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Pop-up Archival Transmitting (PAT) Tags: A Method to Investigate the Migration and Behavior of Pacific Halibut *Hippoglossus stenolepis* in the Gulf of Alaska

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Abstract: Pop-up archival transmitting (PAT) tags provide a fisheries–independent method of collecting environmental preference data (depth and ambient water temperature) and migration distance. In this study, we evaluate the use of pop-up archival transmitting tags as a method to investigate demersal fish. We report the results from eight pop-up archival transmitting tagged Pacific halibut *Hippoglossus stenolepis* (from 107 to 165 cm FL) that were released in and around Resurrection Bay, Alaska. Commercial fishermen recovered three tags, while five tags transmitted data to Argos satellites. Horizontal migration was not consistent among fish as four Pacific halibut remained in the vicinity of release while the other four traveled up to 358 km from the release site. Vertical movement was not consistent among fish or over time; however, they spent most of their time at depths of 150 to 350 m. The minimum and maximum depths reached by any of the Pacific halibut were 2 m and 502 m, respectively. The fish preferred water temperatures of approximately 6°C, but experienced temperatures between 4.3 and 12.2°C. Light attenuation with depth prevented geolocation software and light sensing hardware from accurately estimating geoposition for the majority of days. The methods, adapted from investigations on large pelagic fish, proved to be effective for studying Pacific halibut in the northern Gulf of Alaska. PAT tags allowed us to obtain high accuracy locations of the fish at the end of the tag deployments as well as preliminary data to identify approximate seasonal locations and to characterize their depth and temperature characteristics. By using PAT tags, we will be able to ensure tag returns during the winter season (which is closed to fishing) and gain valuable biological information even if fish migrate large distances or to unexpected locations.

INTRODUCTION

Pacific halibut *Hippoglossus stenolepis* inhabit continental shelf areas from California to the Bering Sea, and from Russia to Japan. Because of their large size (up to 250 kg) and fine flesh quality, Pacific halibut have experienced sustained commercial exploitation for the last century (IPHC 1998). The fishery is managed as a single stock by the International Pacific Halibut Commission (IPHC), a convention between Canada and the United States of America.

The Pacific halibut population supports one of the most valuable fisheries in the Gulf of Alaska and eastern Bering Sea. Coastwide landings over the last five years have averaged around 70 million pounds annually, with annual landed values estimated at between $100 and $170 million (T. Loher, International Pacific Halibut Commission, Seattle, Washington, personal communication). Recently, the IPHC has been confronted with a number of local depletion issues, which suggests that movement by adults may be relatively limited. If a geographic pattern of subpopulations exists, it may bear a substantial impact on landing patterns, especially for individuals and communities whose fishing operations are prosecuted close to their home port. The debate over the relative biological independence of stocks is likely to become more controversial in the near future as IPHC recruitment models indicate that total exploitable biomass has been declining since about 1999 (Clark and Hare 2001). This decline is expected to continue over the next decade as recruitment responds to changes in large-scale environmental forcing (Clark and Hare 2002). It is therefore necessary to investigate the

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movement and environmental preferences of Pacific halibut for a better understanding of their population structure so management practices can be adapted to changes in environmental forcing and predicted declines in abundance.

The IPHC has conducted hundreds of tagging studies since 1925 (Kaimmer 2000) to address management issues including migration among fishing regions and stock identity (Skud 1977; Trumble et al. 1990). All of these tagging studies employed conventional tags with a numeric identifier for which geoposition and biological data of each tagged fish were recorded upon release and recapture. Tagging results have been used in the management approach, regulations, and population biology of Pacific halibut (Trumble et al. 1990). IPHC conventional tag studies indicate the existence of a single panmictic stock from northern California through the eastern Bering Sea (Skud 1977). However, differential non-reporting over time and area, tag shedding, and tagging mortality limit the usefulness of conventional tagging data to only discerning general movement patterns. Additionally, correctly recovered conventional tags are limited in that they only provide beginning and end positions, with no information concerning the behavior of the fish while at-large. Because the commercial Pacific halibut fishing season runs from March to November, the vast majority of tag returns occur during these months when fishing takes place. This leaves a three-month gap in migration information.

To overcome the limitations associated with conventional tagging of flatfishes, studies using electronic tags, or tags with miniaturized onboard computers, have been conducted on species including Pacific halibut (Hooge and Taggart 1993), North Sea plaice *Pleuronectes platessa* (Arnold and Holford 1978; Metcalfe et al. 1991) and Greenland halibut *Reinhardtius hippoglossoides* (Baldur Sigurgeirsson, Star-Oddi, Vatnagardar 14, 104 Reykjavik, Iceland, personal communication). These tags have electronic sensors and can provide detailed information on one or more of the following parameters: depth, ambient temperature, light, and swimming speed. Although electronic tags provide more information than conventional tags, they still have drawbacks. One type of electronic tag uses acoustic telemetry; these tags are devices that emit a high-frequency "ping" and are attached to an animal (Siebert 2001). Data retrieval from these tags requires physically following the animal's "ping" with a hydrophone deployed from a vessel, thus rendering the tags spatially and temporally limited. A second type, archival tags, are miniature computers containing a clock integrated with a variety of sensors (Siebert 2001) that provide detailed records on depth, temperature, and ambient light. Archival tags are dependent on fish recapture for data recovery.

The pop-up archival transmitting (PAT) tag, a third type of electronic tag, provides some solutions to the aforementioned problems of fish tagging. The PAT tag is the first method of studying fish that does not rely on data collection by commercial or research vessels. To elucidate movement patterns and behavior, PAT tags have been successfully deployed on a variety of large pelagic fish in temperate and subtropical latitudes including: tuna *Thunnus* spp. (Lutcavage et al. 1999; Block et al. 2001a, b; Gunn and Block 2001; Marcinek et al. 2001), tiger sharks *Galeocerdo cuvier* (Holland et al. 2001), white sharks *Carcharodon carcharias* (Boustany et al. 2002), sharptail mola *Masturus lanceolatus* (Seitz et al. 2002a) and blue marlin *Makaira nigricans* (Graves et al. 2002). Though PAT tags only have been deployed on pelagic fish to date, the large size of Pacific halibut suggests that PAT tags may be an appropriate technique for studying their migration and behavior. In this paper, we present the results of a preliminary study to evaluate the feasibility of using pop-up satellite tags as a method to investigate migration and behavior of Pacific halibut (hereafter referred to as halibut) in the Gulf of Alaska.

