ISSN: 0074-7246

INTERNATIONAL PACIFIC HALIBUT COMMISSION

Established by a Convention Between
Canada and the United States of America

Scientific Report No. 85

Seasonal movements and environmental conditions experienced by Pacific halibut along the Aleutian Islands, examined by pop-up satellite tags

by

Andrew C. Seitz[a], Timothy Loher[b], and Jennifer L. Nielsen[c]

[a] U.S. Geological Survey/University of Alaska, Fairbanks
[b] International Pacific Halibut Commission
[c] U.S. Geological Survey

SEATTLE, WASHINGTON
2008

The International Pacific Halibut Commission has three publications: Annual Reports (U.S. 0074-7238), Scientific Reports, and Technical Reports (U.S. ISSN 0579-3920). Until 1969, only one series was published (U.S. ISSN 0074-7246). The numbering of the original series has been continued with the Scientific Reports.

INTERNATIONAL PACIFIC HALIBUT COMMISSION
P.O. BOX 95009
SEATTLE, WASHINGTON 98145-2009, U.S.A.
www.iphc.washington.edu

Seasonal movements and environmental conditions experienced by Pacific halibut along the Aleutian Islands, examined by pop-up satellite tags

Andrew C. Seitz, Timothy Loher, and Jennifer L. Nielsen

Contents

Abstract

Currently, Pacific halibut are managed as one population extending from California to the Bering Sea. However, we hypothesize that a sub-population of Pacific halibut may exist in the Bering Sea and Aleutian Islands. In this study, we examined the seasonal migration and depth-specific behavior of Pacific halibut along the Aleutian Islands, which serve as indicators of possible population structure. We tagged 25 adult halibut in July and August, 2004 near Attu and Atka Islands with Pop-up Archival Transmitting (PAT) tags. Externally attached to the fish, PAT tags recorded depth, temperature, and ambient light intensity. PAT tags released from the fish on 15 February 2005 and transmitted the historical data and their locations to Argos satellites. Data were recovered from 16 tags that released from the fish and reported to satellites. The tagged fish ranged from 110 to 176 cm forklength and were at-liberty from 193 to 206 days. Distance traveled from the release site ranged from 0.5–166.6 km. Fish visited a range of depths between 32 and 748 m where temperatures ranged from 2.6–9.0°C. There was no evidence that any of the halibut moved away from the island group at which they were tagged. The lack of movement during the winter spawning season is consistent with the hypothesis that the Aleutian Islands support at least one locally resident subpopulation with respect to spawning structure.

Seasonal movements and environmental conditions experienced by Pacific halibut along the Aleutian Islands, examined by pop-up satellite tags

Andrew C. Seitz, Timothy Loher, and Jennifer L. Nielsen

Introduction

The Pacific halibut (*Hippoglossus stenolepis*) fishery is an important resource throughout western Alaska, with just under seven million pounds (estimated at nearly $20 million ex-vessel) of product landed during 2005 in the Aleutian Islands and southeast Bering Sea directed fishery. About two million pounds are harvested annually by western Alaska communities under their Community Development Quotas (CDQ). The CDQ program was established by the North Pacific Fishery Management Council in 1992 to provide income to disadvantaged coastal communities with access to Aleutian Island and Bering Sea marine resources. The program has been hailed by the National Research Council as a critical innovation for local economic development (NRC 1999) and relies upon sound management on regional scales to remain effective.

Currently, the International Pacific Halibut Commission (IPHC) manages Bering Sea/ Aleutian Island (BSAI) halibut not on a regional scale with independent population dynamics, but as part of a single population of halibut in the entire eastern Pacific Ocean (Fig.1) (see review in Seitz et al. 2007). However, it has been recently recognized that several marine fish species appear to have a more complex population structure than is recognized, and in many cases, management units contain population complexes with several spawning components (Stephenson 1999). Unfortunately, these spawning components are typically difficult to define from traditional fisheries data or conventional stock identification techniques (Stephenson 1999). Failure to recognize complex population structure in management may lead to extinction of spawning components with unknown ecological consequences (Stephenson 1999).

Little is known about the ecology of Pacific halibut along the Aleutian Islands. It is generally assumed that throughout their range in the eastern Pacific Ocean, adult halibut feed in shallow, nearshore areas during the summer, undertake a spawning migration to deeper water during winter and return to their summer grounds during spring (Dunlop et al. 1964, Best 1981). Spawning appears to be concentrated in relatively discrete winter spawning grounds near the edge of the continental shelf of the eastern Pacific, from at least British Columbia through the Pribilof Canyon (Fig. 1) in the southeast Bering Sea (St. Pierre 1984). However, there have been no winter surveys conducted along the Aleutian Islands; the westernmost documented spawning ground is the Pribilof Canyon (Fig. 1). It is likely that previously unidentified spawning grounds occur along the Aleutian Islands and identification of these local spawning groups may change our interpretation of the population structure of Pacific halibut in the northeast Pacific Ocean.

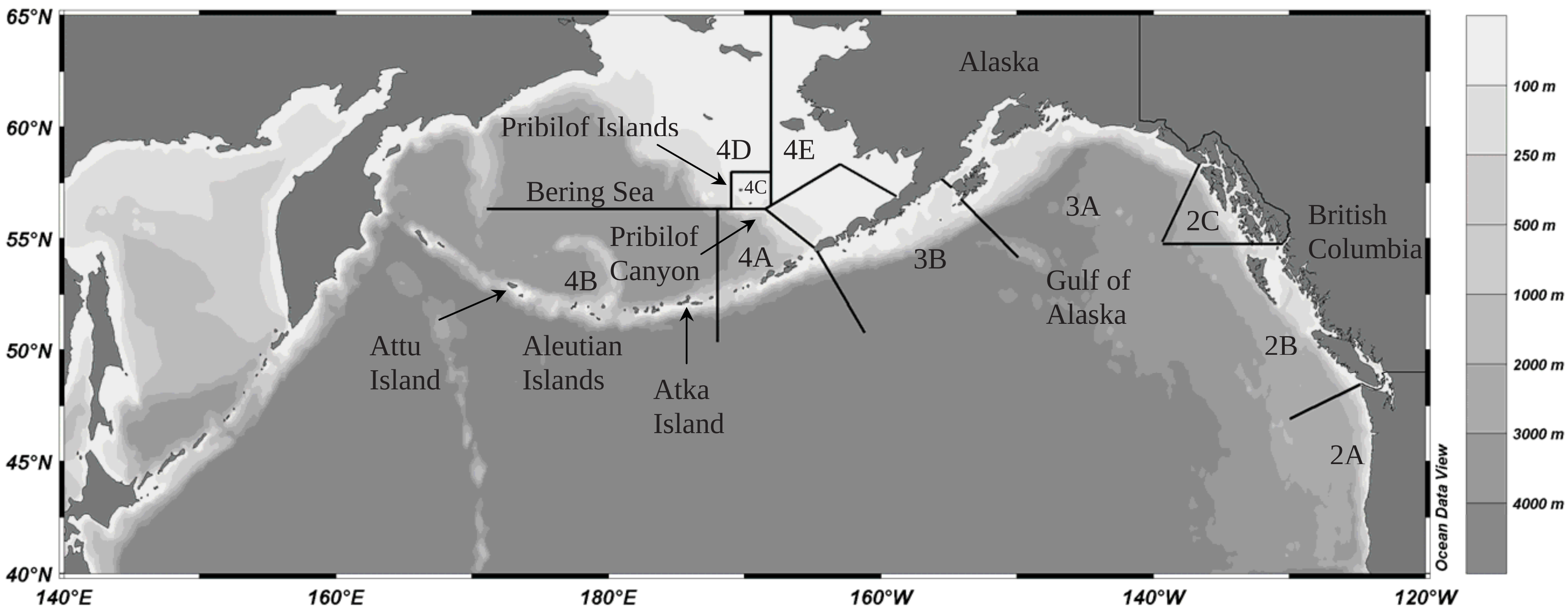

Figure 1. Map of North Pacific Ocean, Bering Sea and International Pacific Halibut Commission Regulatory Areas (delineated by black lines).

We hypothesize that Pacific halibut in the BSAI region may constitute a separate spawning component or sub-population of halibut in the eastern Pacific Ocean (see review in Seitz et al. 2007). If there is indeed a sub-population of halibut in the BSAI region, this may have a substantial impact on local recruitment dynamics, affecting productivity near communities whose fishing operations are located close to their homeport, such as CDQ holders. The debate over the relative biological independence of BSAI halibut is likely to become more controversial in the near future because IPHC recruitment models indicate that total exploitable biomass has been declining since about 1999 (Clark and Hare 2002a). The decline is expected to persist through the early 2010s as recruitment responds to changes in large-scale environmental forcing (Clark and Hare 2002b).

