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The effect of oceanographic variability and interspecific competition on juvenile pollock (*Theragra chalcogramma*) and capelin (*Mallotus villosus*) distributions on the Gulf of Alaska shelf

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Abstract

Results from this study suggest that small-scale variability in the Alaska Coastal Current (ACC) and competition between juvenile pollock and capelin are potential mechanisms affecting the distribution and abundance of fishes in the Gulf of Alaska (GOA). Fish distributions in Barnabus Trough, off the east coast of Kodiak Island, were assessed using acoustic data collected with a calibrated echosounder during August–September 2002 and 2004. Trawl hauls were conducted to determine the species composition of the fish making up the acoustic backscatter. Oceanographic data were collected from moorings, conductivity–temperature–depth (CTD) probes, trawl-mounted microbathythermographs (MBT) and expendable bathythermographs (XBT). National Centers for Environmental Prediction (NCEP) reanalysis data were used to assess area winds, and information on regional transport was derived from current meters deployed on moorings north and south of Kodiak Island. The distribution of water-mass properties and fish during 2002 showed variability at the temporal scale of weeks. Juvenile pollock (age-1 and age-2) were initially most abundant in warm, low-salinity water on the inner shelf, whereas capelin were distributed primarily on the outer shelf in cool, high-salinity waters. During a 2-week period juvenile pollock distribution expanded with the offshore expansion of warm, low-salinity water, and capelin abundance in outer-shelf waters decreased. We hypothesize that wind-driven pulsing of the ACC resulted in increased transport of warm, low-salinity water through the study area. In 2004, warm, low-salinity water characterized the inner shelf and cool, high-salinity water was found on the outer shelf. However, the distribution of water-mass properties did not show the weekly scale variability observed in 2002. Area winds were consistently toward the southwest during 2004, such that we would not expect to see the wind-driven pulsing of ACC water that occurred in 2002. Age-1 and age-2 pollock were not observed in Barnabus Trough in 2004. Instead, the midwater acoustic backscatter was composed of capelin mixed with age-0 pollock, and these capelin were not restricted to the outer-shelf waters, but were found primarily in warm, low-salinity inner-shelf waters that had been previously occupied exclusively by age-1 and age-2 pollock. We suggest that this is consistent with inner-shelf waters being preferred foraging habitat for juvenile pollock and capelin. Further study of the

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mechanisms linking climate change with variability in the ACC is needed, as are studies of the potential for competition between juvenile pollock and capelin.

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Keywords: Gulf of Alaska; Walleye pollock; Capelin; Geographical distribution; Competition; Oceanography

1. Introduction

Most assessments of the effect of ecosystem change on fish populations rely on correlations between climate indices and time series of variables such as fish recruitment or catch (Hollowed and Wooster, 1992, 1995; Beamish and Bouillon, 1993, 1995; Mantua et al., 1997). Although hypotheses regarding cause and effect have been proposed, explicit mechanisms linking climate variability and fish survival or growth remain largely uncertain (Baumann, 1998; North Pacific Research Board, 2005). By relating temporal and spatial variability in fish distribution to physical and biological features of the pelagic habitat, we attempt to illustrate potential mechanisms linking climate variability and the fish community of the Gulf of Alaska (GOA).

Walleye pollock (*Theragra chalcogramma*) and capelin (*Mallotus villosus*) play central roles in the GOA ecosystem. They are prey of several species of fish (Jewett, 1978; Yang and Nelson, 2000), seabirds (Hatch and Sanger, 1992) and marine mammals, including the endangered Steller sea lion (*Eumetopias jubatus*) (Sinclair and Zeppelin, 2002). The Alaska pollock fishery is one of the most valuable in the US, with an ex-vessel value of $312 million in 2003 (Hiatt et al., 2004). Pollock and capelin are planktivorous, consuming primarily copepods and euphausiids (Hart, 1973; Brodeur and Wilson, 1996).

The spatial distributions of pollock and capelin on the GOA shelf appear to be related to differences in habitat preferences. Hollowed et al. (in press) have shown that capelin are associated with intrusions of cool slope water onto the shelf, whereas pollock are most abundant in warm, inner-shelf waters where summer wind events produce high levels of primary production.

The research presented in this paper is a continuation of the work of Hollowed et al. (in press). Whereas they have documented consistency in patterns within and between years, we examine variability, at weekly and interannual time scales, in the distribution of water-mass properties, juvenile pollock and capelin. We present data that support the hypothesis that variability at the scale of weeks is driven by variability in along-shore winds and transport of the Alaska Coastal Current (ACC). The data suggest that variability of fish distributions at the interannual scale is due to variability in pollock year-class strength. Further study of the effects of climate on small-scale variability in the ACC, and of the potential for competition between juvenile pollock and capelin, is needed to advance our understanding of the processes driving production of fish in the GOA.

In 2000, scientists from NOAA's Alaska Fisheries Science Center initiated a multi-year investigation of the effects of fishing on Steller sea lion prey distribution and abundance in a commercial fishing ground located on the east side of Kodiak Island, GOA. In 2001, investigators from NOAA's Pacific Marine Environmental Laboratory joined the project, providing enhanced biophysical sampling to characterize the marine habitat. Barnabus and Chiniak Troughs were selected as the study sites for a controlled field experiment (Fig. 1). Barnabus Trough served as the treatment site where commercial fishing was allowed and Chiniak Trough served as the control site where fishing was prohibited. Hollowed et al. (in press) report on observations made in 2000 and 2001. Adult and juvenile pollock distributions were restricted to waters within the troughs, whereas capelin were found both within the troughs and over the flats between troughs. We report on biophysical and fish distribution data from Barnabus Trough in 2002 and 2004 (no field work was conducted in 2003). Barnabus Trough was selected for the analyses presented here because previous work had demonstrated a link between water-mass characteristics and fish distribution (Hollowed et al., in press), and the 2002 and 2004 data provided an opportunity to explore the factors driving temporal variability in the oceanography and fish distribution.

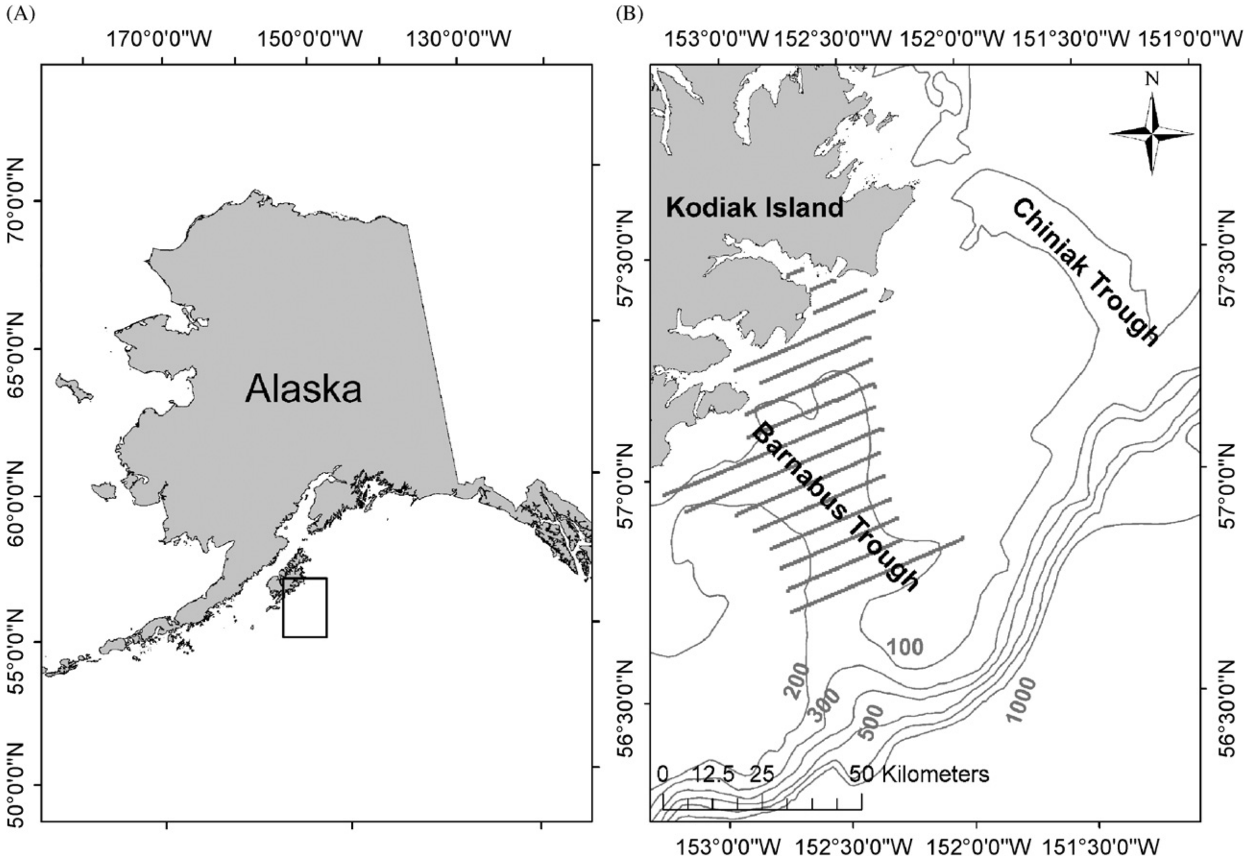


Fig. 1. Location of study area: (A) large-scale view of Barnabus Trough study area off the east coast of Kodiak Island in the Gulf of Alaska and (B) small-scale view of study area with acoustic survey transects. Depth contours are in meters.

