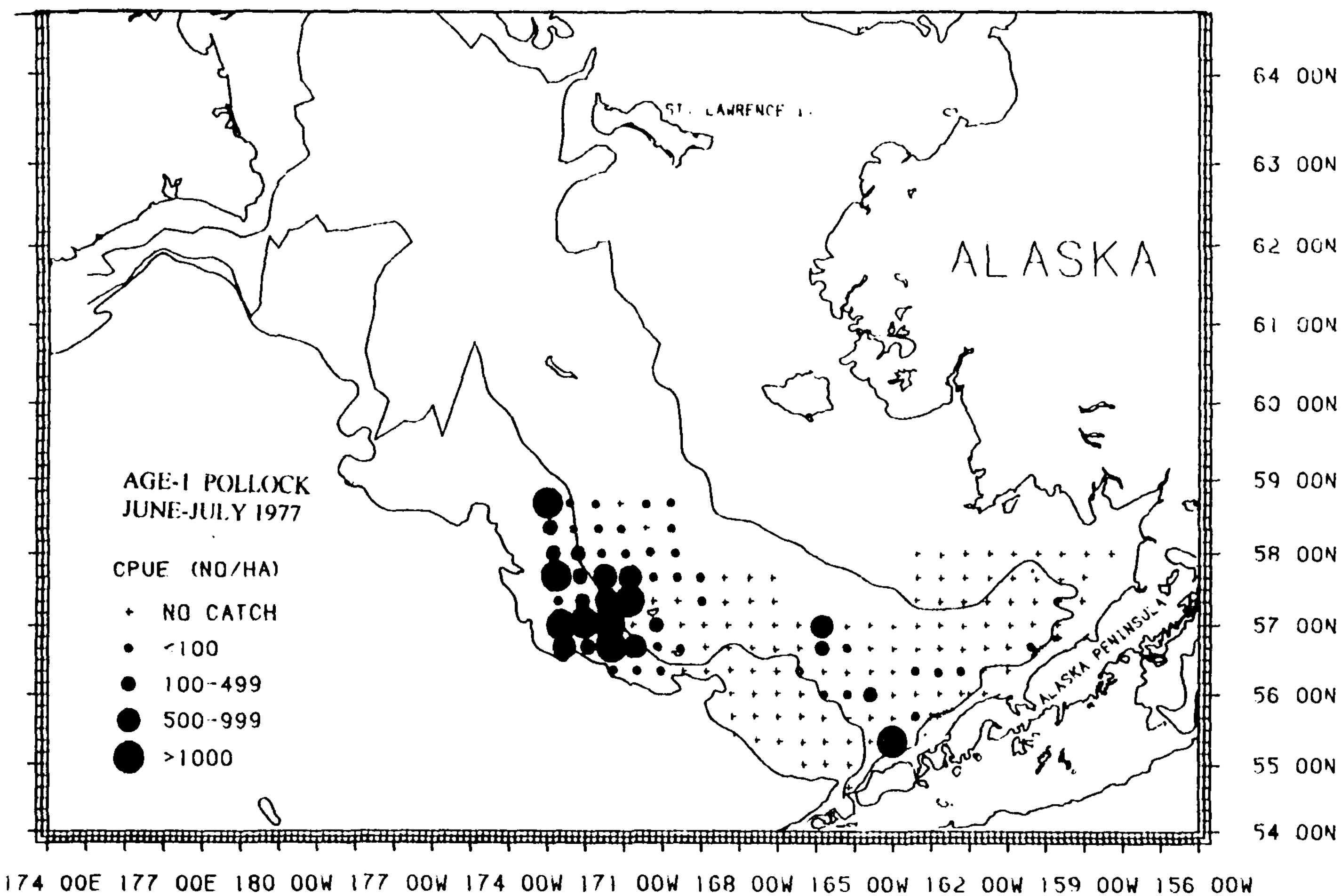
AGE-1 POLLOCK
JUNE-JULY 1977
CPUE (NO/HA)
+ NO CATCH
<100
100-499
500-999
>1000
ALASKA
ST. LAWRENCE I.
ALASKA PENINSULA
64 00N
63 00N
62 00N
61 00N
60 00N
59 00N
58 00N
57 00N
56 00N
55 00N
54 00N
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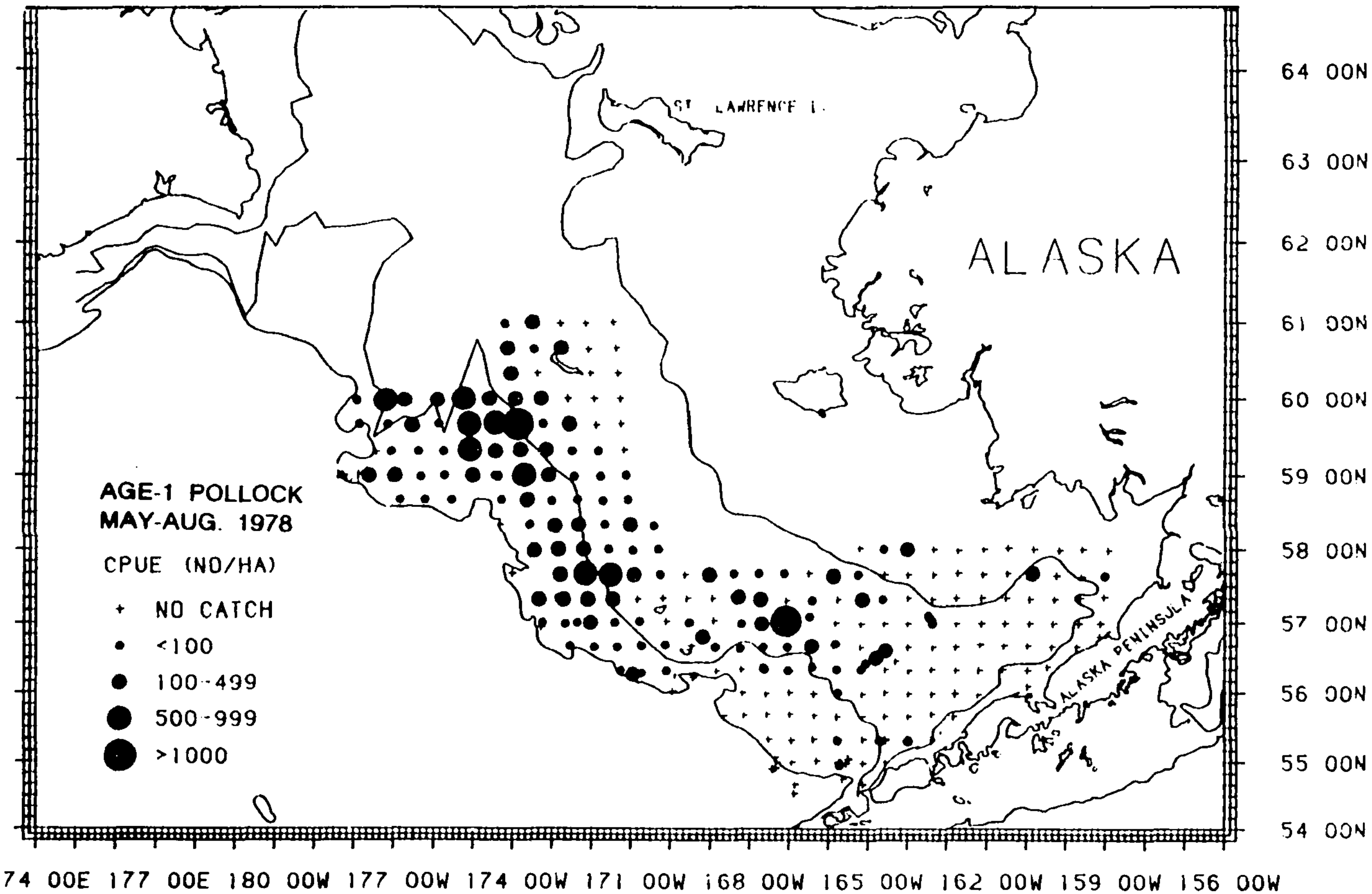
162 00W
159 00W
156 00W


AGE-1 POLLOCK
MAY-AUG. 1978
CPUE (NO/HA)
+ NO CATCH
<100
100-499
500-999
>1000
ALASKA
ST. LAWRENCE I.
ALASKA PENINSULA
64 00N
63 00N
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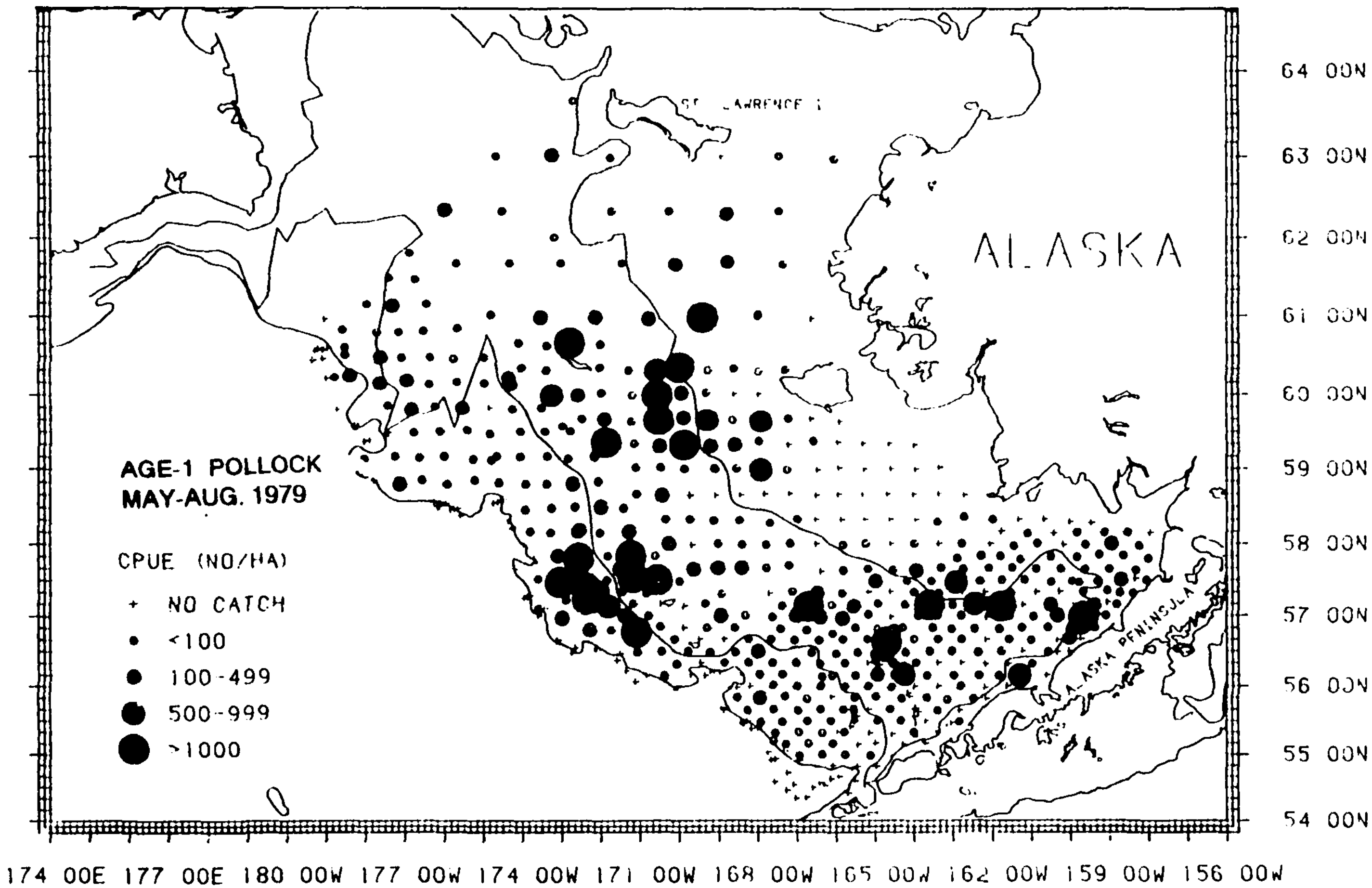
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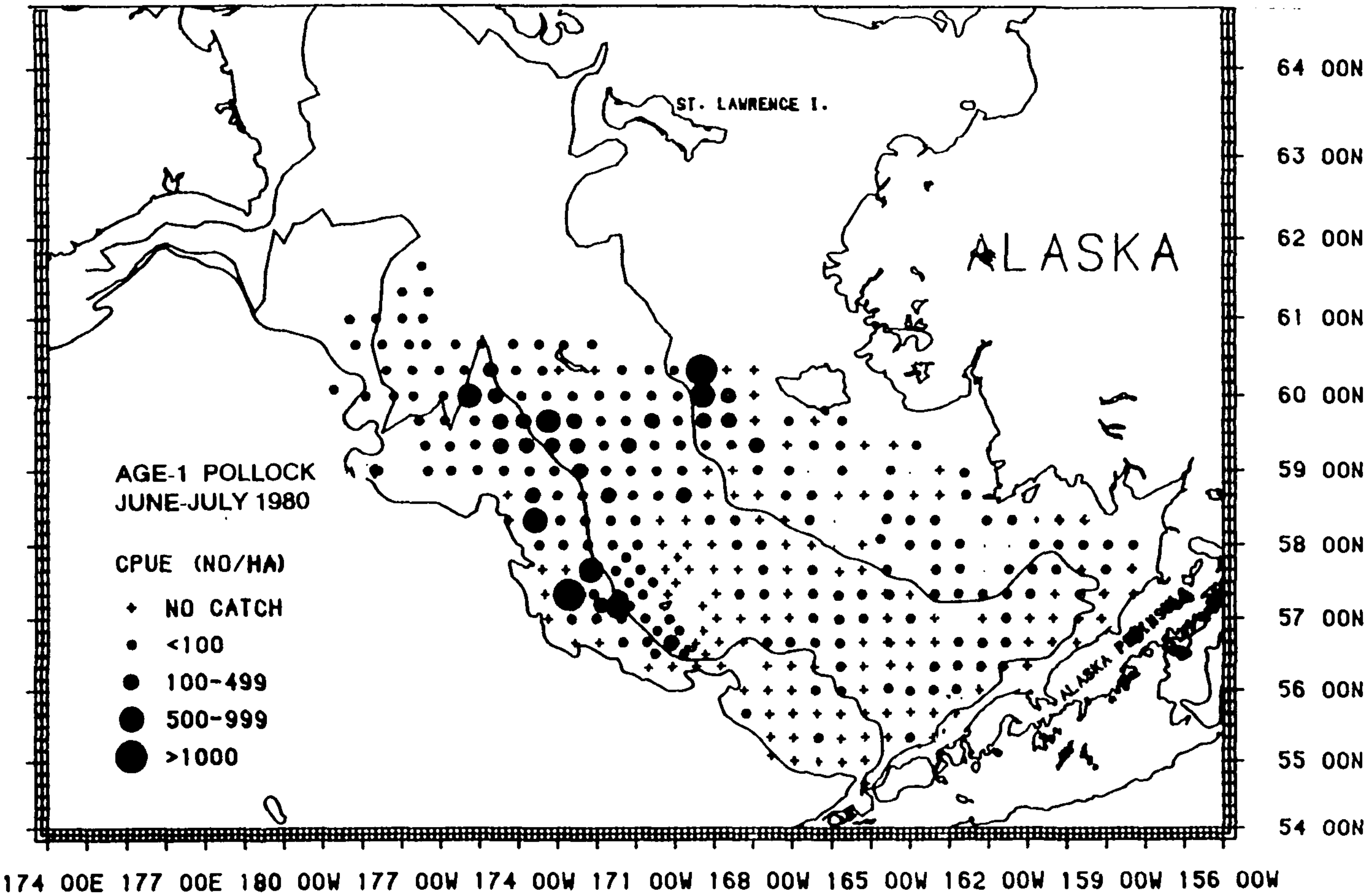
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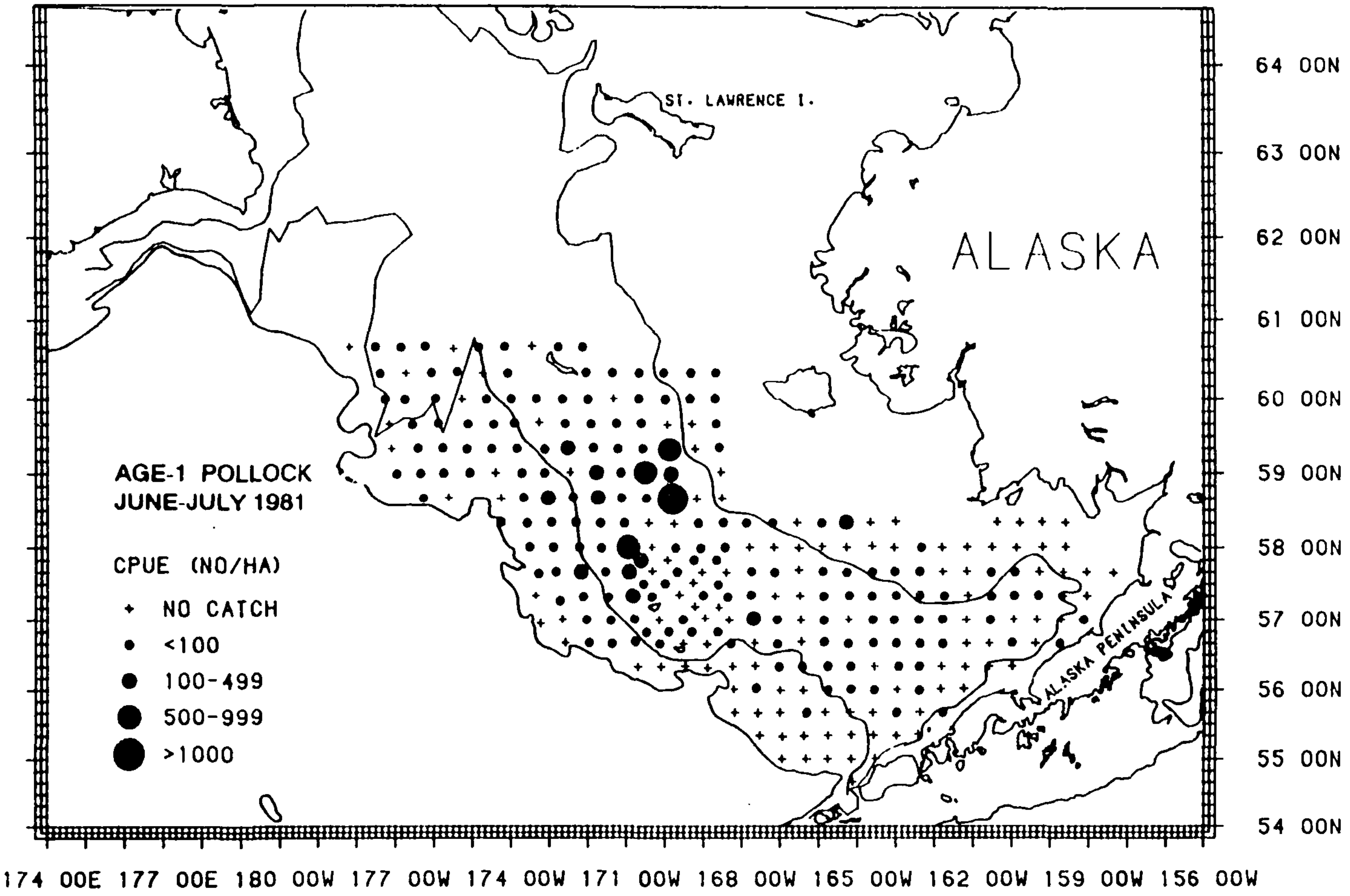
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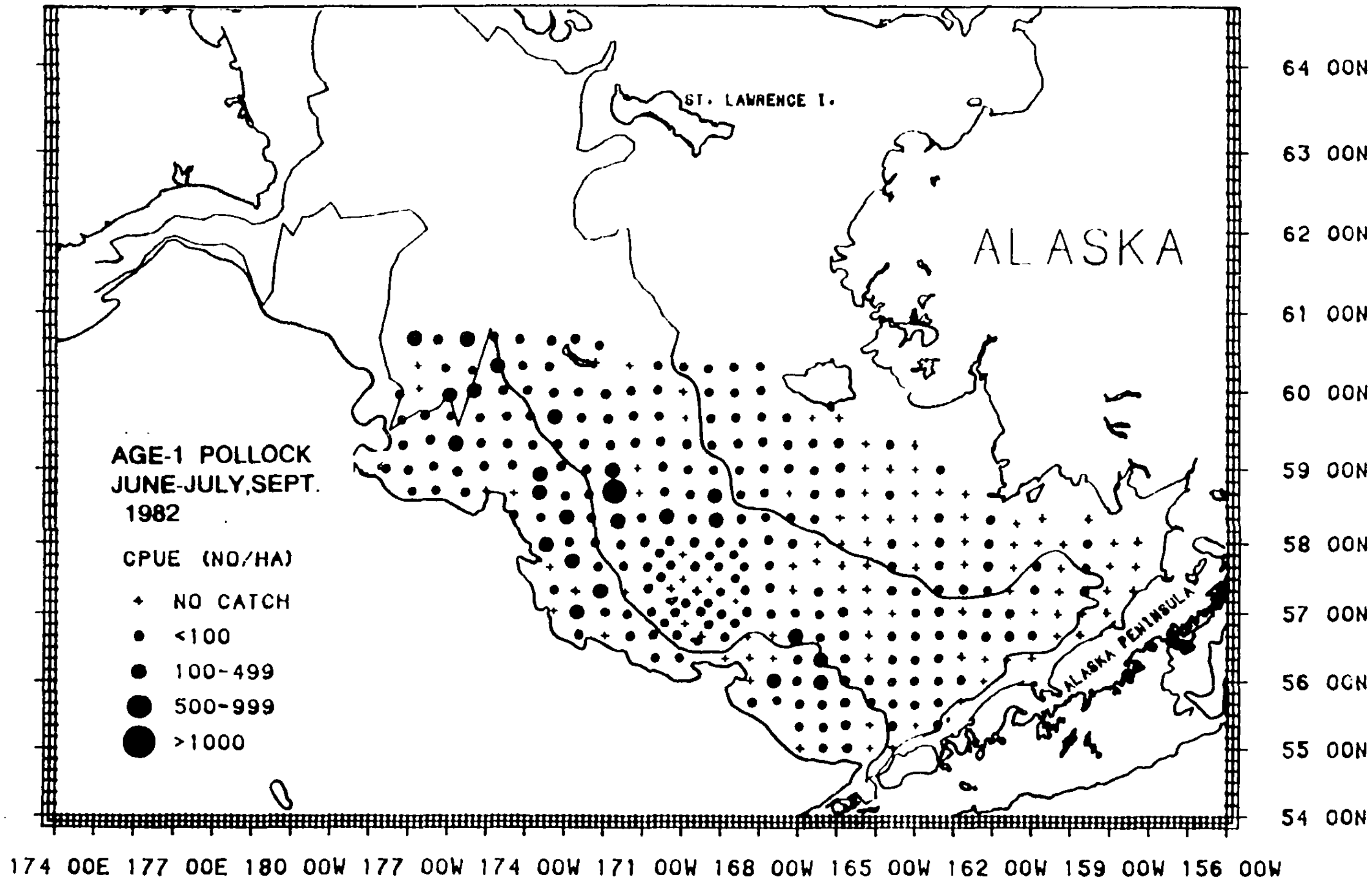
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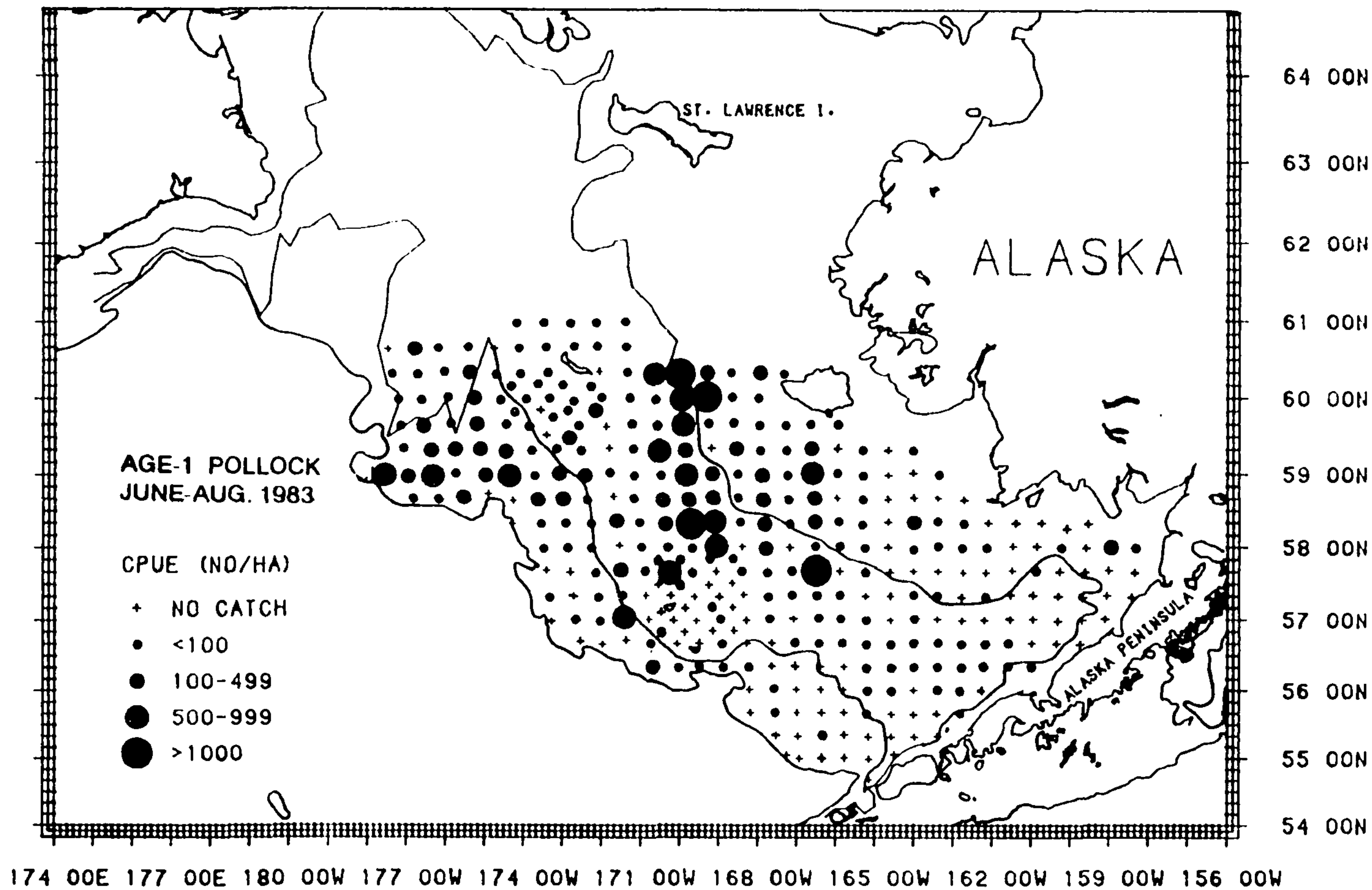