In 2002, an investigation was begun examining the putative spawning locations and migration pathways of halibut in the Bering Sea, which serve as indicators of possible population structure (Seitz et al. 2007). We tagged adult halibut near the Pribilof Islands (Fig. 1) along the southeast Bering Sea shelf-edge with Pop-up Archival Transmitting (PAT) tags. The PAT tag is a miniature computer that is externally attached to the fish, containing a clock integrated with sensors that collect detailed records of depth, temperature, and ambient light intensity at user-specified intervals (Sibert 2001). On a user-programmable date, the PAT tag releases from the fish, floats to the surface, and transmits the historical data to satellites operated by Service Argos (Largo, MD, www.argosinc.com; hereafter “Argos”) to be retrieved by the investigator. Location information during time at liberty can also be derived indirectly from the PAT tag. This new technology allows us to determine winter location of the tagged fish and some aspects of their migration routes without depending upon winter fisheries to recapture the tagged individuals.

This report represents the continuation of our ongoing investigation of Pacific halibut in the BSAI region. The goals of the present study were to determine winter locations of halibut tagged at two areas along the Aleutian Island chain and use depth experienced during their time at liberty to infer migration timing and pathways used during their spawning migration. This information can be used to refine our understanding of regional population structure and to infer whether BSAI halibut spawn locally and are likely to contribute primarily to western Alaskan recruitment potential.

Methods

Wildlife Computers[1] PAT tags were externally tethered to Pacific halibut following a previously successful protocol (Seitz et al. 2003). Captured halibut were deemed appropriate for PAT tagging and release if they were in good condition (i.e. likely to survive) and were at least 110 cm forklength (FL), as this was the smallest size of halibut successfully tagged in a previous study (Seitz et al. 2003). Additionally, this study aims to monitor spawning movements as the vast majority of halibut ≥110 cm FL are sexually mature (Clark et al. 1999).

Twenty-five adult halibut were tagged and released near the Aleutian Islands during July and August 2004: 13 near Attu Island and 12 near Atka Island (Fig. 2). All tags were programmed to release on 15 February 2005 to determine the halibuts’ winter grounds, as adult halibut are known to spawn from approximately December through February (St. Pierre 1984). Because a satellite-determined location was provided on pop-up, mid-winter location could be obtained even if the tagged fish were too deep to estimate geolocation using light data (described subsequently).

Each PAT tag contained three electronic sensors that recorded ambient water temperature, depth of the tag, and ambient light (i.e., environmental data; for PAT tag details, see Seitz et al. 2003). On the pop-up date, the PAT tags actively corroded the pin to which the tether was attached, thus releasing the tag from the animal. The tag then floated to the surface and transmitted

[1] Redmond, Washington, USA

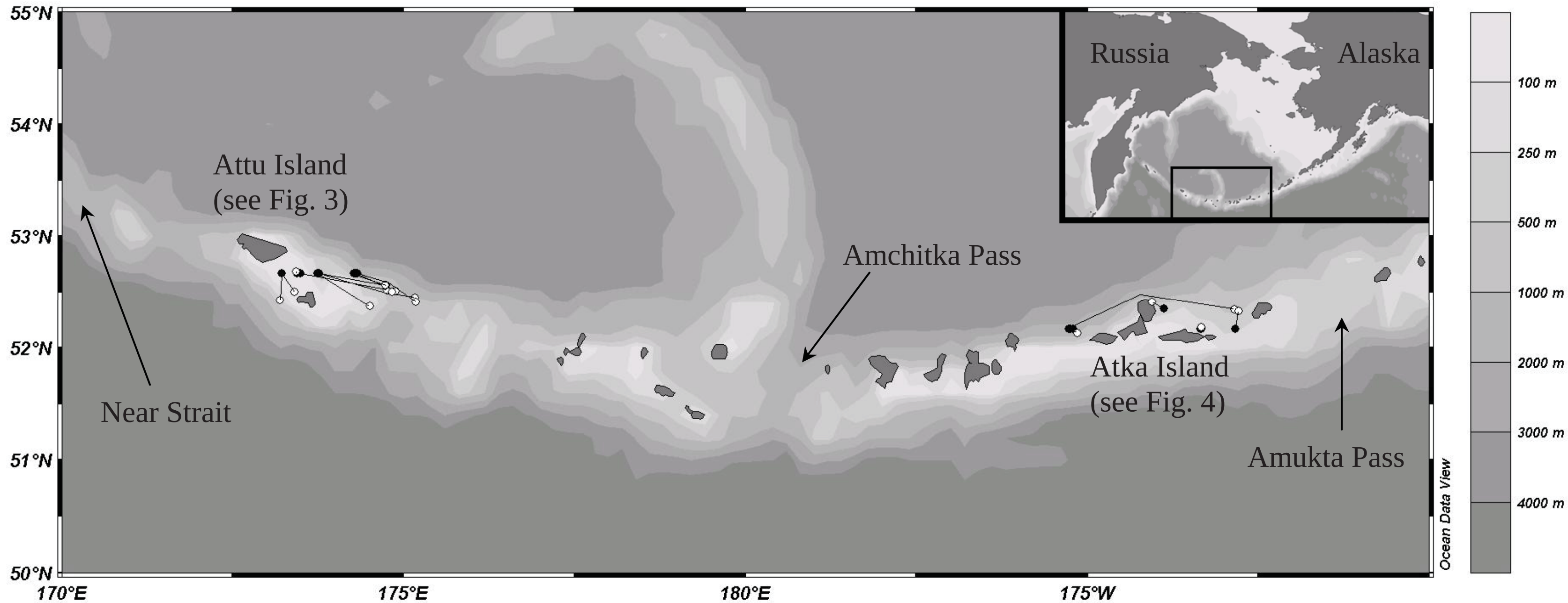

Figure 2. Release (●) and recovery sites (o) of PAT-tagged halibut along the Aleutian Islands, summer 2004.

summarized historical data records to the Argos satellite system. Upon popping up, each tag's endpoint position was determined from the Doppler shift of the transmitted radio frequency in successive uplinks received during one satellite pass (Keating 1995). The transmitted data then were processed further by Wildlife Computers' PC-based software.

The environmental data were sampled at two minute intervals and were subsequently summarized into 12-hour periods by software within the PAT tag, thus providing four types of data: 1) percentage of time spent within specific depth ranges, 2) percentage of time spent within specific temperature ranges, 3) depth-temperature profiles from which minimum and maximum depths and temperatures may be extracted and, 4) daily geoposition estimates for the time the tag was attached to the fish. Light-based longitude estimates were produced by Wildlife Computers' proprietary software, Global Position Estimator (GPE), using the ambient light data (for details, see Seitz et al. 2006). Latitude estimates have been found to be highly variable in previous PAT tagging experiments (Seitz et al. 2006) and therefore were not used for determining movement of halibut.

Light-based longitude estimates were qualitatively examined. The number of days with longitude estimates was defined as the days that produced longitude estimates, after outliers were removed. Daily error magnitude was estimated as the absolute value of the fish's true position (defined subsequently) minus the estimated position. Daily positional bias was estimated as the true position minus the estimated position. If positions were accurate, they should have a bias of zero. A negative bias meant that a longitude estimate was east of the true position and a positive bias meant that a longitude estimate was west of the true position. It was impossible to know the true daily position of each fish for the duration of the experiment, thus we were unable to calculate error and bias estimates for the duration of the track. However, we did know each fish's true position on the days of tagging and recovery (either recapture or reporting to Argos satellites) and used these as true positions. We then compared the estimated positions of the tags for the six days immediately following release and the six days previous to recovery to the respective true positions (*sensu* Seitz et al. 2006). For each comparison, we calculated the mean error and bias assuming the fish was stationary (or nearly so) during this time. Because individual longitude estimates may be subject to occasional large errors, one must practice caution when using these estimates to represent the true position of the fish. However, examining trends in estimates has proven useful for determining the direction of movement, which is the approach used in this study (Loher and Seitz 2006*a*).

For all tagged fish, we report fish size, release and recovery locations, number of days with geolocation estimates, estimated daily position, and the minimum and maximum depths and temperatures recorded for each 12-hour period. The minimum and maximum depths and temperatures for the 12 hours immediately following release were excluded. Large, abrupt changes in maximum depth were defined as the autumn offshore migration from the continental shelf to the continental slope (Seitz et al. 2003).

Results

Attu Island tags

The tagged fish ranged from 110 to 154 cm FL and were at-liberty approximately 205 days. Data were recovered from 11 tags (85%) and two tags did not transmit (Table 1; Figs. 2 and 3). The maximum horizontal displacement from the release site was 98.0 km while the minimum was 0.5 km (Table 1; Fig. 3).