2. Methods

2.1. *Acoustic survey*

Fish distributions were assessed using standard acoustic-trawl survey methods during daylight hours aboard the NOAA ship *Miller Freeman* (Simmonds and MacLennan 2005; Traynor, 1997; Wilson et al., 2003). Surveys consisted of a set of uniformly spaced (3 nmi) parallel transects (Fig. 1). Completion of all transects within a set consisted a survey pass. Multiple survey passes were conducted to gauge the temporal variability in fish abundance and distribution during the study period (Table 1). Briefly, acoustic data were collected along transects with a calibrated Simrad EK 500 echosounder operating at 38 kHz. These data were logged and later processed using Echoview software (SonarData Pty. Ltd., Hobart, Tasmania, Australia). Catch data were also collected opportunistically along transects using a large midwater Aleutian trawl, bottom trawl, or other smaller nets to identify the species composition and to collect other biological samples of the backscatter (Wilson et al., 2003; Honkalehto et al., 2005). After the acoustic data were classified to a particular taxonomic group (e.g., walleye pollock, capelin, plankton) based on patterns identified in trawl catches and echo signatures, estimates of fish distribution patterns were constructed based on area backscattering values (i.e., nautical area

Table 1
Dates of multiple surveys, or "passes", in Barnabus Trough during 2002 and 2004

Pass	2002	2004
1	16–19 August	15–17 August
2	22–24 August	21–24 August
3	30 August–September 20	26–30 August
4	2–4 September	2–4 September

scatterering coefficient (S_A) defined in MacLennan et al., 2002).

2.2. Oceanography

Two taught-wire moorings were deployed in Barnabus Trough in 2002 only (Fig. 2). The mooring on the west side of the Trough was designed to measure near-bottom temperature, salinity and currents. The eastern mooring measured temperature at 10 depths (between ~2 and 130 m) and salinity at two depths. A 300 kHz acoustic Doppler current meter measured currents in 4-m bins to within ~15 m of the surface. Data were recorded internally every hour. The current meter data are represented in stick plots wherein the orientation of each stick indicates the direction towards which the current is flowing, and the length indicates the current velocity.

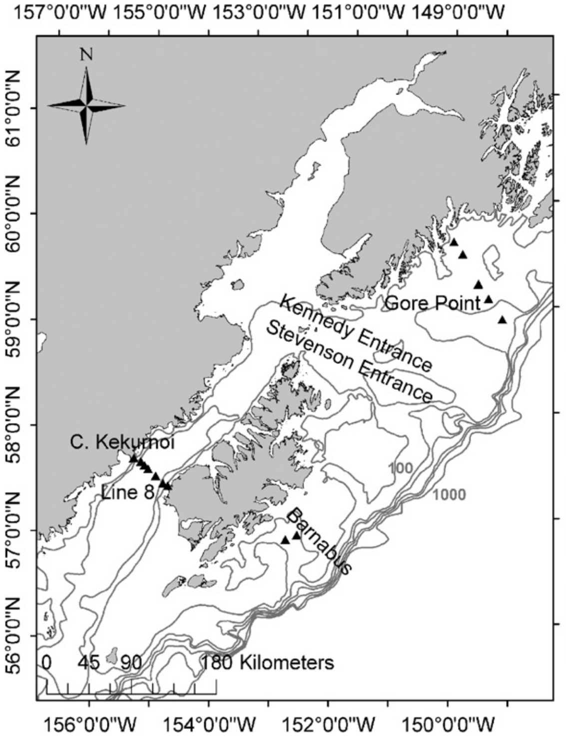


Fig. 2. Locations (triangles) of moorings at Gore Point, along Line 8 at Cape Kekurnoi and in Barnabus Trough (2002 only).

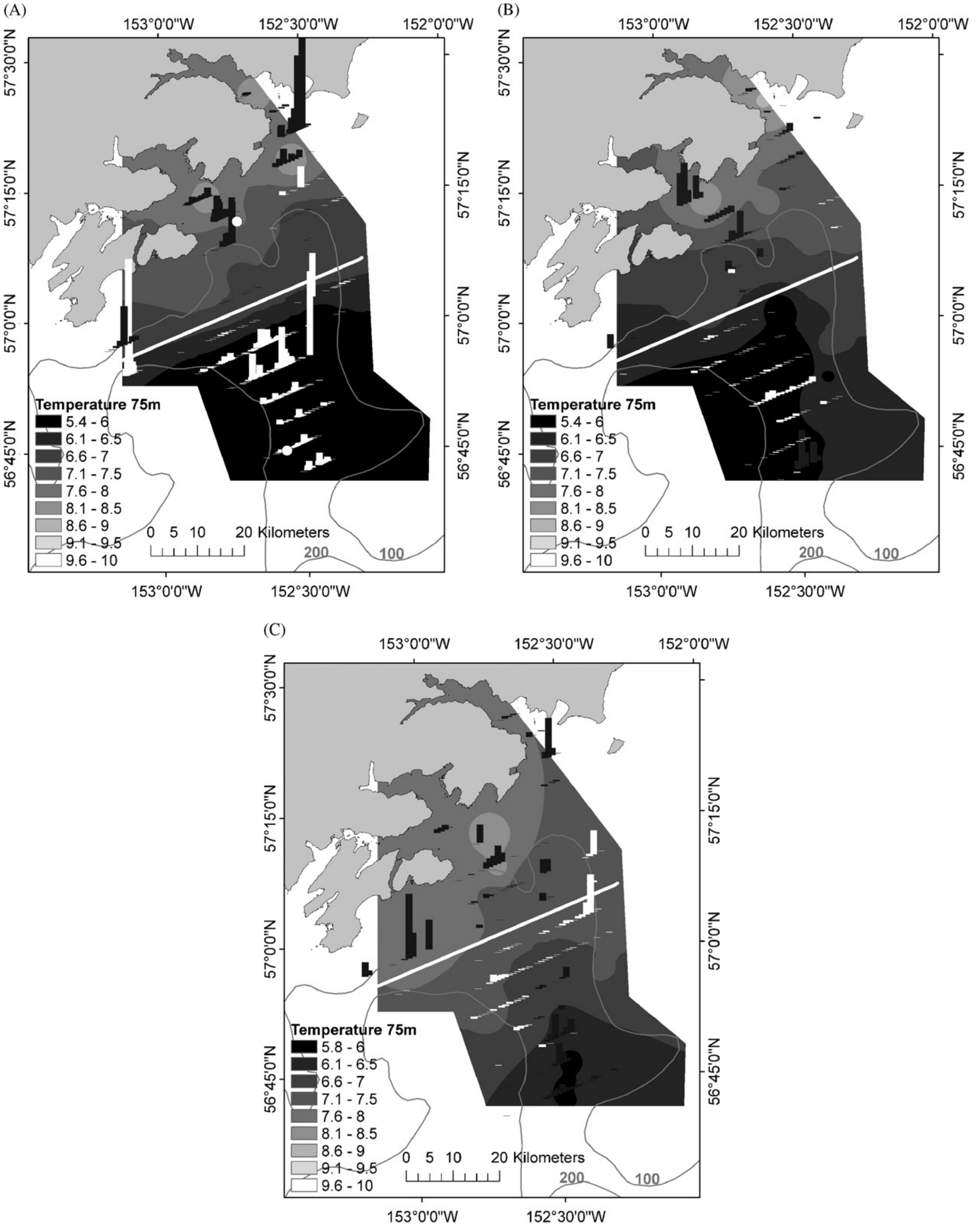
In addition, conductivity–temperature–depth (CTD) data were collected at selected sites using a Seabird SBE9plus system with dual temperature and salinity sensors. Data were recorded during the downcasts. Chlorophyll samples were collected from water samples taken on the CTD upcast at 10-m intervals from the surface to 50 m depth. Temperature and depth were also measured with a trawl-mounted microbathythermograph (MBT) and expendable bathythermographs (XBT).

For information on wind strength and direction in the Kodiak Island region, National Centers for Environmental Prediction (NCEP) Reanalysis wind data at 59°N, 150°W were rotated to 240°T and modified following Stabeno et al. (2004). Positive values on the resulting plots of wind speed versus time indicate winds blowing to the southwest, and negative values indicate winds to the northeast. Information on regional transport patterns was derived from current meters deployed on moorings at Gore Point and at Cape Kekurnoi at the exit of Shelikof Strait (Line 8, Fig. 2). The data were integrated across depth and among moorings at each transect as described in Stabeno et al. (1995, 2004). This method produces reliable estimates of total transport. The data also were rotated so that the positive y-axis on a plot of transport (y-axis) versus time (x-axis) indicates downstream flow. Similar to the wind data, positive values on the resulting plots of transport versus time indicate transport to the southwest, and negative values indicate transport to the northeast.

2.3. Data analyses

The distributions of juvenile pollock and capelin were assessed by mapping the area backscatter (S_A) attributed to each species. The S_A is linearly related to fish density for a given species and size distribution (Simmonds and McLennan, 2005). The spatial resolution of acoustic data used to construct

Fig. 3. 2002 survey data. Contours are water temperature (°C) at 75 m. Acoustic backscattering (S_A, $m^2 nmi^{-2}$) attributed to juvenile pollock (age-1 and age-2) are shown as black bars. Acoustic backscattering attributed to capelin are shown as white bars. Height of bars is scaled similarly among Passes and among years. Locations of selected inshore and offshore CTD stations are solid white circles. Location of the mid-trough front is indicated by bold white line. Mean temperature and salinity were calculated from data collected inshore and offshore of the white line. Data are from: (A) Pass 1 (16–19 August); (B) Pass 2 (22–24 August); and (C) Pass 3 (30 August–2 September). Insufficient hydrographic measurements were made during Pass 4 to characterize the water-mass properties during that pass.


(A)
(B)
(C)
153°0'0"W
152°30'0"W
152°0'0"W
57°30'0"N
57°15'0"N
57°0'0"N
56°45'0"N
Temperature 75m
5.4 - 6
5.8 - 6
6.1 - 6.5
6.6 - 7
7.1 - 7.5
7.6 - 8
8.1 - 8.5
8.6 - 9
9.1 - 9.5
9.6 - 10
0 5 10 20 Kilometers
200
100

fish distribution maps in the vertical was the backscatter for each species integrated over the entire water column between about 14 m depth to within about 0.5 m of the bottom echo, and in the horizontal was 926 m (0.5 nmi). Scales of S_A on the maps generated are equivalent among passes and between years.