MATERIALS AND METHODS

We used Wildlife Computers (Redmond, Washington, USA) PAT tags, which had three electronic sensors that measured ambient water temperature, depth of the tag and ambient light. These sensors were fully cast in a tube (21 mm diameter, 175 mm overall length not including antenna, 75 g total weight in air) that, along with the float (40 mm at its widest point), could withstand pressure at a water depth of 1,750 m. PAT tags were externally tethered to the study animal; at a user-specified date and time the PAT tag 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 summarized data records via the Argos satellite system (<www.argosinc.com>). Upon popping-up, the tags' endpoint positions were determined from the Doppler shift of the transmitted radio frequency in successive uplinks received during one Argos satellite pass (Keating 1995). The transmitted data then were processed further by Wildlife Computers' PC-based software. If the fish was captured and the tag retrieved before the pop-up date, the full archival data record could be obtained. The design, function, data collection and data processing of PAT tags are fully described in the Wildlife Computers Pop-up Archival Transmitting (PAT) tag User's Manual (available online).

The environmental data were measured and recorded at user-specified intervals and were subsequently summarized by software onboard the PAT tag thus providing four types of data: percentage of time spent within specific depth ranges (depth histograms); percentage of time spent within specific temperature ranges (temperature histograms); depth-temperature profiles; and daily geoposition estimates calculated from a light-based geolocation algorithm. In this study, the PAT tags were programmed to sample environmental parameters every one or two minutes which provided high resolution data if the tag was recaptured, yet allowed for archival records of approximately 6 and 12 month durations, respectively. More frequent sampling would result in higher resolution data, but shorter data records and vice versa. To reduce the size of the data record transmitted to Argos satellites, the data were summarized into proportion of time spent in user-defined histogram bins for 12-hour periods. The summary period was also user-programmable, and we chose 12-hour periods to maximize the resolution of the data while minimizing gaps in the data record. Gaps in the data record exist because of incomplete transmission of the entire data set. This results from the fact that PAT tags transmit their data continuously even though Argos satellites are overhead and receive data approximately 12 times per day at latitudes in the northern Gulf of Alaska. This method of data transmission results in repeats of some blocks of data while other data are missing. Twelve-hour summaries were chosen as a compromise between high-resolution data and gaps in the tag record. The resolution of the time-at-depth and time-at-temperature summaries was fixed at 12 user-adjustable bins in PAT tags. We chose the bin limits according to known depth ranges of halibut caught in commercial and sport fisheries (IPHC 1998), but do not report the percentage of time spent in depth and temperature bins here because the histograms were of low resolution and did not provide much information.

For all tagged fish, we report fish size, release and recovery locations, and minimum and maximum depths and temperatures recorded for each 12-hour period. The minimum and maximum depths for the 12 hours immediately following release were excluded. We only report the depth-temperature profile sampled by the PAT tag if the fish moved vertically greater than 150 m and visited waters shallower than 50 m during a 12-hour summary period. This facilitates comparison to water column profiles sampled by research vessels. If the tags were recovered in the commercial fishery, we also report mean monthly temperature and depth of each fish. Post processing of data recpeived through Argos satellites is described in detail in Block et al. (2001b) and Gunn and Block (2001). Light-based geolocation estimates are not reported for any of the tags.

We followed several criteria to minimize stress of the halibut associated with applying and carrying large external tags. A PAT tag was tethered to a titanium dart using 130 kg test monofilament fishing line wrapped in adhesive-lined shrink-wrap. The tether was adapted from Gunn and Block (2001) and Block et al. (2001b). The monofilament line was secured at both ends using stainless steel crimping sleeves. The shrink-wrap was used to give the tether a larger circumference thus decreasing possible muscle and skin damage caused by a moving tag while the fish was swimming. Additionally, the shrink-wrap increased the rigidity of the tether system, which maintained its vertical position and kept the tag away from the fish. The tags were attached to the halibut by inserting a titanium dart (6.0 cm long, 1.2 cm wide, 0.5 cm thick) through the dorsal musculature and pterygiophores, anchoring it in the bony fin-ray supports. This prevented muscle damage and premature rejection of the dart caused by tearing through muscle tissue due to hydrodynamic drag of the tag. Only halibut greater than 105 cm were tagged and the position of the dart was about 2.5 cm medially from the halibuts' dorsal fin on the eyed-side of the fish where the body began to taper towards the tail. This combination of fish size and tether position ensured that the antenna did not interfere with the tail and that the float did not rub against the skin of the fish during swimming. A single cruciate suture was used to close the 1.0 cm insertion wound to minimize infection and hasten healing time.

To test the feasibility of PAT tagging halibut, wild fish were captured, transported live to aquaria, and tagged to monitor the effects of the attached PAT tags. On 7–8 August 2000, seven Pacific halibut (from 107 to 137 cm FL) were captured by a chartered commercial longline fishing vessel off Bear Glacier, Resurrection Bay, Alaska (lat 59.89° N, long 149.49° W) and transported live to the Alaska SeaLife Center (ASLC), in Seward, Alaska. Every other day, the captive halibut were fed Pacific herring *Clupea pallasii* until satiation. On 19–20 October 2000, six captive fish were tagged with PAT tags and one captive halibut was left untagged as a control. To facilitate the tagging process, the halibut were anesthetized in a small pool of water containing buffered MS-222 (100mg/l; Malmstrøm et al. 1993) and a local anesthetic (bupivicaine, 2.0 mg) was injected at the tag insertion point. Once the captive fish were tagged, their response to daily feeding, skin coloration, and insertion wound size was monitored for the next month as indicators of general health to determine the feasibility of PAT tagging halibut. On 20 November 2000, the control fish was tagged with a PAT tag, and subsequently, five of the seven captive halibut were released close to the original capture location in Resurrection Bay. The tags were programmed to release from the fish on 15 June 2001. On 5 July 2001, the remaining two captive halibut were released at the same location and their tags were programmed to release on 15 November 2001.