Seven of eleven fish moved east-southeast to deeper water ~60 km east of Agattu Island (Figs. 3 and 4). All of these fish ranged in size from 111 cm to 146 cm and were tagged in water shallower than ~100 m (Fig. 3 and 4). Offshore migrations occurred as early as 13 Sept. (04P0053) and as late as 14 Nov. (04P0050). On the date of tag pop-up, all of these fish were

Table 1. Deployment summary for PAT tags on Pacific halibut near Attu Island. The fish were tagged and released between 24 July and 28 July 2004 and the tags popped up on 15 February 2005.

Tag #	04P0047	04P0048	04P0049	04P0050	04P0051	04P0052	04P0053	04P0055	04P0056	02P0675	04P0064
Length (cm)	110	154	135	146	111	112	115	144	144	129	142
Horizontal displacement (km)	22.3	27.3	2.1	87.6	67.1	61.3	98.0	43.3	33.3	64.4	0.5
Minimum depth (m)	76	72	88	56	84	84	68	36	40	32	240
Maximum depth (m)	152	236	564	568	564	748	576	556	664	520	644
Minimum temp. (°C)	3.4	3.4	3.2	3.6	3.4	3.4	3.4	3.6	3.4	3.6	3.4
Maximum temp. (°C)	7.6	7.8	7.6	7.4	6.2	6.4	6.6	9.0	8.8	8.6	4.8
Days with longitude	19	15	15	7	11	3	5	18	22	10	4
% of days with longitude	9.2	7.3	7.3	3.4	5.4	1.5	2.4	8.9	10.9	5.0	2.0
# of comparison days	0	1	0	0	1	0	0	2	5	0	0
Long. error magnitude (º ± SD)	NA	0.0	NA	NA	0.2	NA	NA	0.6	0.6	NA	NA
Long. bias (º ± SD)	NA	0.0	NA	NA	-0.2	NA	NA	-0.6	-0.2	NA	NA

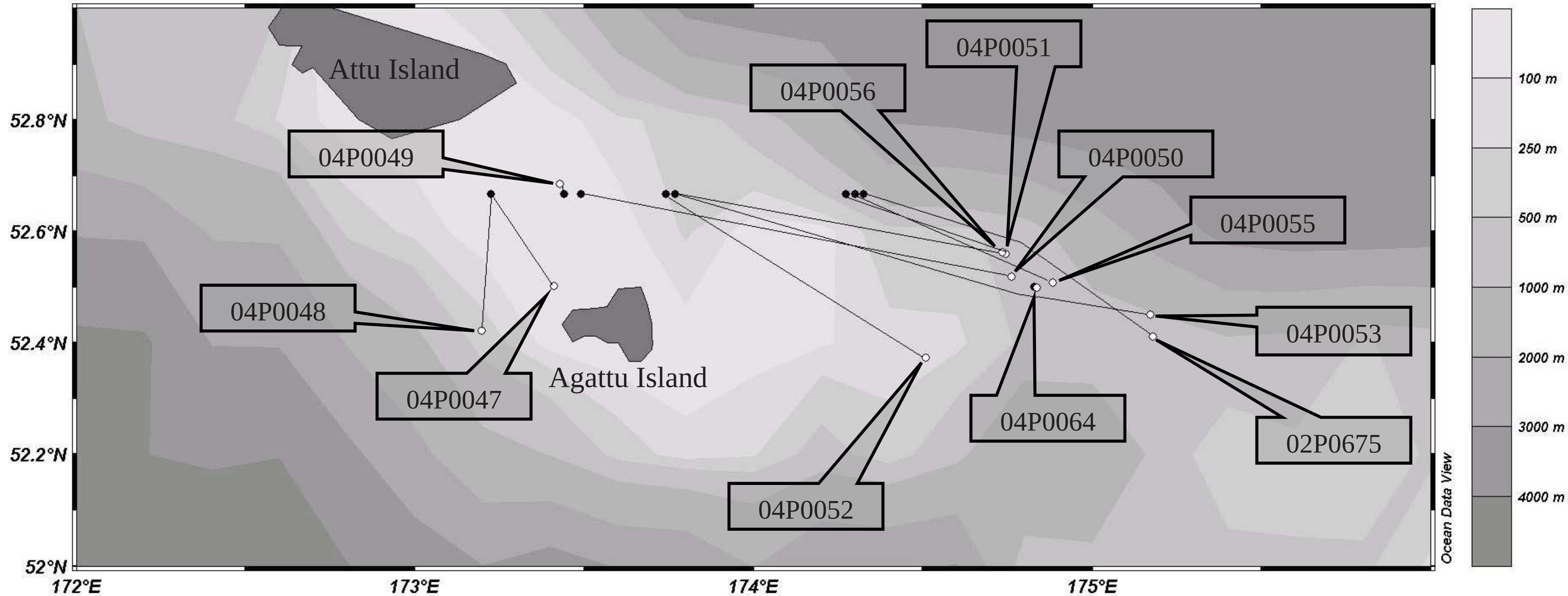

Figure 3. Release (●) and recovery sites (o) of PAT-tagged halibut near Attu Island, summer 2004. Numbers are equivalent to the PAT tag numbers given in Table 1.

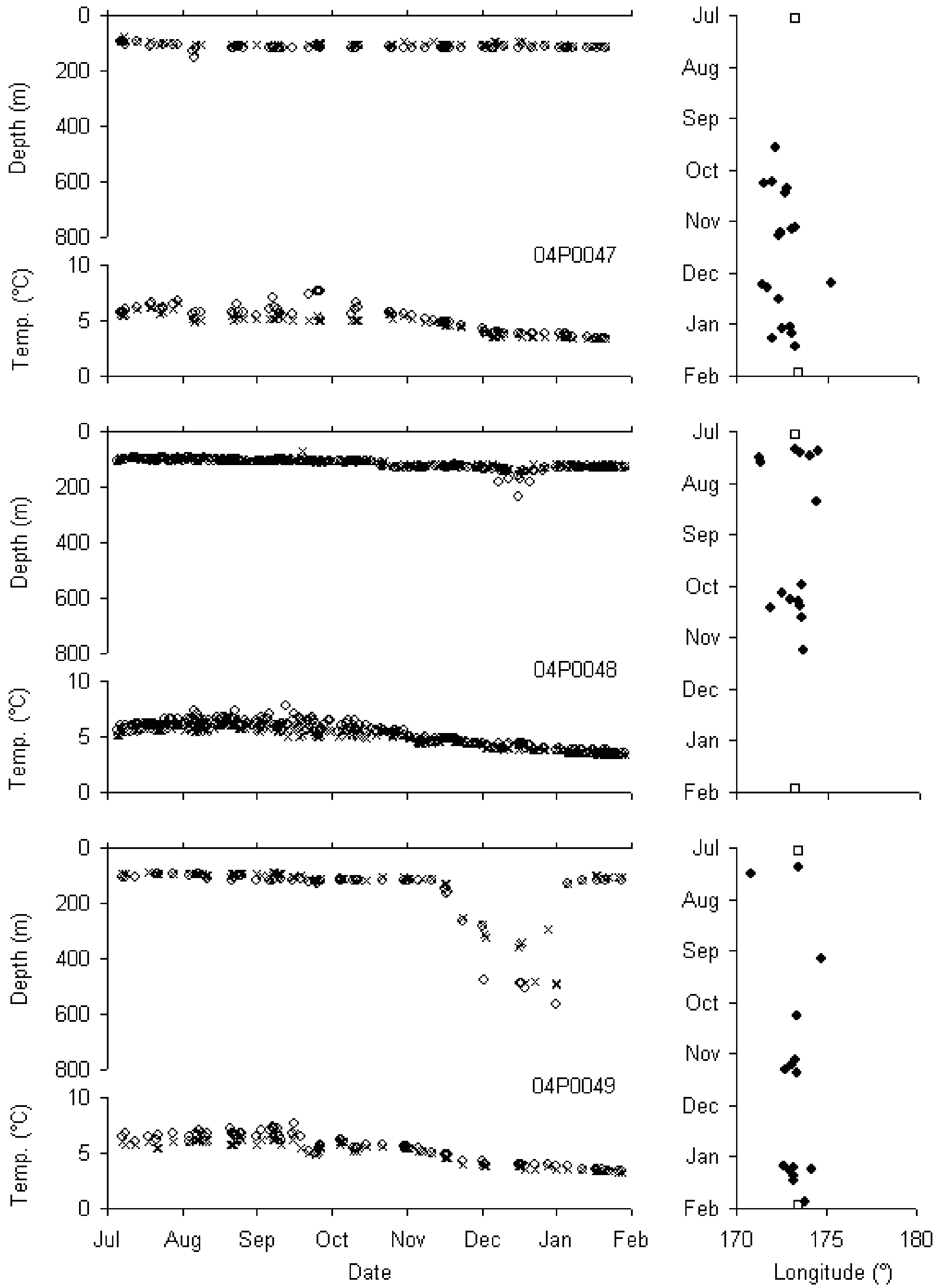

Figure 4. Maximum (o) and minimum (x) depths and temperatures of Pacific halibut near Attu Island for each 12-hour summary period, and daily longitude estimates after outliers were removed. For longitude plots, □ = release position and location at which the tag reported to Argos and ● = estimated position.