Horizontal contours of water temperature and salinity at 75 m and integrated chlorophyll biomass were constructed and mapped using the Inverse Distance Weighted method with power equal to 2 and a variable-distance 12-point search radius (ArcMap 8.2, ESRI). Temperature and salinity data at 75 m were selected because that was the depth at which juvenile pollock and capelin aggregations were generally observed (see also Hollowed et al., in press). Temperature, salinity and chlorophyll biomass scales on the maps are equivalent among passes and between years. Means and standard deviations of temperature at 75 m during each pass were calculated from CTD, XBT and MBT data. Means and standard deviations of salinity at 75 m were calculated from CTD data.

3. Results

3.1. Comparison of 2002 and 2004 surveys

During both surveys, water-mass properties varied from inshore to offshore. Temperature at 75 m was warmer over the inner shelf and cooler over the outer shelf with a front evident in the middle of the trough (Figs. 3 and 4). In 2002, mean temperature inshore of the mid-trough front was 1–1.6 ° C greater than mean temperature offshore (Table 2). In 2004, mean temperature inshore of the front was 0.8–1.4 °C greater than mean temperature offshore of the front (Table 3). In both years, warmer inner-shelf water had relatively low-salinity at 75 m, whereas the cooler outer-shelf water had high salinity (Figs. 5 and 6). In 2002, mean salinity inshore of the front was approx. 0.3 psu less than mean salinity offshore of the front (Table 2). In 2004, mean salinity was approx. 0.2 psu less inshore than offshore of the front (Table 3).

Inner-shelf waters were relatively well-mixed, and the outer-shelf waters were more stratified, as evidenced by vertical profiles of density at selected CTD stations inshore and offshore of the mid-trough front (Figs. 7 and 8). The locations of those CTD stations are shown in Figs. 3 and 4. The data from those stations are representative of data from nearby stations, so single profiles are shown for simplicity. During both surveys, the well-mixed inner-shelf waters had greater integrated chlorophyll biomass than the stratified outer-shelf waters (Figs. 9 and 10), likely the result of mixing of nutrient-rich bottom water upward into the euphotic zone.

Trawl haul data from the 2002 survey indicated that the midwater acoustic backscattering was composed of juvenile pollock (age-1 and age-2) and juvenile capelin (age-1 and age-2). The age compositions of pollock and capelin were determined from length–frequency distributions (Brown, 2002; Wilson et al., 2003). In contrast to the 2002 survey, no age-1 or age-2 pollock were observed during the 2004 survey. Instead, the mid-water acoustic scattering was composed of a mix of age-0 pollock and age-1 capelin, averaging 75% and 25% by number, respectively . During Pass 1 of the 2002 survey, juvenile pollock were distributed inshore of the mid-trough front in relatively warm, low-salinity water, whereas capelin were found throughout the area offshore of the temperature front in cool, high-salinity water (Fig. 3A). The change in fish distribution between passes 1 and 3 during 2002 will be explored in detail below. During 2004, age-0 pollock and capelin were not found in the cool, high-salinity outer-shelf waters where capelin were distributed in 2002, but in the warm, low-salinity inner-shelf waters of the trough, which had been occupied by age-1 and age-2 pollock in 2002 (Fig. 4).

3.2. Changes in water-mass properties and fish distribution during the 2002 survey

During the 2002 survey, water-mass properties in Barnabus Trough, particularly temperature,

Fig. 4. 2004 survey data. Contours are water temperature (°C) at 75 m. Acoustic backscattering (S_A, $m^2 nmi^{-2}$) attributed to age-0 pollock/capelin mix are shown as white bars. Height of bars is scaled similarly among Passes and among years. Locations of selected inshore and offshore CTD stations are solid white circles. Location of mid-trough front is indicated by bold white line. Mean temperature and salinity were calculated from data collected inshore and offshore of the white line. Data are from: (A) Pass 1 (15–17 August); (B) Pass 2 (21–24 August); (C) Pass 3 (26–30 August); and (D) Pass 4 (2–4 September).

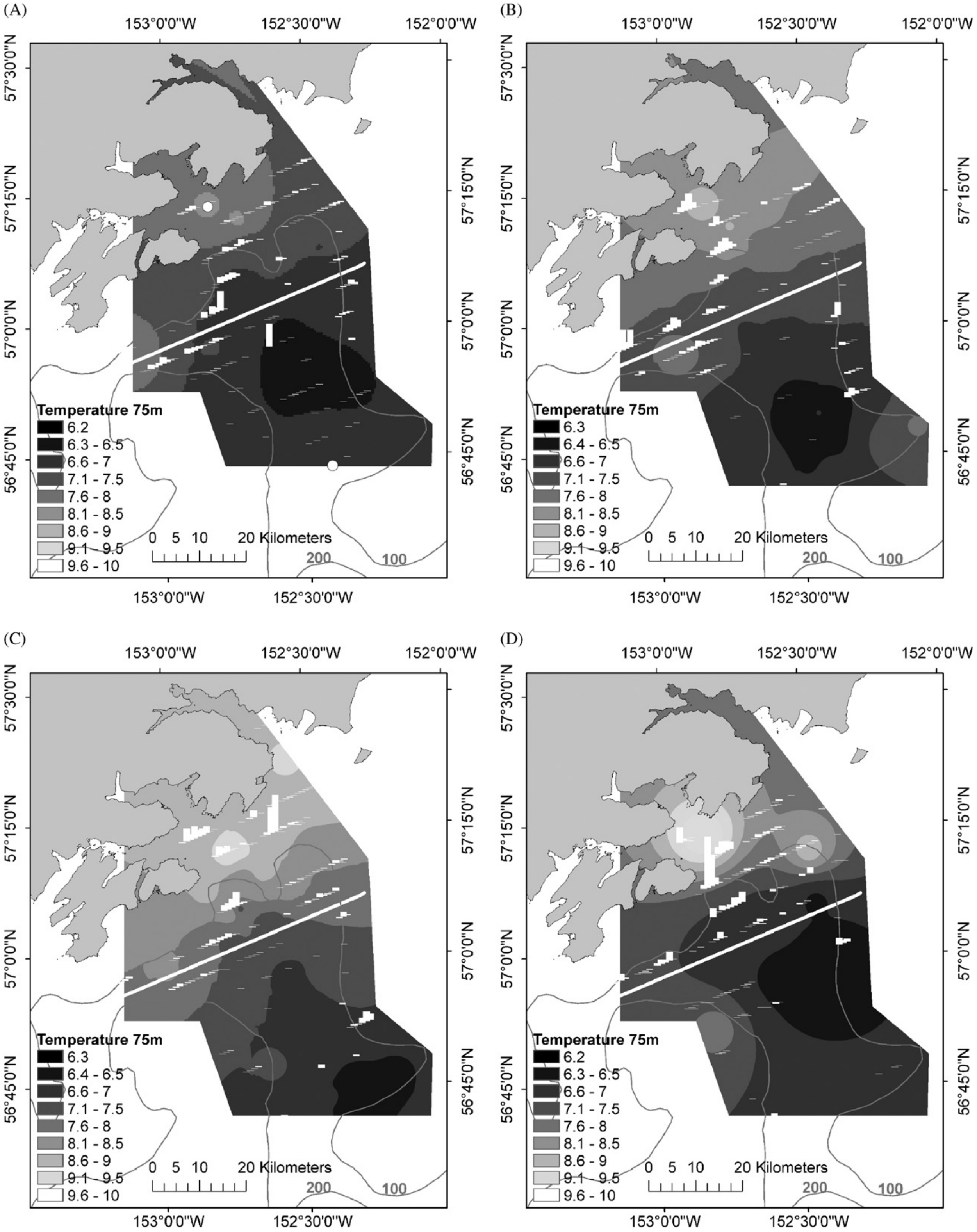

(A)
153°0'0"W
152°30'0"W
152°0'0"W
57°30'0"N
57°15'0"N
57°0'0"N
56°45'0"N
Temperature 75m
6.2
6.3 - 6.5
6.6 - 7
7.1 - 7.5
7.6 - 8
8.1 - 8.5
8.6 - 9
9.1 - 9.5
9.6 - 10
0 5 10 20 Kilometers
200
100
(B)
Temperature 75m
6.3
6.4 - 6.5
6.6 - 7
7.1 - 7.5
7.6 - 8
8.1 - 8.5
8.6 - 9
9.1 - 9.5
9.6 - 10
(C)
Temperature 75m
6.3
6.4 - 6.5
6.6 - 7
7.1 - 7.5
7.6 - 8
8.1 - 8.5
8.6 - 9
9.1 - 9.5
9.6 - 10
(D)
Temperature 75m
6.2
6.3 - 6.5
6.6 - 7
7.1 - 7.5
7.6 - 8
8.1 - 8.5
8.6 - 9
9.1 - 9.5
9.6 - 10

Table 2
Temperature and salinity in 2002, inshore and offshore of the mid-trough front

	Temperature (°C)						Salinity (psu)					
	Inshore			Offshore			Inshore			Offshore		
	Mean	*n*	SD	Mean	*n*	SD	Mean	*n*	SD	Mean	*n*	SD
Pass 1	7.34	16	0.61	5.72	13	0.28	32.18	5	0.12	32.52	4	0.03
Pass 2	7.29	11	0.61	5.98	21	0.48	32.24	6	0.10	32.51	7	0.08
Pass 3	7.63	11	0.55	6.60	17	0.51	–	–	–	–	–	–

Mean, sample size (*n*) and standard deviation (SD) are shown. Insufficient CTD casts were made during Pass 3 to determine mean salinity.