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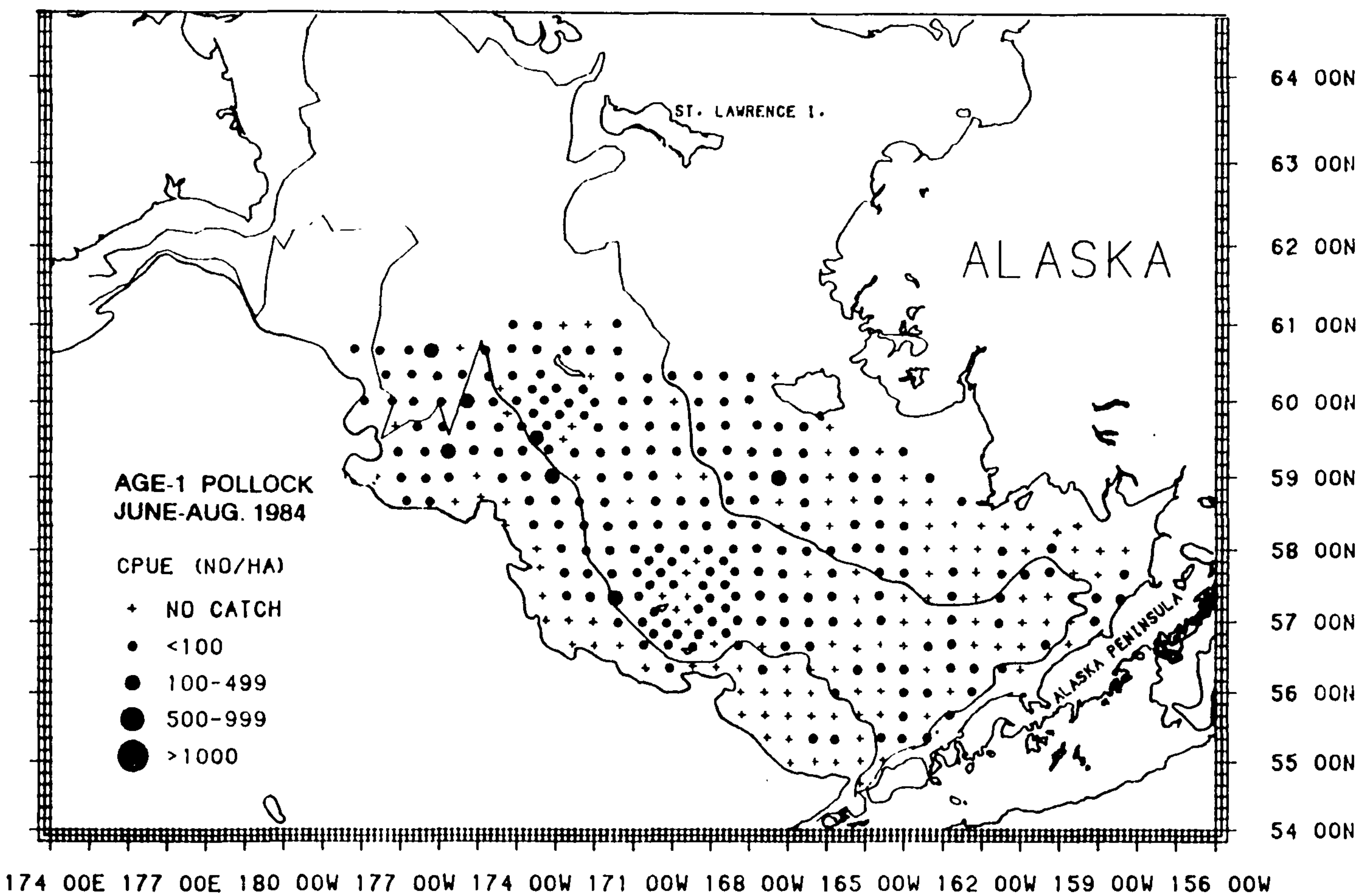
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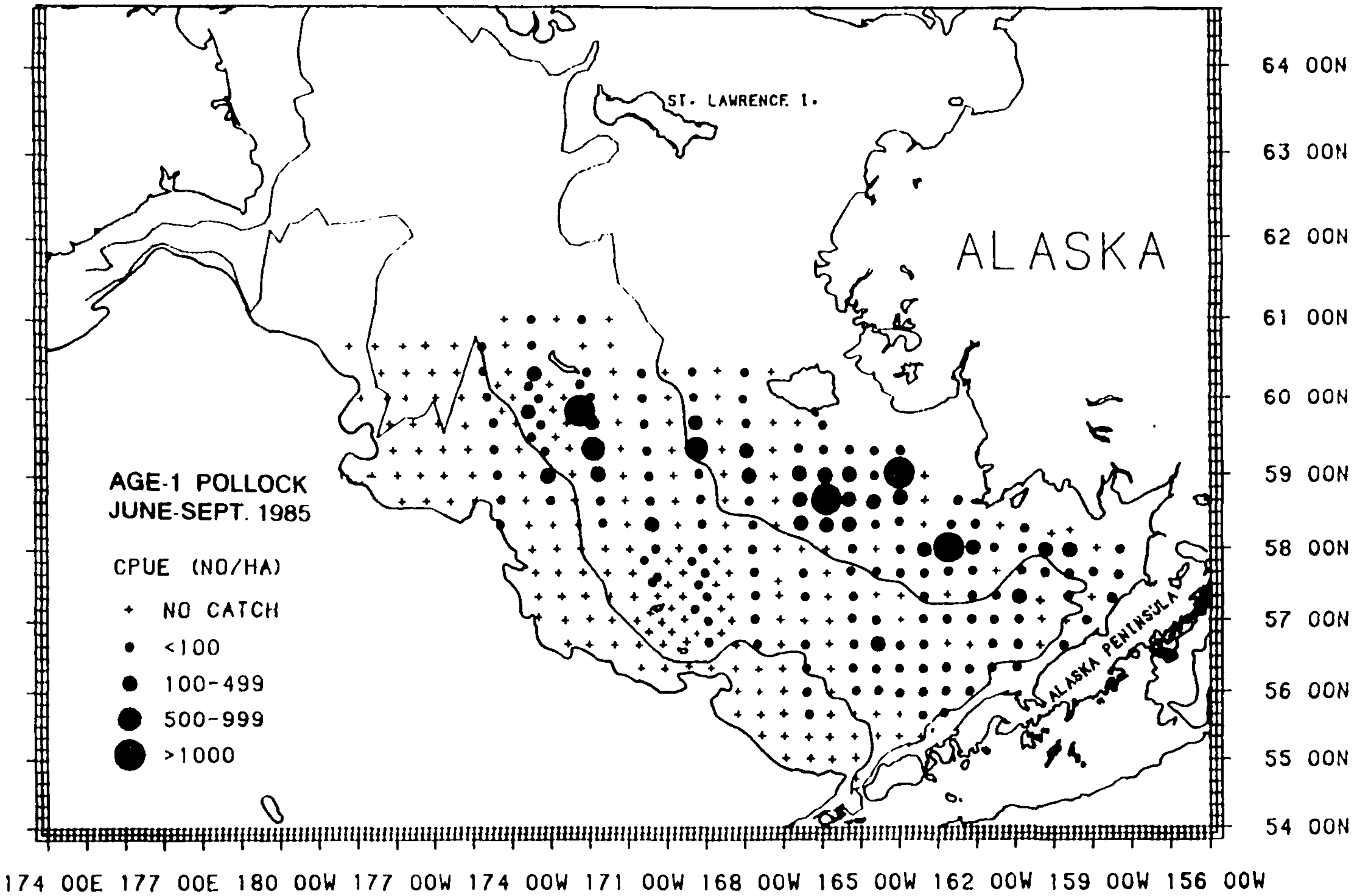

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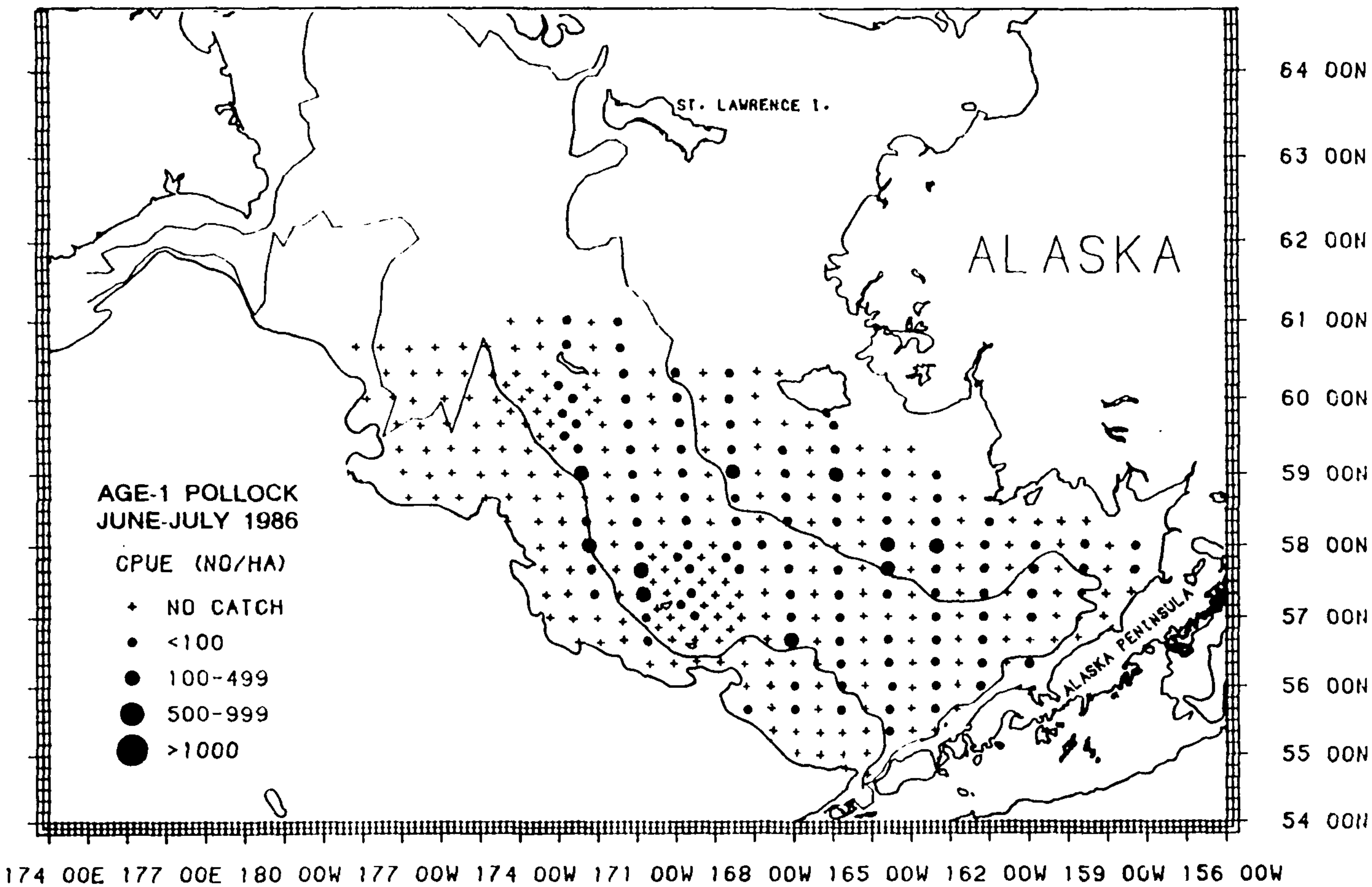
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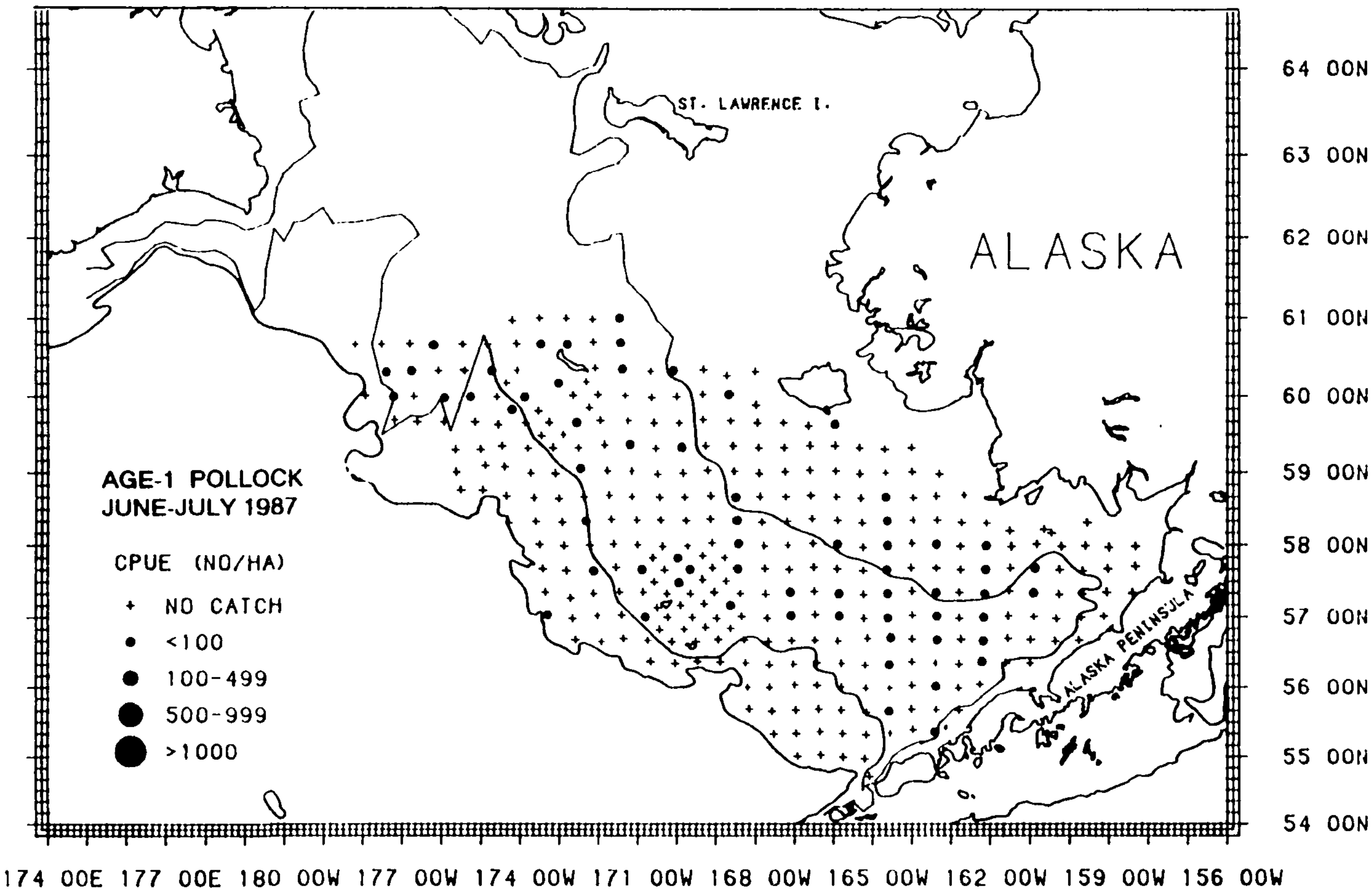

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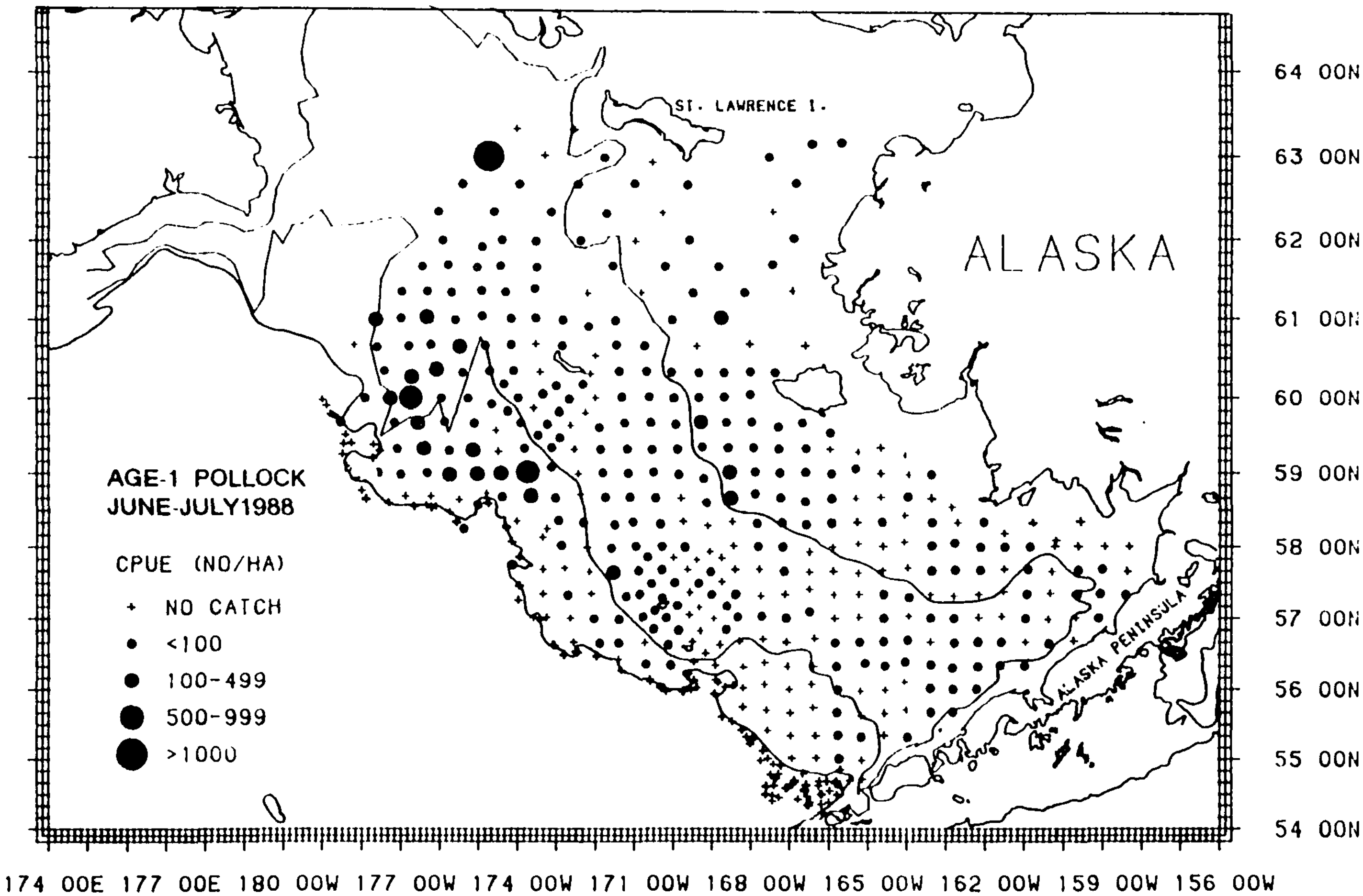
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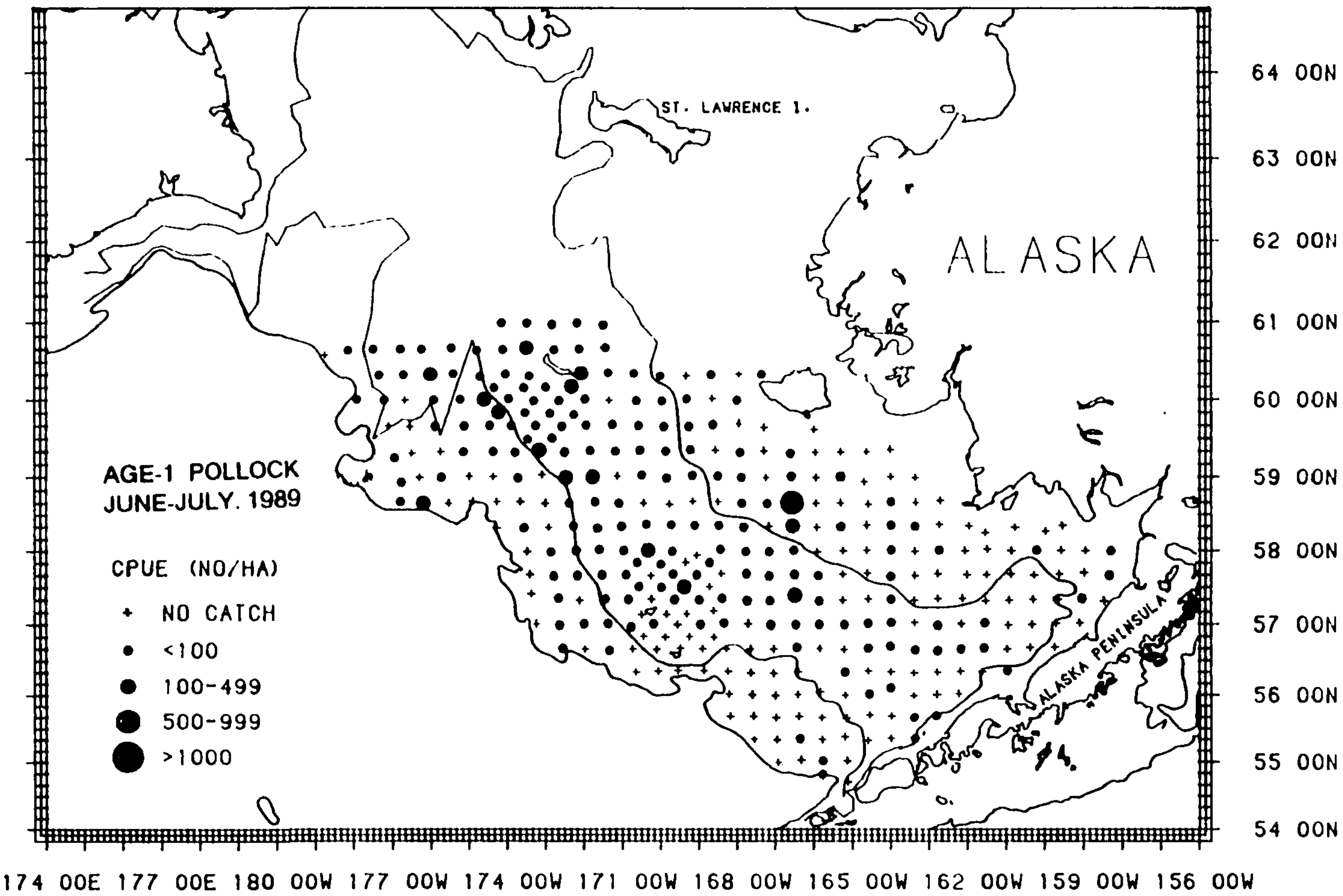
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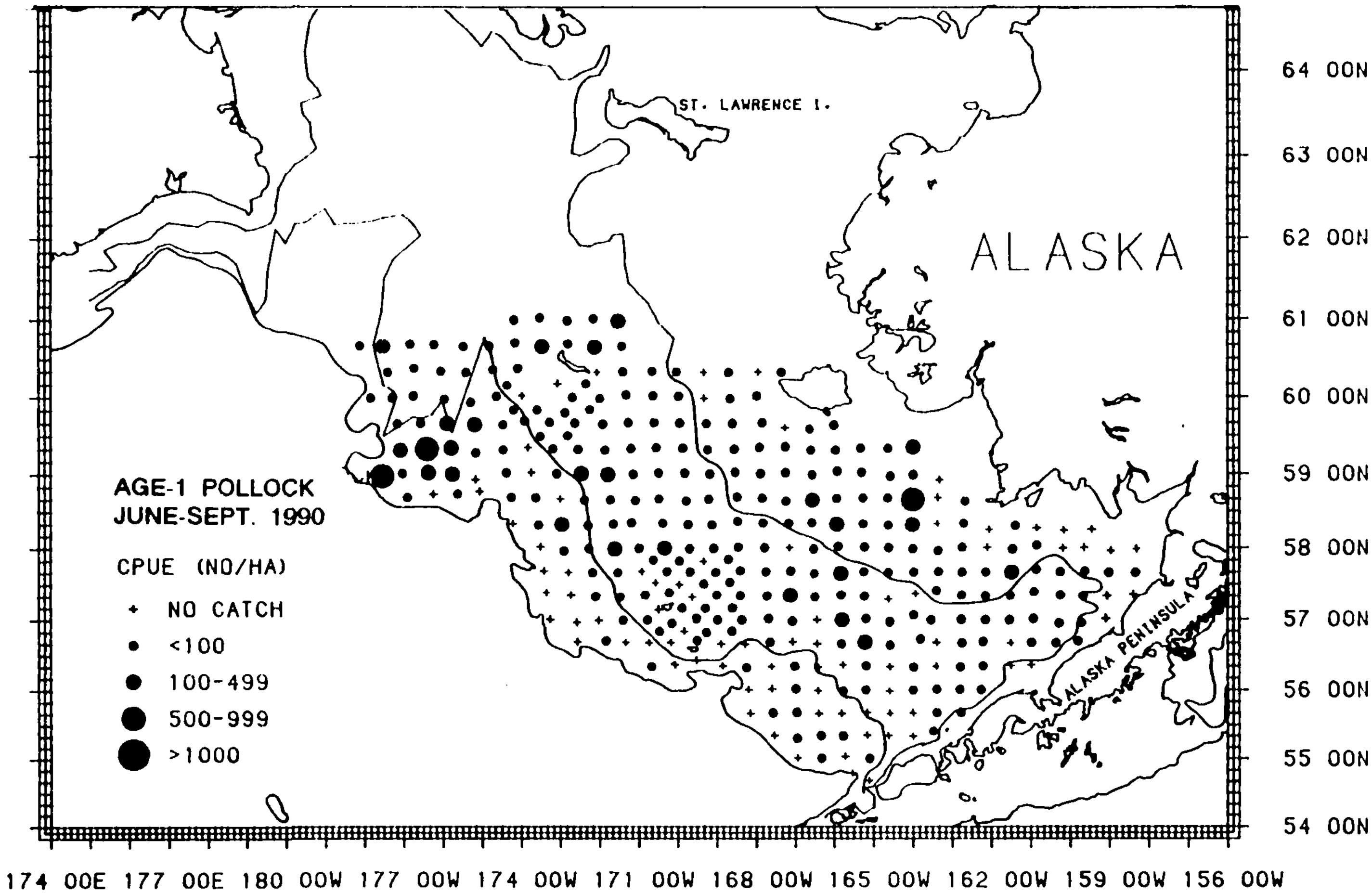
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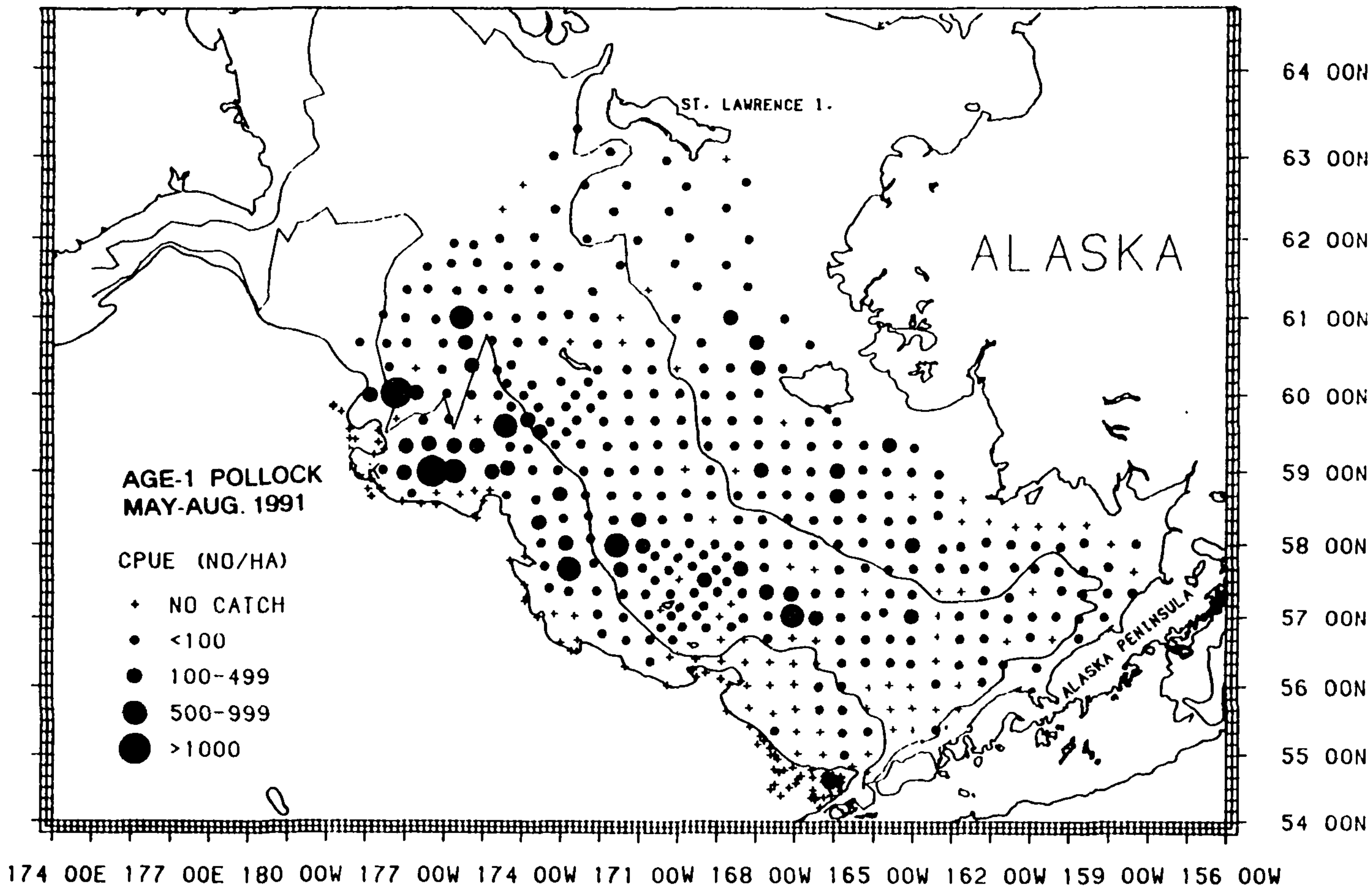
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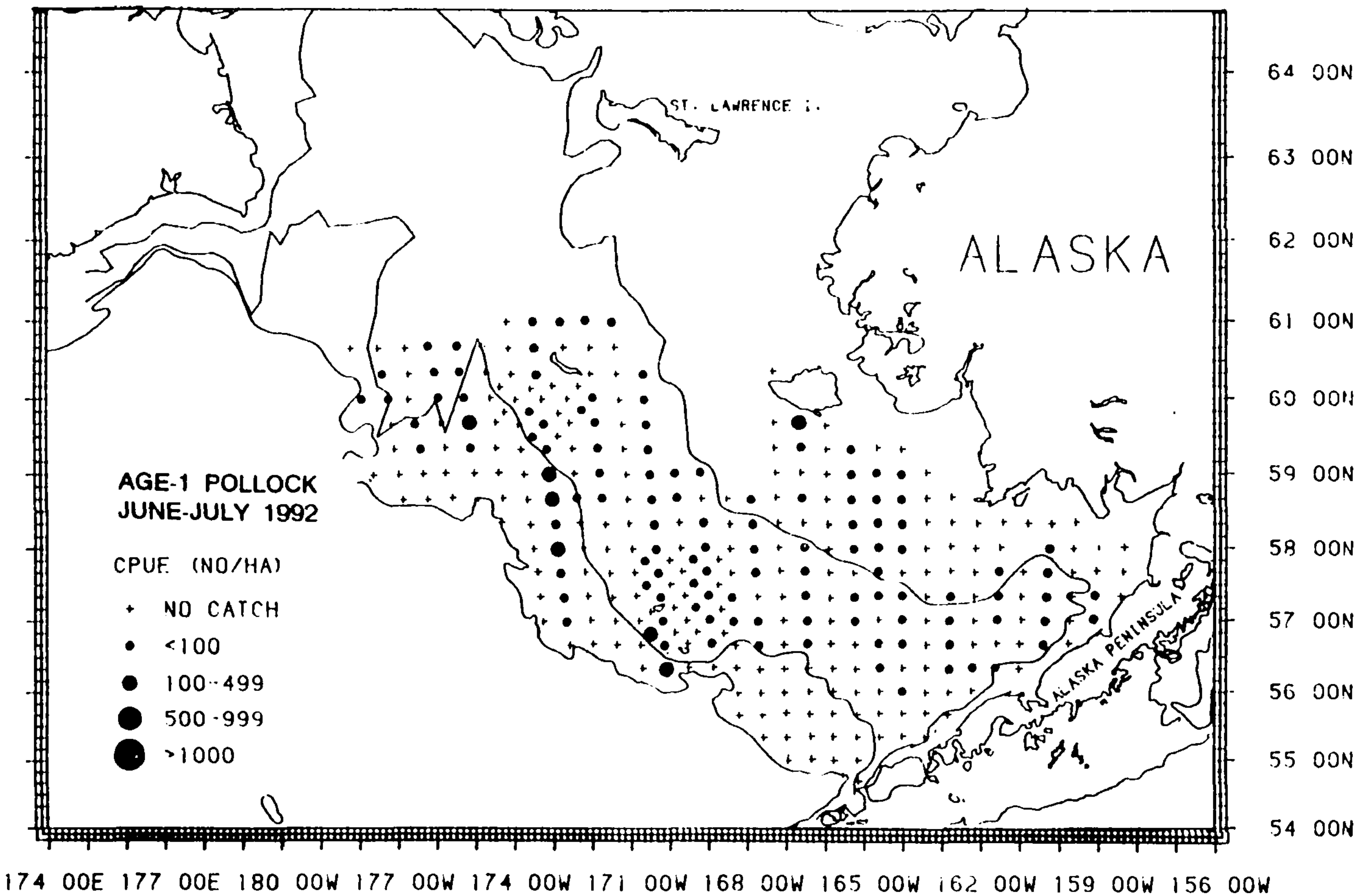
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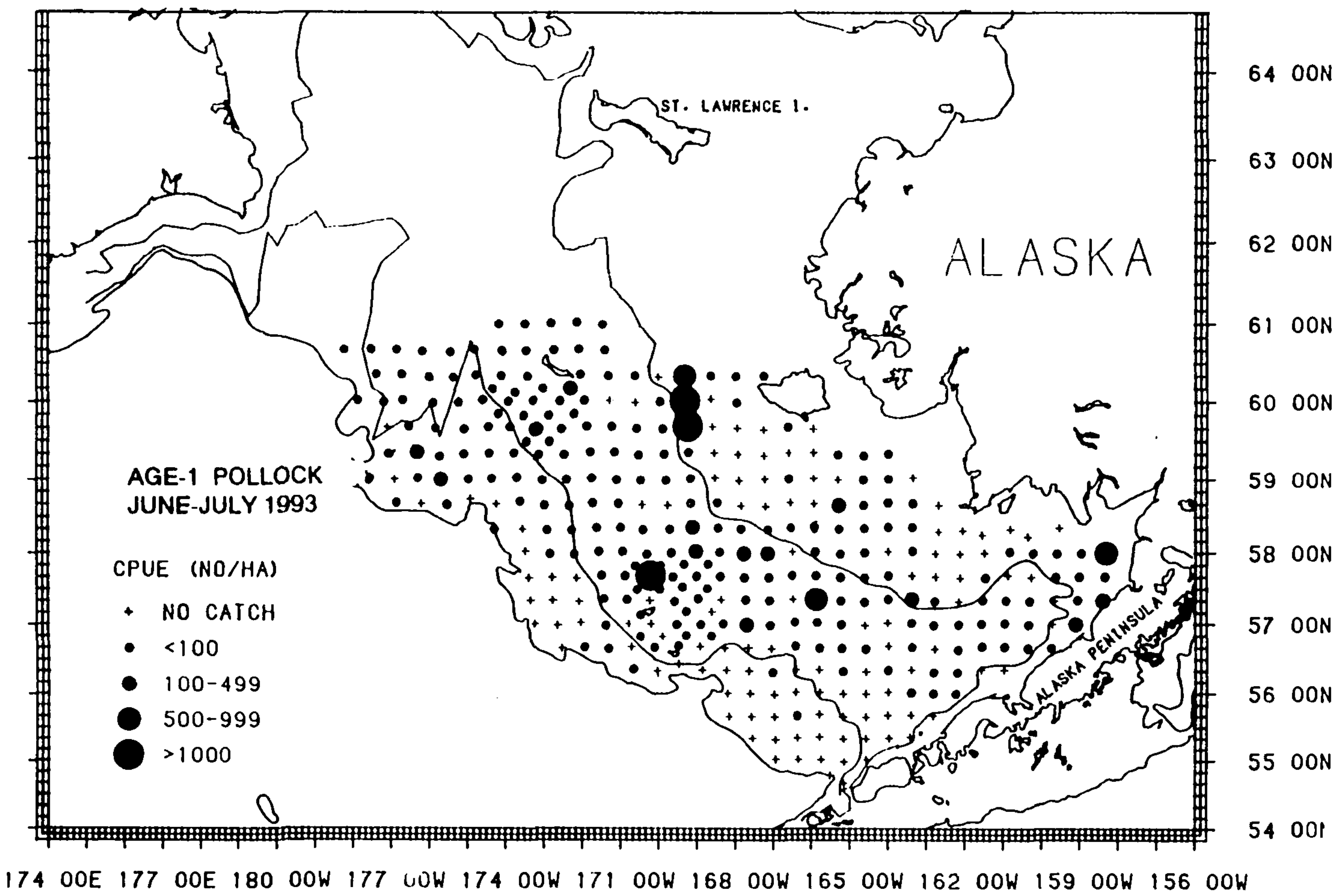