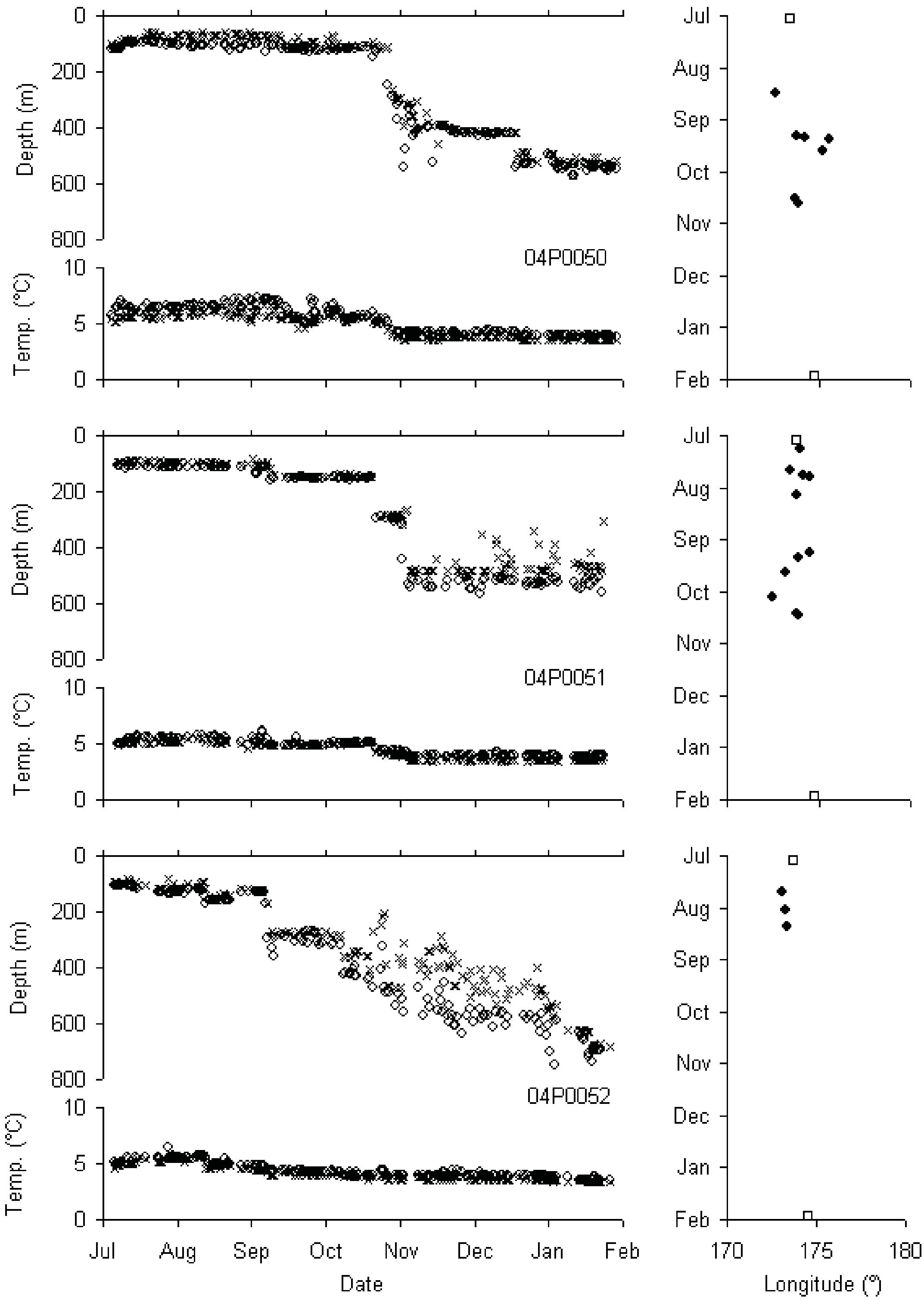

Figure 4. Continued

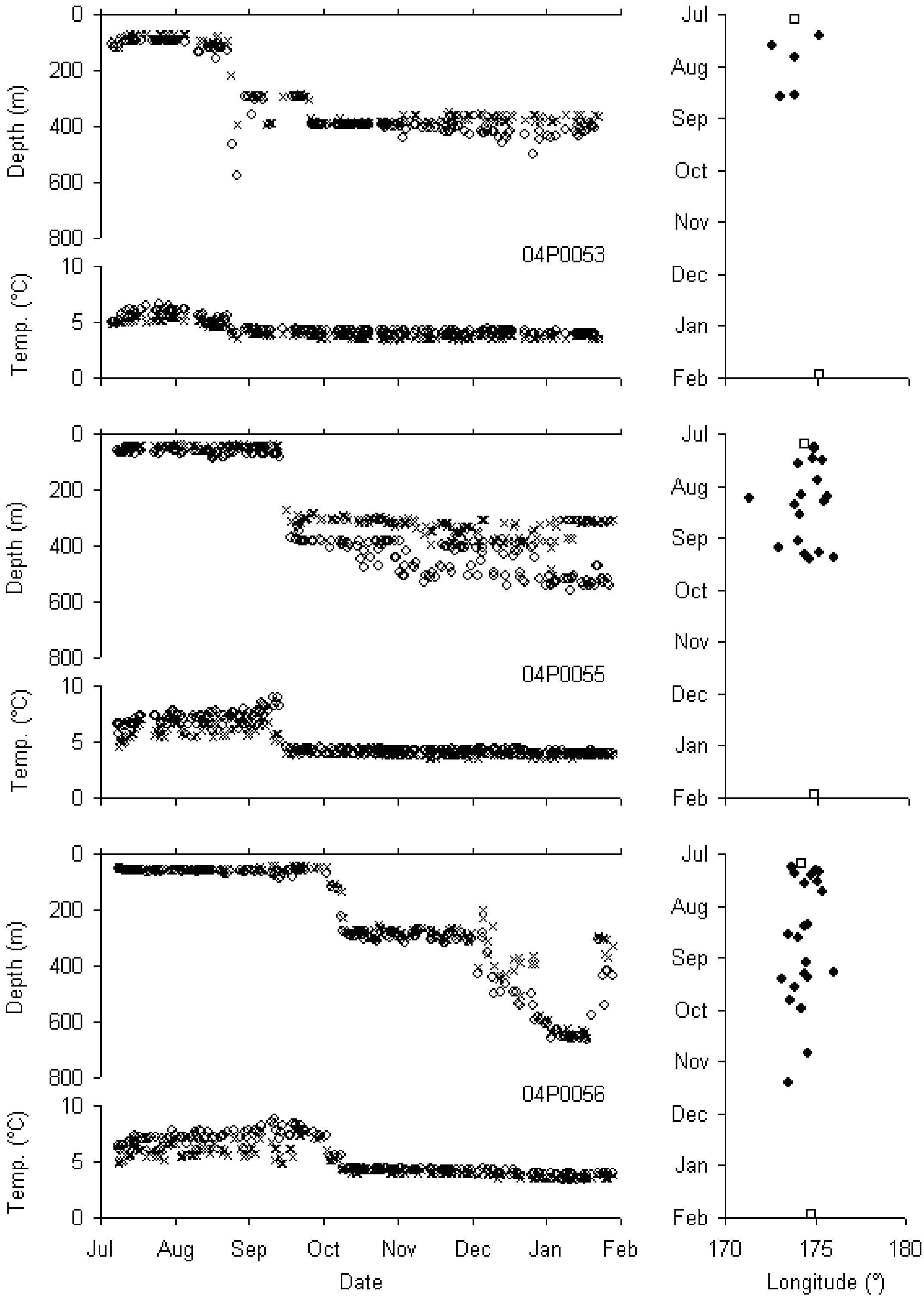

Figure 4. Continued.