Additional wild halibut were tagged with PAT tags and released. On 16 March 2001, three wild halibut were captured on longline gear aboard a chartered commercial fishing vessel outside of Resurrection Bay near Cape Aialik, Alaska (lat 59.59 N, long 149.74 W). The fish were pulled to the surface while hooked and brought onto the vessel in a net. They were placed on a pre-wetted, smooth piece of marine plywood, blindfolded to remain calm, and the scientists and captain assessed the halibuts' condition for post-release viability by examining their opercular movement, muscle strength, and gammarid sand flea infestation. After determining they were healthy, the fish were measured, tagged, and released (Table 1 and Figure 1). On 5 July 2001, in addition to the captive halibut that were released, four wild halibut were captured, tagged and released at the same location in Resurrection Bay following the protocol described for the previous wild fish. All of the tags on the wild halibut were programmed to pop off on 15 November 2001. Neither wild nor captive fish were sexed because we were unable to determine our accuracy rate for sexing halibut based on external morphology (St-Pierre 1992).

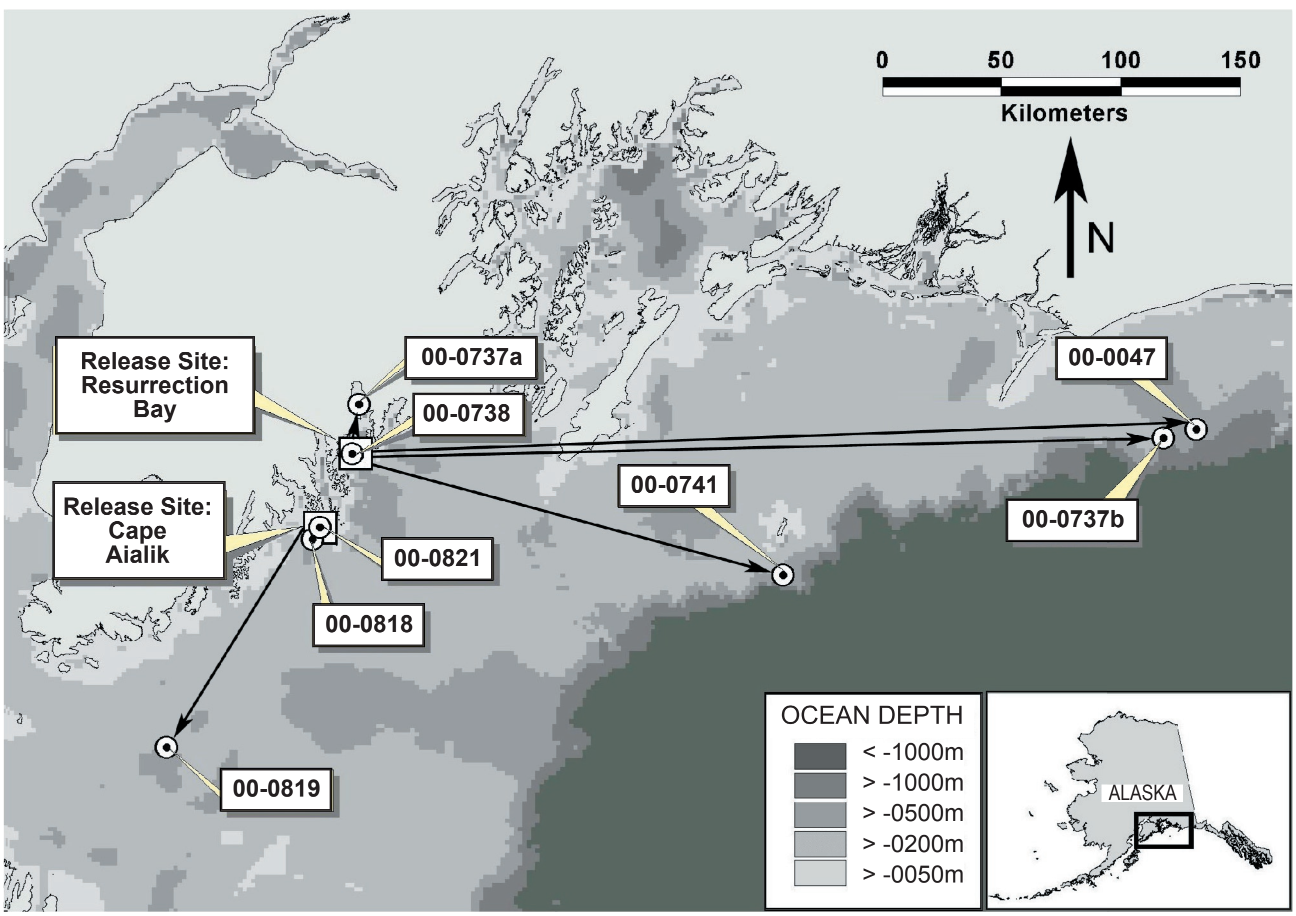

Figure 1. Release and recapture sites of PAT-tagged halibut in the Gulf of Alaska, 2000–2001. Numbers are equivalent to the PAT tag numbers given in Table 1. Circles (O) indicate locations where tags first reported to Argos satellite or were recovered by commercial fishermen; squares (□) indicate release areas.

Table 1. Deployment summary for 8 PAT tags on Pacific halibut in and near Resurrection Bay, Alaska. Tag 00-0737a was recovered by a commercial fisherman and returned. After downloading the data, the tag was deployed on another fish. Boldface print denotes tags recaptured while on the fish before the scheduled pop-off date.

	PAT #							
	00-0737a	**00-0738**	00-0818	00-0819	**00-0821**	00-0737b	00-0741	01-0047
Release location	Resurrection Bay	Resurrection Bay	Cape Aialik	Cape Aialik	Cape Aialik	Resurrection Bay	Resurrection Bay	Resurrection Bay
Release date	11/21/00	11/21/00	3/16/01	3/16/01	3/16/01	7/5/01	7/5/01	7/5/01
Fish length (cm)	129.5	129.5	129.5	165.1	121.9	119.4	109.2	108.0
Recovery date	4/5/01	9/22/02	11/15/01	11/15/01	11/5/01	11/15/01	11/15/01	11/15/01
Days at large	135	670	244	244	234	133	133	133
Horizontal displacement (km)	20.3	2.5	6.5	112.1	0.0	336.9	190.7	358.3
Minimum depth (m)	2	26	4	136	174	72	96	80
Maximum depth (m)	502	466	212	212	210	436	396	404
Minimum temp. (°C)	4.3	4.5	4.8	5.4	5.4	4.4	4.8	4.8
Maximum temp. (°C)	8.6	8.3	12.2	6.4	6.3	8.8	7.4	7.8

RESULTS

The halibut appeared unaffected by the presence of the tags and their swimming was unimpeded. The captive halibut resumed feeding in 2 to 7 days and their skin coloration returned to pre-tagging color in 1 to 2 days. The insertion wounds healed in 2 to 3 weeks, at which point the fish were deemed fit to be returned to the wild.

