

Using Pop-up satellite archival tags for understanding Pacific halibut movement in and around Glacier Bay National Park

A report to the National Park Service on research activities conducted during 2013

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Abstract

The commercial Pacific halibut fishery in the interior waters of Glacier Bay is projected to cease sometime between 2050 and 2060 because of attrition of lifetime access permit (LAP) holders. To assess whether this future release from commercial harvest mortality could lead to changes in halibut abundance and/or size structure, information is needed on the frequency and timing of movement by individual fish out of Glacier Bay. Such information will provide insights into the probability of exposure to harvest mortality from the commercial fishery that operates outside the park from March to November as well as the recreational fishing that will continue within it from February to December. The goal of this research project is determine whether halibut undertake winter spawning migrations outside of the park, and if so, whether they return to Glacier Bay the following summer. Twenty five pop-up satellite archival tags (PSATs) were externally attached to Pacific halibut (>105 cm FL) captured within Glacier Bay during their summer feeding season in 2013. All tags measured and recorded daily summaries of ambient temperature, depth, and light intensity, and 15 of the tags additionally measured magnetic field strength and acceleration. Fifteen PSAT tags were programmed to release from the fish during the peak of the Pacific halibut spawning season in early February 2014 to assess migratory movement characteristics, while ten tags were programmed to release 365 days after deployment (e.g. summer 2014) to assess fidelity to summer feeding grounds. The 15 fish with geomagnetic tags were double-tagged with acoustic transmitters and tracked bi-weekly for two months following tagging to obtain independent position estimates. Relocations of acoustic tagged fish and archived data recorded by the PSAT tags each day were analyzed to characterize summer residency and spawning migrations out of Glacier Bay, and in some cases, site fidelity to summer feeding locations within Glacier Bay. Although data for this project are still being collected and analyzed as of March 2014, some preliminary insights about Pacific halibut that feed in Glacier Bay are available. Ten out of fifteen tags successfully reported to the Argos satellite network on February 1, all of which were located inside Glacier Bay. An additional tagged fish with a July 2014 pop-up date was captured outside of Glacier Bay in March 2014, which constitutes the only observation of a fish that definitively left Glacier Bay during the winter. However, similar patterns in the archival tag depth and temperature data documented in two of the other fish whose tags popped-up suggest that they may have left Glacier Bay in late December 2013 and returned to Glacier Bay prior to February 1, 2014. In summary, the preliminary results indicate that a majority of fish demonstrate year-round residence within Glacier Bay, while a small proportion of fish demonstrate interannual site fidelity to Glacier Bay following winter migrations to locations outside of Glacier Bay. Following the July 1, 2014 pop-up date, we will receive archival tag data from the remaining PSATs and will be able to conduct analyses based on the full data set. Acoustic tracking will continue during summer 2014 to obtain additional independent observations of tagged animal locations for comparisons with archival tag data. We are also in the process of developing a geolocation model based on the archival tag data that will provide daily position estimates during the time the tagged fish were at liberty.

Introduction

Commercial fishing for Pacific halibut in the interior waters of Glacier Bay National Park (subsequently referred to as “Glacier Bay”) is expected to cease sometime between 2050 and 2060. After this time, Glacier Bay (1295 km²) will be the largest marine area in Alaska that is off-limits to commercial fisheries resource extraction. Thus Glacier Bay, which also was designated a Marine Protected Area (MPA) in 2009, joins a nation-wide system of MPAs designed to advance marine conservation and sustainable use.

Conservation benefits such as increasing spawning stock abundance or changing size structure of previously exploited fish and shellfish stocks have been observed in other species in Glacier Bay (Taggart et al. 2004). However, in order to predict the benefits of commercial fisheries closures for halibut, information on movement characteristics as well as the timing and proportion of individual animals that cross the MPA regulatory boundary is needed.