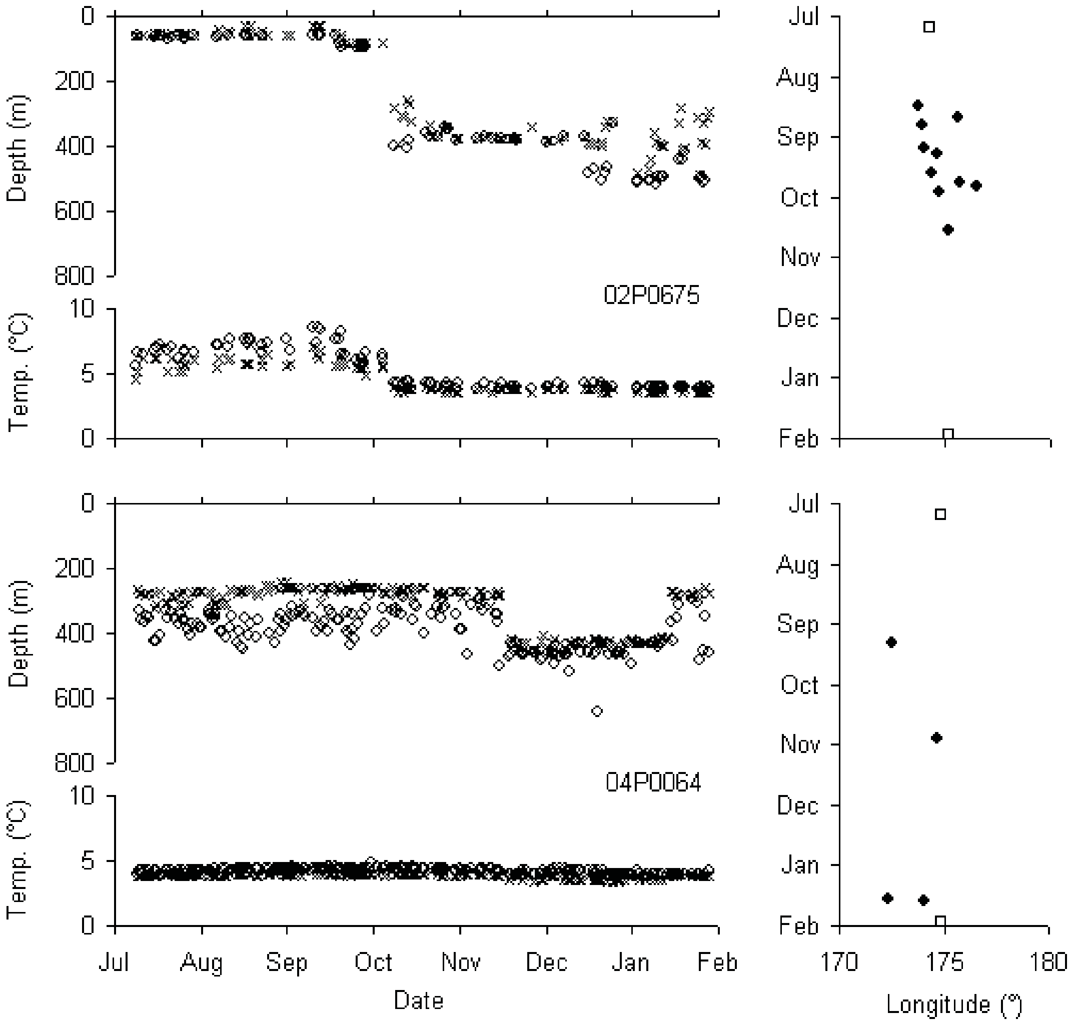

Figure 4. Continued.

located in water deeper than ~250 m. The longitude records indicate that none of the fish traveled a large distance and they probably remained in the area between the release and pop-up dates (Fig. 4).

Two of the halibut (04P0049 and 04P0064) released near Attu Island displayed homing to their summer feeding sites (Figs. 3 and 4). These fish were 135 and 142 cm, and their PAT tags reported to Argos within 2 km of their respective release locations. However, they could not have remained near their tagging locations throughout the tagging period because the fish experienced maximum depths of approximately 400–600 m from early-December to late January. Depths of this magnitude do not exist on the continental shelf, indicating that the fish moved off the shelf to the slope. The longitude records do not provide any evidence that these fish undertook large migrations during their time at-liberty.

The remaining two fish tagged near Attu Island (04P0047 and 04P0048) moved in a southerly direction, but did not leave the continental shelf (Figs. 3 and 4). These fish were the smallest and largest fish tagged near Attu Island with lengths of 110 and 154 cm. The longitude records do not indicate appreciable east-west movement during their time at-liberty.

For the tags released near Attu Island, the percentage of days with longitude estimates ranged from 2.0% to just over 10.9% (Table 1). Geolocation estimates were produced for the six-day period after release and the six-day period before recovery for four of the eleven tags, although only two tags had multiple estimates (Table 1). Mean longitude error magnitude ranged from 0.0° to 0.6° (~0–40 km), while mean longitude biases ranged from -0.6° to 0.0° (appr. -40–0 km).

Ambient water temperatures ranged from 3.2°C to 9.0°C for the fish released near Attu Island in depths between 32 and 748 m (Fig. 4; Table 1). The minimum temperature range experienced by an individual halibut was 1.4°C (04P0064) while the maximum was 5.4°C (04P0055 and 04P0056). In general, water temperatures were warmer and fluctuated more in the late summer and fall than in winter when they were relatively constant and cooler. For the fish that migrated to the continental slope, some of the fish experienced abrupt temperature changes associated with abrupt changes in depth. For the fish that remained on the continental shelf, water temperatures were warmest in early-autumn and gradually declined starting in late-autumn.

Atka Island tags

The tagged fish ranged from 111 to 147 cm FL and were at liberty approximately 195 days. Data were recovered from five tags (42%) and seven tags did not transmit (Table 2; Figs. 2 and 5). The maximum horizontal displacement from the release site was 166.6 km while the minimum was 1.8 km (Table 2; Fig. 5).

Only one of the five fish (04P0067) was located farther than 20 km away from its release site (Fig. 5). This was the smallest fish tagged near Atka (111 cm). It appears to have left its tagging location immediately after release because its depth gradually increased until early October at which point the fish left the continental shelf, where it remained on the continental slope until the date of tag pop-up (Fig. 6). One other fish (04P0073), 128 cm, was located on the continental slope on the date of tag pop-up, although it was only 13.5 km away from its release site. This halibut apparently remained near its tagging location until early November because its depth did not change nor were there any consistent changes in longitude estimates (Fig. 6). In early November, the fish moved to the continental slope in depths of 240–712 m until the date of tag pop-up.

Table 2. Deployment summary for PAT tags on Pacific halibut near Atka Island. The fish were tagged and released between 1 August and 6 August 2004, and the tags popped up on 15 February 2005.

Tag #	04P0067	04P0068	04P0073	04P0075	04P0077
Length (cm)	111	147	128	117	127
Horizontal displacement (km)	166.6	7.6	13.5	1.8	18.2
Minimum depth (m)	144	176	124	84	132
Maximum depth (m)	696	692	712	480	460
Minimum temp. (°C)	2.6	3.4	3.6	3.4	3.4
Maximum temp. (°C)	6.8	6.4	7.8	8.0	7.8
Days with longitude	1	1	11	8	4
% of days with longitude	0.5	0.5	5.7	4.1	2.1
# of comparison days	0	0	0	1	0
Long. error magnitude (º ± SD)	NA	NA	NA	3.2	NA
Long. bias (º ± SD)	NA	NA	NA	-3.2	NA