Of the 14 halibut released with PAT tags, data were recovered from 8, a recovery rate of 57%. Three fish were recaptured by commercial longline vessels, providing archival data records, while five tags popped off the fish and reported to Argos satellites as scheduled (Table 1 and Figure 1). None of the five tags deployed in November 2000 popped off the fish because an outdated software file was loaded on the tags' microcomputers, which was not discovered until after their release. Two of those tags were recaptured by commercial fishermen while three tags remain at-large and if captured, they will provide archival data records. In summary, we have accounted for 11 tags (79%) and 3 (21%) are missing.

The tagged fish ranged from 107 to 165 cm FL and were at-large from 133 to 670 days. The maximum distance traveled from the release site was 358.3 km while the minimum was 0 km (Table 1). All of the fish released in Resurrection Bay swam east or were recovered less than 25 km from the release site. The fish released off of Cape Aialik either migrated southwest or remained in the vicinity of their release location (Figure 1).

Daily vertical movement and behavior of the halibut were varied among fish (Figure 2). Five fish, 00-0737a, 00-0738, 00-0737b, 00-0741 and 01-0047, displayed a wide range of depths during their time at-large. All of these fish ranged in depth from less than 100 m to deeper than 400 m. Fish 00-0737a showed the greatest depth range, and it experienced the deepest and shallowest depths experienced by any of the fish as it swam from 2 to 502 m (Table 1). Fish 00-0818 displayed different vertical movement than the previous five fish. It visited shallow depths less than 100 m on several occasions during its time at-large, but did not show the amplitude of depth range as the previous five fish. The fish never visited deeper water, which may indicate that it apparently remained on the continental shelf and thus was limited in its vertical movement below 200 m. The remaining two fish, 00-0821 and 00-0819, never showed any appreciable vertical movement during their time at large.

Daily temperature minima and maxima also varied among fish (Figure 3). Fishes 00-0821, 00-0819, 00-0737b, 00-0741 and 01-0047 all remained in approximately 5.8 to 6.2°C water, but occasionally experienced water temperatures outside of this range (Figure 3). In contrast, fishes 00-0737a, 00-0738 and 00-0818 experienced a broader range of temperatures.

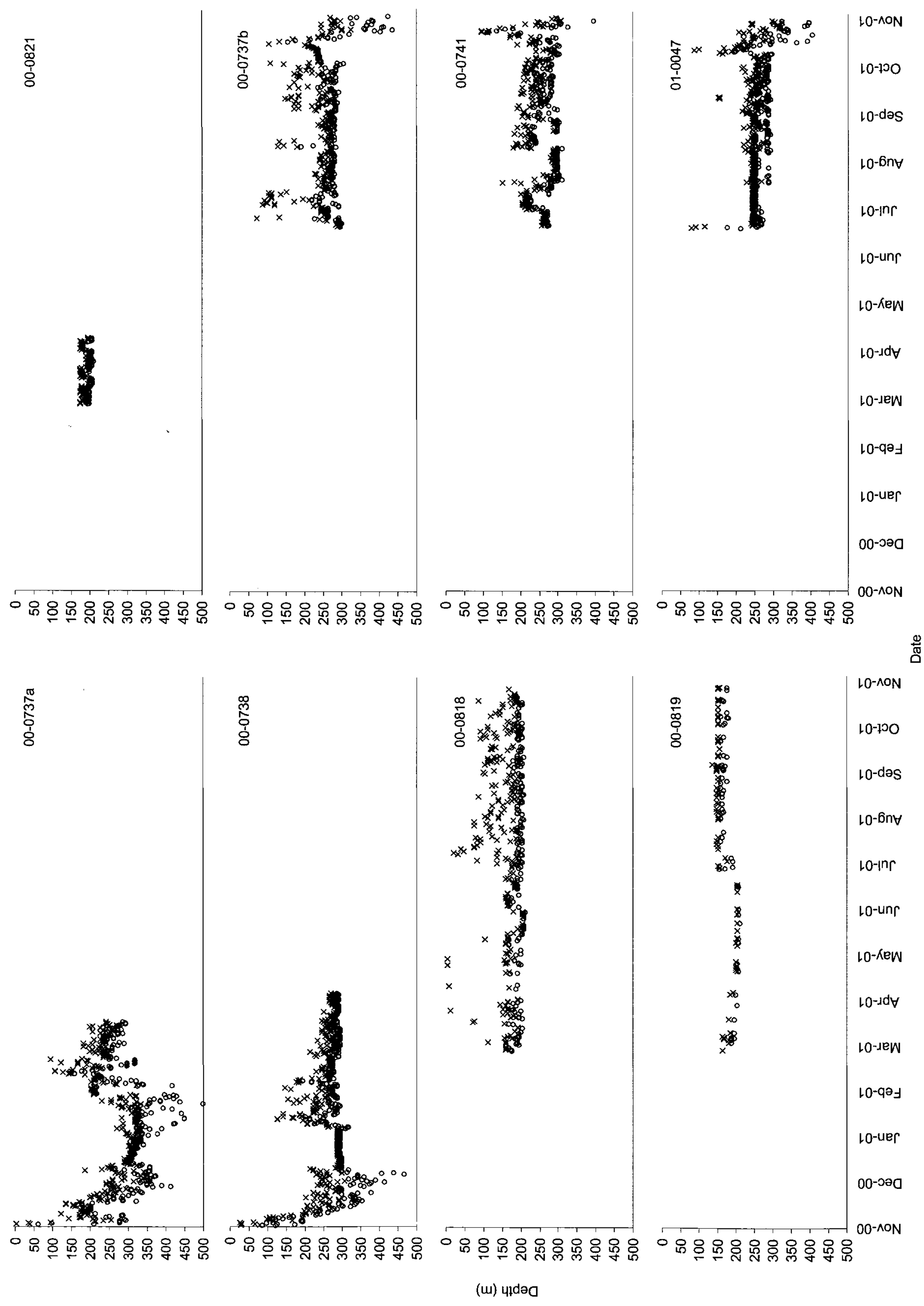

Figure 2. Maximum (O) and minimum (×) depths occupied by eight Pacific halibut within each 12-hour period. Though the same time and depth scales are used to allow comparisons among fish, data are only recorded for the time period each fish was at-large.