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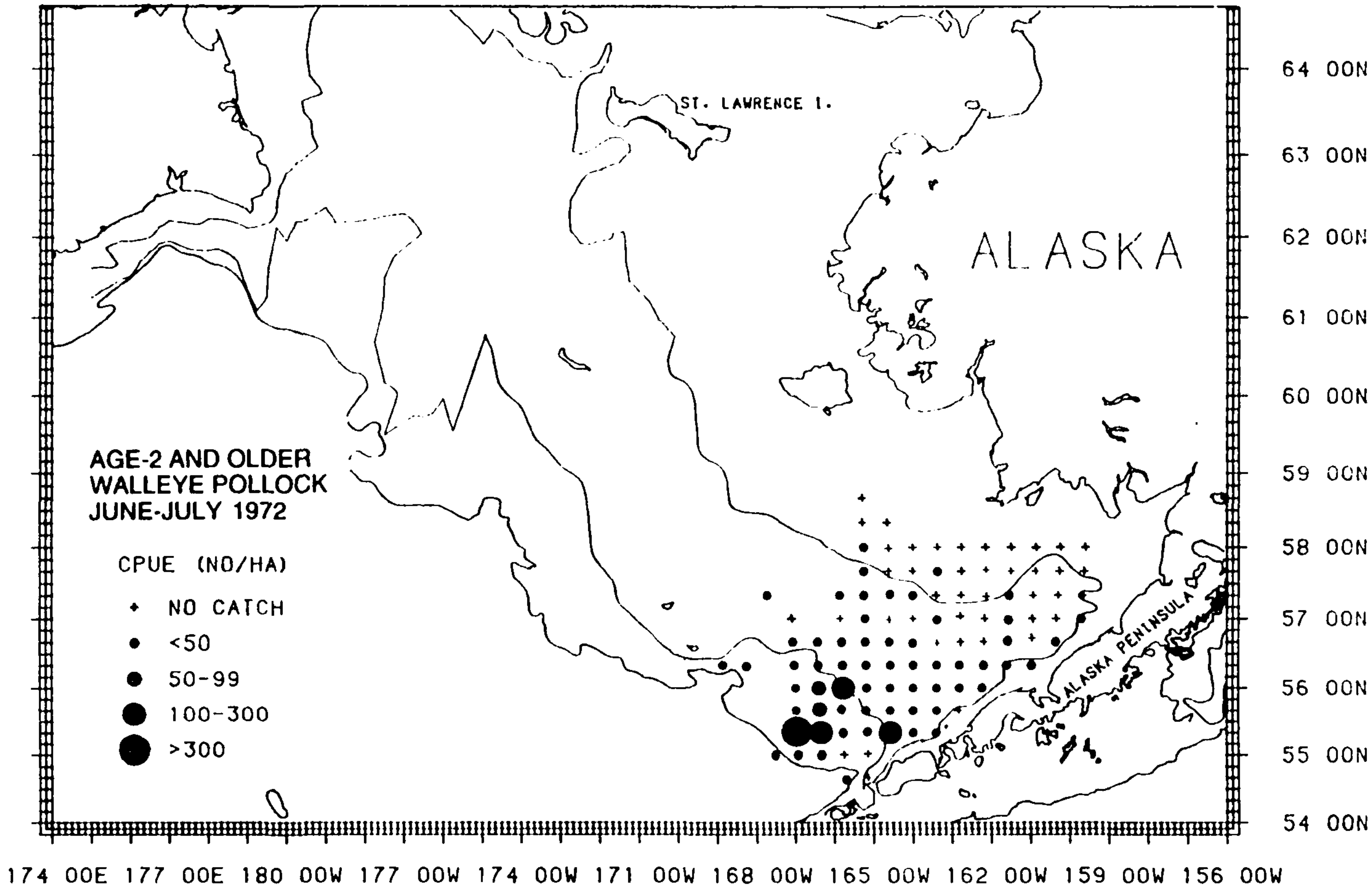
APPENDIX 3. - Distribution and abundance maps for age 2+ and older walleye pollock for 1972-1993.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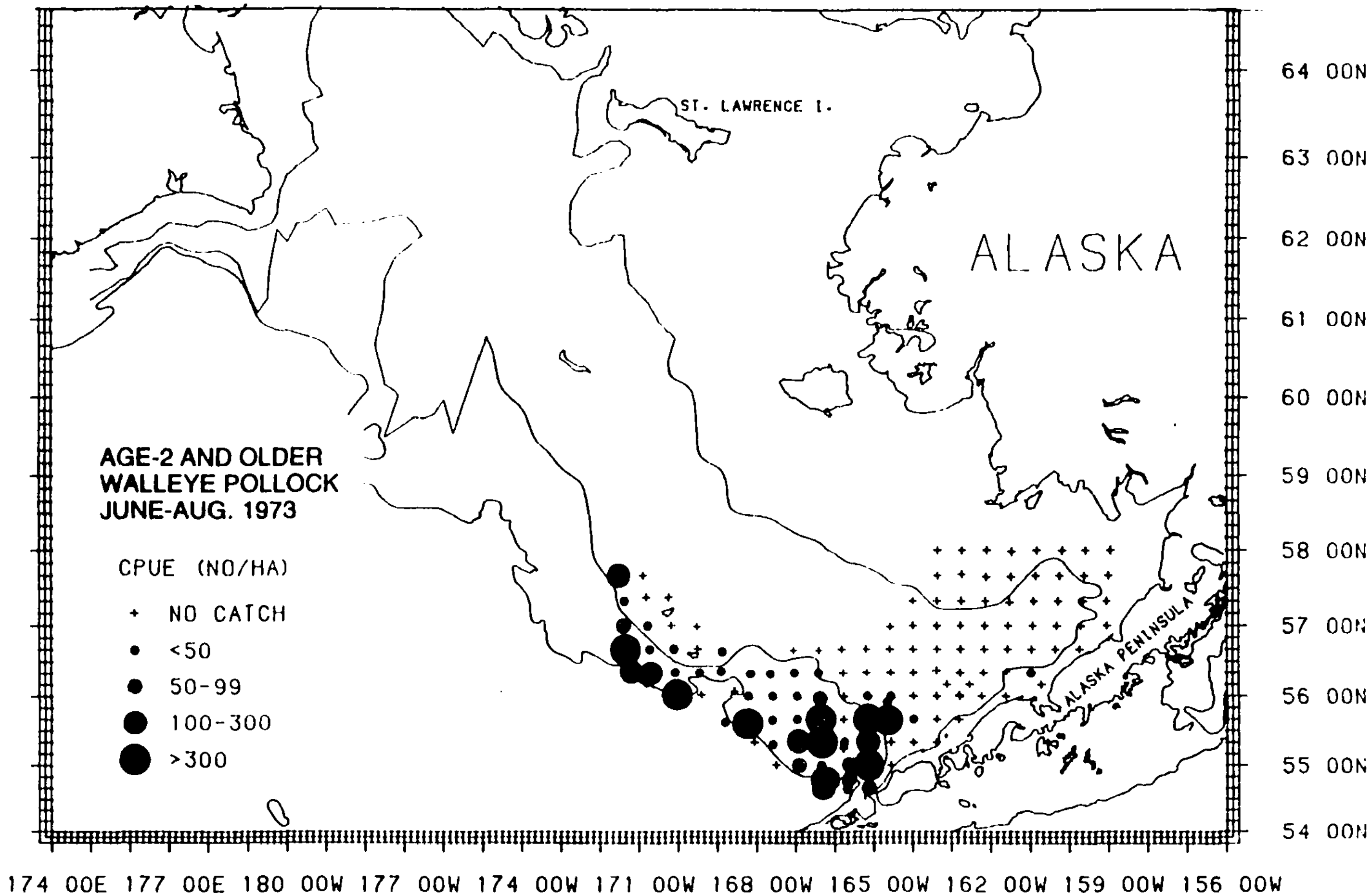

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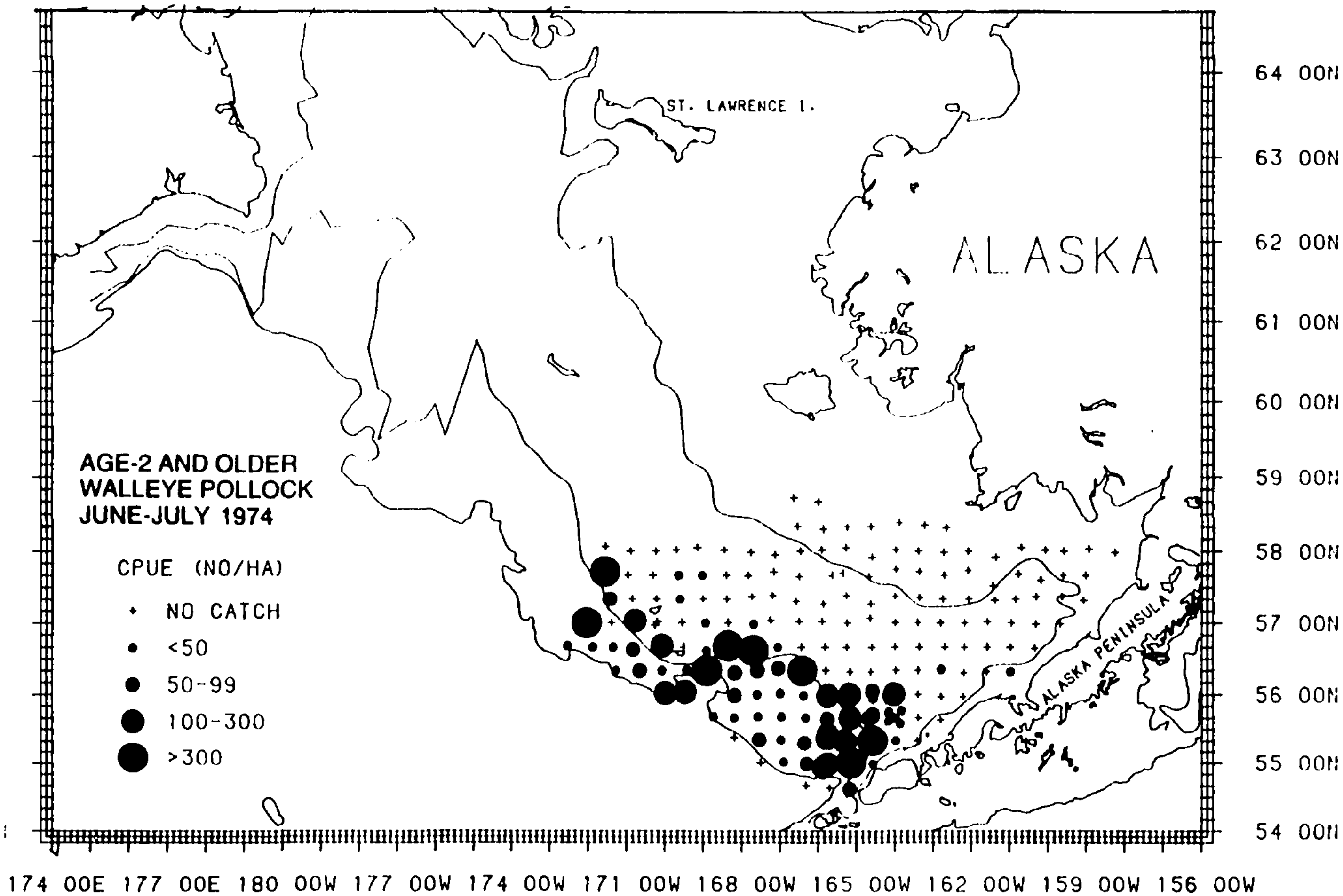
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CPUE (NO/HA)
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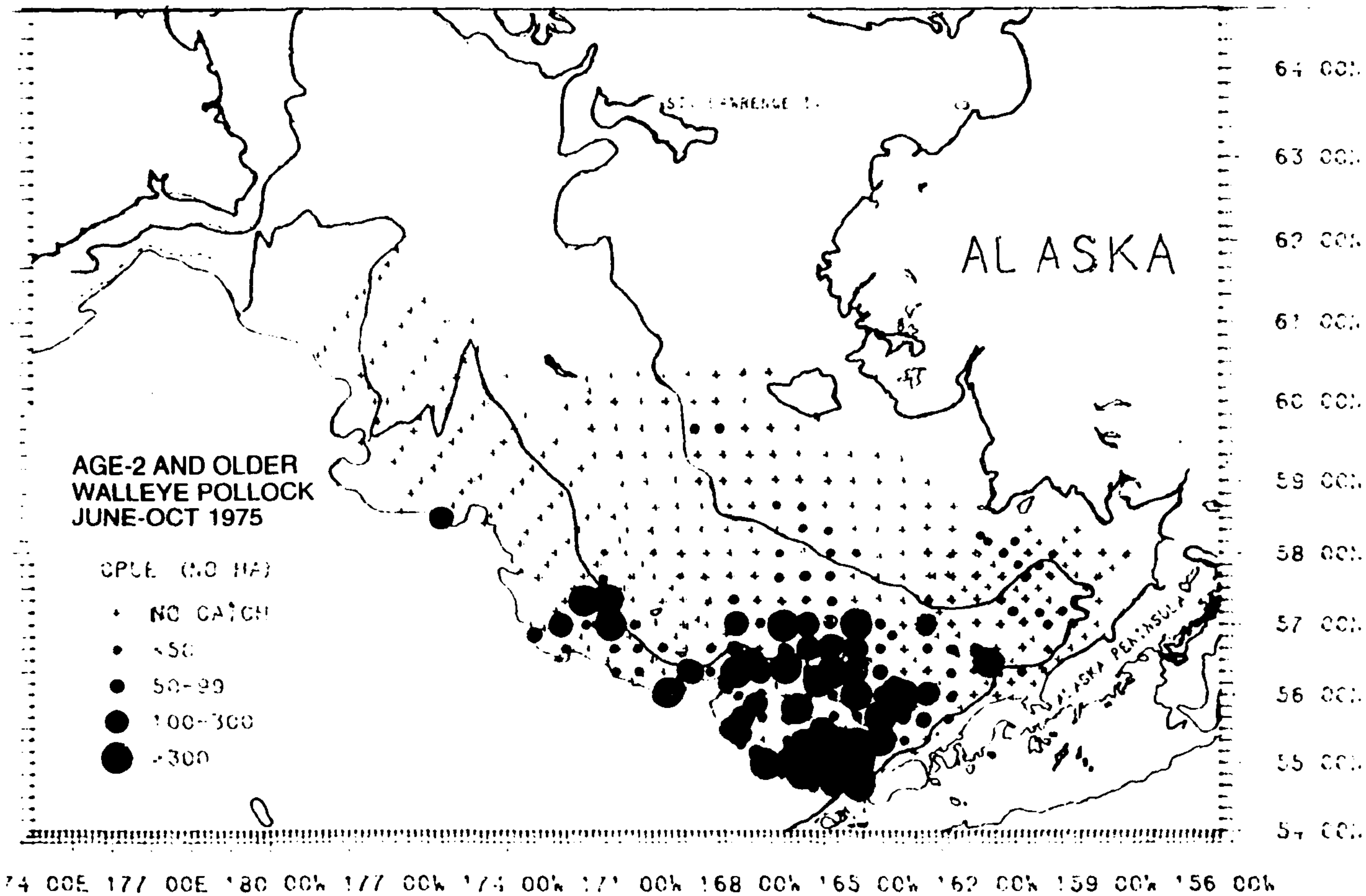
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JUNE-OCT 1975
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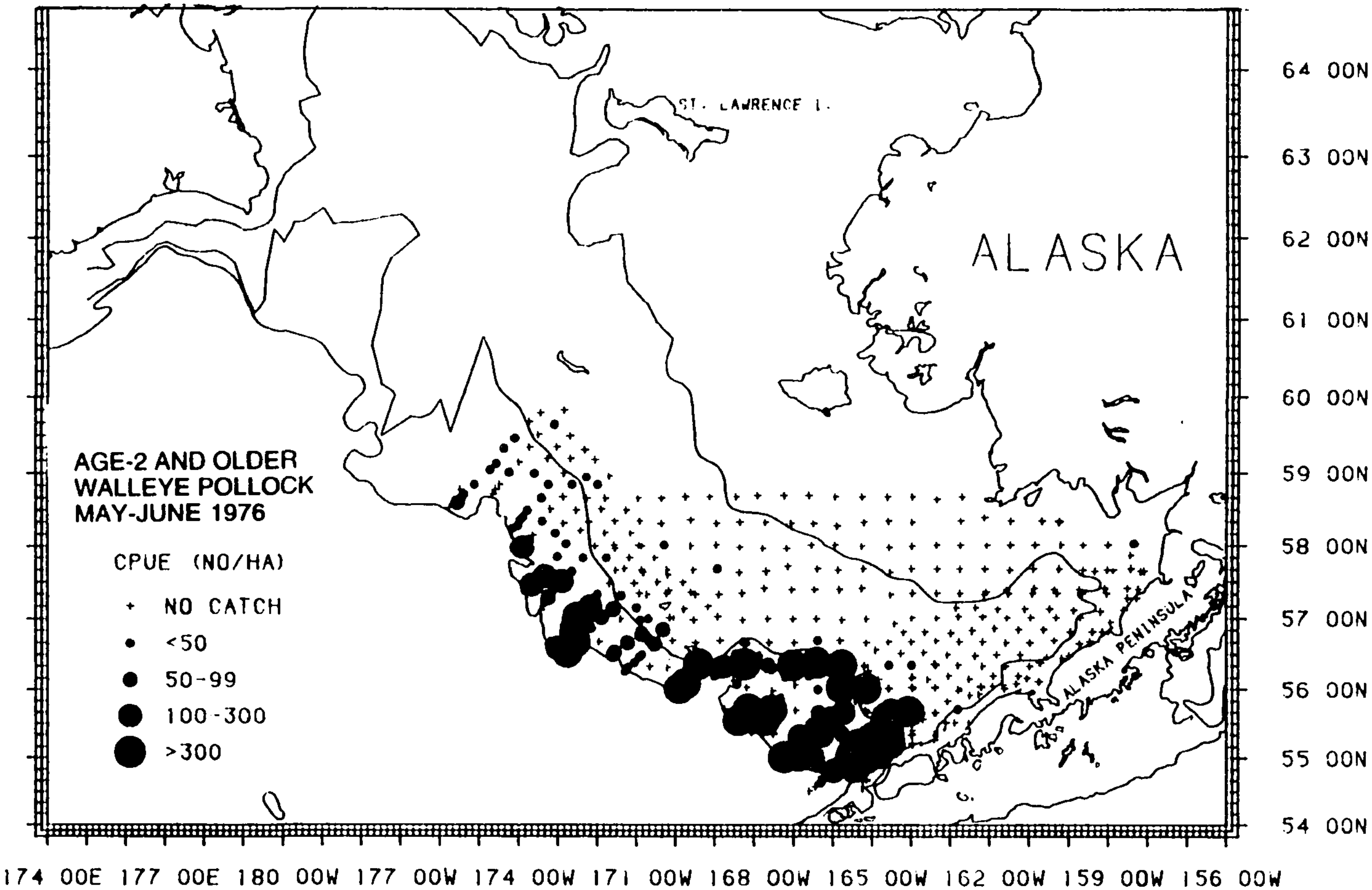
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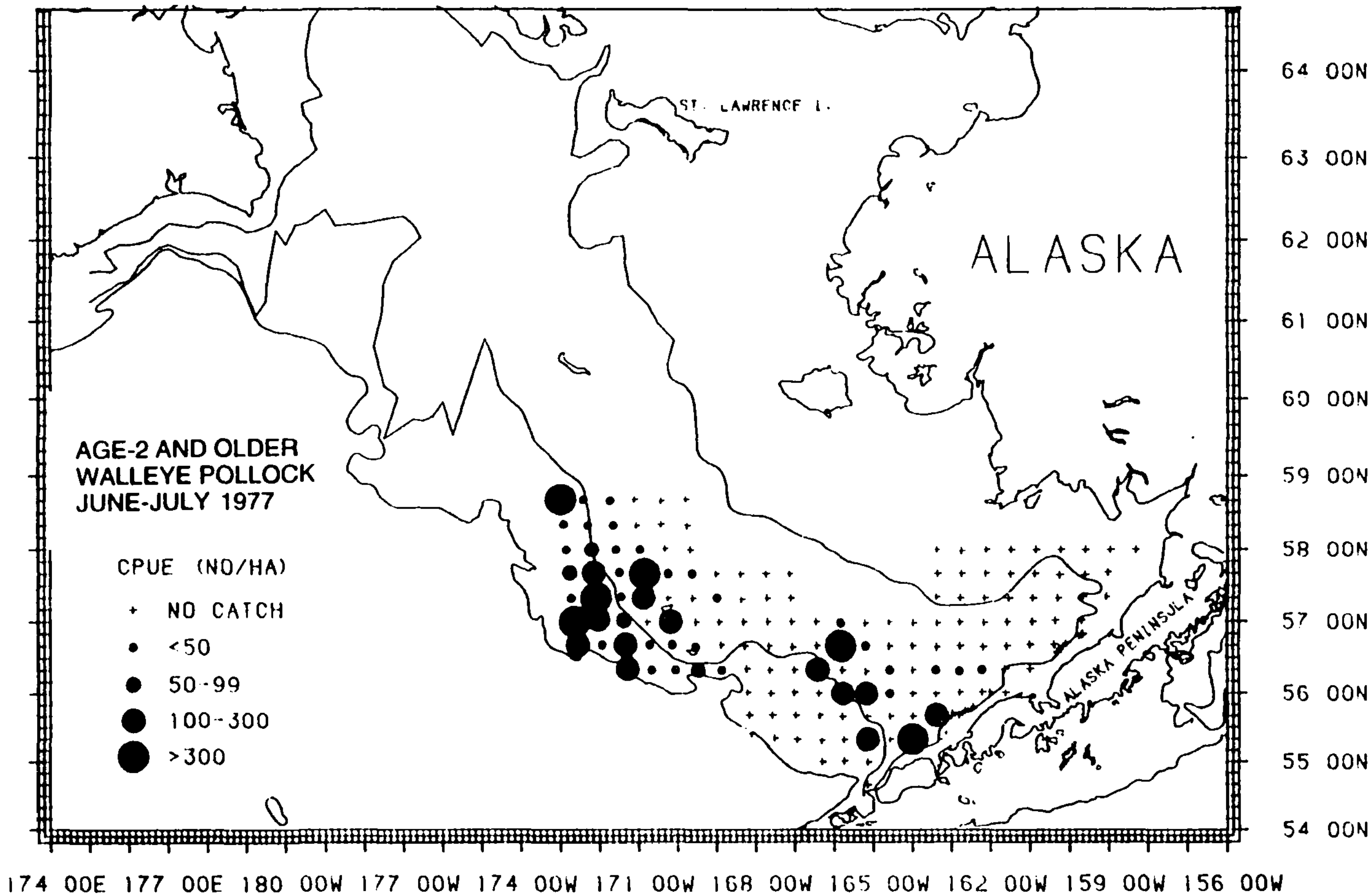
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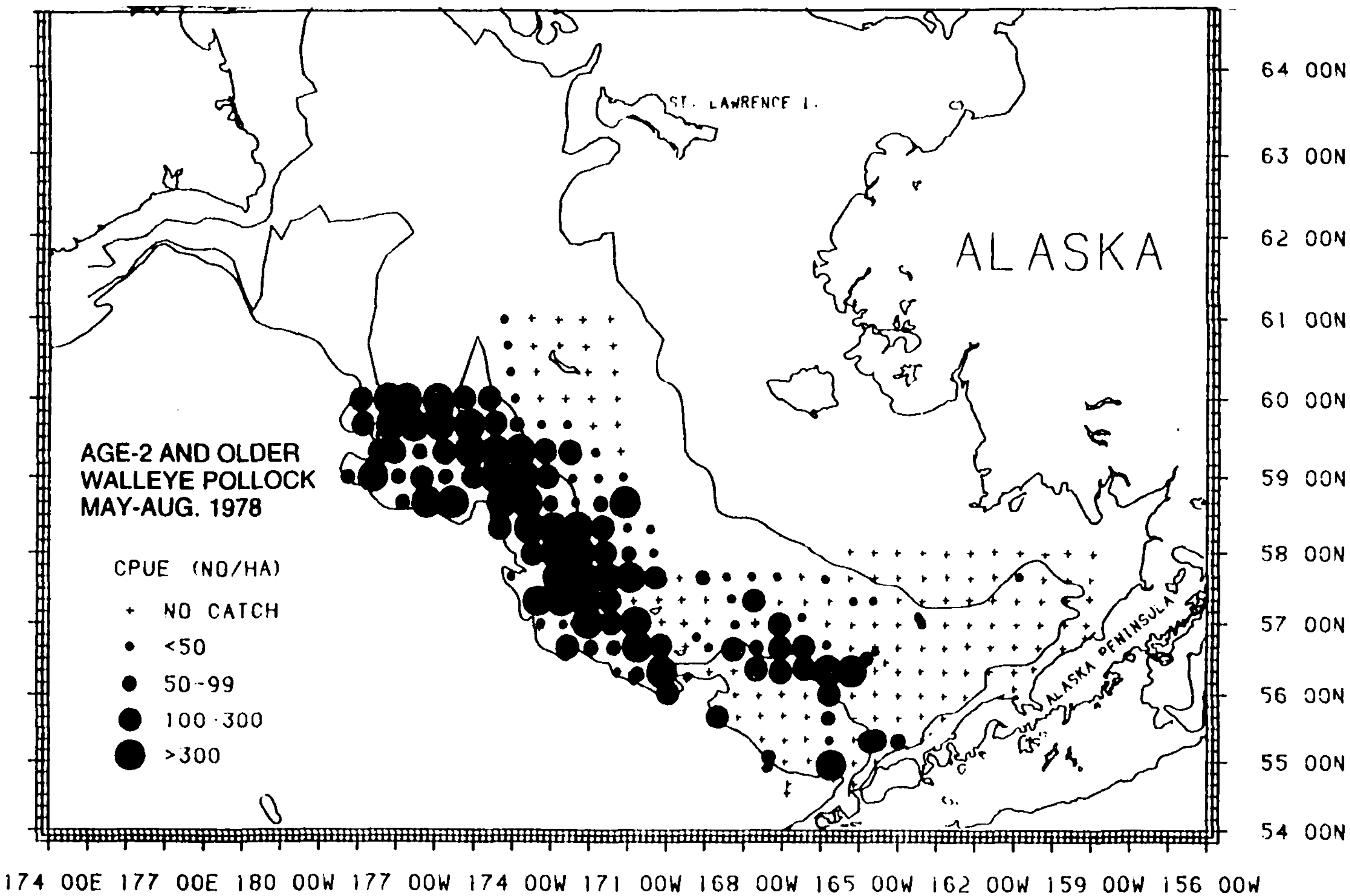