Table 3
Temperature and salinity in 2004, inshore and offshore of the mid-trough front

	Temperature (°C)						Salinity (psu)					
	Inshore			Offshore			Inshore			Offshore		
	Mean	*n*	SD	Mean	*n*	SD	Mean	*n*	SD	Mean	*n*	SD
Pass 1	7.37	11	0.54	6.53	9	0.29	32.21	7	0.11	32.36	6	0.06
Pass 2	8.00	17	0.62	6.88	20	0.41	32.05	5	0.14	32.33	6	0.05
Pass 3	8.32	25	0.72	6.92	20	0.49	32.05	5	0.14	32.28	6	0.06
Pass 4	7.52	6	1.53	6.51	6	0.61	–	–	–	–	–	–

Mean, sample size (*n*) and standard deviation (SD) are shown. Insufficient CTD casts were made during Pass 4 to determine mean salinity.

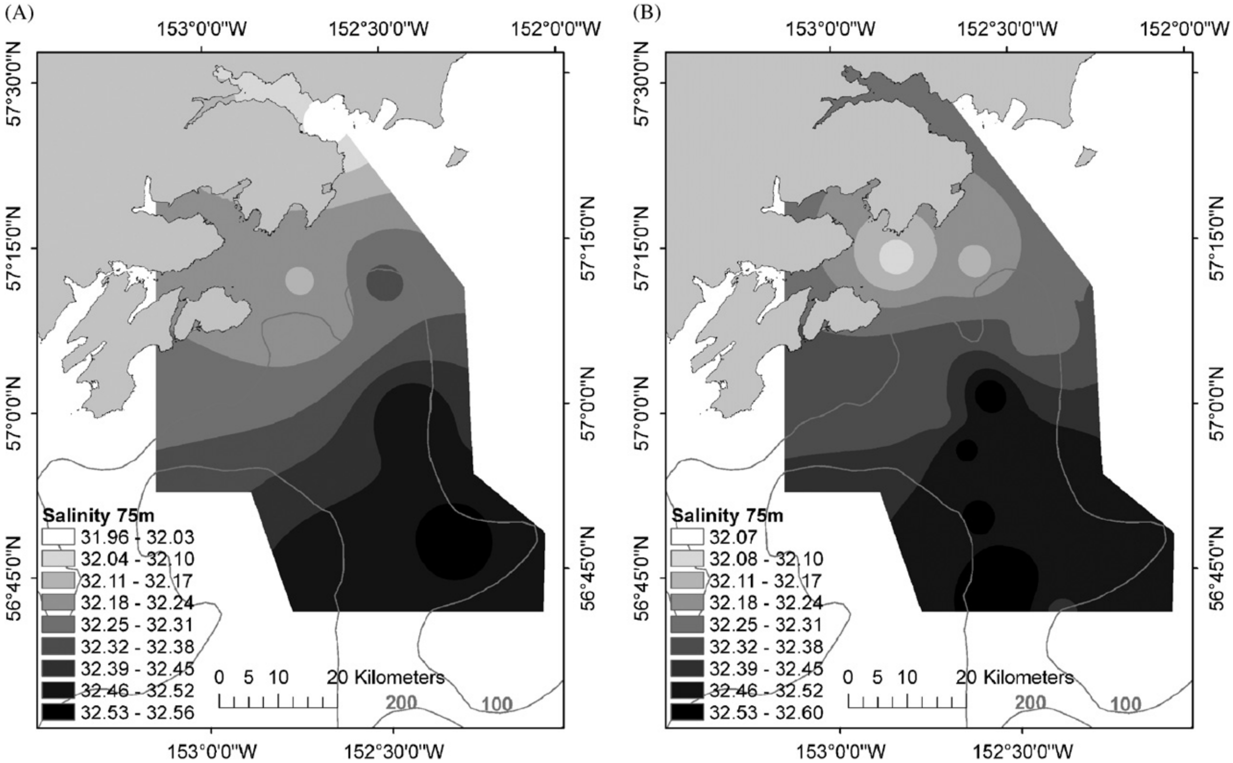


Fig. 5. Contours of salinity (psu) at 75 m during the 2002 survey: (A) Pass 1 (16–19 August) and (B) Pass 2 (22–24 August). Insufficient salinity measurements (CTDs) were made during Passes 3 and 4 to characterize water-mass salinity during those passes.

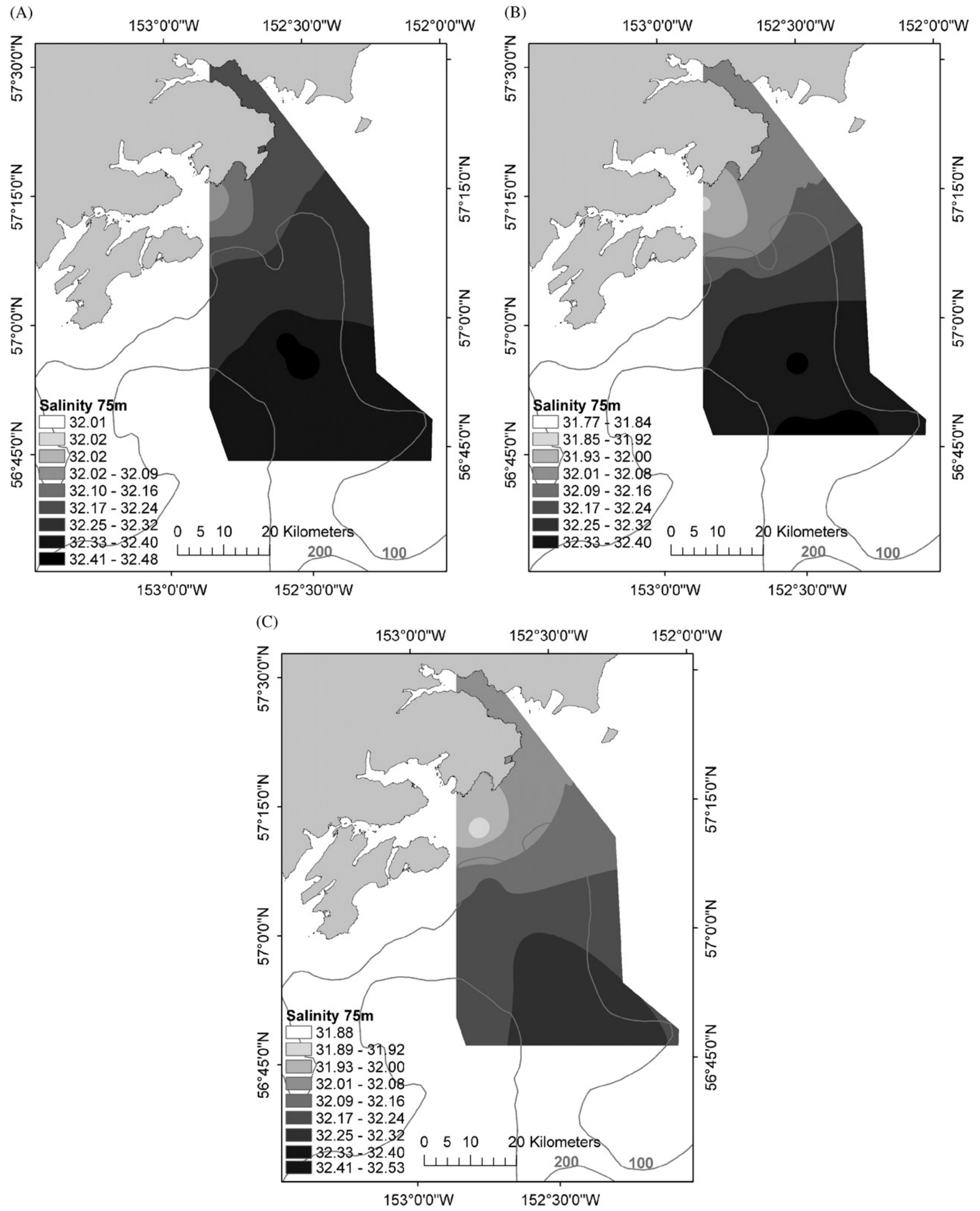


Fig. 6. Contours of salinity (psu) at 75 m during the 2004 survey: (A) Pass 1 (15–17 August); (B) Pass 2 (21–24 August) and (C) Pass 3 (26–30 August). Insufficient salinity measurements (CTDs) were made during Pass 4 to characterize water-mass salinity during that pass.

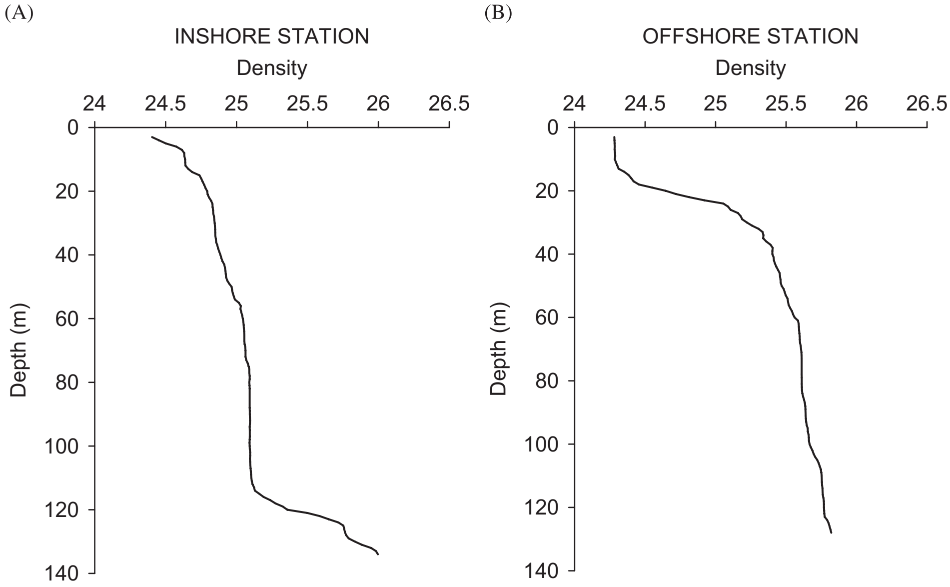


Fig. 7. Profiles of water density (σ_t) with depth (m) at selected CTD stations shown in Fig. 3, during the 2002 survey: (A) inshore station and (B) offshore station.