Halibut are known to move large distances during ontogenetic and winter spawning migrations (Skud 1977) and are consequently managed as a panmictic population (Clark & Hare 2006, Webster et al. 2013). However, growing evidence suggests that adult halibut movement may be more complicated as some tend to have site fidelity to summer feeding grounds (Loher 2008) while others may forego large spawning migrations altogether (Seitz et al. 2011). In Glacier Bay, a previous acoustic telemetry study indicated that most adult female halibut remained in Glacier Bay during the summer while occupying home ranges at scales of hundreds to thousands of square meters (Nielsen et al. In review). However, information on the movement of Glacier Bay halibut during winter, when adults are thought to undertake migrations to spawning areas, is not currently available due to the challenges of acoustic tracking fish over very large scales of space and time.

Pop-up satellite archival tags (PSATs) provide a method for understanding large-scale movements of fishes over yearly timescales (Sibert et al. 2006, Lam et al. 2008). PSATs continuously record data such as maximum daily depth, temperature, light intensity (the time of local noon provides information on longitude), and the magnetic field. On a specified date, the PSAT releases from the animal, floats to the surface of the ocean, and broadcasts the data to the Argos satellite network. While transmitting, an accurate location of the tag (<150 m) can be determined by successive uplinks to Argos satellites. The archived data from the tag are then matched to maps of these variables in the study area, a process is known as “geolocation.” By this process, estimated positions for the tagged animal are obtained for each day the tag was deployed on the fish.

The goal of the proposed study is to assess the effectiveness of Glacier Bay as a Marine Protected Area for Pacific halibut by examining the frequency and timing of movement by individual fish out of the Bay. To determine whether Pacific halibut leave Glacier Bay during spawning migrations, and thus are potentially vulnerable to interception by fisheries outside of the park, we attached electronic tags to Pacific halibut to understand their movements over the course of a year. Information on the proportion of fish that

leave Glacier Bay, the timing and temporal extent of migrations, and the proportion of fish that return to Glacier Bay the next summer will help us begin to explore the effectiveness of Glacier Bay as an MPA for protecting adult Pacific halibut.

Methods

Study area

The study was conducted in the interior waters of the Marine Protected Area of Glacier Bay National Park (Figure 1), a glacial fjord estuary with active glacial input. Fish were captured and tagged in an area of approximately 5 km² in the central portion of the bay, which is located in a transition zone between the shallow sill at the entrance to the bay (approximately 50 m depth) and the deeper waters of the fjords in the northern portion of the bay (to approximately 450 m). A large magnetic anomaly spans the width of the bay between the tagging area and the entrance to the bay.

Electronic tags

Two types of electronic tags were attached to adult Pacific halibut during the summer of 2013. The first type, pop-up satellite archival tags (PSATs), was deployed to provide data from which migratory characteristics of Pacific halibut can be inferred on yearly timescales. The second type, acoustic tags, was deployed to characterize horizontal movements of tagged fish during summer, to validate archival tag data, and to provide independent locations of PSAT-tagged fish for validation of geolocation models.

Two types of pop-up satellite archival tags (PSATs) were deployed on adult fish. Fifteen fish were tagged with Desert Star SeaTag MOD geomagnetic archival tags. These tags were programmed to record depth, temperature, light, magnetic field in three dimensions, and acceleration in three dimensions at a 4-minute measurement interval. Information summarized over a 24-hour period for transmission to satellites included depth (maximum, minimum, and average), temperature (average), time of local noon (e.g., longitude), the total magnetic field (vector sum of X, Y, and Z magnetic field axes), and total acceleration (vector sum of X, Y, and Z acceleration axes) for each day of deployment. Ten fish were tagged with Wildlife Computers MK-10 tags that measure depth, temperature, and light. Tags were programmed to record measurements at 10 second intervals. Information summarized over 12-hour bins (2:00 and 14:00 UTC) for transmission to satellites included depth (maximum, minimum, and histograms), and temperature at depth. Ambient light profiles at sunrise and sunset were also recorded to calculate daily latitude and longitude.

PSATs were programmed to release from the fish on one of two pop-up dates. Fifteen PSATs (8 Desert Star, 7 Wildlife Computers) were programmed to release from the fish and broadcast summarized data to satellites on February 1, 2014 to determine whether tagged fish were inside or outside of Glacier Bay during the winter spawning season. Ten PSATs (7 Desert Star, 3 Wildlife Computers) were programmed to release from the fish on July 1, 2014 to determine whether tagged fish were located inside Glacier Bay one full year after tagging. The position of first transmission (or re-capture locations for tagged

fish recovered in the fishery) are defined as “end locations” that assign a spatial location to the end of an archival tag data set.