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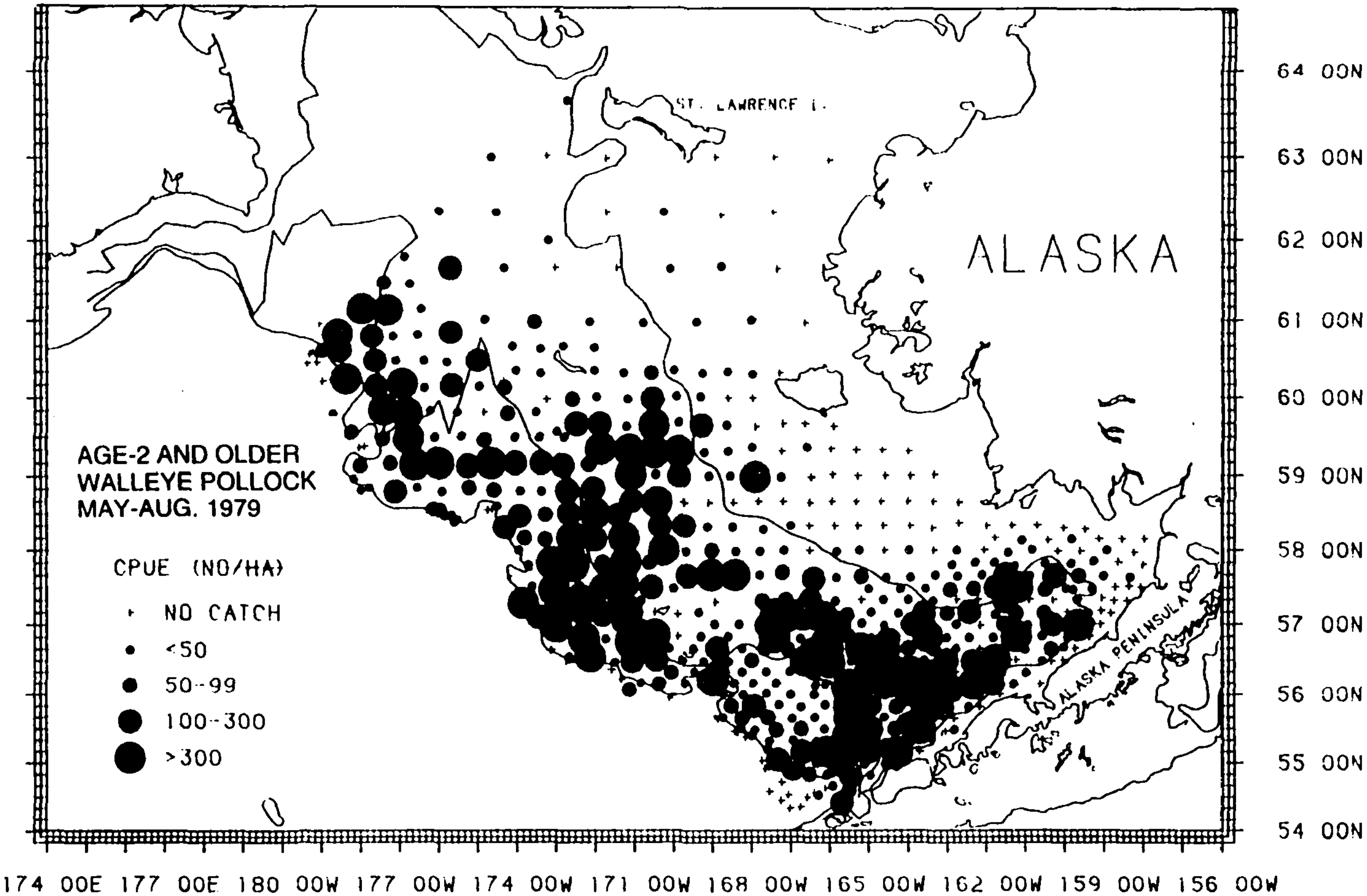
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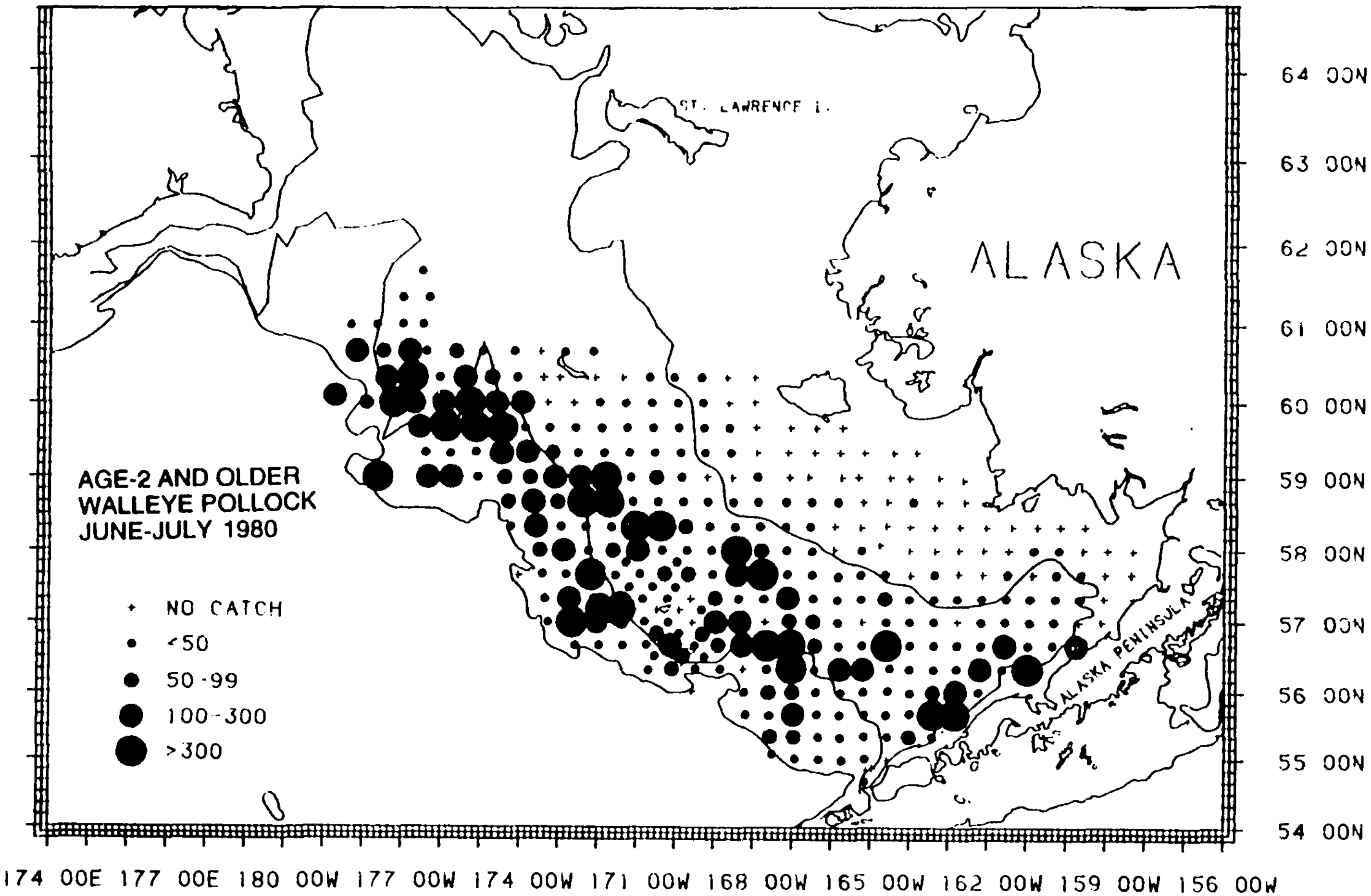

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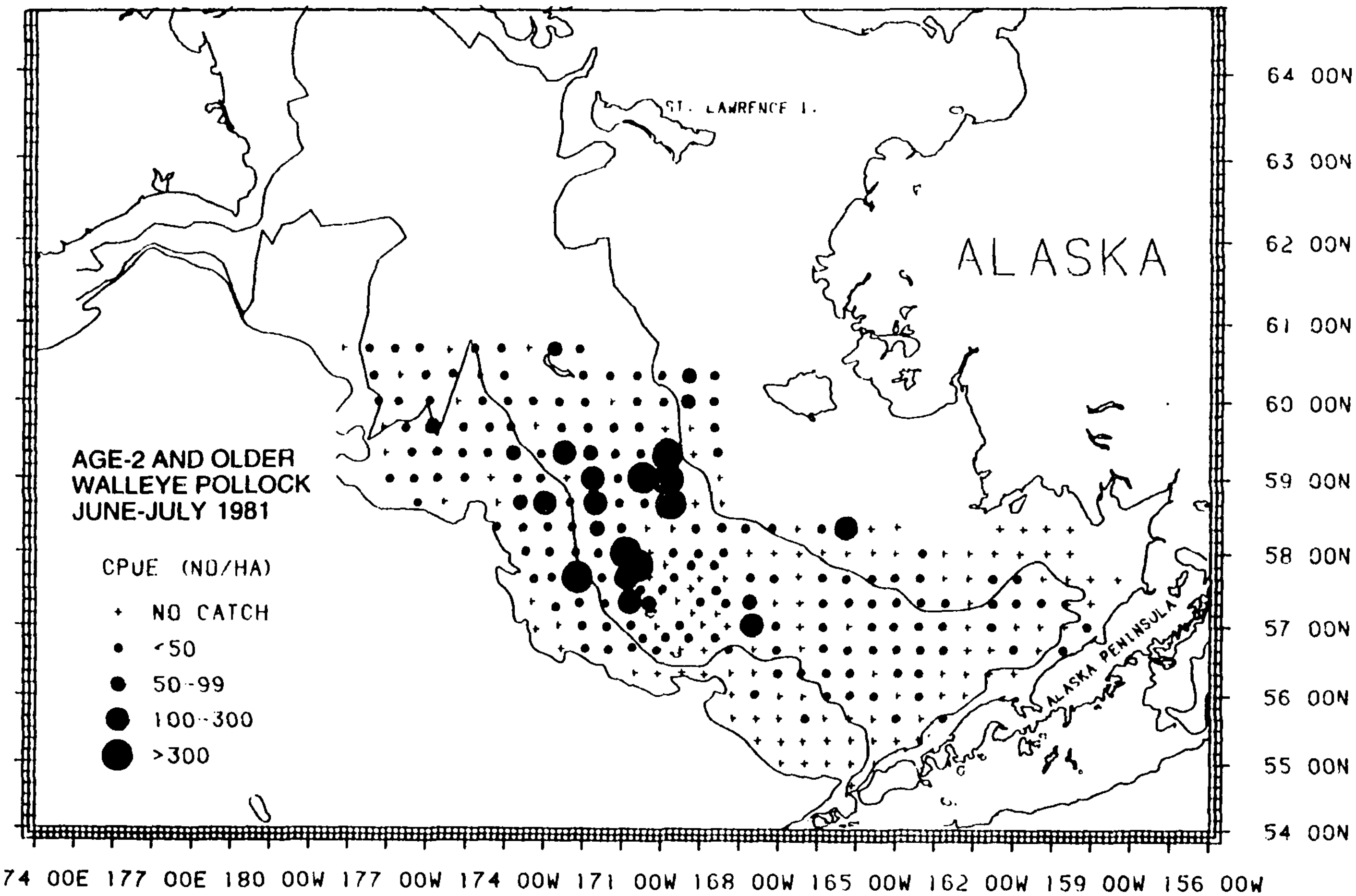
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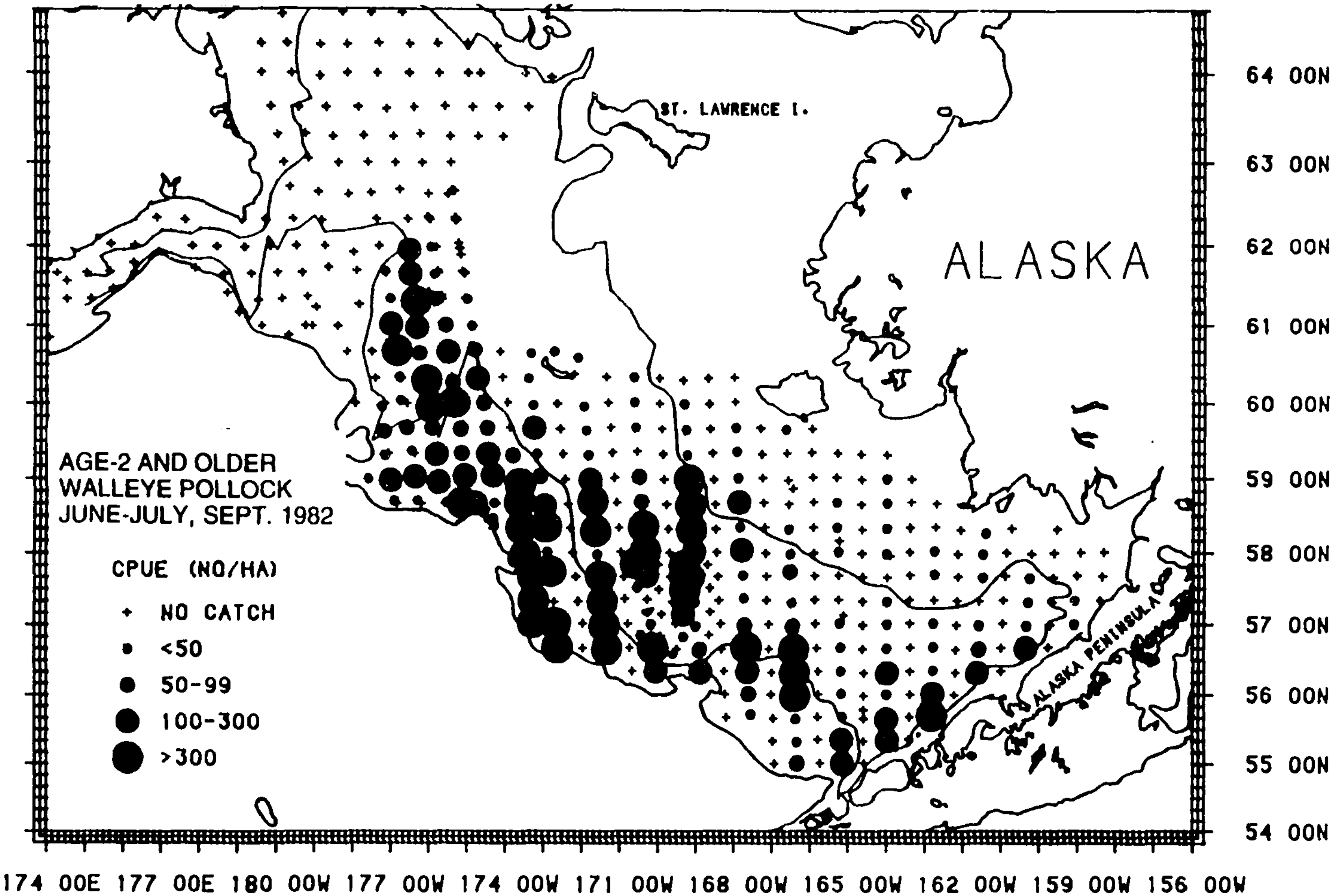
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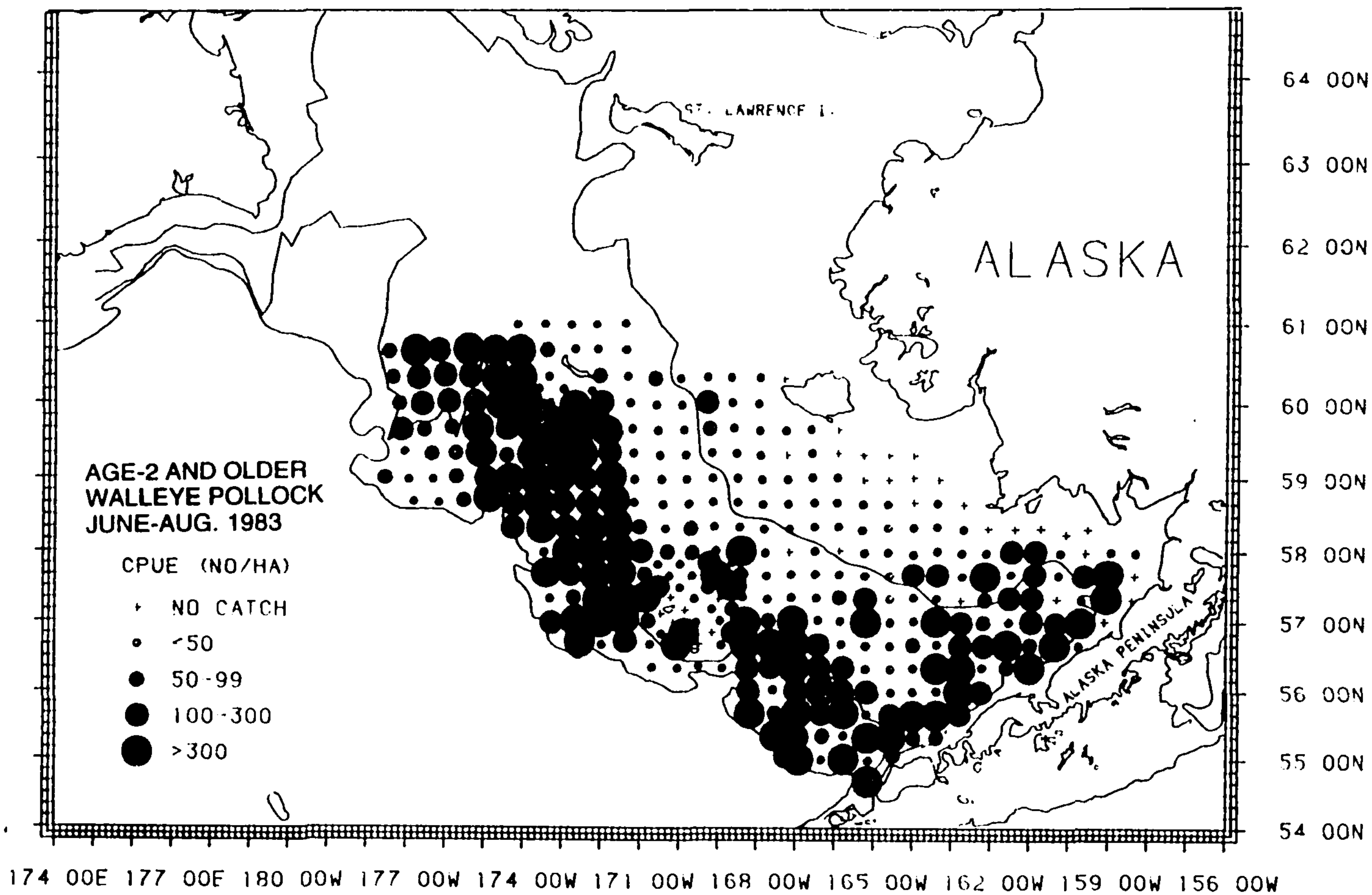

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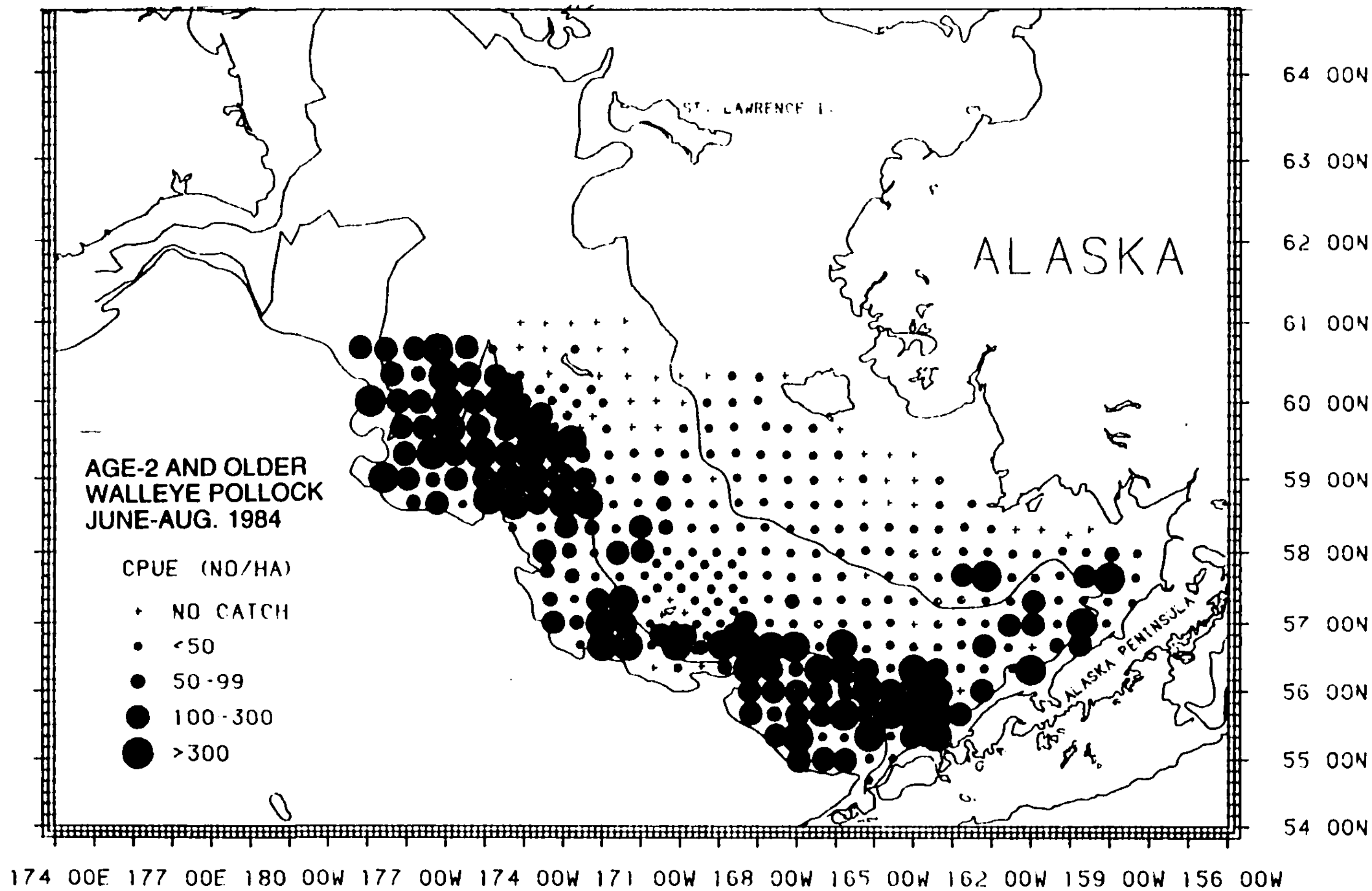
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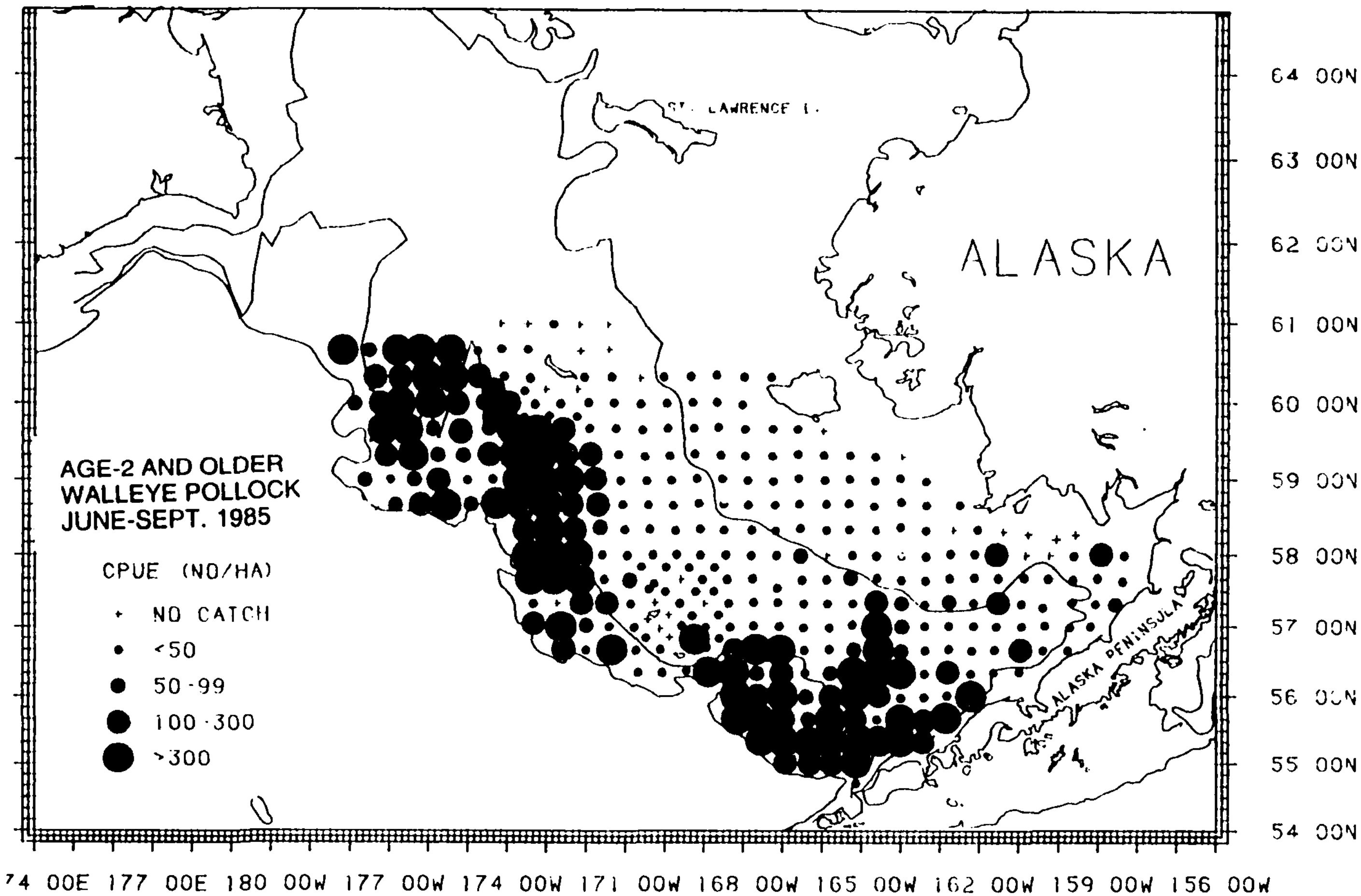
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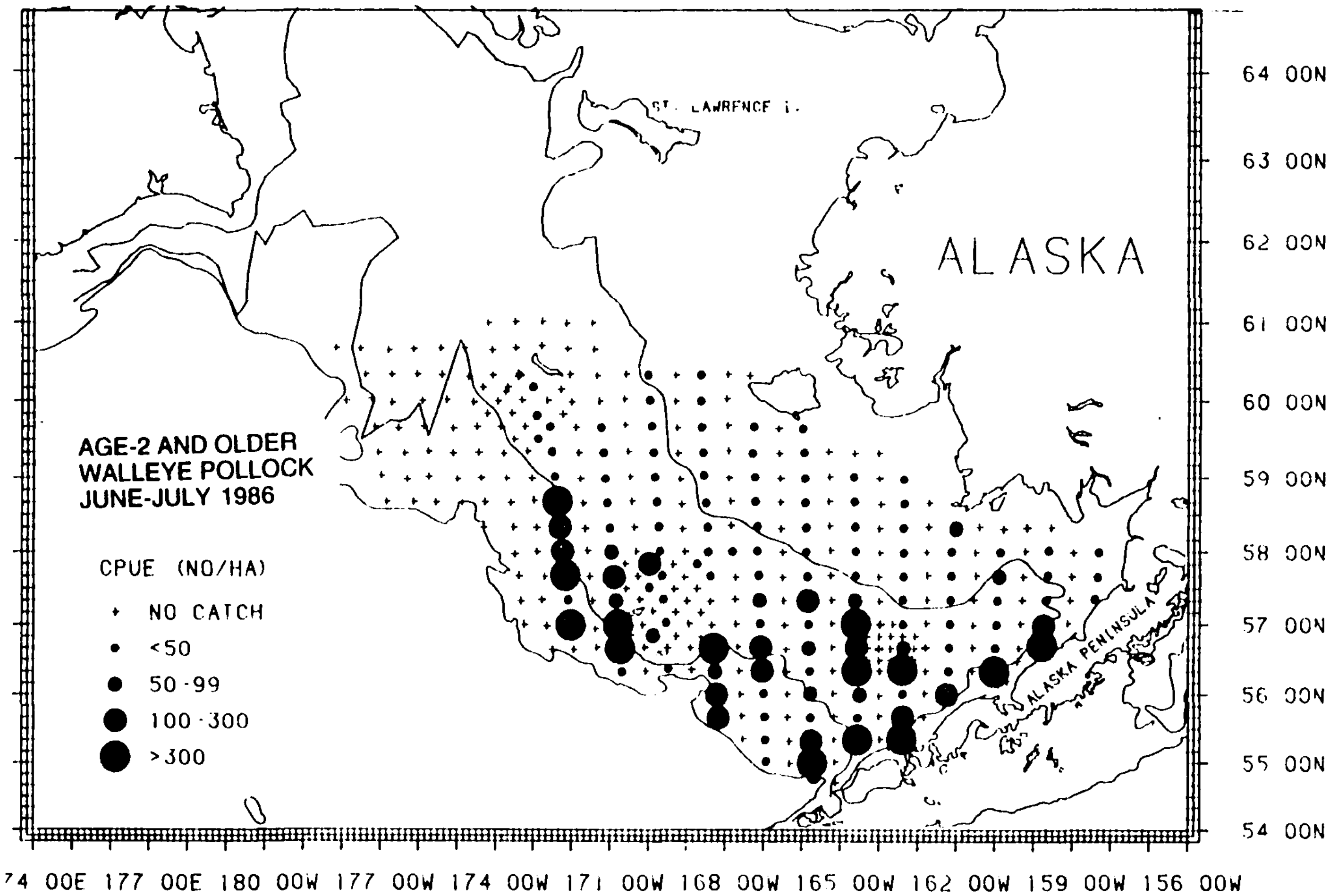
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WALLEYE POLLOCK
JUNE-JULY 1986
CPUE (NO/HA)
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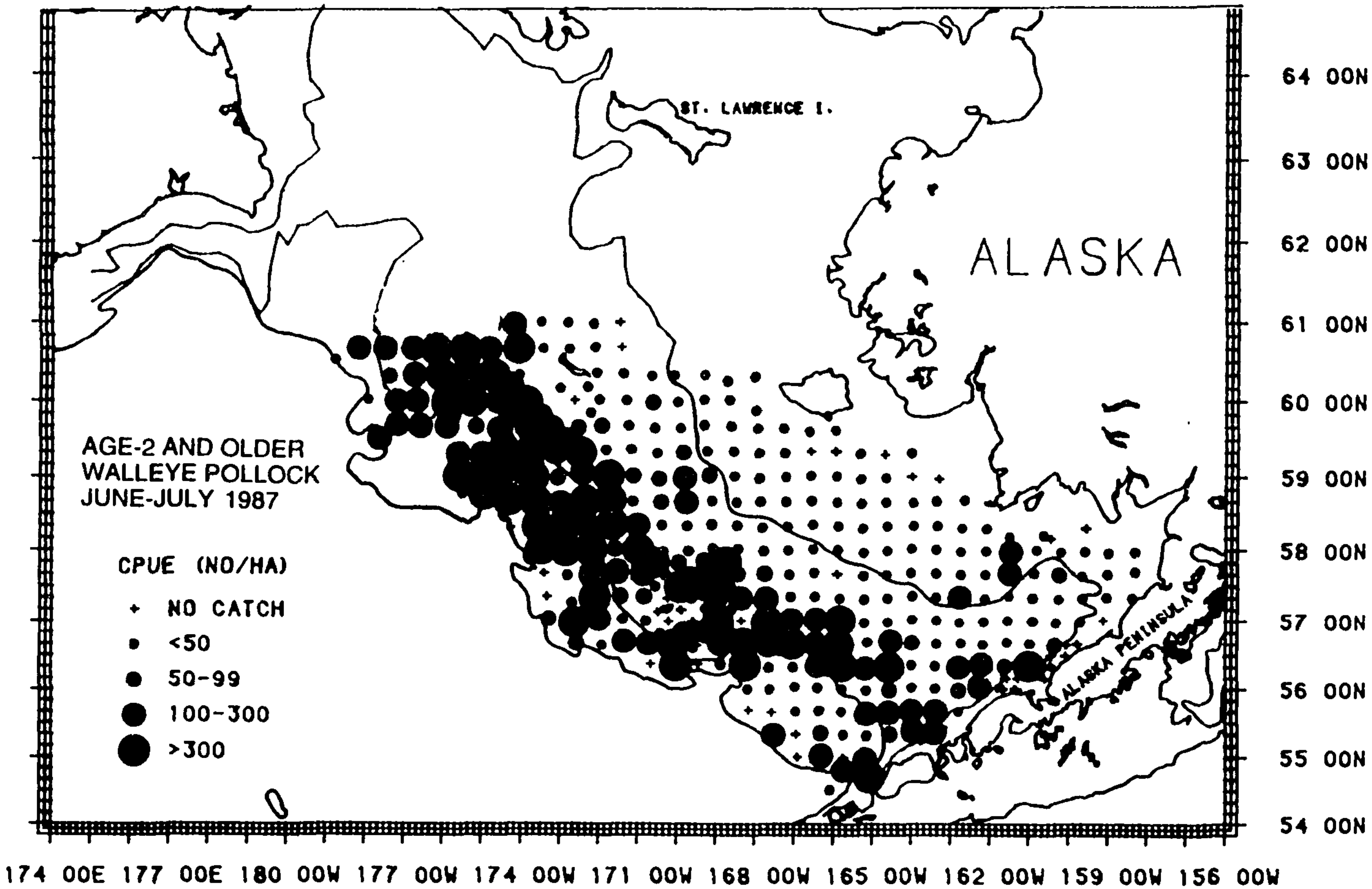