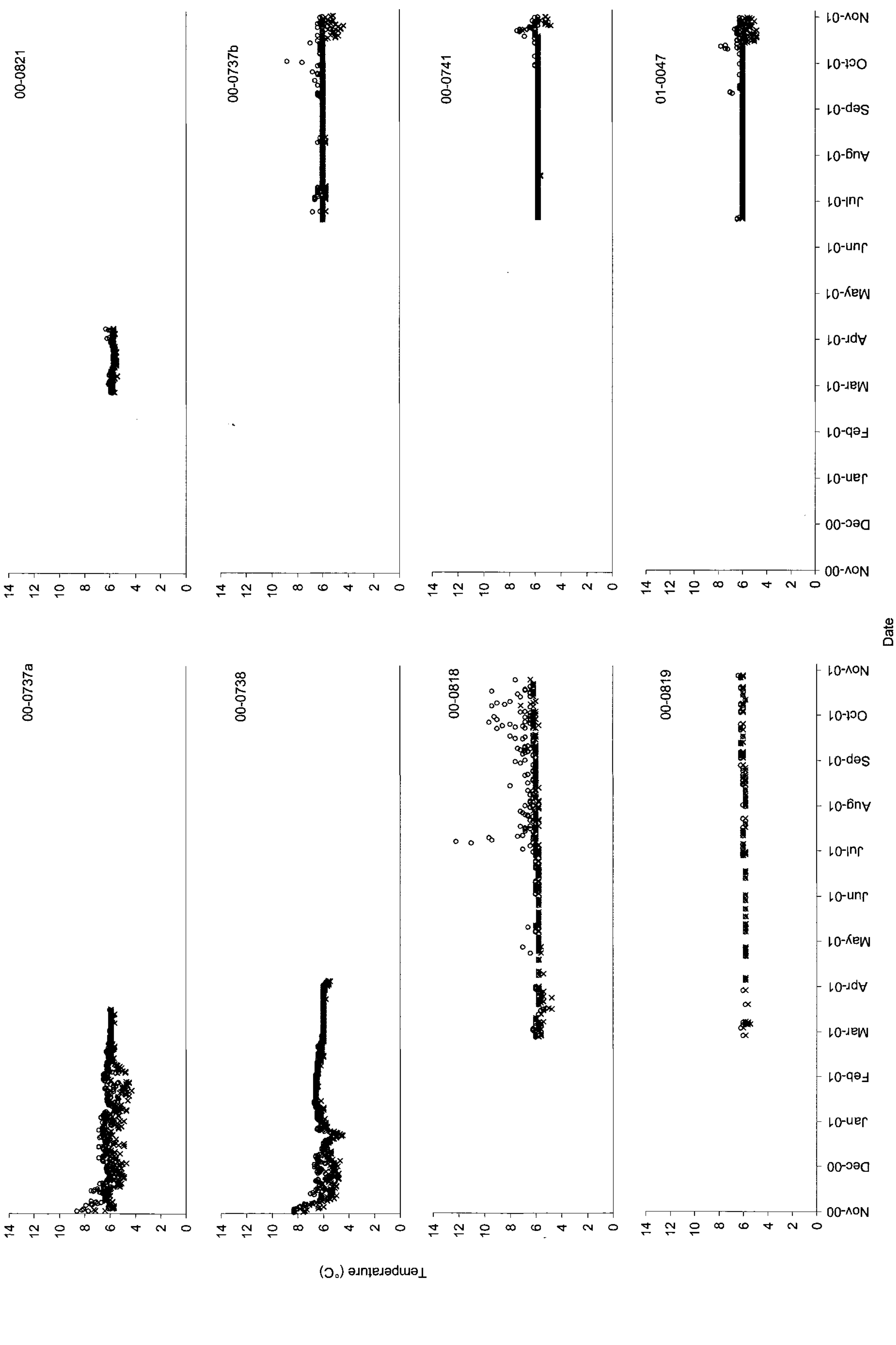

Figure 3. Maximum (O) and minimum (×) water temperatures inhabited by five Pacific halibut within each 12-hour period.

Fishes 00-0737a and 00-0738 generally remained in water between 4.5 and 8°C, while fish 00-0818 generally stayed in the 5.8 to 10°C temperature range. This fish experienced the greatest range and the warmest temperatures, 4.8 to 12.2°C. Fish 00-0737a experienced the coldest temperature of all fish, 4.3°C.

Fish 00-0818 moved vertically greater than 150 m to depths shallower than 50 m on five occasions and was the only halibut whose tag reported informative temperature-depth profiles (Figure 4). The changes in temperature encountered by this fish were directly related to water depth. The temperature between 180 and 200 m was relatively constant around 6°C while temperatures in the near-surface water ranged from 4.8 to 12.0°C.

Three PAT tags were recovered while still externally attached to the fish. Tag 00-0737a provided an archival record of temperature, depth, and light readings for the full duration of deployment, 135 days. Tag 00-0821 was recaptured after 234 days; however, it provided archival readings for only the first 42 days because the battery died for unknown reasons on 27 April 2001. Tag 00-0738 was recaptured after 670 days at-large and recorded data for the first 155 days until the tag reached its storage capacity.