All fifteen fish tagged with Desert Star PSATs were double-tagged with Lotek MAP acoustic telemetry transmitters (MM-M-16-50). These tags alternately transmit information on tag depth (7 m depth bins) and motion (12 hours) every 8 seconds. Tags were programmed to transmit on a 20 week on/off period, and when in the “on” mode transmitted from 7:00 a.m. to 7:00 p.m. With this programming schedule, battery life is expected to last through July 2015.

Fish capture and tagging

Fish were captured with longlines deployed from the 30' F/V Taurus between June 29 and July 2, 2013. Thirteen sets with approximately 100 snap-on circle hooks (16-0) baited with salmon were made. Soak times averaged 12.2 hours and ranged from 1.6 to 23.7 hours. All halibut and bycatch were counted and bycatch was recorded to species. Halibut that met minimum size requirements (total length > 105 cm) were brought on board using careful handling techniques and were then blindfolded with a wet cloth to keep them calm as their condition for post-release viability was assessed and measurements of total length were obtained. PSATs with 5" monofilament tethers were attached by inserting a surgical-grade titanium dart through the skin and pterygiophores (fin ray supports), roughly 2.5 cm medially from the dorsal fin on the eyed-side of the halibut where the body began to taper towards the tail.

Acoustic tags were surgically implanted in the peritoneal cavity. Tags were placed in autoclave envelopes and sterilized with ethylene oxide prior to deployment. Separate sterilized packs of surgical tools were used for each fish. A 2 cm (0.8 in) incision was made through the peritoneal wall roughly parallel to the long axis of the fish, positioned about 1 cm (0.4 in) dorsal to the anterior end of the first interhaemal spine. The tag was then inserted into the peritoneum and the entry incision closed using three to five sutures of 2-0 prolene suture material with a reverse cutting FS needle. Once tagged, fish were gently released head-first back into the ocean. Time on board, depth at release, and position at release were recorded for each tagged animal.

Fish tracking

Acoustic tracking was conducted on the 28' R/V Ishkeen. Two hydrophone configurations were employed that provided either fine-scale position estimates for tagged fish at slow vessel speeds (e.g., a maximum of 2.5 knots) or coarser-scale positions along transects at vessel speeds of up to 8 knots. For the fine-scale configuration, two Lotek LHP1 hydrophones were deployed on each side of the vessel from an aluminum outrigger mounted on the bow. Each hydrophone was attached to a weight-bearing line 1 m above a 20-lb lead cannon ball. Hydrophones were approximately 3 m apart at a depth of 3 m when the vessel was under way. This configuration allowed real-time navigation to tagged animals using the Lotek MAP-RT two-port receiver. For conducting higher-speed searches along transects, one hydrophone was attached to a weight-bearing line 1 m above a v-fin. The v-fin was towed 13 m behind the vessel at a depth of 12 m. Test tags at 2 depths were deployed on a temporary

fixed mooring during each trip to determine detection range, verify that the real-time navigation was working properly, and collect information on precision for post-processing positioning methods.

Tracking trips were conducted every other week for 2 months following the release of tagged animals. During each 2 – 2.5 day tracking trip, the release area was searched with both fine-scale positioning methods and v-fin transects. We tried to obtain at least one fine-scale position estimate for each tagged animal during each tracking trip. After searching the release area, adjacent areas at similar depths and habitat types were searched to locate animals that were not found in the release area.

Results

Fish capture

The average total length for tagged fish was 131 cm (s.d. 17 cm) and ranged from 105 to 170 cm (Table 1). The average time on board during the tagging procedure was 2 minutes for those fish that received only PSATs and 7 minutes for those that received both PSATs and acoustic tags. The average depth at release locations was 41 m (s.d. 12 m).

Table 1. Date of tagging, fish size (total length), type of PSAT (WC = Wildlife Computers, DS = Desert Star), release position, and release depth.