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AGE-2 AND OLDER
WALLEYE POLLOCK
JUNE-JULY 1987
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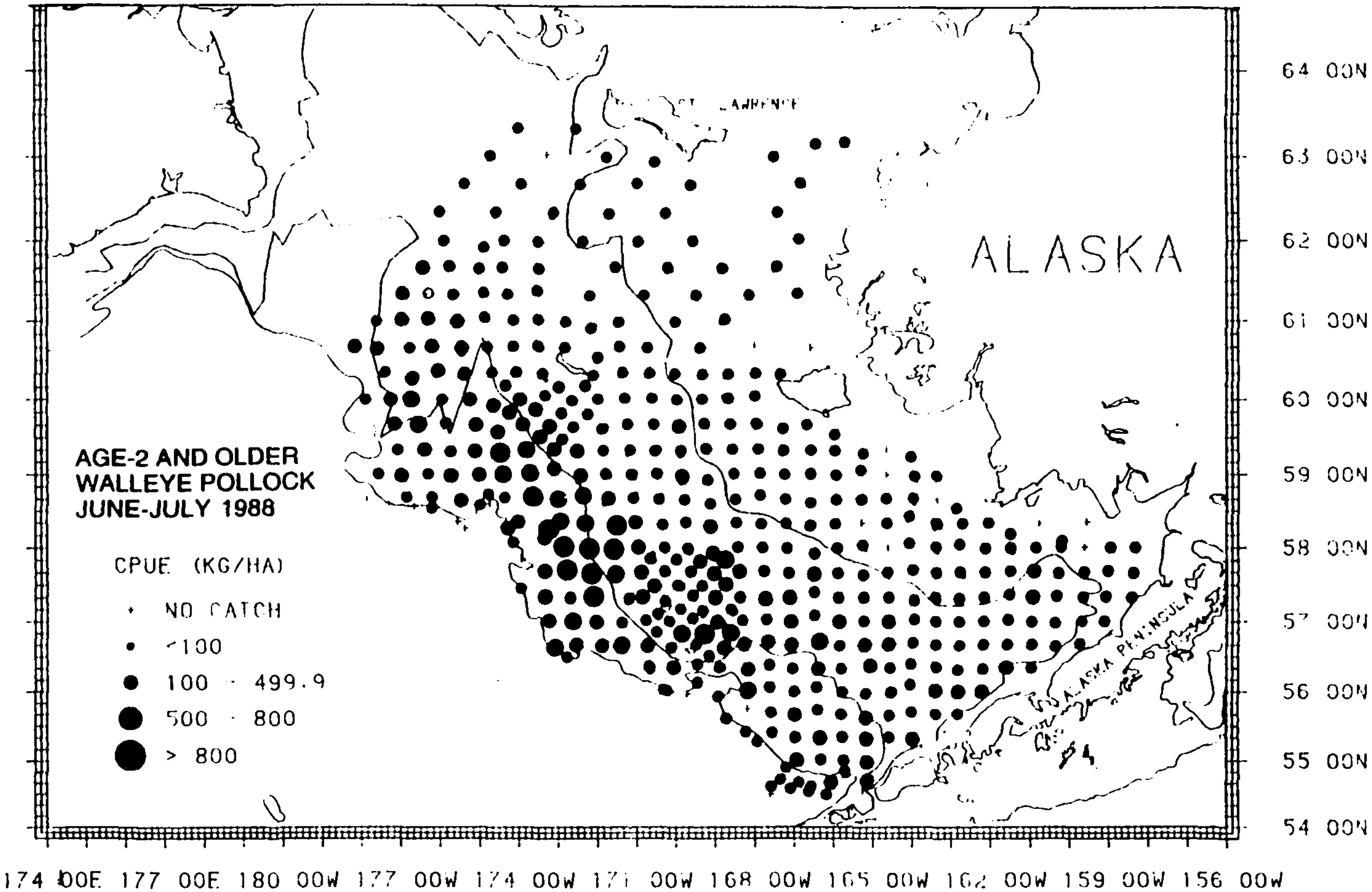
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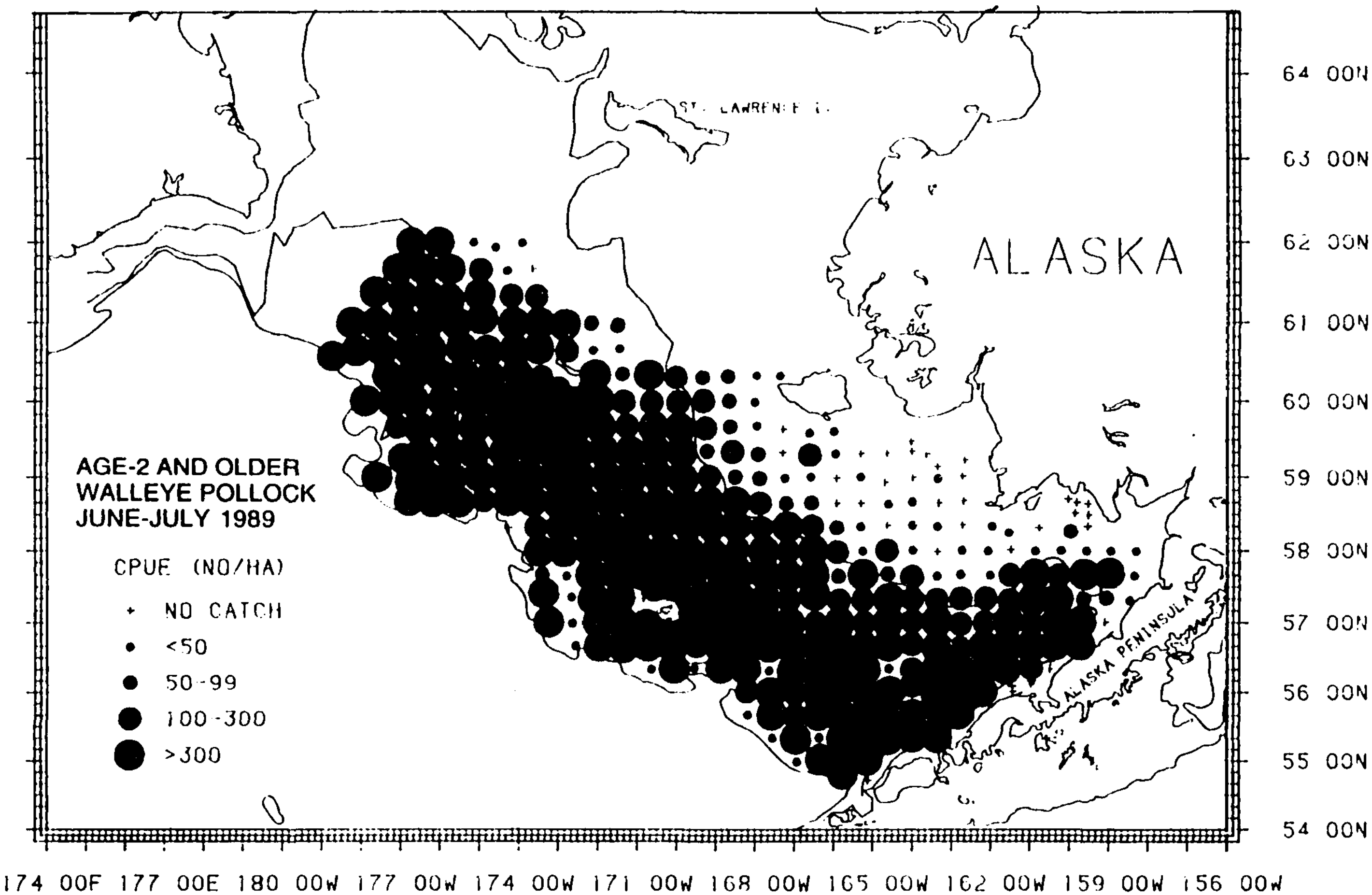
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AGE-2 AND OLDER
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JUNE-JULY 1989
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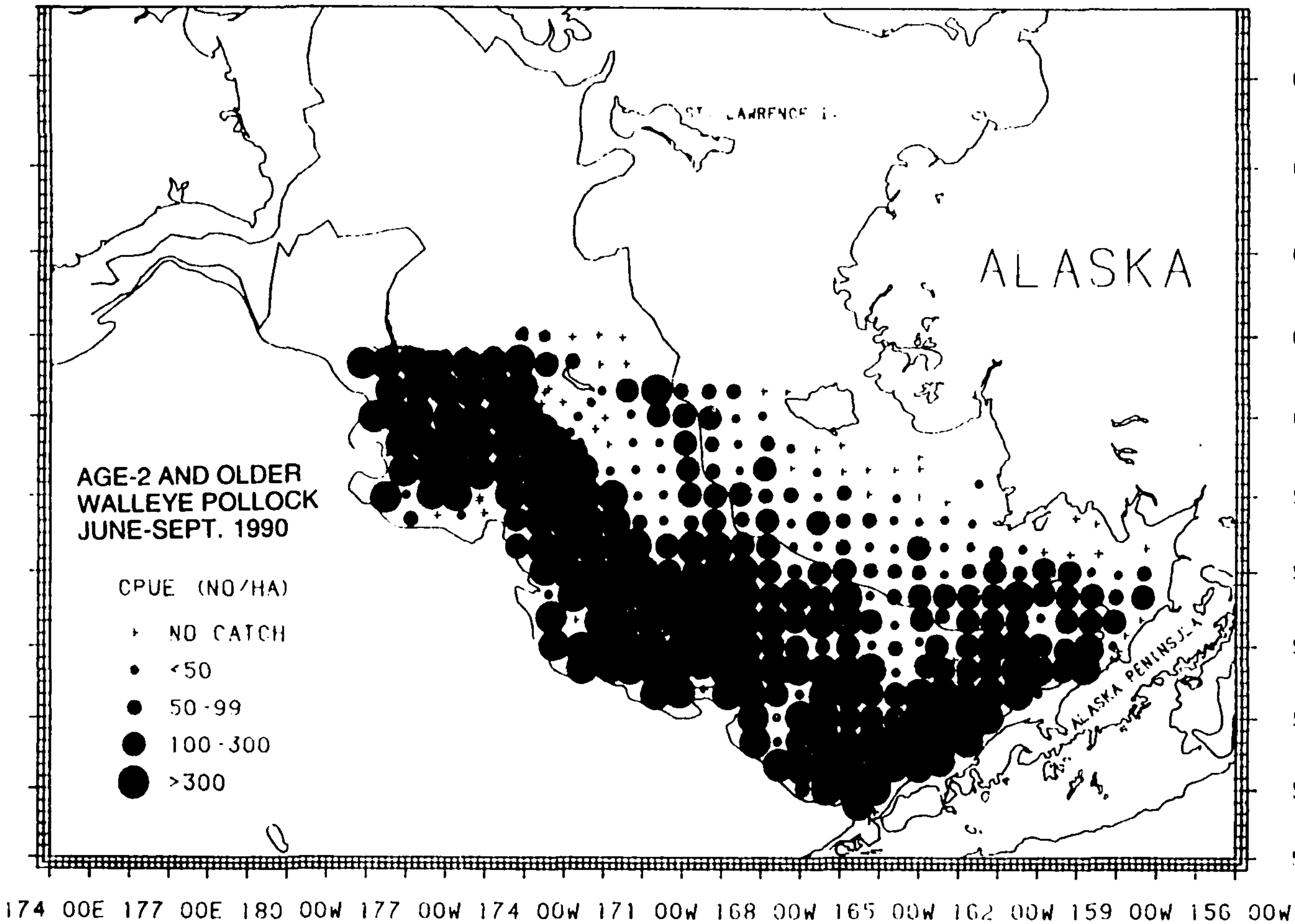

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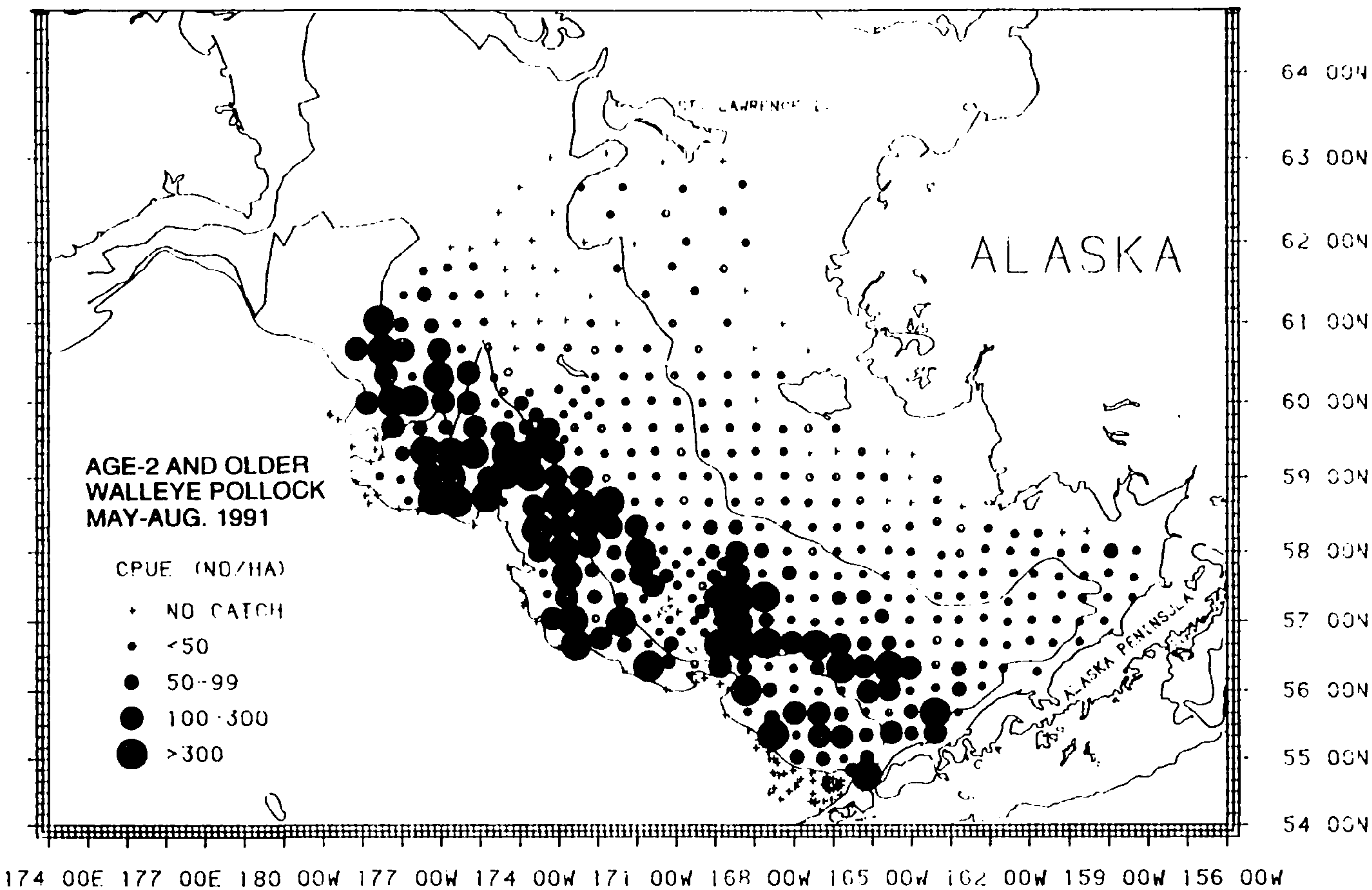
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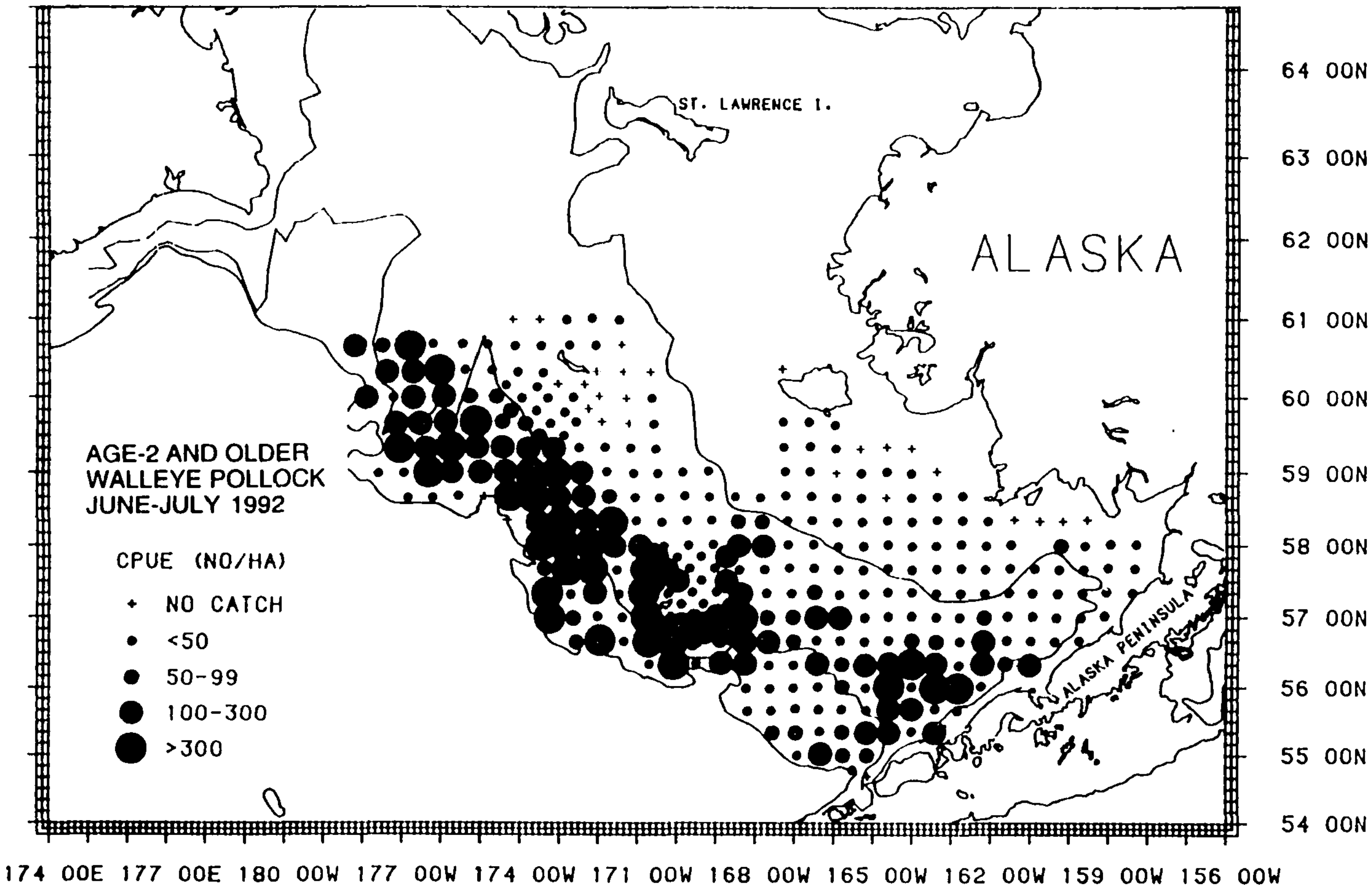
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AGE-2 AND OLDER
WALLEYE POLLOCK
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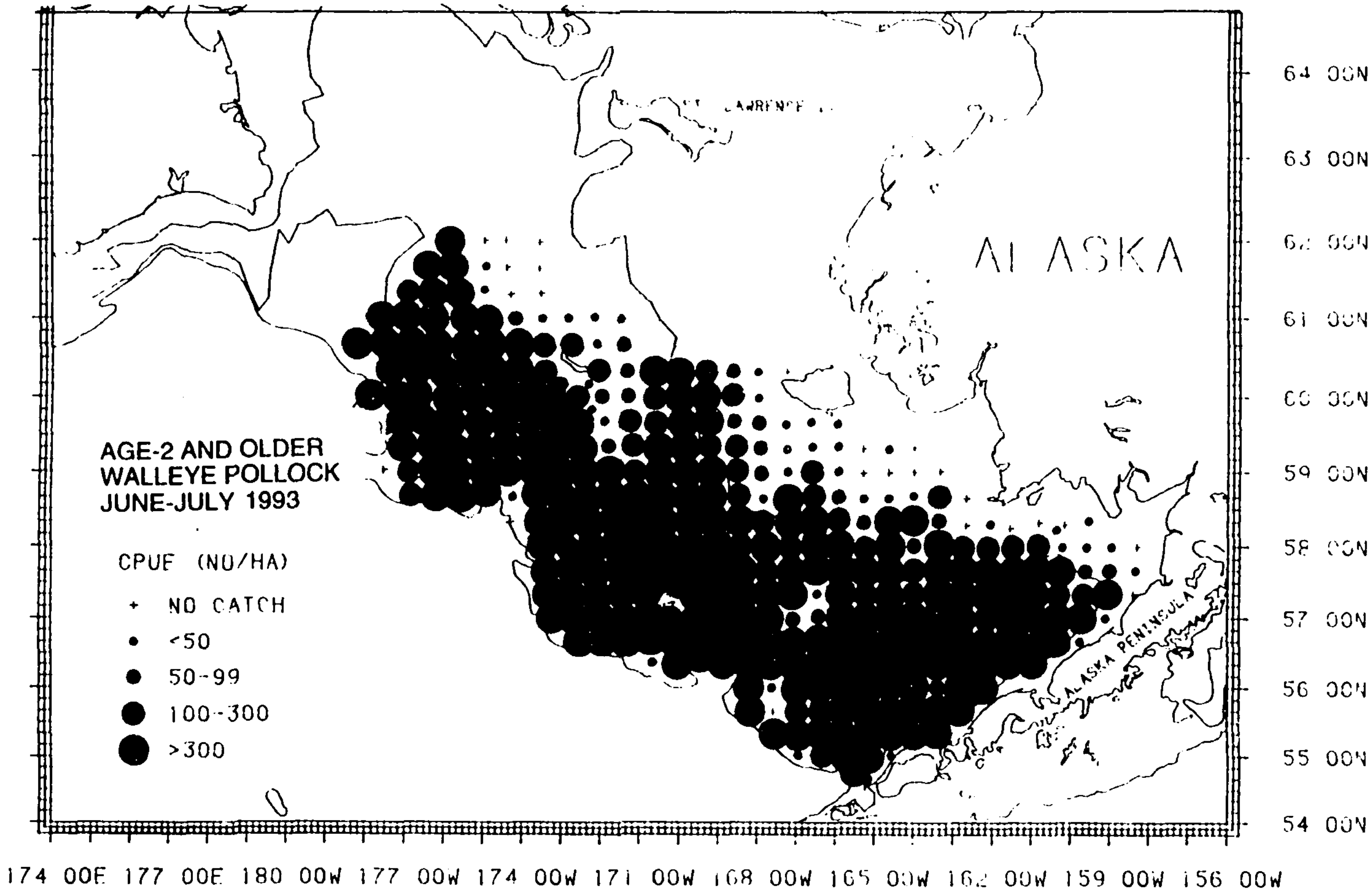
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WALLEYE POLLOCK