The tags recovered in the commercial fishery provided minutely archival records that allow examination of fine-scale vertical movement. Fish 00-0737a showed three distinct vertical migration behaviors (Figure 5). The first, (Figure 5; 27 November 2000) was a gradual vertical migration up and down during both day and night. The frequency, amplitude, and slope changed during each vertical migration. The halibut assumed this behavior immediately upon release and continued it until the end of December. On 31 December 2000, the halibut commenced the second type of behavior (Figure 5; 17 February 2001), which consisted of long periods of remaining at virtually the same depth (up to 22 consecutive days). In the third vertical migration behavior, seen only in late January and early February (Figure 5; 3 February 2001), the fish moved to deeper water, abruptly ascended 100 to 175 m in less than 5 min, returned to the pre-ascent depth in less than 7 min, and then gradually ascended. This routine occurred seven times, and after the final occurrence of this behavior in early February through its recapture in April, the fish displayed only the first two behaviors. Fishes 00-0821 and 00-0738 displayed only extended stays at the same depth and gradual vertical migrations, and not abrupt ascents.

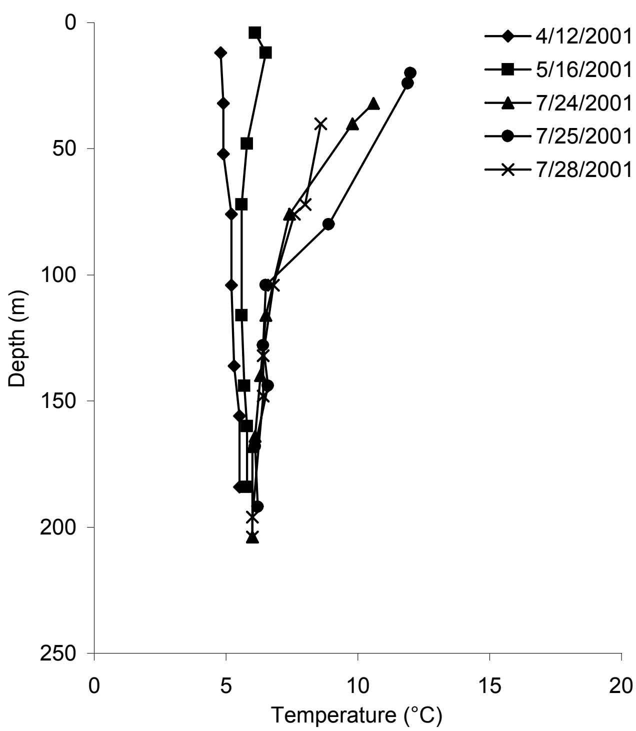

Figure 4. Water column temperature profiles sampled by a PAT tag for five days of greatest vertical movement of halibut 00-0818.

The continuous minutely archival records also allow for the calculation of average monthly depth and temperature of the halibut recaptured in the commercial fishery (Table 2). This is in contrast to the PAT tags that reported to Argos, whose records have gaps because of discontinuous satellite coverage previously described. From these mean depths and temperatures, we can quantify monthly trends and variation in depth and temperature of the halibut.

Though we collected light data, the PAT tags estimated daily geopositions in the Gulf of Alaska only 15% of the time; thus, the results are not reported here.

DISCUSSION

PAT tags have been successfully deployed on a variety of pelagic species, but this is the first investigation evaluating their use as a method to study demersal fish. In some pelagic fish studies, pop-up tags were used primarily to determine movement patterns (Block et al. 1998; Lutcavage et al. 1999; Sedberry and Loefer 2001) while other studies investigated both movement patterns and the fishes' environmental preferences of depth and temperature (Holland et al. 2001; Boustany et al. 2002). Halibut grow to large sizes, are relatively abundant, and are easy to capture, so using PAT tags to investigate the same issues as studied for pelagic fish appeared feasible. However, for species that previously

Table 2. Monthly summaries of depth and ambient water temperature data collected once per minute for 2000–2001. Tags 00-0737a, 00-0738, and 00-0821 were recovered by commercial fishermen before the programmed pop-off date of the tags.

00-737a	Depth (m)				Temperature (°C)			
Month	Maximum	Minimum	Mean	SD	Maximum	Minimum	Mean	SD
November	294.0	2.0	197.2	57.4	8.6	5.7	6.4	0.7
December	414.0	134.0	272.0	56.4	7.5	4.7	6.0	0.4
January	450.0	270.0	320.6	18.0	6.9	4.7	6.0	0.4
February	502.0	198.0	287.2	61.0	6.5	4.3	5.7	0.5
March	318.0	94.0	234.1	35.3	6.3	5.6	5.9	0.1
April	294.0	198.0	265.2	21.6	6.0	5.6	5.9	0.1
00-738								
November	262.0	26.0	156.3	57.5	8.3	5.2	6.9	0.9
December	466.0	202.0	291.6	33.7	7.0	4.7	5.8	0.4
January	318.0	126.0	276.7	34.4	6.6	4.5	5.9	0.5
February	294.0	142.0	249.1	29.0	6.7	6.2	6.5	0.1
March	294.0	214.0	272.9	12.7	6.4	6.0	6.1	0.1
April	290.0	246.0	280.0	6.9	6.0	5.5	5.9	0.1
00-0821								
March	206.0	174.0	192.0	7.7	6.1	5.4	5.8	0.1
April	210.0	174.0	191.7	9.7	6.3	5.5	5.7	0.1

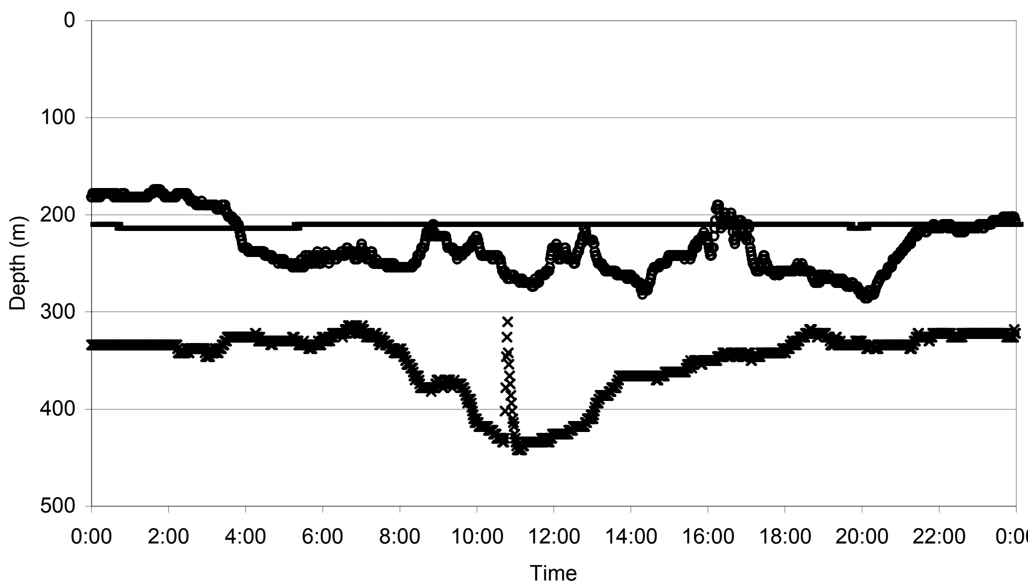

Figure 5. Three days of depth readings sampled every minute by halibut 00-0737a: 27 November 2000 (o), 17 February 2001 (–), and 3 February 2001 (×).