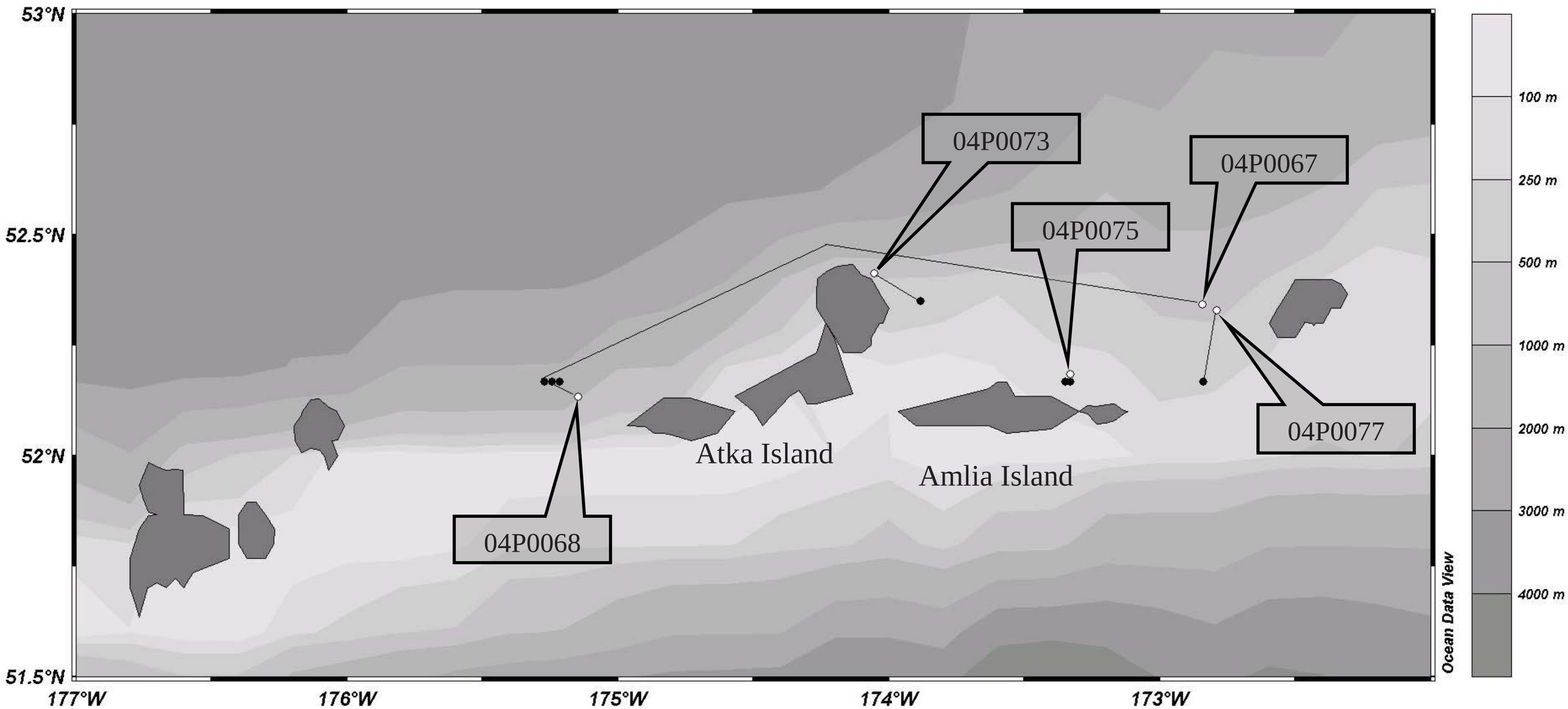

Figure 5. Release (●) and recovery sites (o) of PAT-tagged halibut near Atka Island, summer 2004. Numbers are equivalent to the PAT tag numbers given in Table 2.

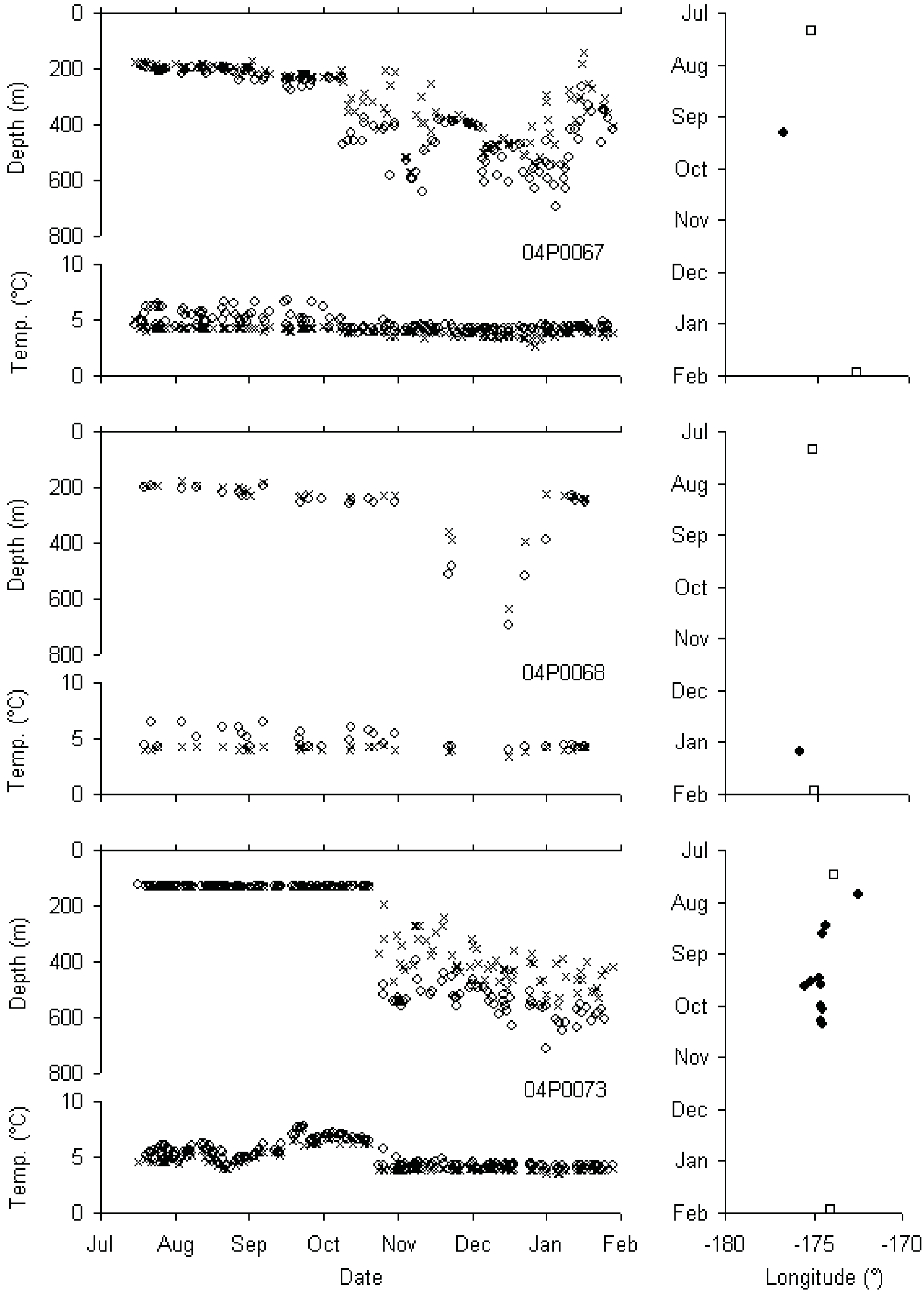

Figure 6. Maximum (o) and minimum (x) depths and temperatures of Pacific halibut near Atka Island for each 12-hour summary period, and daily longitude estimates after outliers were removed. For longitude plots, □ = release position and location at which the tag reported to Argos and ● = estimated position.

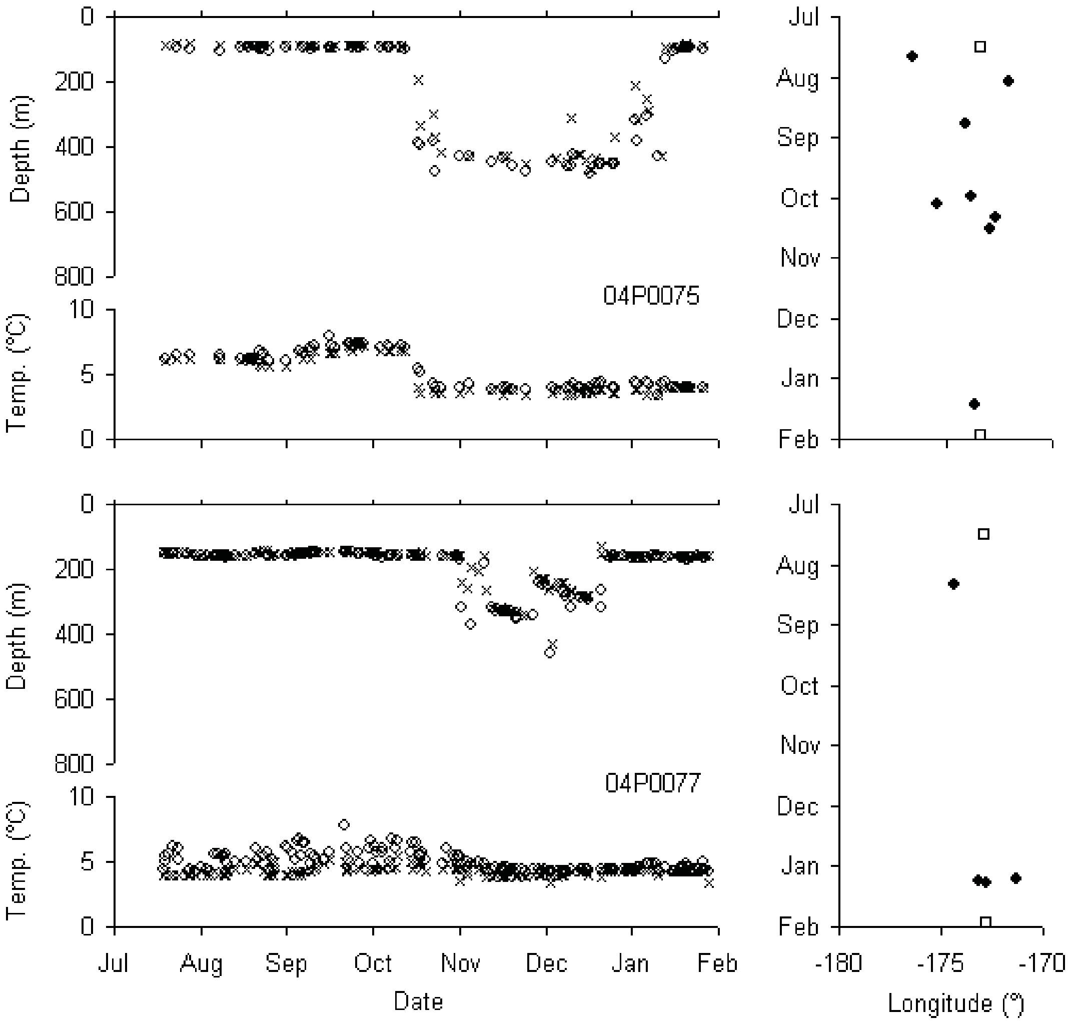

Figure 6. Continued.