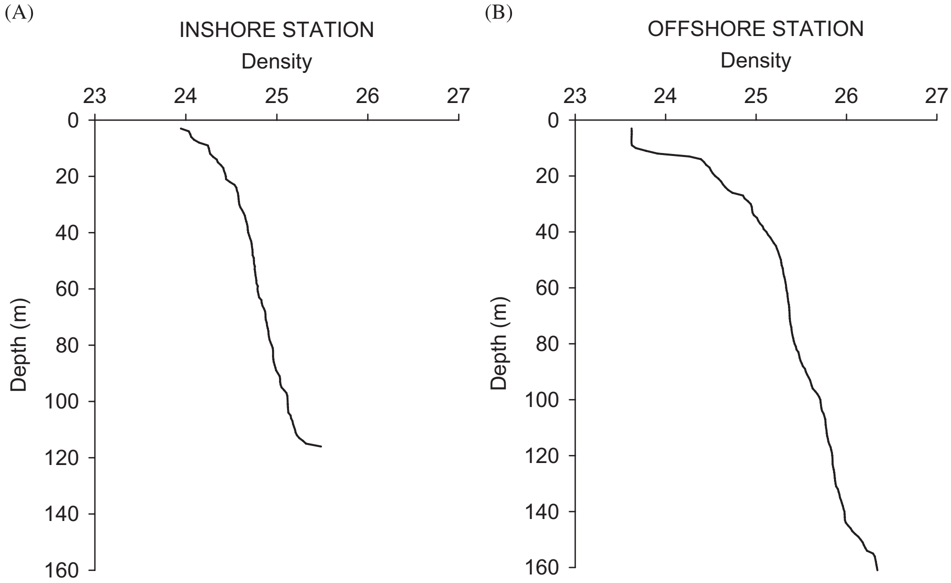


Fig. 8. Profiles of water density (σ_t) with depth (m) at selected CTD stations shown in Fig. 4, during the 2004 survey: (A) inshore station and (B) offshore station.

changed from Pass 1 to Pass 3 (Fig. 3). Insufficient hydrographic measurements were made during Pass 4 to characterize the water-mass properties during that pass. During Pass 1, the temperature at 75 m was warmer over the inner-shelf and cooler over the outer-shelf, with a sharp front evident in the middle of the trough (Fig. 3A). During Pass 2 the front began to shift offshore, and by Pass 3 warmer waters occupied the entire trough (Figs. 3B and C).

The distributions of juvenile pollock (age-1 and age-2) and capelin changed with the change in water properties from Pass 1 to Pass 3 (Fig. 3). During

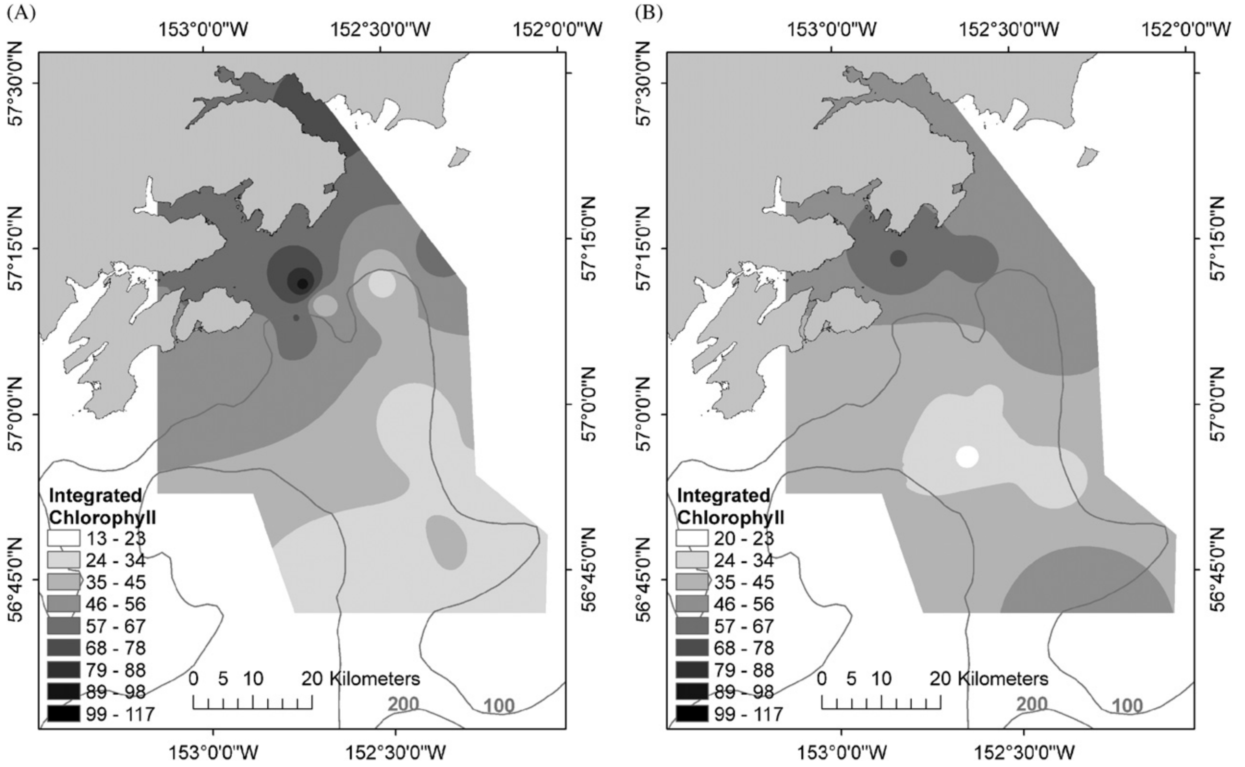


Fig. 9. Contours of integrated chlorophyll biomass density (mg m^{-2}) during the 2002 survey: (A) Pass 1 (16–19 August) and (B) Pass 2 (22–24 August). Insufficient chlorophyll measurements were made during Passes 3 and 4 to characterize water-mass chlorophyll density during those passes.

Pass 1, juvenile pollock were distributed inshore of the mid-trough front in relatively warm, low-salinity water, whereas capelin were found throughout the area offshore of the temperature front in cool, high-salinity water (Fig. 3A). During Pass 2 the distribution of juvenile pollock began to shift offshore and the abundance of capelin offshore decreased (Fig. 3B). By Pass 3, juvenile pollock were distributed throughout the trough and capelin were found in aggregations only in a few isolated locations on the east edge of the trough (Fig. 3C). Mean S_A of capelin, which is proportional to biomass, decreased from 207.3 m^2 nmi^{-2}($\pm$73.7, 95% confidence interval) during Pass 1 to 86.2 m^2 nmi^{-2}($\pm$25.3) during Pass 2 and then increased to 126.8 m^2 nmi^{-2} ($\pm$76.8) during Pass 3.

The movement offshore of warm, low-salinity water during Pass 2 is evident in temperature and salinity data at depth from the two moorings located on the east and west sides of Barnabus Trough (Fig. 2). A strong diurnal tidal signal is clearly evident in both the temperature and salinity records. Temperature increased and salinity decreased at both moorings during Pass 2 (Fig. 11). Temperature increased and salinity decreased around August 25 at the eastern mooring (Fig. 11A), 3 days after the start of Pass 2. The change in water-mass properties occurred later at the western mooring (Fig. 11B), around August 27. This is consistent with the spatial pattern of temperature change at 75 m (Fig. 3).

The strength of along-shore winds and ocean transport also changed during Pass 2. Negative values on the plot of wind speed versus time indicate winds blowing towards the northeast, and positive values indicate winds towards the southwest. Winds changed from generally weak and toward the northeast (fluctuating around −2.00 m/s) to strong and toward the southwest (increasing to 6.00 m/s) at the start of Pass 2, August 22 (Fig. 12). Coincident with this change in wind direction was a change in transport on the shelf in the Kodiak Island area. Transport increased at Gore Point increased from around 0.25 Sverdrups to the southwest to almost 1.0 Sverdrups to the southwest at the start of Pass 2. Transport to the southwest also increased along