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CPUE (NO/HA)
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55 00N
54 00N
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177 00E
180 00W
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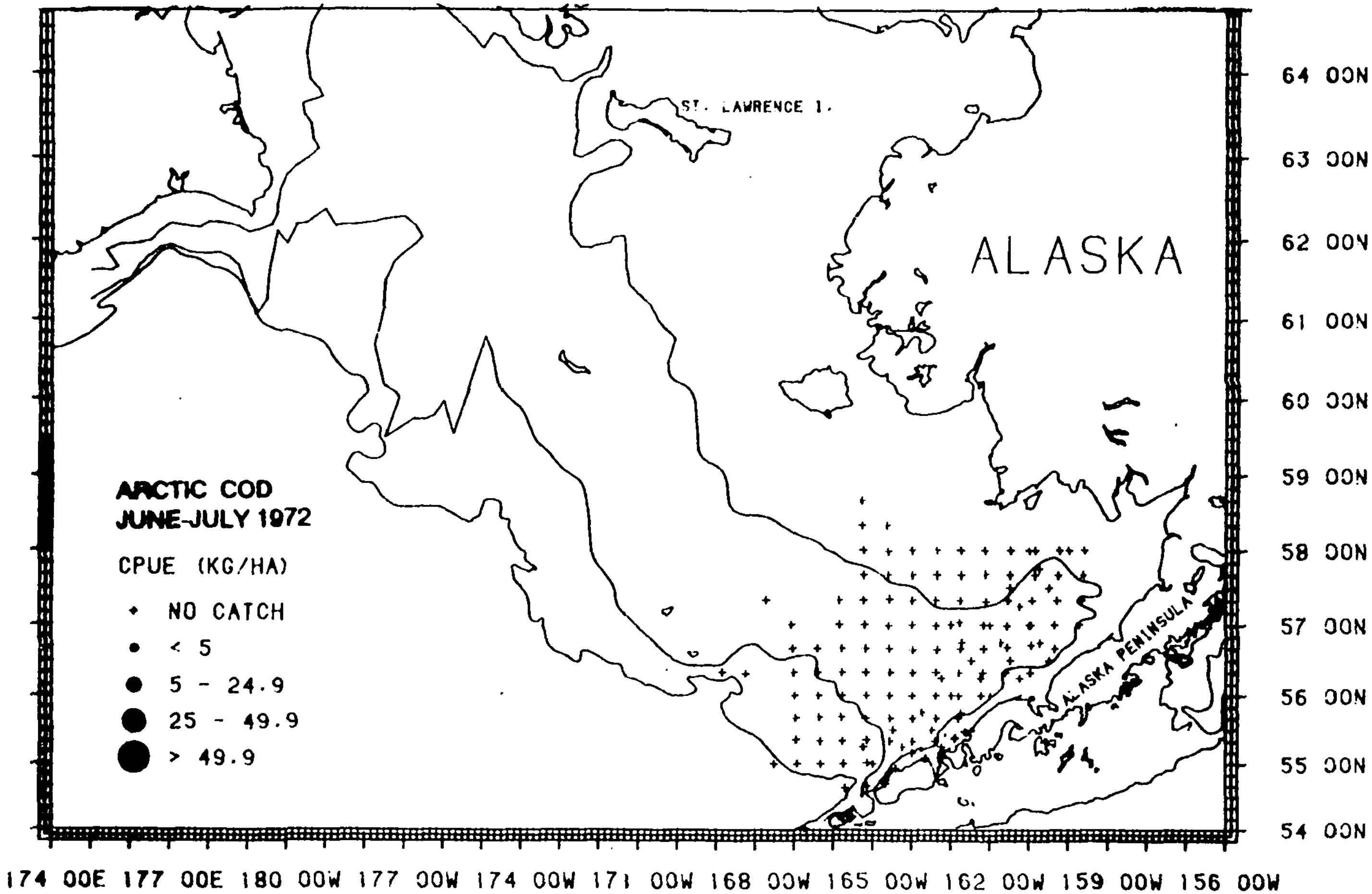
156 00W

APPENDIX 4. - Distribution and abundance maps for Arctic cod for 1972-1993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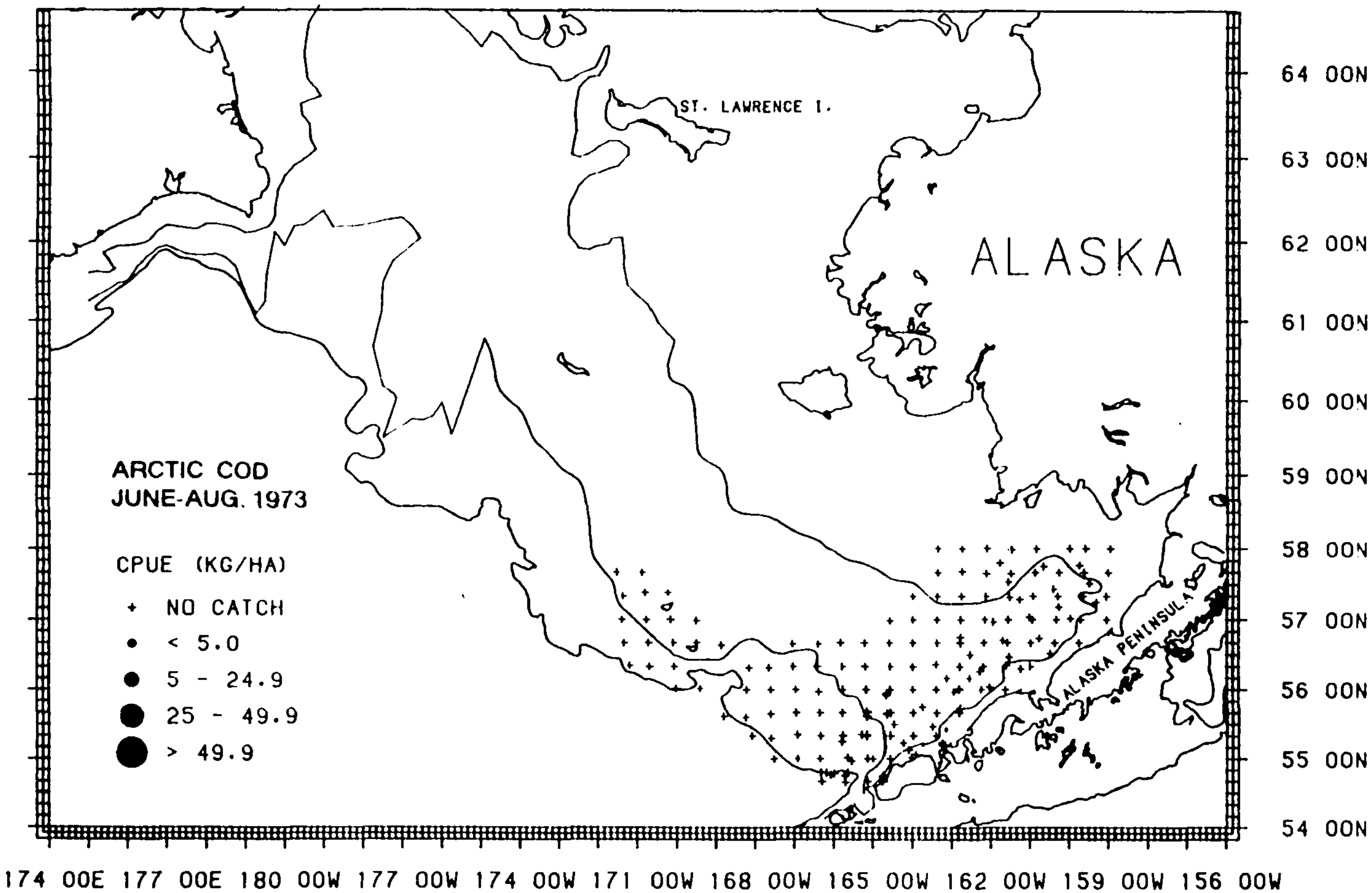
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CPUE (KG/HA)
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25 - 49.9
> 49.9
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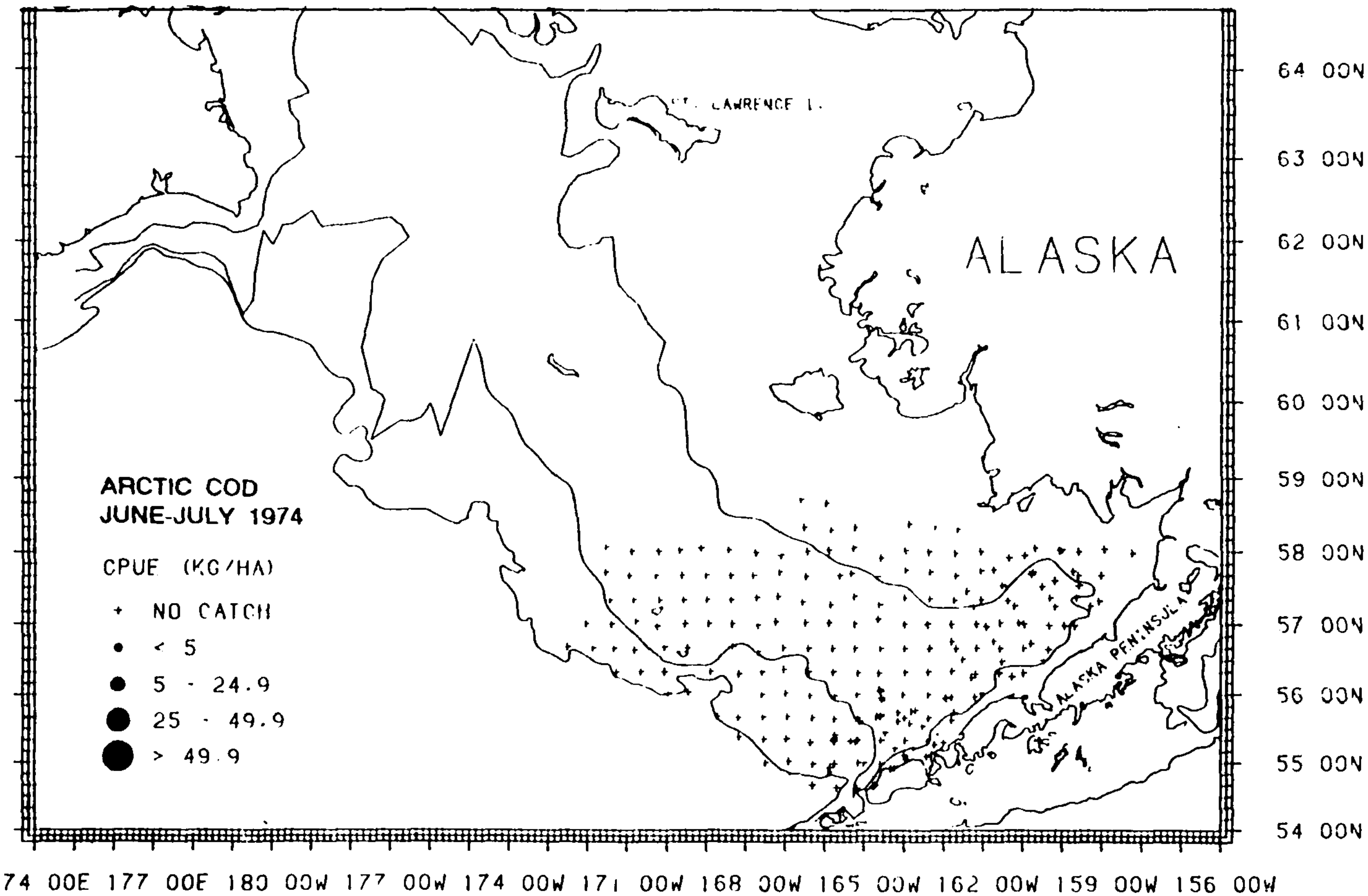

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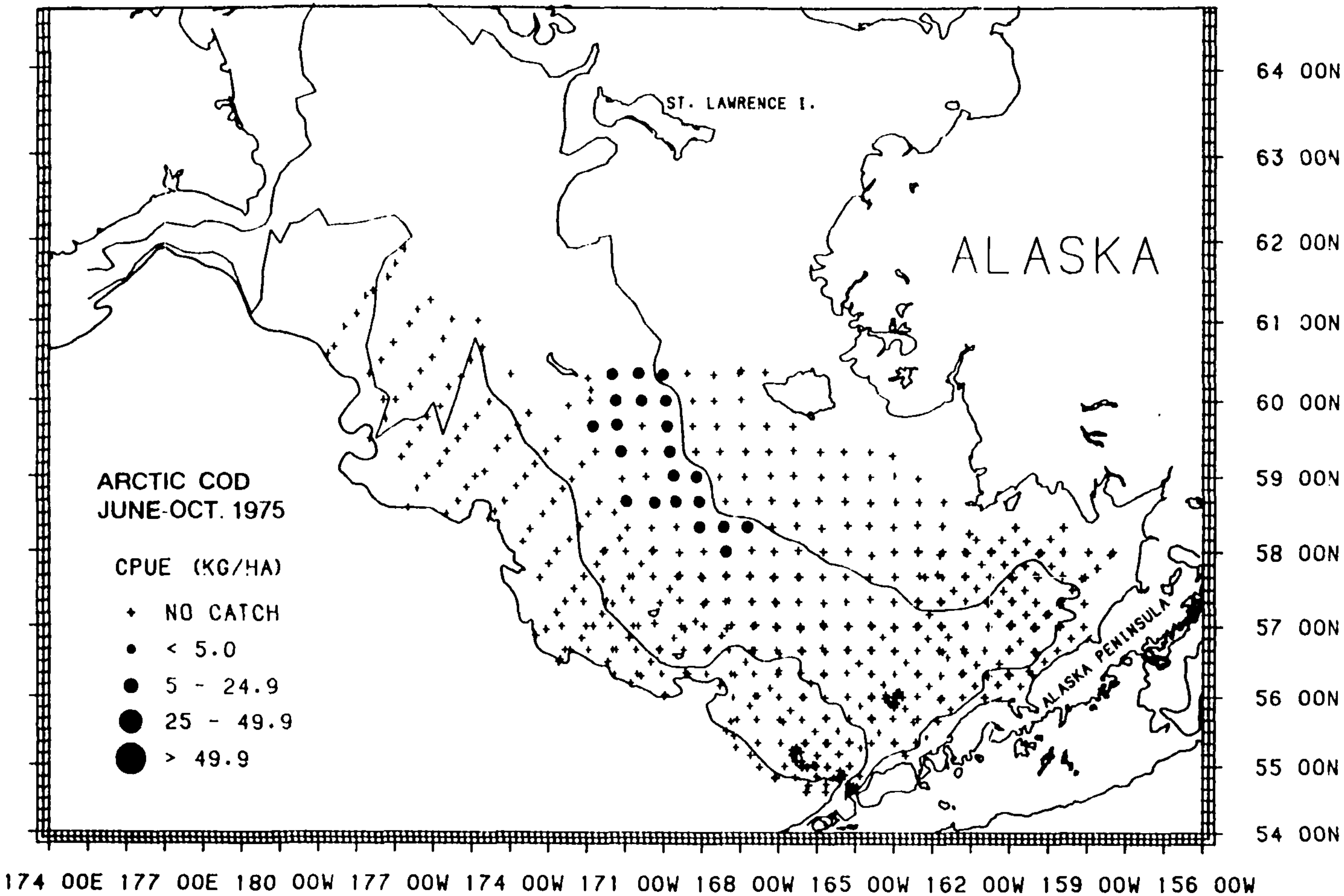
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JUNE-OCT. 1975
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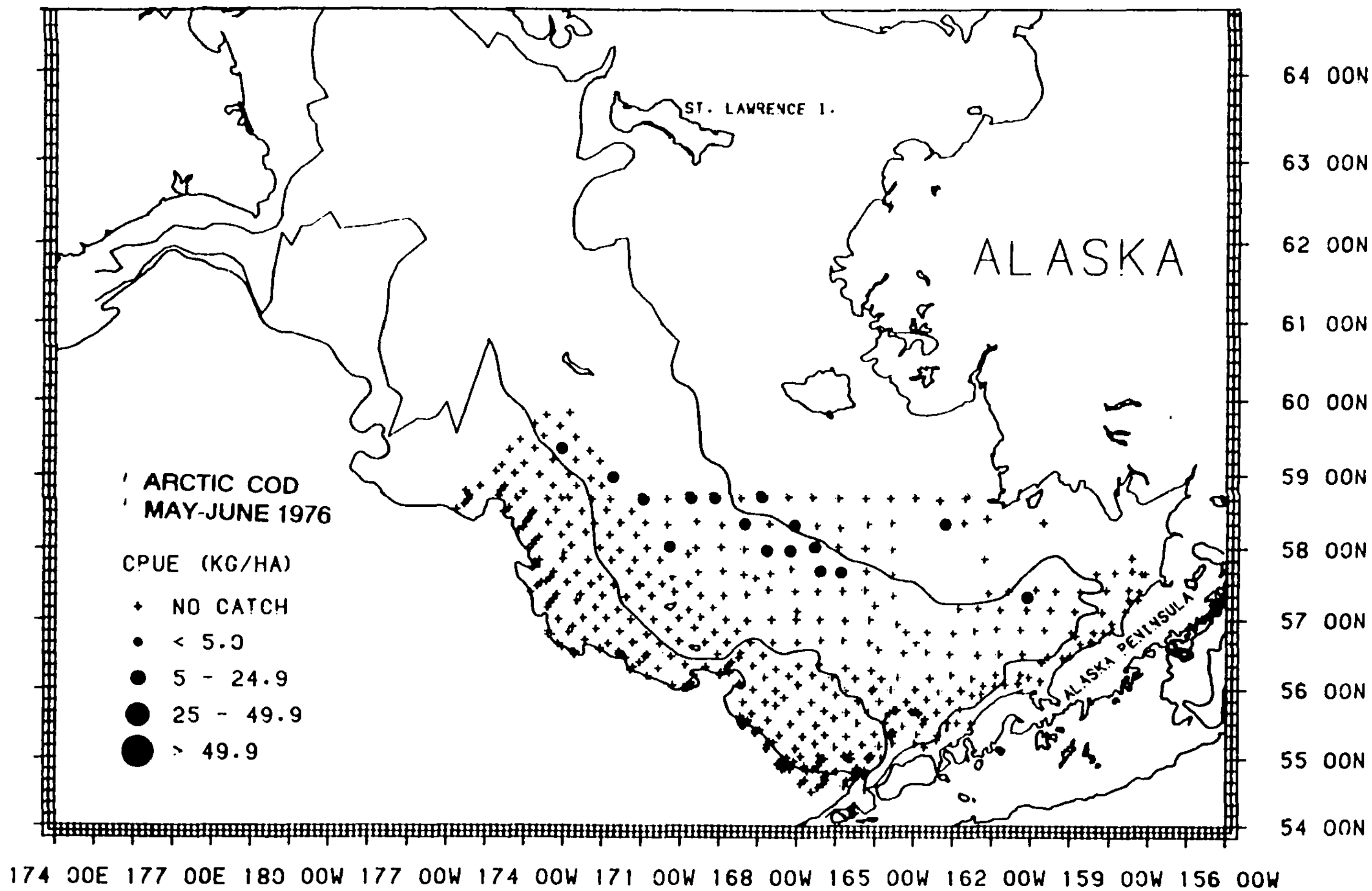