Three halibut (04P0068, 04P0075 and 04P0077) displayed homing behavior similar to the fish tagged near Attu Island. These fish were 147, 117 and 127 cm, and their PAT tags reported to Argos within 20 km of their respective release locations (Fig. 5). None of these could have remained near their tagging locations during the winter because they experienced maximum depths of greater than 400 m during the winter (Fig. 6).

For these tags, the percentage of days with longitude estimates ranged from 0.5% to just over 5.7% (Table 2). A geolocation estimate was produced during the six-day period after release and the six-day period before recovery for only one of the five tags (Table 2). The longitude error magnitude was 3.2° (220 km) and was biased eastward.

The fish released near Atka experienced ambient water temperatures from 2.6°C to 8.0°C in depths between 84 and 712 m (Fig. 6; Table 2). The minimum temperature range experienced by an individual halibut was 3.0°C (04P0068) while the maximum was 4.6°C (04P0075). Similar to around Attu Island, halibut experienced temperatures that were warmer and fluctuated more in the late summer and fall than in winter when they were relatively constant and cooler. One tag (04P0073) recorded water temperature fluctuations from 4.2°C to 7.8°C even though the fish never changed depth.

Discussion

Unlike Pacific halibut tagged and released in the Gulf of Alaska (Seitz et al. 2003, Loher and Seitz 2006*a*) and the Pribilof Islands of the southeast Bering Sea shelf (Seitz et al. 2007), seasonal migrations observed in the Aleutian Islands were relatively small. None of the halibut in this study were observed more than 170 km away from their release locations during the winter spawning season. At the end of the tagging period, all of these fish were located in the vicinity of the island near which they were released and light-based longitude estimates provided little evidence that they moved away from their island group.

We hypothesize that deep passes along the Aleutian Island chain may restrict the east-west movement of the size or sex of halibut studied here. The depth of Amchitka Pass (1155 m) exceeds the maximum depth recorded by a Pacific halibut using PAT tagging technology (844 m; Seitz et al. 2007) and may have presented a movement barrier to halibut released in both locations (Fig. 2). Additionally, the halibut released near Attu Island showed no evidence of crossing Near Strait (2000 m) to the west while halibut released near Atka Island showed no evidence of crossing Amukta Pass (430 m) to the east. Halibut are known to be strong swimmers that feed off-bottom, as evidenced by incidental catch limits in salmon troll fisheries. It is therefore possible that halibut might cross deep passes while swimming in the pelagic zone and the shallower Amukta Pass would presumably present a lesser impediment to movement since all fish tagged at Atka exceeded the depth of Amukta pass at some point during their time at-liberty. Conventional tagging has also demonstrated cross-pass movement wherein fish tagged in the Aleutians have been recovered elsewhere. As opposed to representing a complete barrier to movement, we simply suggest that the passes reduce diffusion of fish across them, where diffusion rates are likely to be lesser where pass-depth is greater. As pass depth reaches or exceeds the animal's present activity range, it may be less likely for the fish to descend into the pass or shift to pelagic movement than to remain at its activity depth, and therefore not cross the pass. Thus, rate of exchange between two points separated by a pass would be lower than the rate of interchange between points separated by the same distance across bathymetry of relatively unchanging depth.

Two more lines of evidence corroborate the hypothesis that movement across deep passes may be limited. First, one halibut tagged near St. Paul Island in a previous study (Seitz et al. 2007) migrated to the eastern side of Amukta Pass, but like the halibut in this study, did not cross the pass. Second, recent genetics results indicate that Pacific halibut captured near the Pribilof Islands in the southeastern Bering Sea are more genetically similar to halibut captured near Oregon (~4000 km to the southeast) than to halibut captured near Atka Island (~700 km to the southwest) (Hauser et al. 2006). A discontinuity in reproductive mixing may exist between halibut in the southeastern BSAI, possibly at Amukta Pass. Given the regular capture of early juvenile halibut (age-2) in U.S. National Marine Fisheries Service trawl surveys in the central and western Aleutians, and oceanographic patterns that may retain larvae in the region, the accumulated evidence suggests the possible existence of one or more Aleutian Islands sub-populations.

The mid-winter aggregation pattern associated with fish tagged at Attu suggests that a locally-important halibut spawning ground might be located to the east of Agattu Island. If this is indeed an important spawning ground, it is the first one reported along the Aleutian Island chain and is almost 1000 km to west of the nearest documented spawning area. In contrast, the halibut tagged near Atka Island did not move to a single discrete area and hence no single spawning ground was indicated. However, the lack of any apparent aggregation may have been an artifact of the small tag return rate from Atka Island. Unfortunately, it will be impossible to know whether fish actively spawn at any location in the Aleutians unless future winter work is conducted to survey these areas to assess relative abundance and spawning condition.

Several of the halibut in both locations displayed homing to their feeding sites. While conventional tagging studies have demonstrated site fidelity on interannual time scales, the PAT tag data are unique in that they unequivocally demonstrate movement away from the tagging site followed by active homing. In conventional tag studies, it is impossible to know whether fish ever leave the tagging site. The frequent occurrence of homing in this study and previous studies (Seitz et al. 2003, Seitz et al. 2007, Loher 2008) demonstrates that a large proportion of adults may return to the same area annually, making them vulnerable to local depletions in areas with intensive commercial fisheries.

Two of the halibut released near Attu Island did not move to the continental slope during the winter breeding season. There are several possible explanations for these observations (Loher and Seitz 2006*a*, Seitz et al. 2007). One possibility is mismatch between the programmed tag release and their migration-timing; i.e., that these fish did not move to deep water until after February 15. To date, we have essentially no information regarding variability in migration-timing within the Bering Sea, but an analysis of existing archival depth data from the Gulf of Alaska (Loher and Seitz 2008) suggests that this possibility is rather small. Halibut that moved from shallow summer grounds to deep winter grounds did so over a very protracted period (July-January), but December 27 was the latest date upon which an offshore migration was observed to be initiated. This is well in advance of our February 15 pop-up date. Still, in the Gulf study the sample-size for fish generating full-year archival records was relatively small (n = 23) and migration timing in the Bering Sea may differ considerably. A certain amount of unique behavior would be expected in a very large sample, and more detailed investigation of regional variability in migration timing is warranted. This would require archival tagging with at-liberty periods of at least one year and preferably longer.

A second possibility to explain lack of movement to deep water is that these fish were simply immature and would not have participated in the spawning migration. Female maturity data from the 2004 IPHC survey at BSAI stations indicates that this is relatively unlikely. At 110 and 154 cm FL, these fish had approximately 20% and 0% probability of being immature, respectively, if female (T. Loher, unpublished data). Survey data further indicate that the male population may reach full maturity at sizes smaller than catchable in the survey gear (i.e., <50 cm FL). A third explanation that warrants further mention because of its ramifications for life history and population modeling, is the possibility that halibut skip spawning during some winters (Novikov 1964, Seitz et al. 2005, Loher and Seitz in 2006*a*). Recently, it has been recognized that several iteroparous fish species may be non-annual spawners (Rideout et al. 2005), a phenomenon generally attributable to poor physical condition (Jorgensen et al. 2006). This may explain some of the high variance in some stock-recruitment models (Rideout et al. 2005) because the percentage of non-reproductive fish must be determined if stock-recruitment models are to accurately portray spawning numbers or biomass. Failure to account for non-annual spawners will artificially inflate estimates of effective population size and survival from the egg stages through recruitment will be underestimated. For Pacific halibut, this does not present a major management issue because recruitment forecasts are based more on environmental forcing than on a stock-recruitment relationship, *per se*. However, if skip-spawning is a common feature within the population and varies according to condition index or environmental parameters, effective population size may vary even if total abundance remains static. Understanding the magnitude of such variance would be required to accurately gauge parameters such as threshold spawning biomass. PAT tags may represent a method to gain insight into potential rates of skip spawning, and preliminary analysis suggests that, in the Gulf of Alaska, 10% of mature halibut may not conduct an offshore spawning migration in any given year and 10–15% of fish that migrate to deep water may not actively spawn (Loher and Seitz 2008).