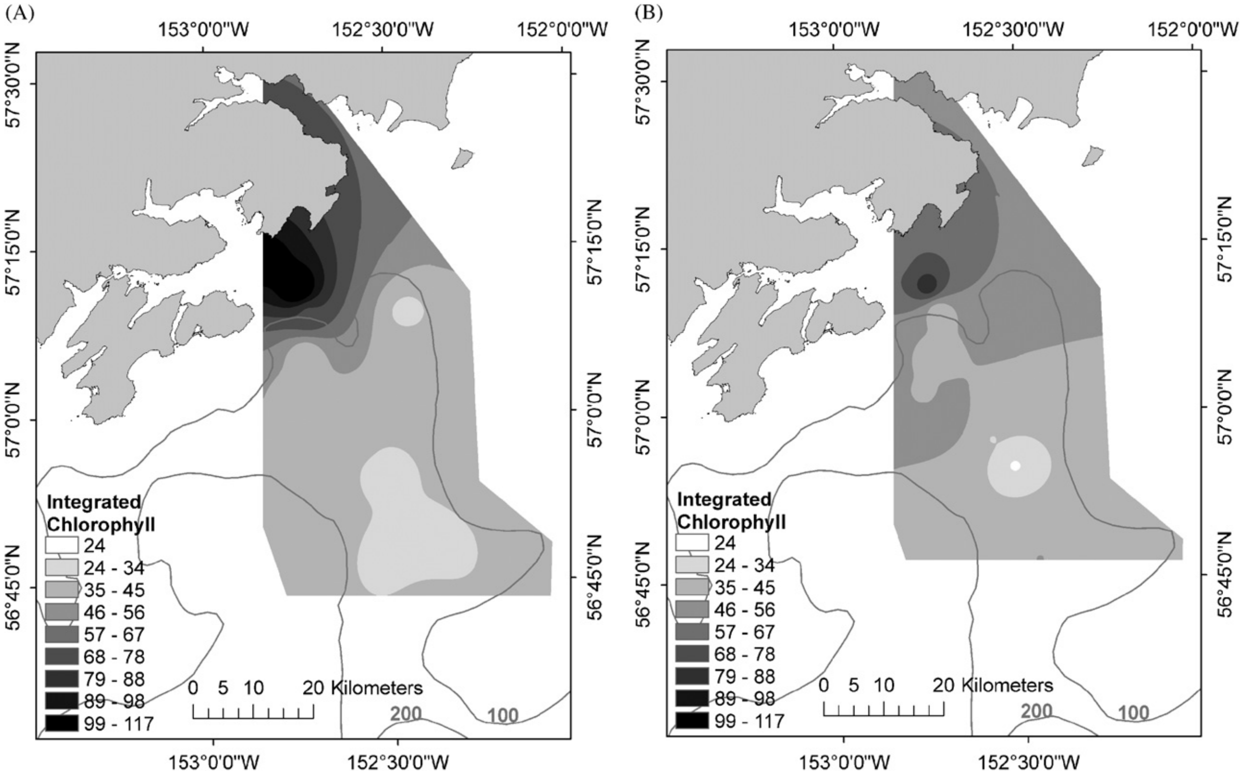


Fig. 10. Contours of integrated chlorophyll biomass density ($mg\,m^{-2}$) during the 2004 survey: (A) Pass 1 (15–17 August) and (B) Pass 2 (21–24 August). Insufficient chlorophyll measurements were made during Passes 3 and 4 to characterize water-mass chlorophyll density during those passes.

Line 8 at Cape Kekurnoi (from around 0 to 0.25 Sverdrups), but not to the degree observed at Gore Point (Fig. 13A). This is evident in the plot of transport differences (Gore Point transport minus Line 8 transport) (Fig. 13B). A positive transport difference indicates greater flow down the east coast of Kodiak Island than through Shelikof Strait. The plot of transport differences shows that these pulses of transport down the east coast of Kodiak Island occurred throughout the late summer and that the greatest pulse during our survey occurred at the start of Pass 2. Current velocity data from the two moorings in Barnabus Trough confirm that there was increased southwesterly flow during Pass 2 (Fig. 14). Current speed and velocity varied between moorings, perhaps due to meso-scale circulation features, but flow was nonetheless predominantly to the southwest at both moorings during approximately the first 10 days of Pass 2 (August 22–September 1).

Area winds and transport during the 2004 survey did not show the temporal variability observed in 2002. Winds were moderately strong to the southwest throughout the cruise, fluctuating around 3.00 m/s (Fig. 15). Transport at Line 8 was near zero or weakly to the northeast during most of the cruise, with a brief reversal to southwest in the middle of the survey, around August 25 (Fig. 16). No transport data were available from the Gore Point moorings during the study period in 2004.

4. Discussion

The distribution of water-mass properties and fish off Kodiak Island during August–September 2002 showed variability that had not previously been observed. Similar to the results of Hollowed et al. (in press) from 2000 and 2001, juvenile pollock (age-1 and age-2) were initially most abundant in warm, low-salinity water on the inner-shelf, whereas capelin were distributed primarily on the outer-shelf in cool, high-salinity waters. Hollowed et al. showed that this pattern of pollock and capelin distribution was stationary throughout the surveys conducted in 2000 and 2001. In contrast, our observations in 2002 revealed that during a 2-week

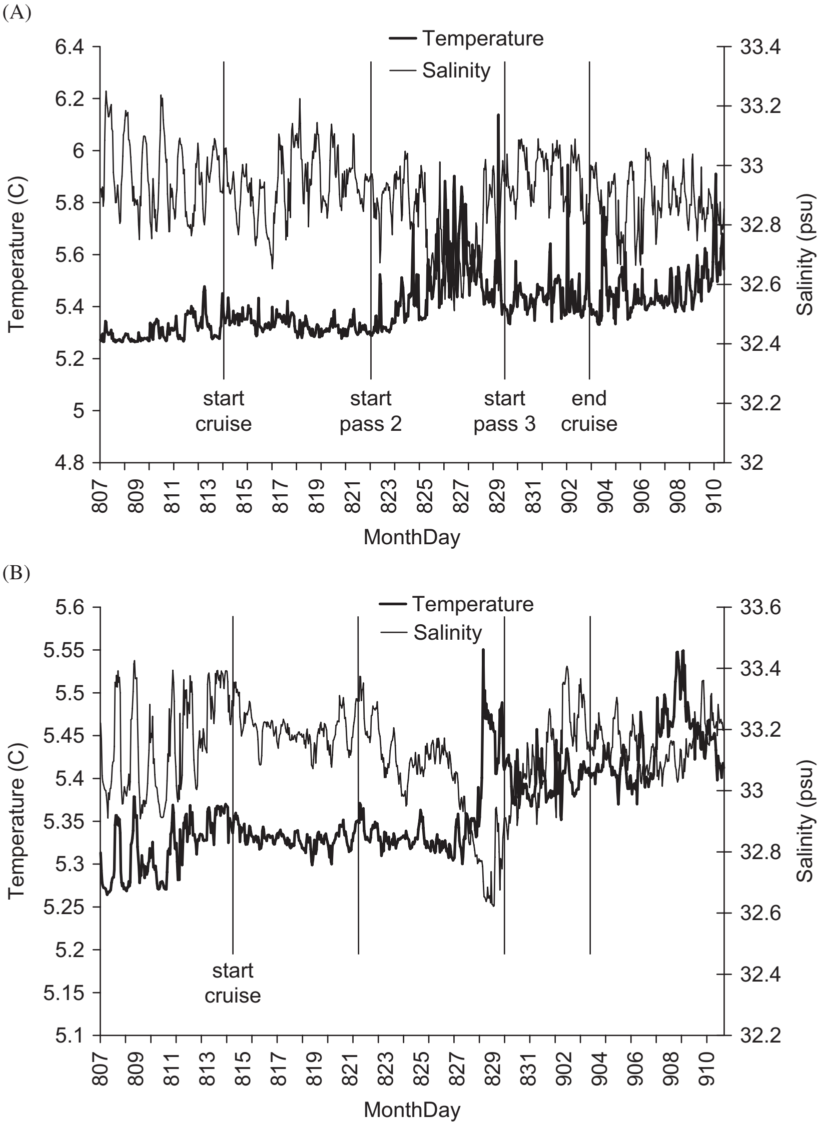


Fig. 11. Temperature (°C; thick line) and salinity (psu; thin line) over time from instruments on moorings in Barnabus trough: (A) eastern mooring, instrument depth 110 m and (B) western mooring, instrument depth 144 m. Data from 7 August to 11 September 2002 are shown. Vertical lines indicate the start and end of the 2002 survey and the start of Pass 2 (22 August) and Pass 3 (30 August).

period, juvenile pollock distribution expanded with the offshore expansion of warm, low-salinity water. Concurrent with the offshore expansion of juvenile pollock, capelin abundance in outer-shelf waters decreased. The shift in water-mass distribution was evident in the distribution of temperature and salinity in Barnabus Trough from Pass 1 to Pass 3. It could also be seen in the time course of temperature and salinity from the two moorings in Barnabus Trough.

Hollowed et al. (in press) related the distribution of pollock and capelin to ocean salinity and temperature but did not examine the role of winds and currents in structuring water-mass properties. The within-survey variability in temperature and salinity distributions that we observed in 2002 provided an opportunity to examine variability in winds and transport as a driver of variability in water-mass properties and fish distributions. The two main current systems in the GOA are the Alaskan Stream, located offshore of the shelf break, and the ACC which flows over the shelf region within 35 km of shore (Stabeno et al., 1995). The ACC is driven by winds and modified by freshwater

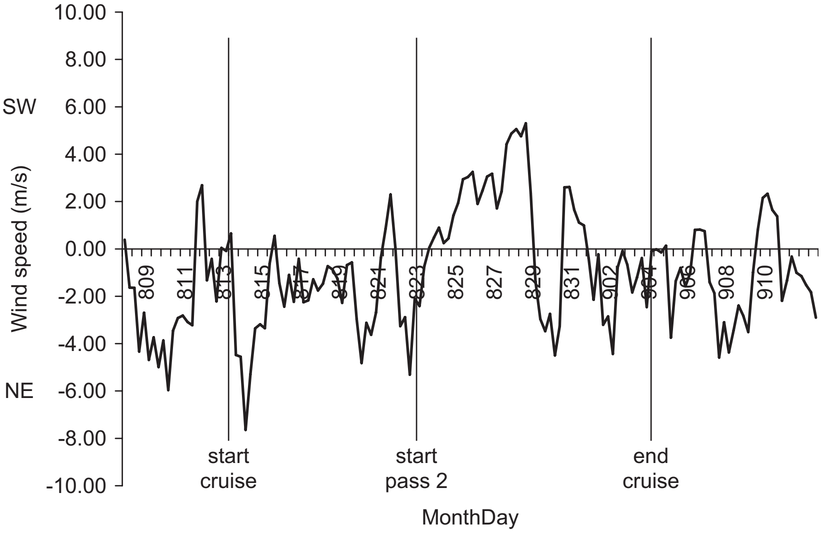


Fig. 12. NCEP reanalysis wind speed (m/s) at 59°N, 150°W, rotated and modified ($V = 240°$T). Positive values indicate winds to the southwest, negative values indicate winds to the northeast. Data from 7 August to 11 September 2002 are shown. Vertical lines indicate the start and end of the 2002 survey and the start of Pass 2 (22 August).

runoff, so the current is characterized by a marked freshwater core (Stabeno et al., 2004). During winter, the ACC flows most strongly along the Kenai Peninsula and down Shelikof Strait, to the west of Kodiak Island. During the summer the ACC is weaker and bifurcates at the Kennedy and Stevenson Entrances to Shelikof Strait. Approximately 50% of the ACC on average flows along the east coast of Kodiak Island during summer (Stabeno et al., 2004).