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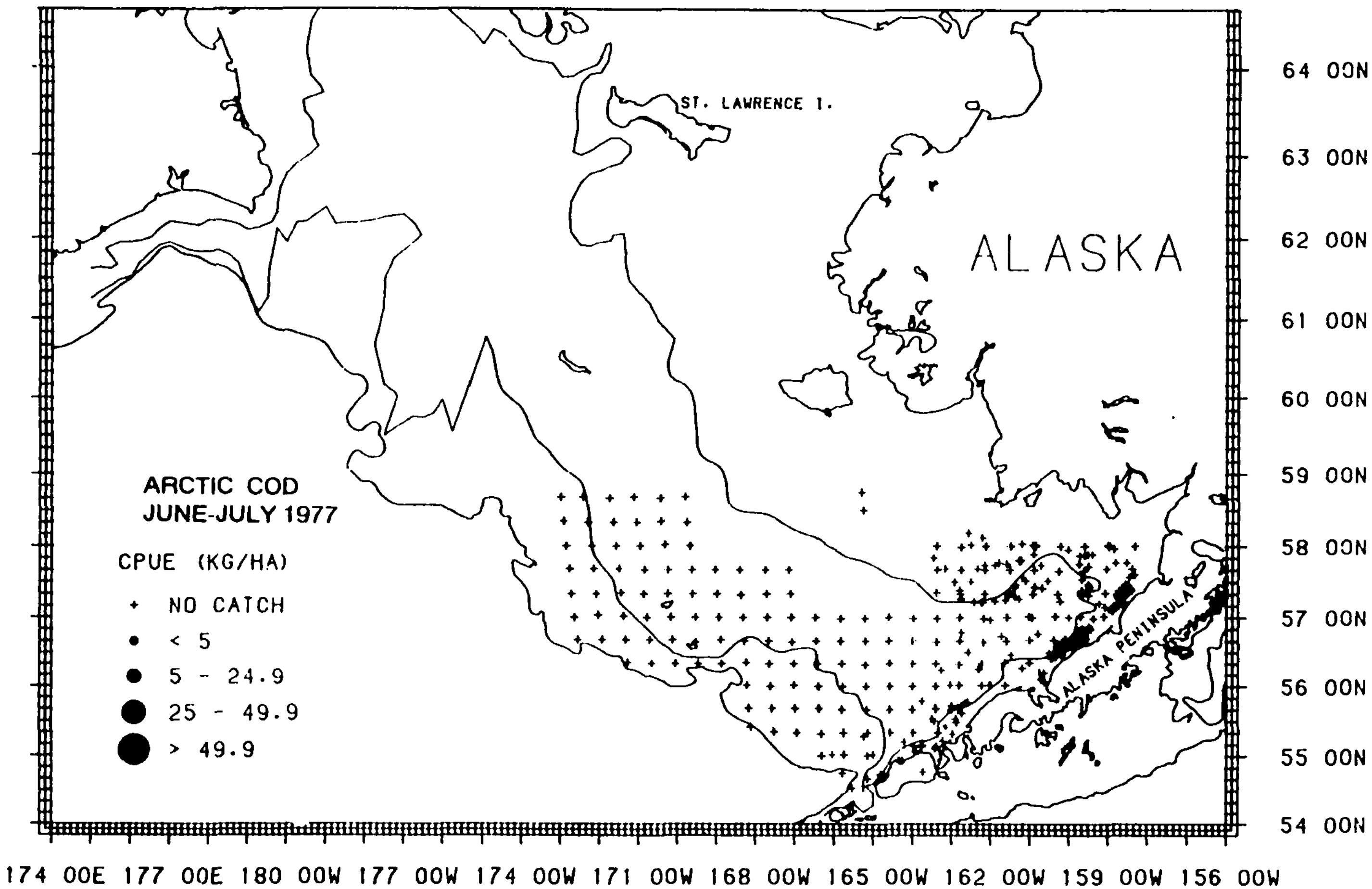
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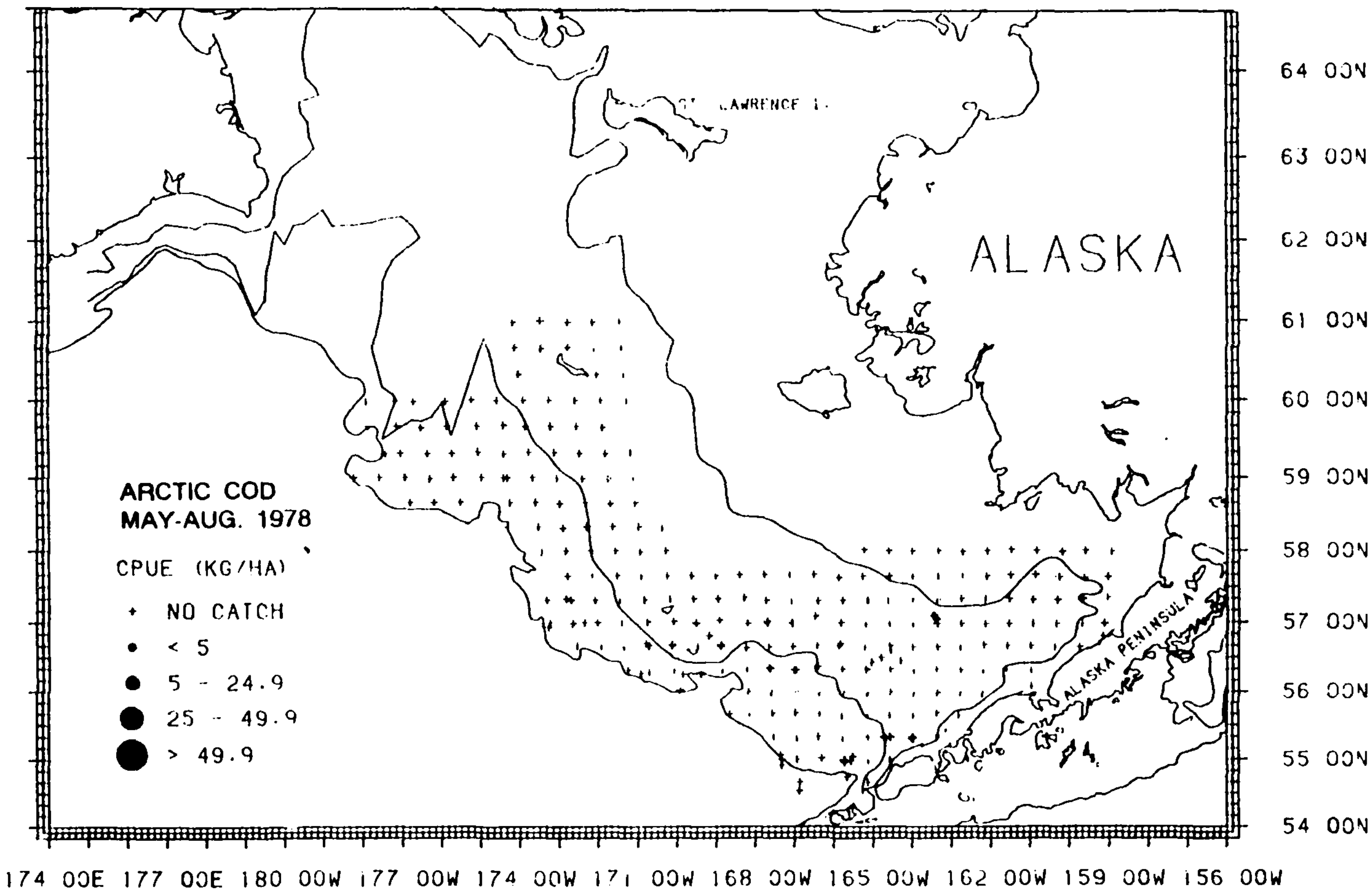
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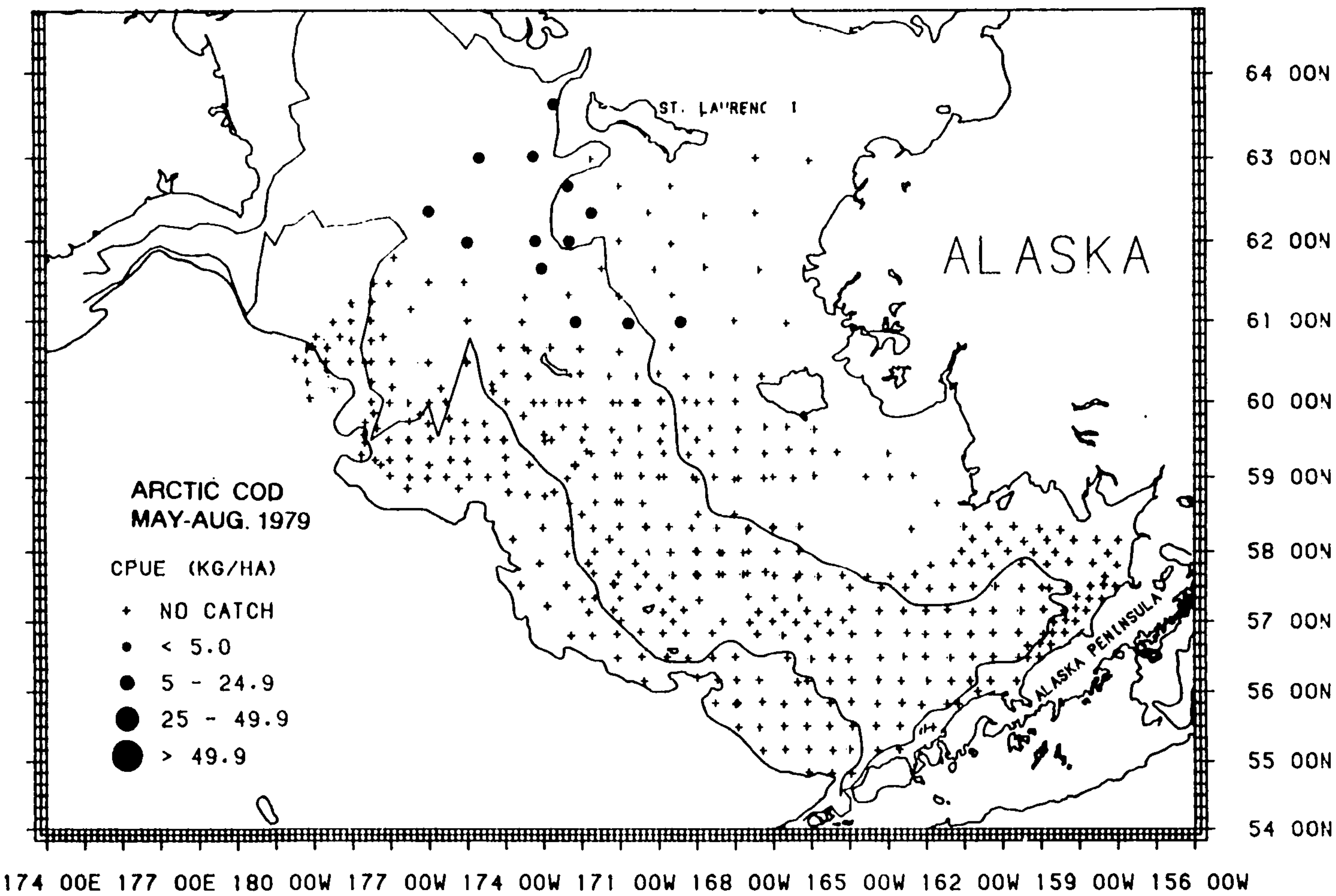
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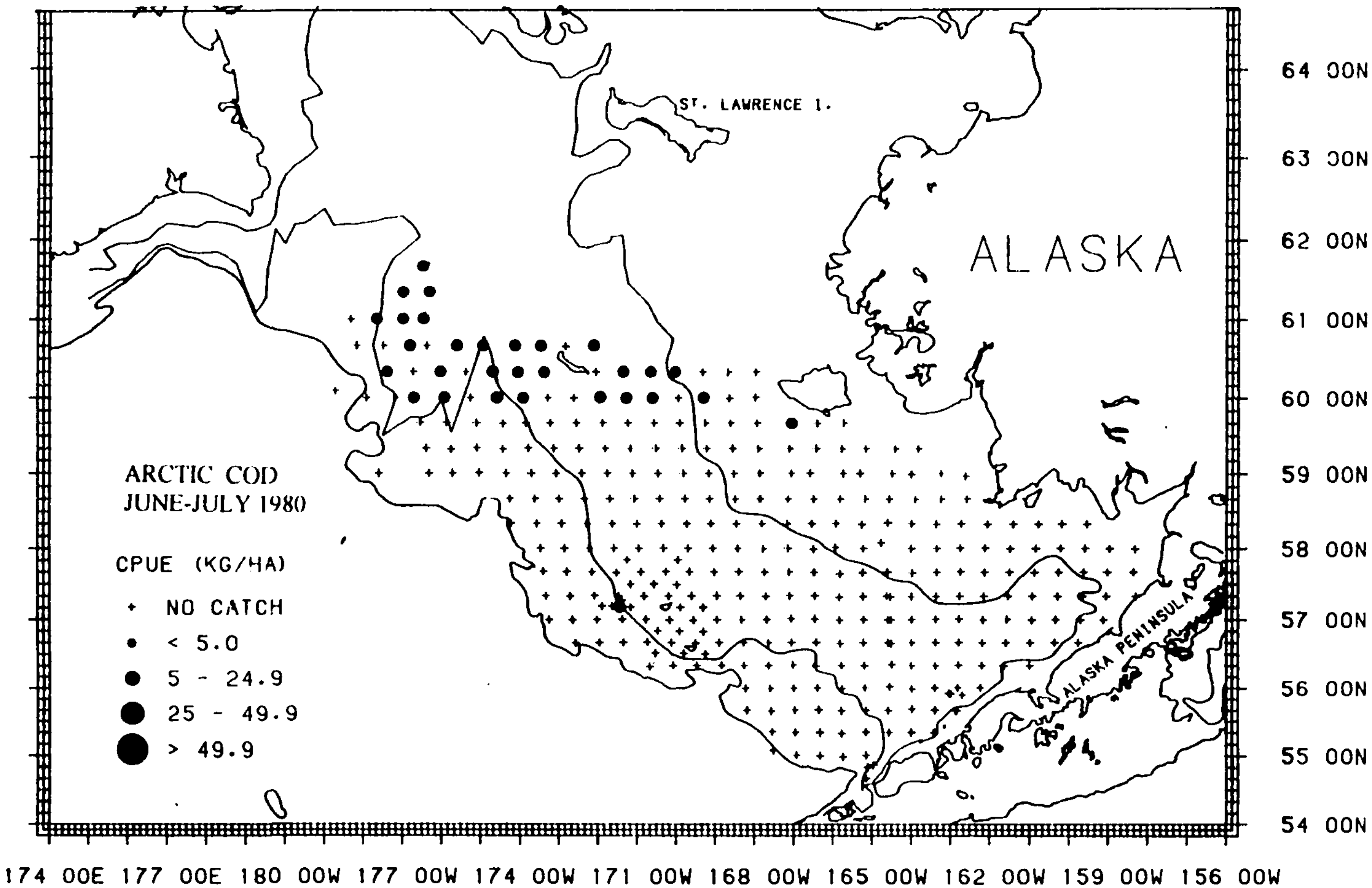
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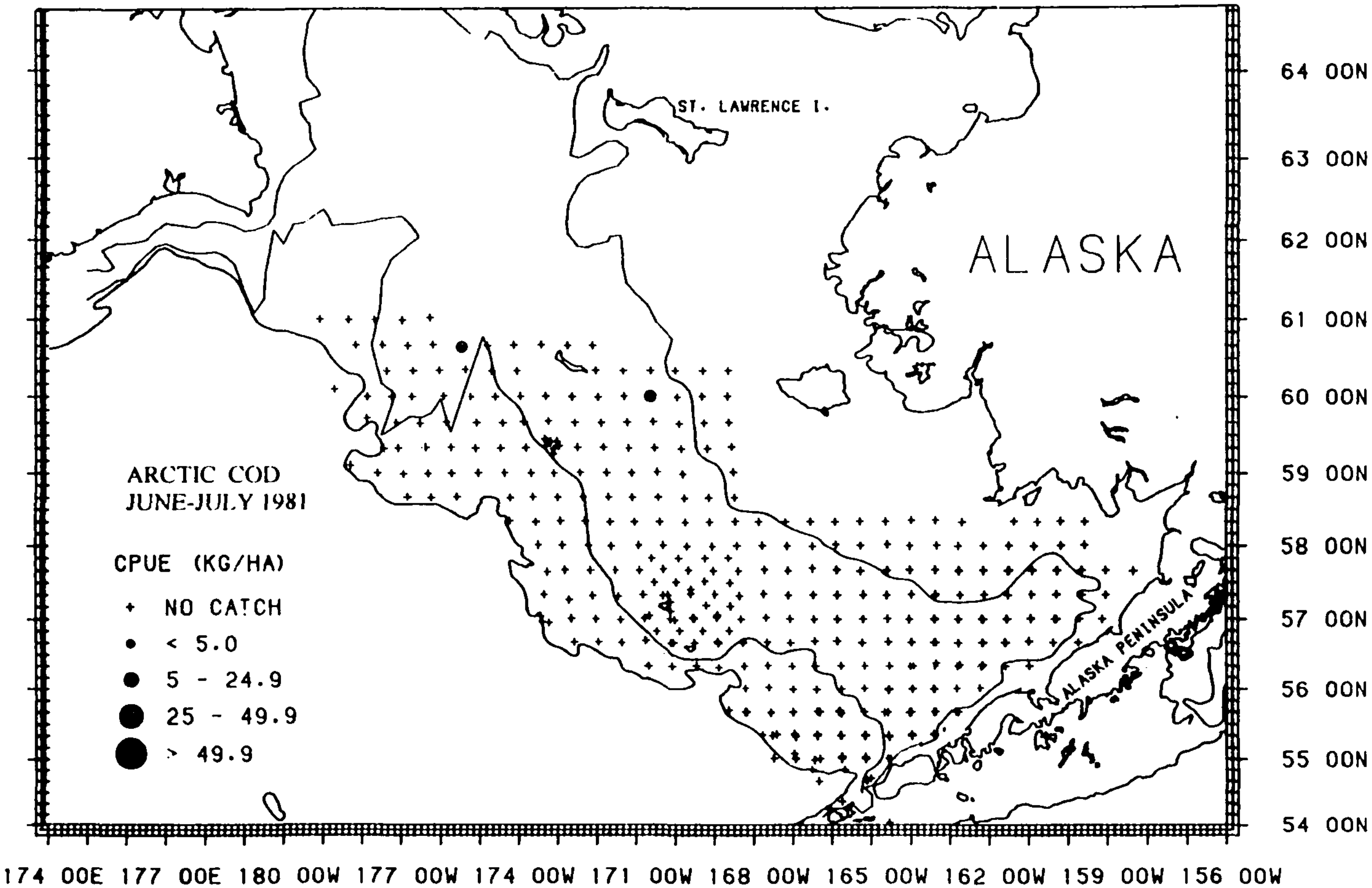
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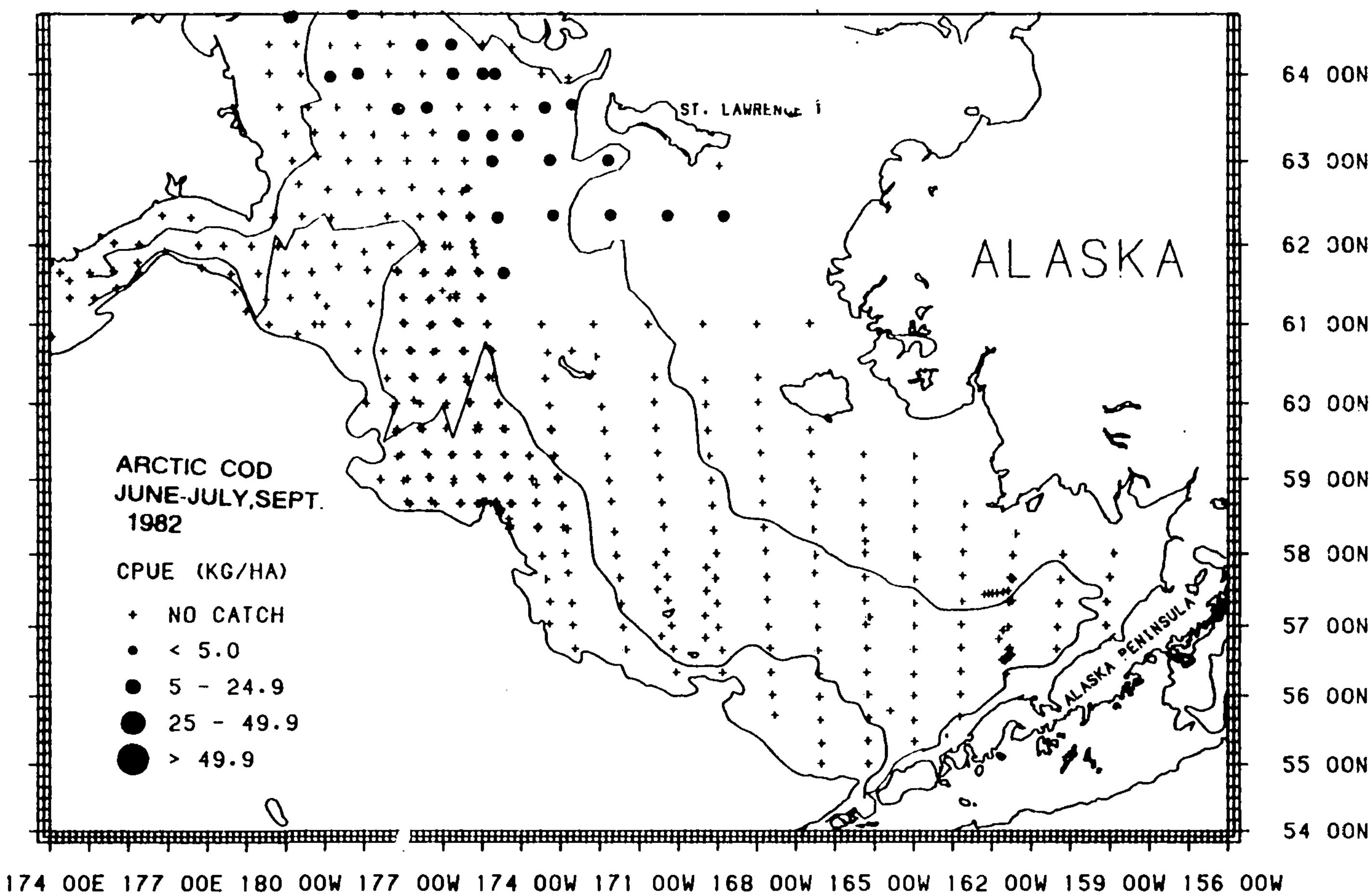
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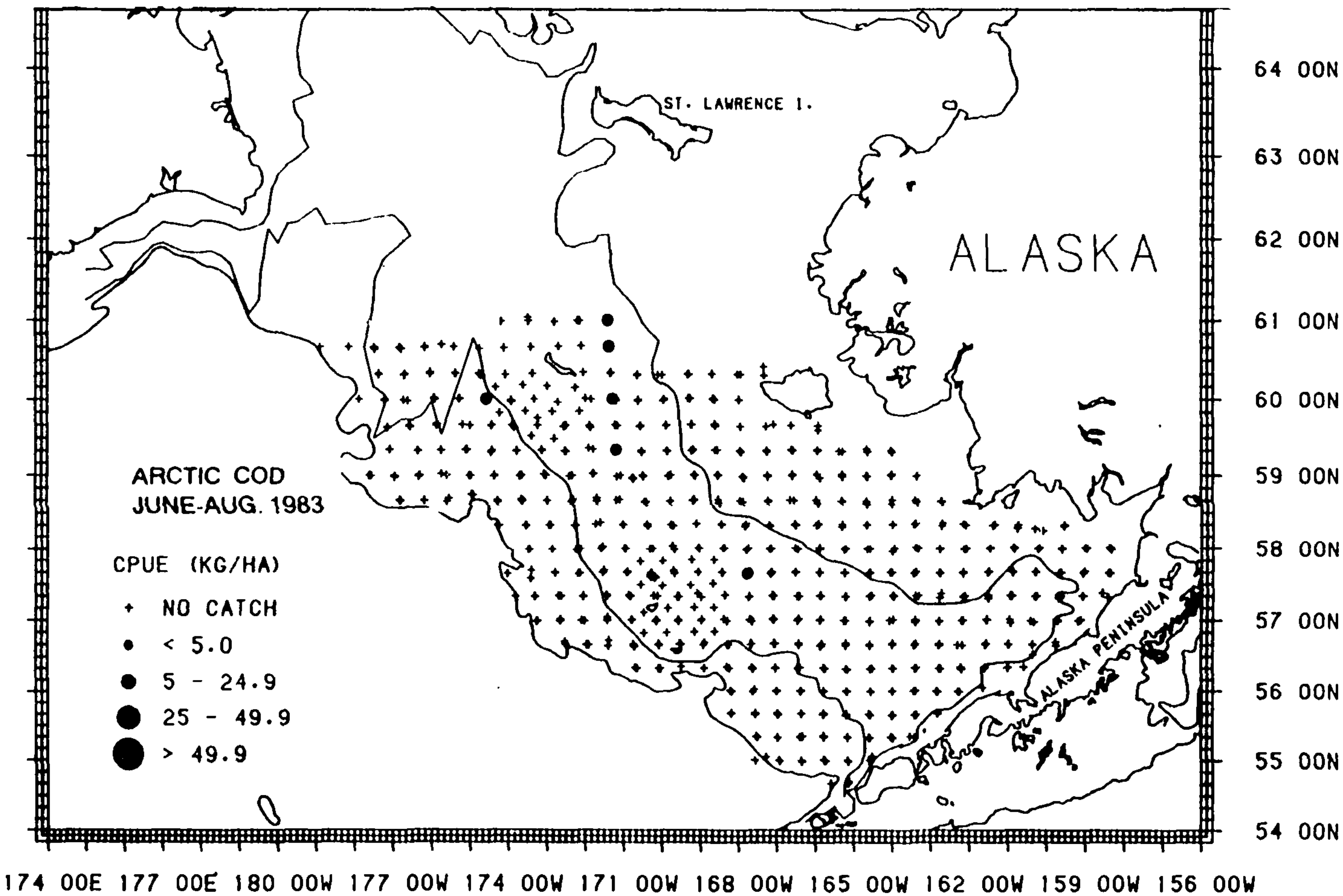
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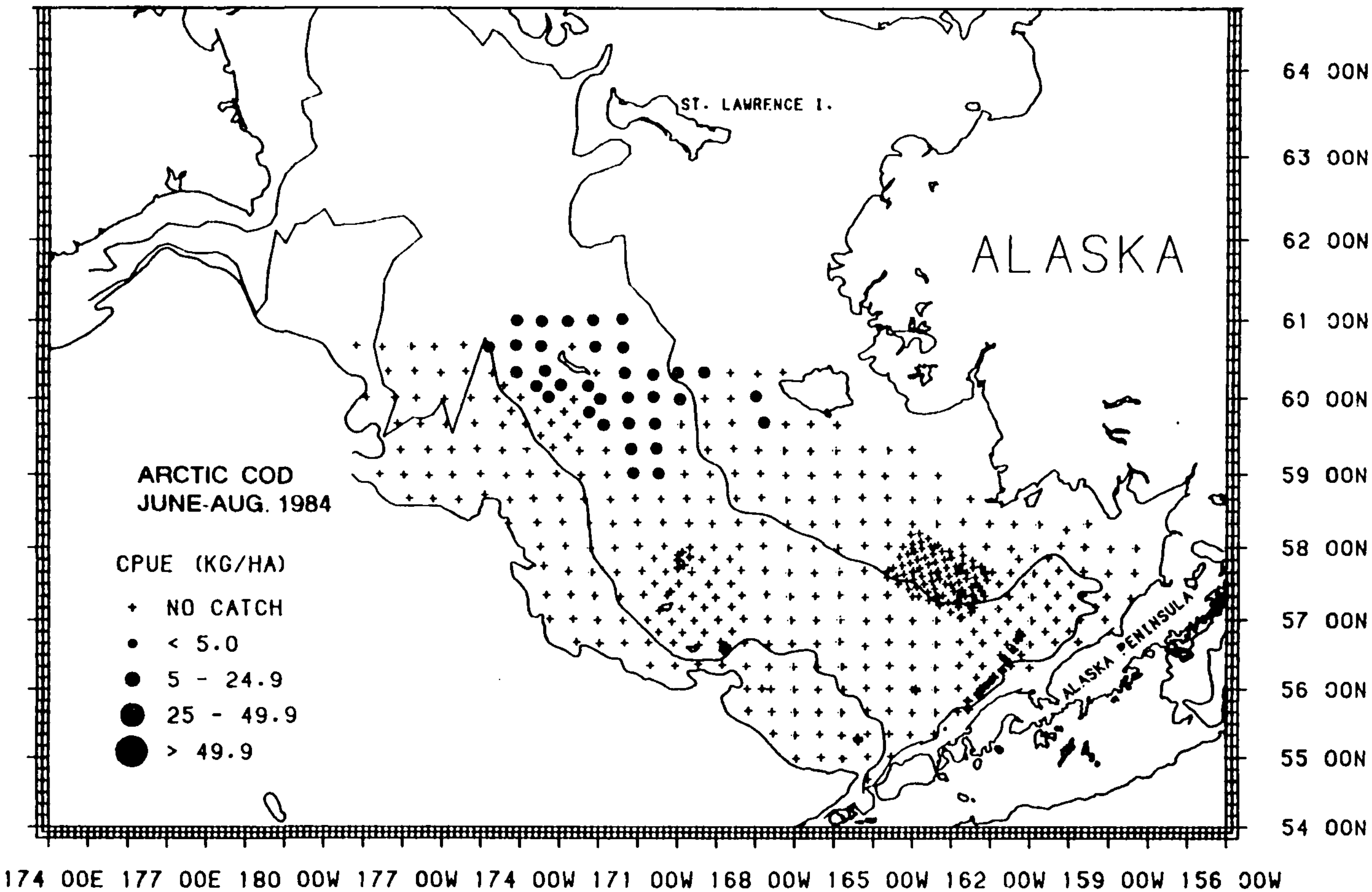
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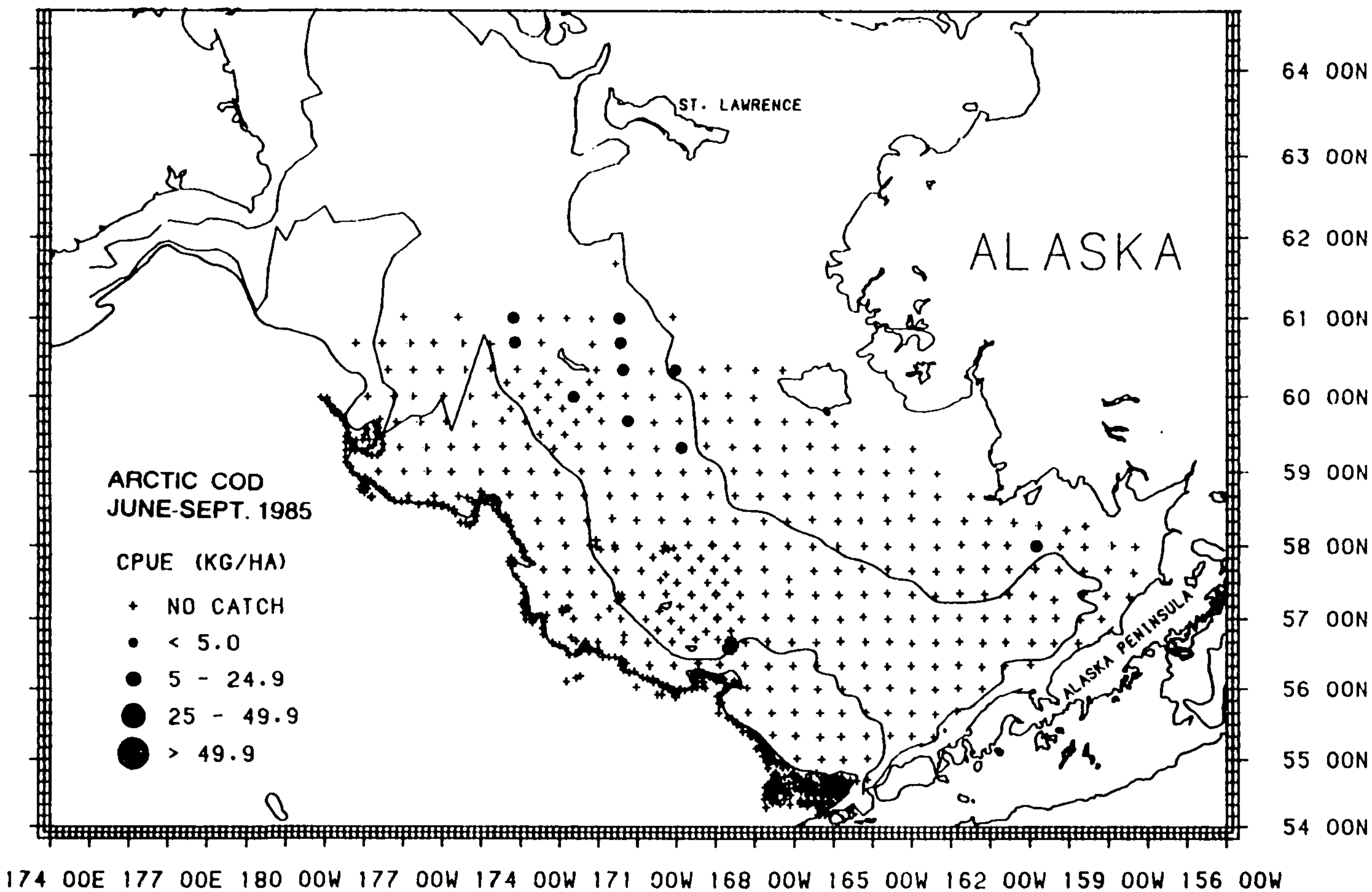
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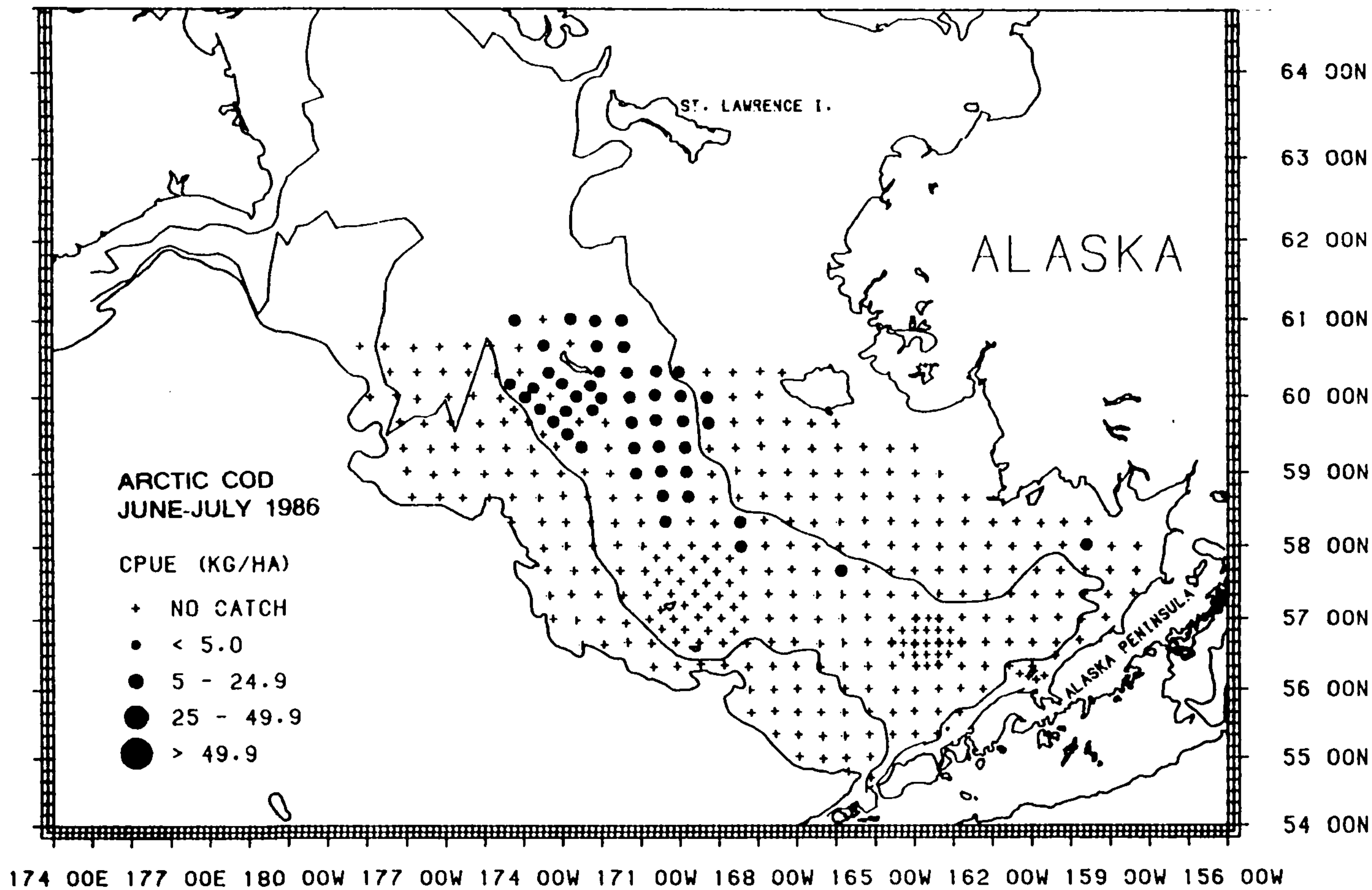