In this study, none of the fish emigrated from IPHC Regulatory Area 4B. In previous satellite tagging studies conducted on halibut in the Bering Sea and the Gulf of Alaska (Loher and Seitz 2006*b*, Seitz et al. 2007), several fish changed Regulatory Areas, often before the close of the commercial fishing season in November. However, IPHC Regulatory Area 4B apparently encompasses the boundaries of a possible sub-population of Pacific halibut identified in this study. It is important to acknowledge that conventional tagging studies as well as ongoing IPHC PIT (Passive Integrated Transponder) tag research have demonstrated movement of fish out of Area 4B following tagging. This is in contrast to the results of the present study and suggests a fundamental difference between PAT and conventional tagging. A variety of reasons might be invoked. One possibility is that the size and/or sex of halibut studied here (probably large females) consistently behave differently than the emigrants observed in other studies, or that such low emigration rates require long-term individual observations to detect, which is a feature of the PIT tagging experiments but has not been attempted with PAT tags. Alternatively, the apparent discrepancies may be due to the fact that conventional tag returns are fishery-dependent while PAT tag returns are not. Fishery-dependence can strongly affect the nature of conventional tagging data and the population-level inferences drawn from them (Hilborn 1995, Kohler and Turner 2001).

One factor that potentially impacted our results was the discrepancy in reporting rates between the tags released near Attu Island and Atka Island. The Attu Island tags had the highest reporting rate of any Pacific halibut satellite tagging experiment, while the Atka Island tags had the lowest (Seitz et al. 2003, Loher and Seitz 2006*a*, Seitz et al. 2007). Considering the tags were deployed by the same scientist within the span of two weeks, the reason for the drastic difference in reporting rates is unknown.

Sample sizes in this study are too small to quantitatively address mixing rates between the Aleutian Islands, Bering Sea, and Gulf of Alaska. However, this study provides qualitative information that can be used to direct future research and suggests that that the Aleutian Islands may display at least some level of sub-population structure. If there is indeed a separate sub-population in this region, largely supported by local spawning and recruitment processes, its dynamics may vary from that of the eastern Bering Sea shelf. Determining its population dynamics will be necessary for correct modeling to predict how the sub-population will respond to future fishing pressure and changes in environmental conditions.

Acknowledgements

The authors would like to thank Capt. Ron Zwahlen and crew of the F/V *Heritage* and Capt. Jim Martindale and crew of the F/V *Pacific Sun* for their fishing expertise; and IPHC Sea Samplers Rob Ames, Elizabeth Ekroth, Lynn Mattes and Anne Williams for tagging assistance. Partial funding for this project was provided by the International Pacific Halibut Commission and the U.S. Geological Survey–Alaska Science Center.

References

Best, E.A. 1981. Halibut ecology. *In* The Eastern Bering Sea Shelf: Oceanography and Resources. Vol. 1. *Edited by* D. W. Hood and J. A. Calder. U.S. Dep. Comm., NOAA, Washington D.C. pp. 495–508.

Clark, W.G., Hare, S.R., Parma, A.M., Sullivan, P.J. and Trumble, R. J. 1999. Decadal changes in growth and recruitment of Pacific halibut (*Hipposlossus stenolepis*). Can. J. Fish. Aquat. Sci. 56:242–252.

Clark, W.G. and Hare, S.R. 2002a. Assessment of the Pacific halibut stock at the end of 2001. Int. Pac. Halibut Comm. Report of Assessment and Research Activities 2001:121–146.

Clark, W.G. and Hare, S.R. 2002b. Effects of climate, stock size, and region on recruitment and growth of Pacific halibut. N. Am. J. Fish. Manage. 22:852–862.

Dunlop, H.A., Bell, F.H., Myhre, R.J., Hardman, W.H. and Southward, G.M. 1964. Investigation, Utilization and Regulation of the Halibut in the Southeastern Bering Sea. Int. Pac. Halibut Comm. Rep. 35.

Hauser, L., Spies, I. and Loher, T. 2006. Microsatellite screening in Pacific halibut (*Hippoglossus stenolepis*) and a preliminary examination of population structure based on observed DNA variation. Int. Pac. Halibut Comm. Sci. Rep. 81.

Hilborn, R., Skalski, J., Anganuzzi, A. and Hoffman, A. 1995. Movements of juvenile halibut in IPHC Regulatory Areas 2 and 3. Int. Pac. Halibut Comm. Tech. Rep. 31.

Jorgensen, C., Ernande, B., Fisken, O. and Deickmann, U. 2006. The logic of skipped spawning in fish. Can. J. Fish. Aquat. Sci. 63:200-211.

Keating, K.A. 1995. Mitigating elevation-induced errors in satellite telemetry locations. J. Wildlife Manage. 59:801–808.

Kohler, N.E. and Turner, P.A. 2001. Shark tagging: a review of conventional methods and studies. Env. Biol. Fish. 60:191-223.

Loher, T. 2008. Homing and summer feeding site fidelity of Pacific halibut (*hippoglossus stenolepis*) in the Gulf of Alaska, established using satellite-transmitting archival tags. Fish. Res. 92:63-69.

Loher T. and Seitz, A.C. 2008. Characterization of active spawning season and depth for eastern Pacific halibut (*Hippoglossus stenolepis*), and evidence of probable skipped spawning. J. Northw. Atl. Fish. Sci. 41:23-36.

Loher, T. and Seitz, A.C. 2008. Characterization of seasonal onshore-offshore migration timing, and active spawning depth and period of Gulf of Alaska halibut, with evidence of possible skipped spawning. Int. Pac. Halibut Comm. Report of Assessment and Research Activities 2007:433–449.

Loher T. and Seitz, A.C. 2006*a*. Seasonal migration and environmental conditions experienced by Pacific halibut (*Hippoglossus stenolepis*), elucidated from pop-up archival transmitting (PAT) tags. Mar. Ecol. Prog. Ser. 317:259-271.

Loher T., and Seitz, A.C. 2006*b*. Seasonal migration and environmental conditions experienced by Pacific halibut in the Gulf of Alaska, elucidated from pop-up archival transmitting (PAT) tags. Int. Pac. Halibut Comm. Sci. Rep. 82.

National Research Council (NRC). 1999. The Community Development Quota Program in Alaska and Lessons for the Western Pacific. National Academy Press, Washington, D.C. 215p.

Novikov, N.P. 1964. Basic elements of the biology of the Pacific halibut (*Hippoglossus hippoglossus stenolepis schmidt*) in the Bering Sea. *In* Soviet Fisheries Investigations in the Northeast Pacific, Part 2. (Translated from Russian by the Israel Program for Scientific Translation). Springfield, Virginia, US Department of Commerce.

Rideout, R.M., Rose, G.A. and Burton, M.P.M. 2005. Skipped spawning in female iteroparous fishes. Fish Fish. 6:50–72.

Seitz, A.C., Loher, T. and Nielsen, J.L. 2007. Seasonal movements and environmental conditions experienced by Pacific halibut in the Bering Sea, examined by pop-up satellite tags. Int. Pac. Halibut Comm. Sci. Rep. 84.

Seitz, A., Norcross, B.L., Wilson, D. and Nielsen, J.L. 2006. Evaluating light-based geolocation for estimating demersal fish movements in high latitudes. Fish. Bull. 104:571-578.

Seitz, A., Norcross, B.L., Wilson, D. and Nielsen, J. L. 2005. Identifying spawning behavior in Pacific halibut, *Hippoglossus stenolepis*, using electronic tags. Environ. Biol. Fish. 73:445–451.

Seitz, A., Wilson, D., Norcross, B.L. and Nielsen, J.L. 2003. Pop-up archival transmitting (PAT) tags: a method to investigate the migration and behavior of Pacific halibut *Hippoglossus stenolepis* in the Gulf of Alaska. Alaska Fish. Res. Bull. 10:124–136.

Sibert, J. 2001. Electronic tagging and tracking in marine fisheries. *In* Electronic tagging and tracking of marine fisheries. *Edited by* J. R. Sibert and J. L. Nielsen. Kluwer Academic Publishers, Dordrecht, The Netherlands. pp. 1–6.

Stephenson, R.L. 1999. Stock complexity in fisheries management: a perspective of emerging issues related to population sub-units. Fish. Res. 43:247–249.

St-Pierre, G. 1984. Spawning location and season for Pacific halibut. Int. Pac. Halibut Comm. Sci. Rep. 70.