Our data suggest that variability in winds leads to variability in the amount of ACC transport along the east coast of Kodiak Island at the temporal scale of weeks. We hypothesize that a wind-driven event resulted in increased transport of warm, low-salinity ACC water through the study area in 2002. Preceding the offshore expansion of pollock and of warm, low-salinity water in Barnabus Trough, winds were relatively weak and towards the northeast. Transport data collected at moorings at Gore Point (northeast of Barnabus Trough) and Cape Kekurnoi (southwest of Barnabus Trough in Shelikof Strait) show weak regional transport during this period of low wind speed. We suggest that coastal water pooled in the Gore Point area, south of Kennedy/Stevenson Entrances, during this time. Winds increased in strength and the direction shifted towards the southwest after the start of Pass 2, when fish distributions began to change. Transport to the southwest also increased at this time but more so at Gore Point than at Cape Kekurnoi (Line 8). This is consistent with greater southwest transport of water offshore of Kodiak Island than inshore, through Shelikof Strait. Current meter data from moorings in Barnabus Trough also indicate increased southwesterly flow during Pass 2 offshore of Kodiak Island. We suggest that with the increase in wind speed to the southwest, some of the pool of fresher, warmer water at Gore Point was advected southwestward along the east side of Kodiak Island, while the remainder was advected down Shelikof Strait. Thus there was a pulse of ACC water along the east coast of Kodiak Island and across Barnabus Trough that coincided with the change in temperature and salinity and the shift in fish distributions.

A plausible alternative explanation for the increase in warm, low-salinity water in our study area in 2002 is an increase in downwelling associated with the increase in southwesterly winds. Although we cannot rule out the possibility that downwelling played a role in the changes we observed, the evidence suggests that this was not an important process. There was no compression of low-salinity water in the onshore direction, as would be expected with increase downwelling and the associated onshore flow. On the contrary, low-salinity water expanded offshore at the time the winds increased to the southwest. Furthermore, there was no vertical depression of the pycnocline

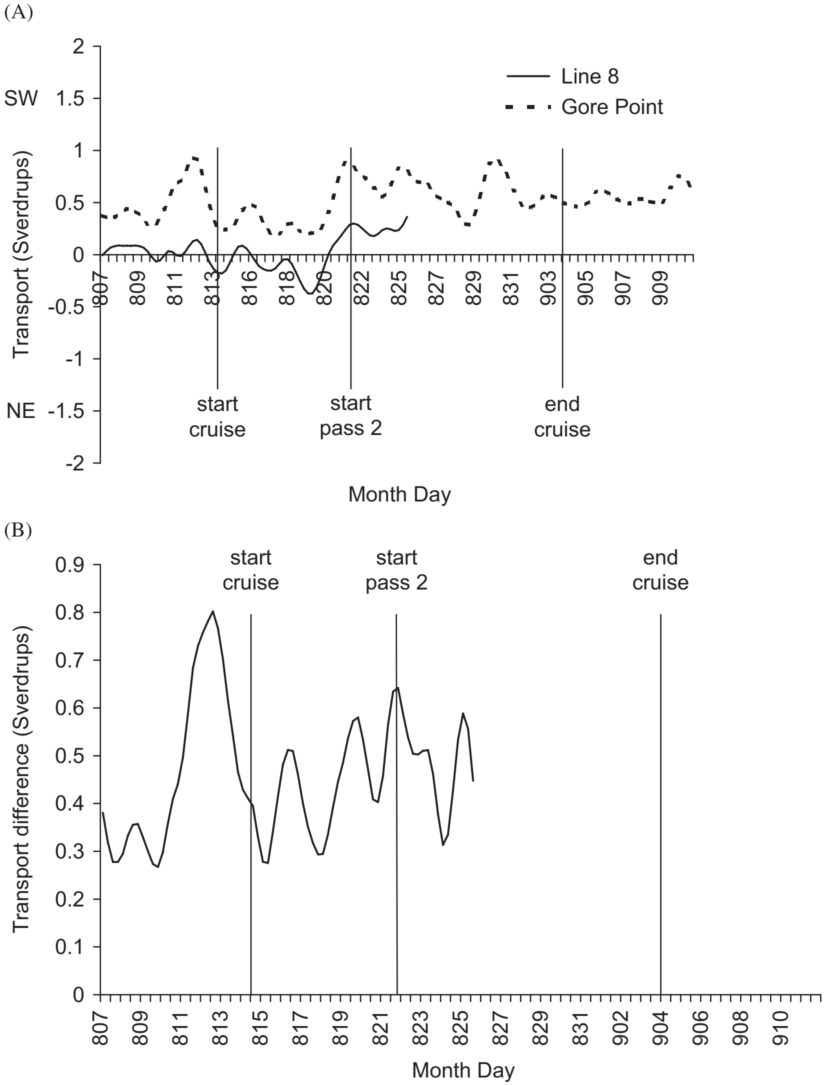


Fig. 13. (A) Transport (Sverdrups) from moorings at Gore Point and Line 8 (see Fig. 2 for mooring locations). Positive values indicate transport to the southwest, negative values indicate transport to the northeast. (B) The difference in transport (Sverdrups) between Gore Point and Line 8 (Gore Point values minus Line 8 values). Data from 7 August to 11 September 11 2002 are shown. Vertical lines indicate the start and end of the 2002 survey and the start of Pass 2 (22 August).

concurrent with the water-mass changes described above, as would occur with increased downwelling.

The distribution of water-mass properties off Kodiak Island during August–September 2004 did not show the variability observed in 2002. Consistent with Hollowed et al. (in press) and our initial observations in 2002, warm, low-salinity water characterized the inner-shelf and cool, high-salinity water was found on the outer-shelf. Area winds were consistently to the southwest during the 2004 study, such that we would not expect the pooling and pulsing of ACC water that we observed in 2002.

Another difference between 2002 and 2004 was that age-1 and age-2 pollock were not observed in Barnabus Trough in 2004. Instead, the midwater acoustic backscatter was composed of capelin mixed with age-0 pollock. Also unlike previous years, capelin in 2004 were not restricted to the outer-shelf waters, but were found primarily in warm, low-salinity inner-shelf waters that had been previously occupied exclusively by age-1 and age-2 pollock. The change in pollock age-composition from 2002 to 2004 is not surprising, given the year-class variability of GOA pollock. Pollock recruitment

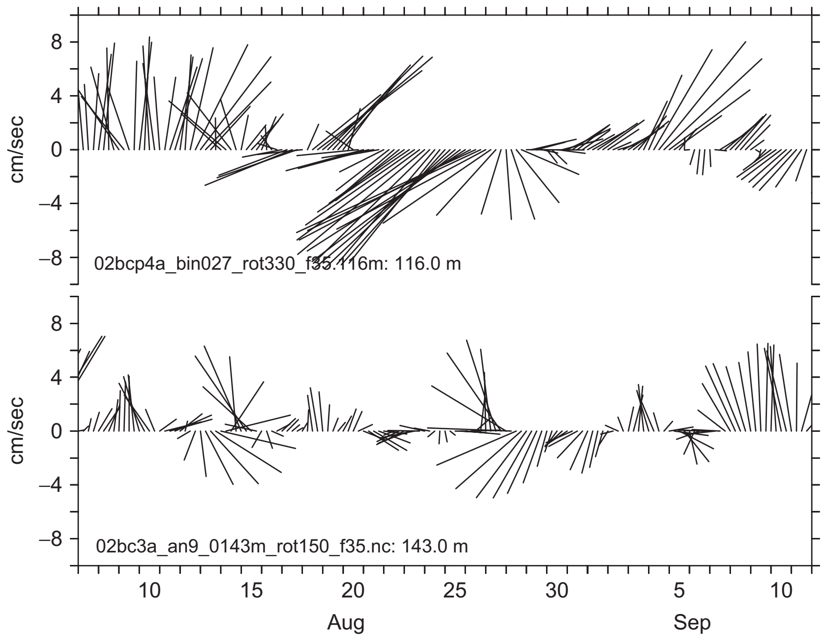


Fig. 14. Current velocity (cm/s) and direction from current meters moored at 116 and 143 m on the eastern mooring (top panel) and western mooring (bottom panel), respectively (see Fig. 3 for mooring locations). The orientation of each stick indicates the direction towards which the current is flowing (e.g., towards the top of the page is north, towards the left is west, etc.). The length of the stick indicates the current velocity. Data from 7 August to 11 September 2002 are shown. The survey started on August 16, pass 2 started on August 22, the survey ended on September 4.