have not demonstrated the ability to carry PAT tags, it is necessary to evaluate the technique on the species in question (Graves et al. 2002). In this study, we evaluated PAT tags' feasibility as a method to examine mesoscale movements for future use in migration and behavior studies of halibut.

Halibut were an excellent candidate for a PAT tagging investigation in the northern Gulf of Alaska. Collection of live adult halibut was relatively easy and fish were successfully captured on each longline set. The fish were hardy and remained calm throughout the capture and transport process. Use of local and general anesthetic, developed by Malmstrøm et al. (1993) for use on the Pacific halibut's congener, Atlantic halibut *Hippoglossus hippoglossus*, greatly facilitated tagging captive halibut, because the fish were uncooperative and struggled when tagged without anesthesia. While tagging wild halibut, anesthetic proved to be unnecessary, because the fish remained calm throughout the tagging process and were generally more cooperative than captive fish.

The methods adopted here for capturing, handling, and tethering tags to the halibut have proven successful in several studies for pop-up satellite tagging of Atlantic bluefin tuna *Thunnus thynnus* up to 450 kg (Block et al. 2001a; Gunn and Block 2001). The halibut in this study behaved similarly to captured bluefin tuna and the techniques were successful for PAT tagging adult halibut for up to 670 days, the longest known deployment of a PAT tag on any species. The relatively small size and docile nature of the halibut in this study allowed us to bring the fish on the boat and apply the tag in a controlled manner at a precise location on the fish. This technique ensures long-term tag retention because the titanium dart is locked in bony fin ray supports. Another common tagging technique, applying the PAT tag while the fish is in the water, has been used for dangerous or aggressive species such as sharks, blue marlin, and swordfish *Xiphias gladius* (Holland et al. 2001; Boustany et al. 2002; Graves et al. 2002; Sedberry and Loefer 2001). When tagging a fish in the water, the investigator is not able to control the fish, which often results in imprecise and inaccurate tagging locations on the fish. The resulting suboptimal tagging locations may result in tag shedding, if not firmly anchored, or damage to the fish. There was no indication in this investigation that halibut should be tagged while in the water and this result is promising for ensuring high return rates and long-term retention in future studies. However, we may have to reevaluate that assessment if we choose to tag very large halibut.

Finding a suitable method for determining the location of halibut from December through March that does not rely on research or commercial vessels is important because no winter fishery is allowed and bycatch rates for halibut in other winter fisheries are typically low. PAT tags provide winter location information determined by Argos satellites (upon popping off the fish) and therefore appear to be a feasible method of investigating possible spawning locations of the fish. In this investigation, we assumed that all of the halibut, whether male or female, were sexually mature because females attain maturity at a larger size than males and virtually all females in the size range of the halibut in this study are mature (from 108 to 165 cm; Clark et al. 1999). The PAT tags show that six of the eight halibut migrated at least 100 km from their release location, and these fish probably undertook seasonal spawning migrations. Mature halibut are known to migrate annually from shallow summer feeding grounds to spawn from November to March (St-Pierre 1984; IPHC 1998). Although major spawning grounds are typically in deeper water on the shelf edge, spawning activity is not limited to these major grounds, and may occur along the entire coast in the northeast Pacific (St-Pierre 1984; IPHC 1998).

One disappointment with the PAT tags was our inability to obtain any geolocation data for the majority of days. These PAT tags were not a consistent estimator of light-based daily geoposition of halibut in their natural environment, probably for a combination of factors. The first is that light does not penetrate past 300 m, even in clear oceanic water, and some of these halibut spent long periods deeper than 300 m. Additionally, the highly productive, coastal shelf water in which the halibut live is turbid because of suspended organic and inorganic matter, thus increasing light attenuation with depth. A final factor is the low amount of ambient light at northern latitudes during winter. All of these factors inhibited the light sensor and the existing geolocation algorithms from accurately calculating daily position. Future examination of this PAT tag data will be directed towards improving the manufacturer's geolocation algorithm to accommodate low light levels characteristic of northern latitudes. Additionally, we will augment our light-based geolocation estimates by comparing the PAT tags' depth data with existing bathymetry data sets collected in and around Resurrection Bay to cross-reference the geoposition estimates.

We were able to infer approximate seasonal location of halibut by combining final recovery locations and environmental sensor data from the PAT tags. Release and recovery locations have been used in conjunction with water temperature to infer the location of bluefin tuna in the western and central Atlantic

Ocean (Block et al. 1998, 2001a; Lutcavage et al. 1999). These studies used sea surface temperature and depth–temperature profiles as an indicator of water masses, such as the Gulf Stream and Labrador Current, to determine approximate seasonal locations. In the present study, the depth record provided by the PAT tag is used satisfactorily to identify the timing and approximate extent of horizontal movement of the halibut. By using the PAT tag depth record, we assume that the halibut were in contact with the bottom at least once during the 12-hour summary periods, thus the maximum depth for each summary period represents the bottom depth. Three of the fish released in Resurrection Bay swam east to known spawning grounds on the continental shelf edge (St-Pierre 1984). The other two fish tagged and released in Resurrection Bay were recovered only 20.3 and 2.5 km from their respective release locations after 135 and 670 days respectively; however, they did not remain near their release location in the Resurrection Bay during the winter. These fish experienced maximum depths of 502 and 466 m, respectively, within two weeks after their release. Depths of this magnitude do not exist in Resurrection Bay, indicating that these two fish migrated out of the bay towards the continental shelf edge. According to their maximum depths, after spending the winter in deep water near the shelf edge, both halibut migrated back to their summer feeding grounds in Resurrection Bay. This is a common pattern because most adult fish tend to remain on the same feeding grounds every year, leaving only to spawn in deep water (IPHC 1998). In contrast to the previous fish, the halibut released off of Cape Aialik in March either migrated southwest or remained in the vicinity of their release location. None of these halibut showed any appreciable changes in maximum depth and, therefore, probably stayed on the shelf for the time they were at-large with tags attached.