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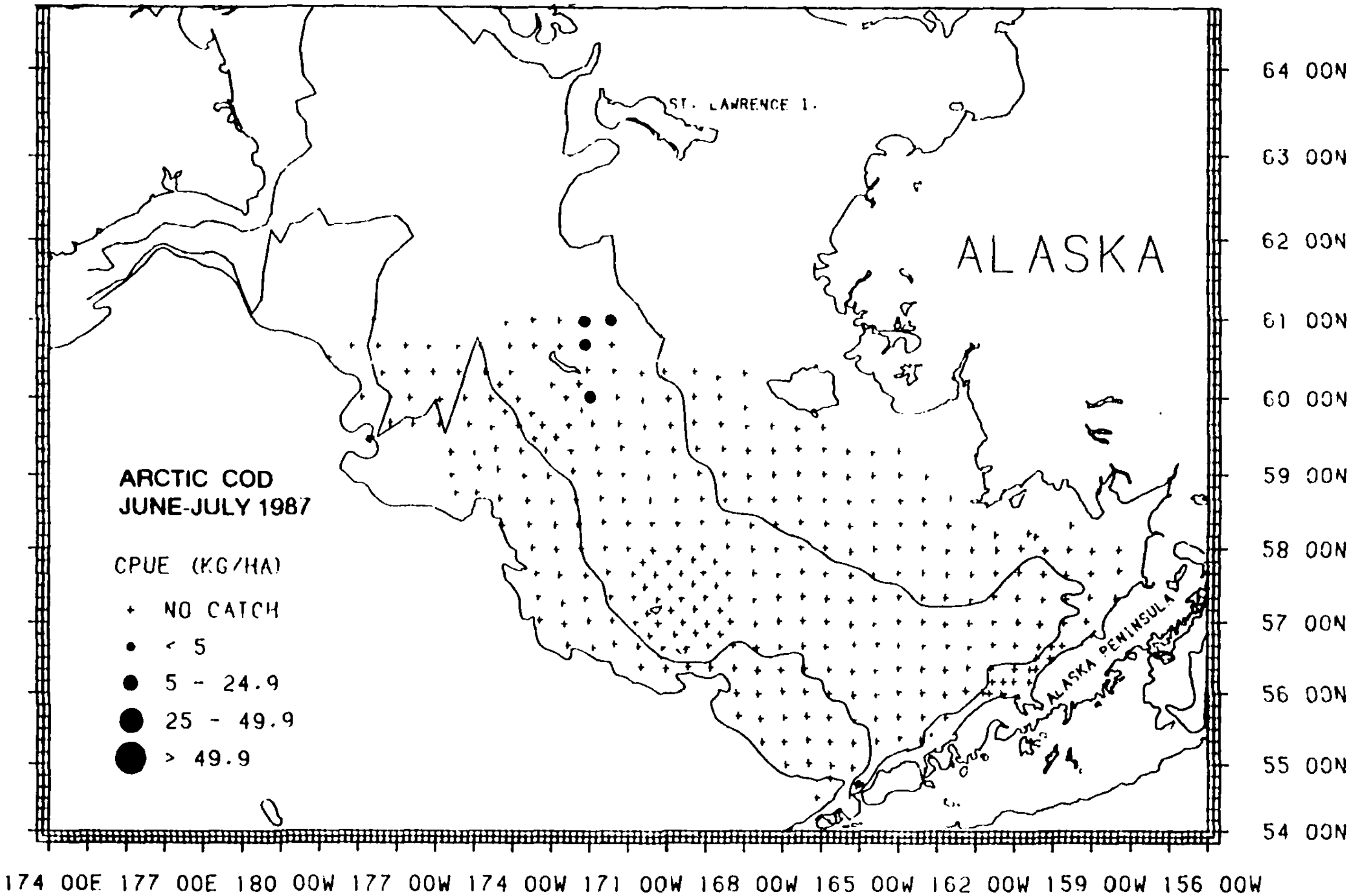
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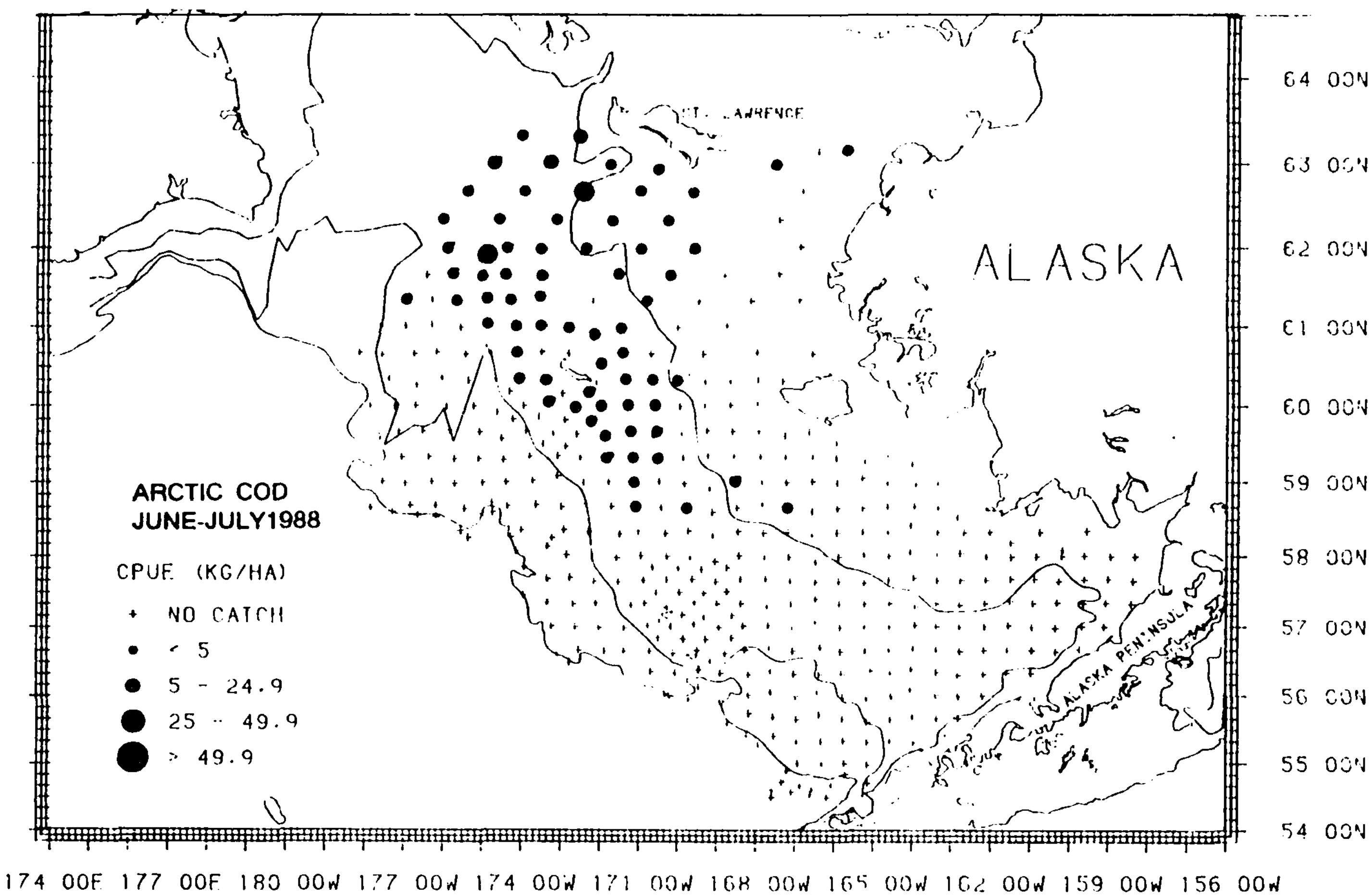
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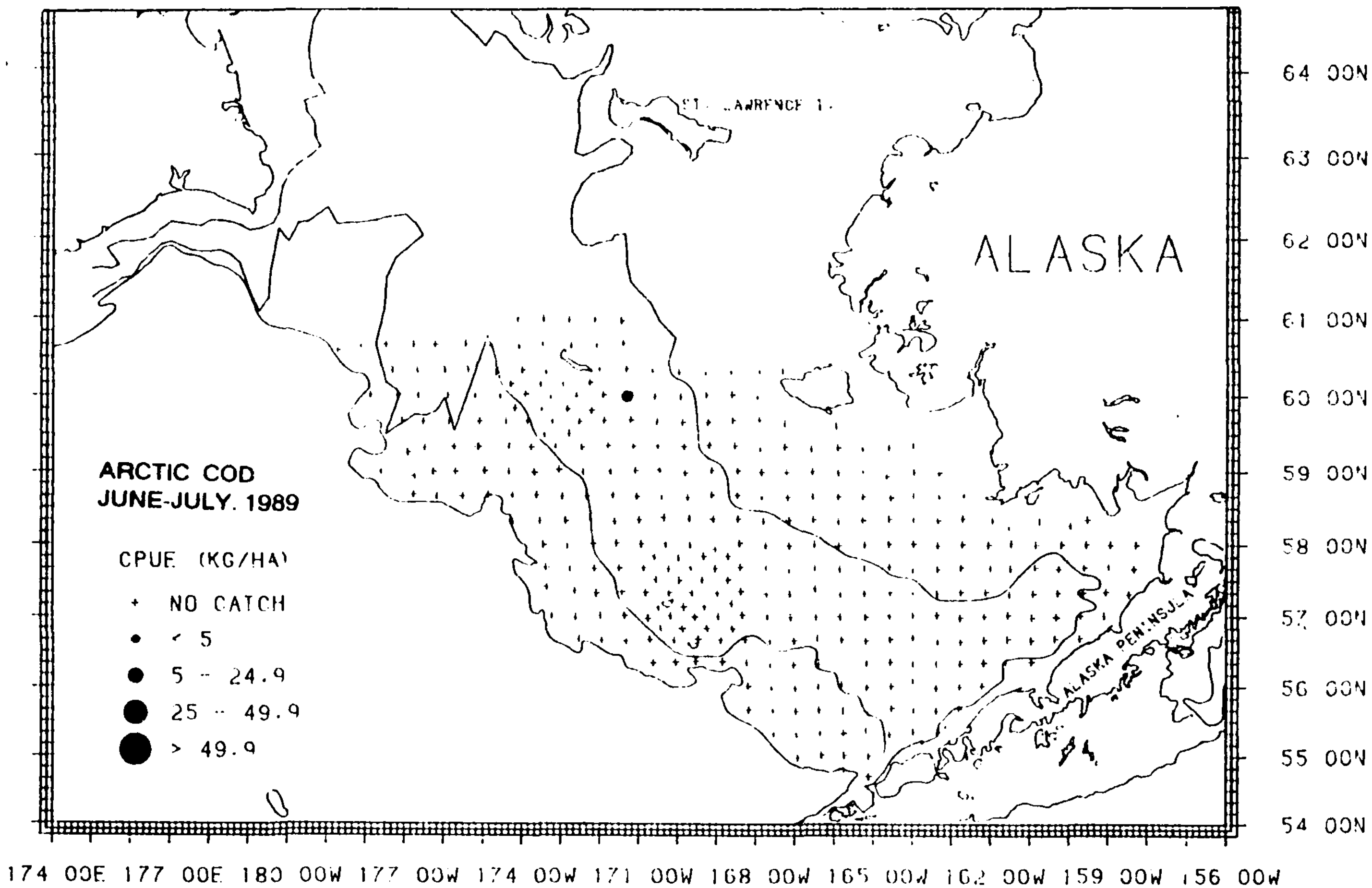
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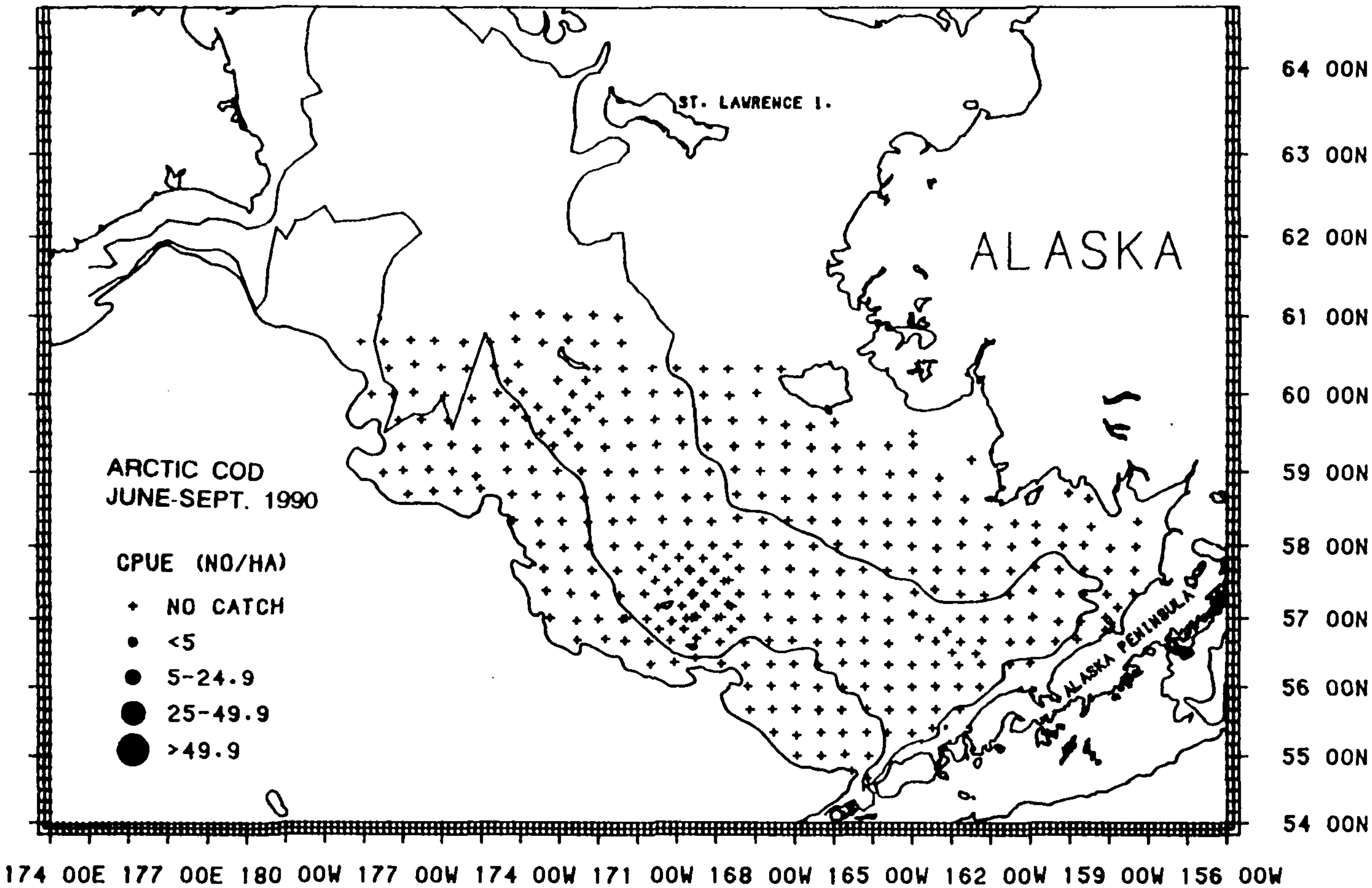
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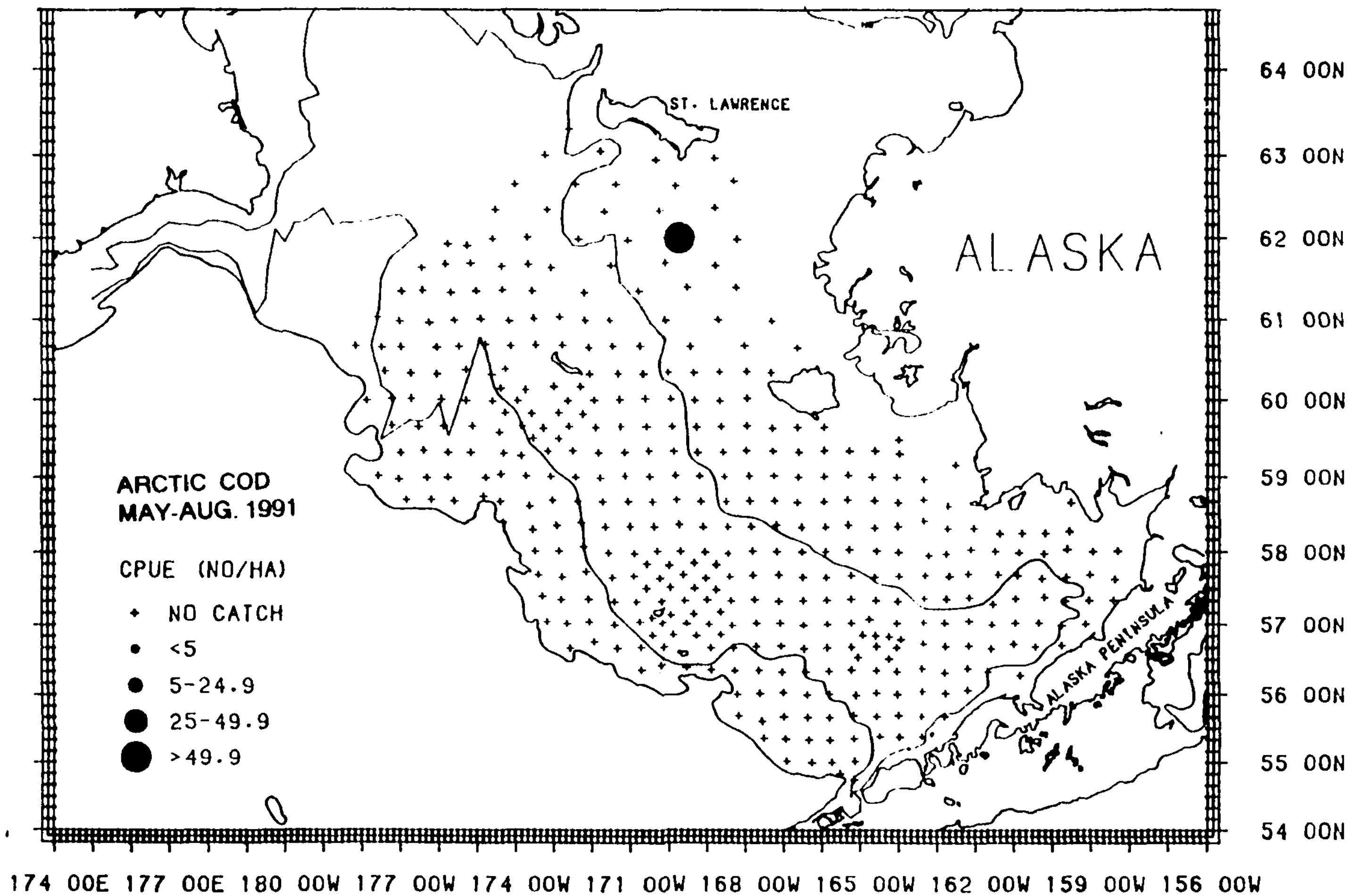
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MAY-AUG. 1991
CPUE (NO/HA)
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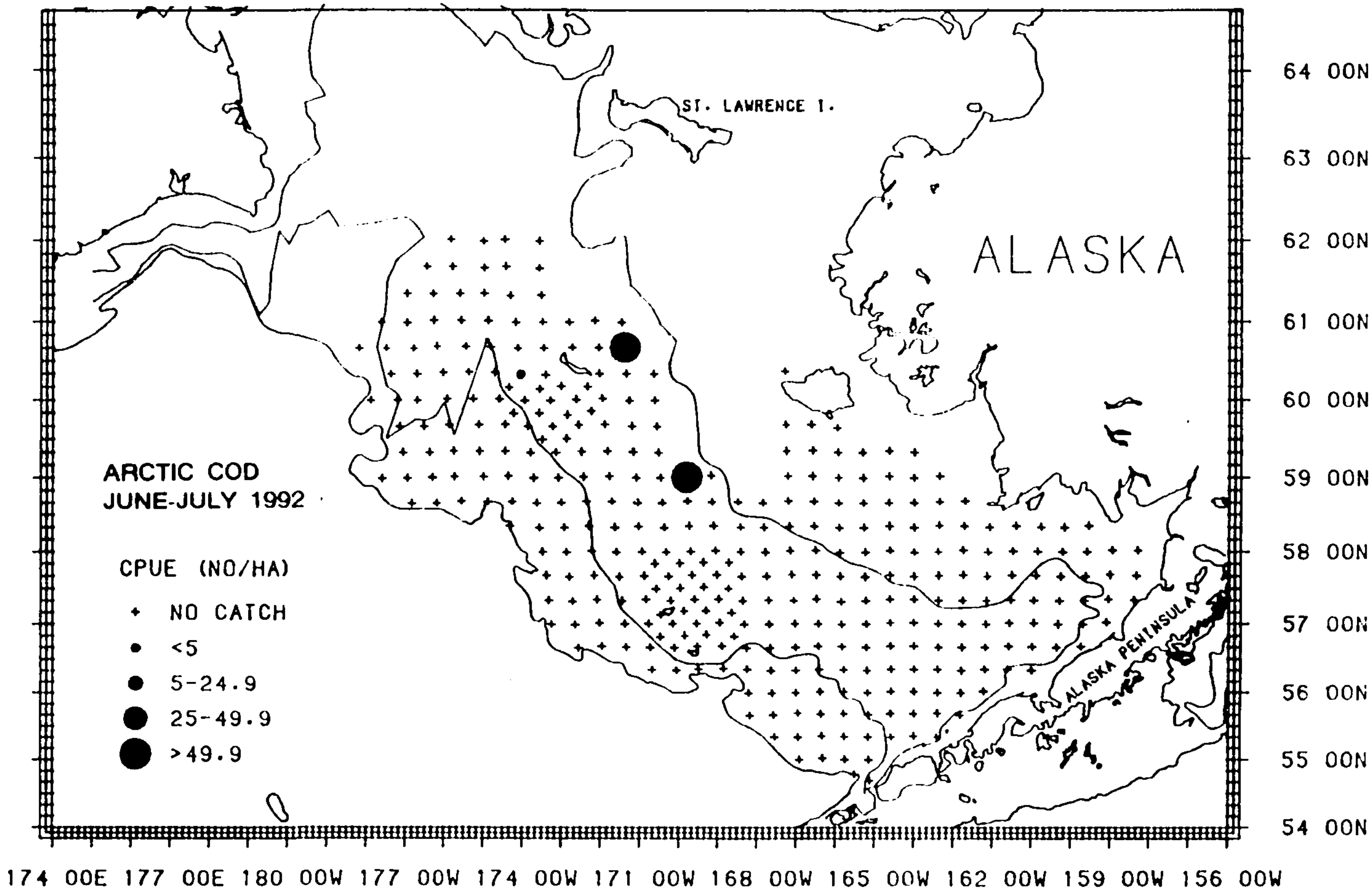
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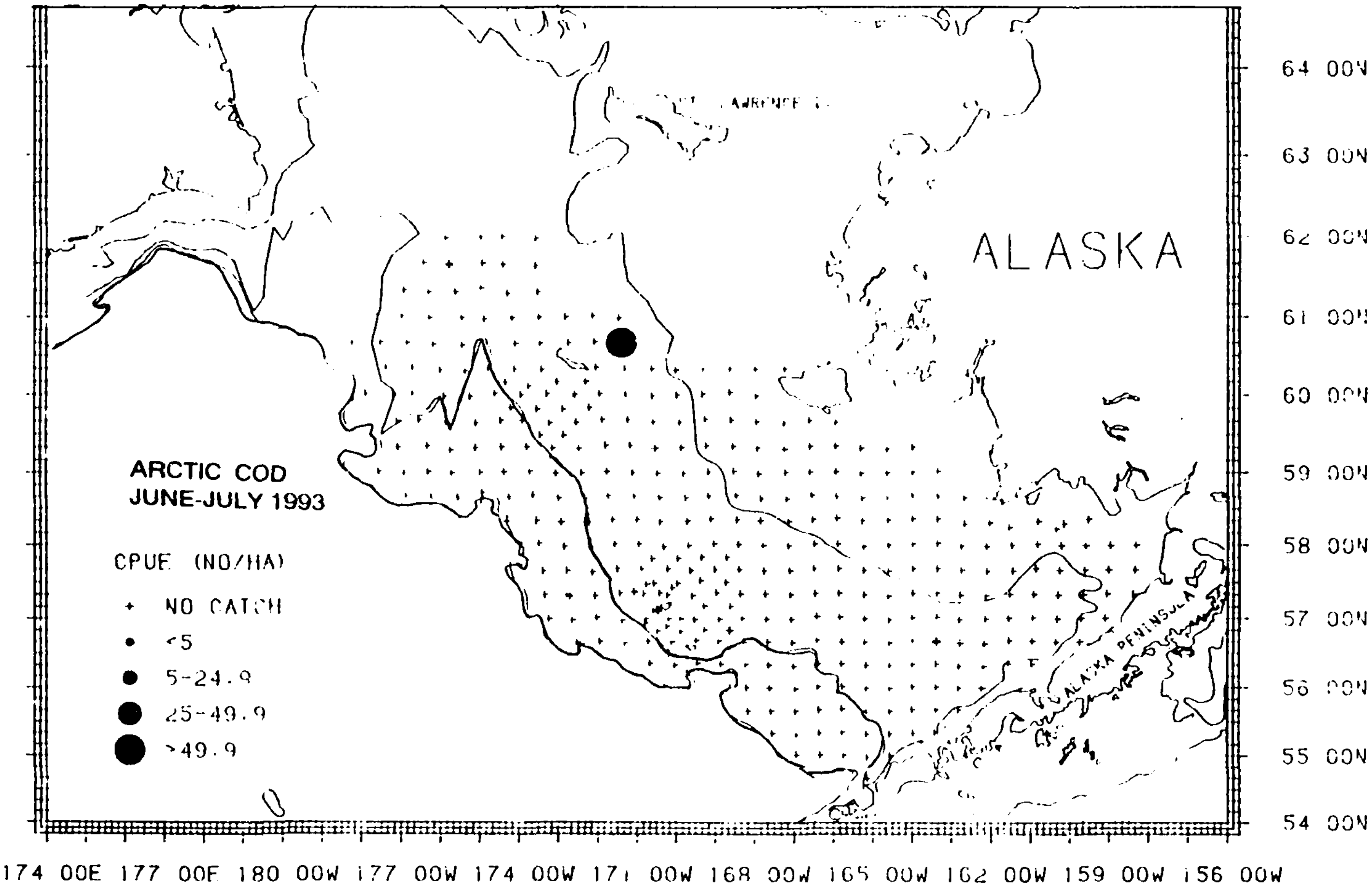
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63 00N
62 00N
61 00N
60 00N
59 00N
58 00N
57 00N
56 00N
55 00N
54 00N
174 00E
177 00E
180 00W
177 00W
174 00W
171 00W
168 00W
165 00W
162 00W
159 00W
156 00W