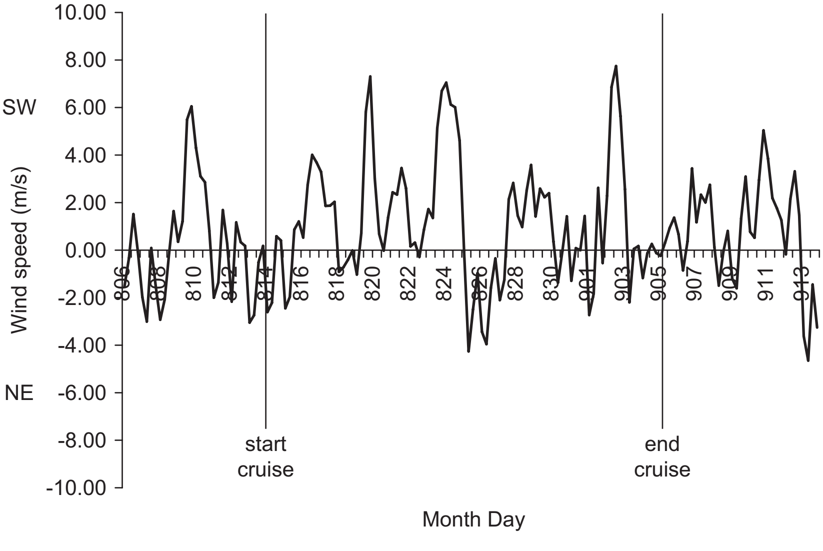


Fig. 15. NCEP reanalysis wind speed (m/s) at 59°N, 150°W, rotated and modified ($V = 240°T$). Positive values indicate winds to the southwest, negative values indicate winds to the northeast. Data from 6 August to 13 September 2004 are shown. Vertical lines indicate the start and end of the 2004 survey.

has been highly variable in the GOA since the 1980s (Dorn et al., 2004). The 2002 and 2003 year classes, which would have been age-1 and age-2 in 2004, were much weaker than the 2000 year class, which would have been age-2 in 2002.

The shift in juvenile pollock distribution with the offshore expansion of inner-shelf ACC water in 2002 suggests that these waters are their preferred pelagic habitat. Similarly, the presence of capelin in inner-shelf waters in 2004 when age-1 and age-2

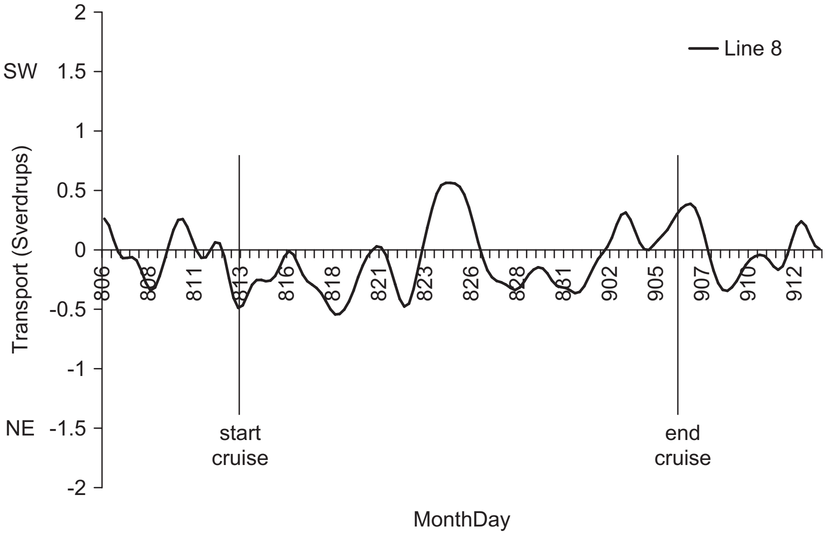


Fig. 16. Transport (Sverdrups) from a mooring at Line 8 (see Fig. 3 for mooring location). Positive values indicate transport to the southwest, negative values indicate transport to the northeast. Data from 6 August to 13 September 2004 are shown. Vertical lines indicate the start and end of the 2004 survey.

pollock were absent suggests that they also prefer inner-shelf waters. GOA shelf waters are characterized by a seasonal phytoplankton bloom of large diatoms and dinoflagellates that supports a copepod-dominated grazing assemblage (Cooney, 2005). In contrast, waters seaward of the shelf break are less seasonally variable and less productive. The offshore phytoplankton community consists of small diatoms, flagellates and cyanobacteria, which are grazed by microconsumers such as protozoans and flagellates (Cooney, 2005). We hypothesize that inner-shelf, ACC waters provide improved feeding habitat compared to outer-shelf waters. Our data on integrated chlorophyll biomass is consistent with increased productivity in ACC water, but further sampling of the zooplankton species composition and abundance is necessary to determine whether these waters do indeed provide good feeding habitat for planktivorous juvenile pollock and capelin. Previous studies in Shelikof Strait, west of Kodiak Island, have shown that the ACC is associated with elevated zooplankton biomass during spring (Napp et al., 1996; Incze et al., 1997). In the Semidi Bank area, south of Kodiak Island, Wilson et al. (M. Wilson, Alaska Fisheries Science Center, pers. com.) have found that, during the fall, juvenile pollock and relatively large zooplankton species (*Calanus marshallae*, *Metridia pacifica*, and *Thysanoessa inermis*) were most abundant in areas associated with the ACC. Juvenile capelin around Iceland mainly occupy well-mixed, zooplankton-rich waters of the north Iceland shelf and East Greenland plateau (Vilhjálmsson, 2002), suggesting a similar habitat preference as we hypothesize for GOA capelin.

The goal of this research was to investigate the possible mechanisms linking climate variability and fish communities in the GOA. We suggest that variability in area winds and transport at the scale of weeks can influence the distribution of water masses and the fish that occupy them. Summer mean along-shore winds in the GOA show no obvious decadal-scale signals or long-term trends (Stabeno et al., 2004). However, it is the variability in along-shore winds, not the mean, that we suggest impacts water-mass distributions on the shelf by way of pooling and pulsing of ACC waters. The mechanisms coupling large-scale climate variability to smaller-scale variability in the ACC are not known, but are likely related to the timing of the increase in freshwater runoff and spin-up of the winds which accelerate the ACC. This typically occurs in late summer and early fall (Stabeno et al., 2004). Research on capelin distributions in other systems have shown that capelin can redistribute themselves over extensive geographic areas in response to changing oceanographic conditions. In the Northwest Atlantic, the distribution of adult and juvenile capelin shifted to the south and east during the 1990s, concurrent with changes in prevailing oceanographic conditions, specifically, lower water temperatures and increased sea-ice extent and duration (Frank et al., 1996; Anderson et al., 2002). The extent to which pollock and capelin growth or survival is impacted by such changes in distribution remains to be determined.

Our results are also consistent with the idea that the distribution of fish is influenced by the distribution of potential competitors, such that competition is another potential mechanism driving variability in fish communities. Capelin were distributed in outer-shelf waters when juvenile (age-1 and age-2) pollock were abundant in inner-shelf waters, but were found in inner-shelf waters when juvenile pollock were absent. For competition to occur between GOA capelin and juvenile pollock, the two species must utilize a common, limiting resource. The diet of juvenile pollock collected in Barnabus Trough in 2000 and 2001 was dominated by invertebrates such as euphausiids and cumaceans (M.-S. Yang, Alaska Fisheries Science Center, pers. com.). The diet of capelin collected in another area of the Gulf of Alaska, 250 km southwest of Barnabus Trough in Shelikof Strait, was similarly dominated by euphausiids (Wilson et al., 2006). If inner-shelf waters are areas of elevated zooplankton abundance, as we hypothesize above, it may be that juvenile pollock (age-1 and age-2) are superior competitors such that capelin distributions are shifted to less productive outer-shelf waters when juvenile pollock are present. Results from trawl surveys off Newfoundland and Labrador suggest that capelin distributions are limited to the southern portion of the study area where zooplankton abundances are relatively low by interspecific competition with juvenile Arctic cod which are abundant in northern, zooplankton-rich areas (Anderson et al., 2002). For competitive exclusion by juvenile pollock to play a role in capelin productivity, feeding in less productive outer-shelf waters must result in decreased capelin growth and/or survival. Although studies of capelin growth and survival in the GOA have not been published, time series analysis of data from Icelandic waters show that reduced capelin growth was associated with reduced zooplankton production during 1970–1998 (Vilhjálmsson, 2002).

The presence of juvenile pollock (age-1 and -2) in Barnabus Trough is likely related to year-class strength variability, perhaps internally regulated or perhaps driven by events occurring in another time or place. Variability in GOA pollock year-class strength has been hypothesized to be driven by variability in basin-scale circulation, wind-mixing and precipitation (Megrey et al., 1996). As discussed above, average summer coastal winds in the GOA do not appear to be linked to decadal-scale climate variability, such as indexed by the Pacific Decadal Oscillation, although wintertime precipitation may be linked to El Niño—Southern Oscillation variability (Stabeno et al., 2004).

Although we propose that competition may occur between capelin and juvenile pollock (age-1 and age-2), we do not think that competition between capelin and the youngest age class of pollock (age-0) occurs or is strong enough to impact capelin foraging success. Wilson et al. (2006) found that age-0 pollock in Shelikof Strait exploit a variety of prey items, whereas capelin specialize on euphausiids.

Anderson and Piatt (1999) suggest that the nearshore GOA community shifted from dominance by forage fish (including capelin) to dominance by groundfish (including pollock) around the time of the 1977 regime shift. This apparent community reorganization was hypothesized to result from changes in the timing of seasonal zooplankton production, augmented by predation by adult groundfish. However, Fritz and Hinckley (2005) demonstrate that the patterns documented in Anderson and Piatt (1999) are not consistent with GOA-wide stock assessments of pollock and forage fish (specifically herring), and thus may not reflect abundance trends for the entire GOA fish community. Not only do GOA-wide patterns in fish abundance need to be re-evaluated in light of recent criticism of the conclusions of Anderson and Piatt (1999), our work suggests that competition between capelin and juvenile pollock should be considered when formulating hypotheses about the factors affecting GOA fish community structure.

5. Conclusion

In summary, our results suggest that both oceanographic variability and competition may influence the distribution and production of GOA fish. Further study of the mechanisms linking climate change with small-scale variability in the ACC is needed to understand how climate change can affect pelagic habitat of GOA fish. In addition, more information is needed on resource limitation and the potential consequences of competition for fish growth and survival in the GOA.

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