In addition to providing approximate seasonal locations, archival depth and temperature records, PAT tags recaptured by commercial fishermen yield insight into the fine-scale vertical movement of the fish. Previous investigations on Pacific halibut have not addressed the extent of vertical movement or whether the fish display pelagic behavior. Confamilial species such as Greenland halibut and North Sea plaice make forays into the pelagic realm during certain seasons or life history stages (Metcalfe et al. 1991; Jørgensen 1997). Pronounced pelagic behavior and variation in vertical distribution can have important implications for stock indices of abundance and on stock assessments if benthic fishing gear is the only component of the assessments. Several halibut in this investigation displayed large depth changes. However, the tags themselves do not provide direct information if the fish remained on or near the bottom and moved over the irregular bathymetry of coastal Alaska or whether they left the bottom and swam through the water column. An example is the behavior of fish 00-0737a on 27 November 2000 (Figure 5). However, from the depth and temperature records, we can infer pelagic behavior of at least one halibut, 00-0818, which almost certainly left the benthos and swam vertically through the water column. Its maximum depths indicate that the fish did not experience any appreciable changes in bottom depths and combined with the proximity of its release and pop-off locations, the PAT tag indicates that the fish did not undergo any extensive horizontal movement during its time at-large. The fish's frequent forays into shallow water are mostly likely indicative of pelagic behavior by the fish. This behavior can be confirmed with improved estimates of geolocation so we can ascertain the bottom depth where the fish is located. If halibut spend an appreciable amount of time in the pelagic environment, this may have stock assessment implications when they are surveyed using bottom trawls and longlines (IPHC 1998). Additionally, the time spent in the pelagic zone, particularly if halibut follow a diel schedule, may be important in developing strategies to reduce halibut bycatch in trawl fisheries.

PAT tags also may help identify spawning behavior in Pacific halibut. The depth data collected by PAT tags may identify spawning events and their duration, timing, and frequency. The abrupt ascent and descent behavior displayed by fish 00-0737a may be representative of spawning behavior. Because this behavior appeared to follow a routine and was found only during peak spawning season (St-Pierre 1984), this could represent a form of spawning behavior common in many flatfish (Moyer et al. 1985; Konstantinou and Shen 1995; Manabe et al. 2000; Manabe and Shinomiya 2001). The spawning behavior in other flatfish species follows a routine wherein a male courts a female by slowly swimming on top of her, which is followed by an abrupt "spawning rise" off of the seafloor where gametes are released and then an immediate return to the benthos by both the male and the female. The abrupt rise from the bottom by fish 00-0737a may be an indicator of spawning activity in halibut.

PAT tags can be used to examine the mean water temperature that the halibut inhabit, and their thermal range. Current descriptions that halibut live in water "at temperatures within a few degrees of 5°C" (Trumble et al. 1993) or they "prefer water temperature ranging from 3 to 8°C" (IPHC 1998) are vague.

A detailed description of the thermal preference and range of demersal fish is necessary to understand their spatial and temporal distributions (Kihara and Uda 1969). The PAT tags are an effective method of understanding the thermal habitat of Pacific halibut. The water temperature data from this investigation generally corroborates the previous descriptions, but additionally quantifies the range of temperature experienced by individuals which was previously unavailable. By examining these data, we can generate a predictive relationship between inhabitation by halibut and water temperature that will aid our understanding of how halibut will respond to changes in their environment.

Additionally, PAT tags attached to fish can be used to reconstruct profiles of the water column in times and places that are otherwise inaccessible (Block et al. 2001b). If the approximate location of the fish is known, temperature versus depth profiles are collected and the tag serves as an autonomous sampler of the immediate environment around the fish. The tag may serve to augment oceanographic data collected by research vessels. In contrast, if the location of the fish is unknown, the temperature versus depth profiles can be used to identify the approximate location of the fish by comparing the PAT tag data to temperature and depth data collected on research vessels. Further, these profiles may be used to identify water masses that may affect the distribution of migratory fishes (Block et al. 2001a). In this investigation, one PAT tag provided water temperature versus depth profiles for three months—providing information on the environmental conditions experienced by the fish. With larger PAT tag deployments, we can characterize the tolerances and favorable environmental conditions of halibut.

The sampling rate, length of time for histogram summaries, and the limits of the histogram bins of PAT tags are user-definable by using Wildlife Computers' software. To optimize data storage, allocation and transmission, one may wish to change any of the parameters of the PAT tags, which may yield different results. To evaluate which parameters are optimal for PAT tagging halibut in the northern Gulf of Alaska, one would have to conduct an experiment using several different PAT tag settings and compare the ensuing results. In this study, we chose to define identical parameters for each PAT tag—with the exception of two different sampling rates—to facilitate comparison among tags. We did not find any apparent differences among the data records of tags that sampled every one versus every two minutes. Additionally, the halibut did not appear to move quickly enough to need minutely sampling, thus the sampling rate of every other minute is probably more beneficial as it allows storage of a longer data record.

In this investigation, we tested the feasibility of using pop-up archival transmitting tags to study large demersal fish. The methods, adapted from investigations on large pelagic fish, proved to be effective for studying Pacific halibut in the northern Gulf of Alaska. PAT tags allowed us to obtain high accuracy locations of the fish at the end of the tag deployments as well as preliminary data to identify approximate seasonal locations and to characterize their depth and temperature characteristics. By using PAT tags, we will be able to ensure tag returns during the winter season (which is closed to fishing) and gain valuable biological information even if fish migrate large distances or to unexpected locations. General patterns of halibut behavior will emerge from larger satellite tag deployments and rigorous data analysis in the future.

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