Fish ID	Date	Fish TL (cm)	PSAT type	Programmed Pop-up Date	Release Latitude	Release Longitude	Release Depth (m)
1	29-Jun	137	WC	2/1/2014	58.61045	-136.14153	35
2	29-Jun	106	WC	7/1/2014	58.62715	-136.14128	35
3	29-Jun	151	WC	7/1/2014	58.62437	-136.14072	41
4	29-Jun	127	WC	7/1/2014	58.65208	-136.18453	41
5	30-Jun	132	WC	2/1/2014	58.62593	-136.13998	31
6	30-Jun	152	WC	2/1/2014	58.61672	-136.14037	30
7	30-Jun	105	WC	2/1/2014	58.65173	-136.18935	31
8	30-Jun	120	WC	2/1/2014	58.65193	-136.18970	31
9	30-Jun	124	WC	2/1/2014	58.65225	-136.19000	30
10	30-Jun	116	WC	2/1/2014	58.65222	-136.18955	30
11	1-Jul	127	DS	2/1/2014	58.62510	-136.13908	33
12	1-Jul	170	DS	7/1/2014	58.62505	-136.13957	35
13	1-Jul	120	DS	2/1/2014	58.64777	-136.18838	68
14	1-Jul	139	DS	7/1/2014	58.65597	-136.18990	43
15	1-Jul	128	DS	7/1/2014	58.65823	-136.19100	39
16	2-Jul	105	DS	7/1/2014	58.65763	-136.19320	40
17	2-Jul	114	DS	2/1/2014	58.65928	-136.19345	44
18	2-Jul	132	DS	2/1/2014	58.66020	-136.19317	59
19	2-Jul	120	DS	2/1/2014	58.63142	-136.19867	51
20	2-Jul	151	DS	2/1/2014	58.63185	-136.19865	47
21	2-Jul	150	DS	2/1/2014	58.63215	-136.20210	47
22	2-Jul	148	DS	2/1/2014	58.66093	-136.19135	76
23	2-Jul	119	DS	7/1/2014	58.65873	-136.19093	38
24	2-Jul	150	DS	7/1/2014	58.63140	-136.19352	31
25	2-Jul	130	DS	7/1/2014	58.63132	-136.20110	27

PSATs

Data collection for this research project is still in progress. However some preliminary results from the February pop-up date are available. For tags programmed to pop-up on February 1, 2014, all seven Wildlife Computers tags released from the fish on schedule and provided pop-up locations with an average accuracy of 283 m (s.d. 94 m) and Argos location qualities of 3 or 2. Only three of the eight Desert Star tags transmitted on February 1 and provided pop-up locations with an average accuracy of 380 m (s.d. 372 m) and Argos location qualities of A or B. Two more Desert Star tags began to transmit data to satellites 15 and 40 days later, and therefore end locations for these fish could not be established. Of the 10 PSATs that provided pop-up locations on February 1, 2014, all 10 tags were located within Glacier Bay at a median distance of 4.8 km from their release locations (range 1.5 – 24.5 km) (Table 2, Figure 2). To date, no tags have reported a depth value that was greater than the depths available within Glacier Bay (e.g. greater than 475 m, accounting for error in both tag measurement and bathymetry accuracy).

Table 2. Winter PSAT end locations, distance from release site, and number of days at liberty by tag type (WC = Wildlife Computers, DS = Desert Star). Note that fish #23 was captured in the commercial fishery.

Fish ID	PSAT type	Programmed pop-up date	Date of first transmission	Date of first position *	Latitude	Longitude	Distance from release (km)	Days at liberty
1	WC	2/1/2014	2/1/2014	2/1/2014	58.58650	-136.07720	5.3	217
5	WC	2/1/2014	2/1/2014	2/1/2014	58.63450	-136.06000	4.7	216
6	WC	2/1/2014	2/1/2014	2/1/2014	58.50600	-136.08410	13.5	216
7	WC	2/1/2014	2/1/2014	2/1/2014	58.62420	-136.12470	4.9	216
8	WC	2/1/2014	2/1/2014	2/1/2014	58.64620	-136.14730	2.5	216
9	WC	2/1/2014	2/1/2014	2/1/2014	58.81140	-136.47800	24.5	216
10	WC	2/1/2014	2/1/2014	2/1/2014	58.64820	-136.16580	1.5	216
11	DS	2/1/2014	1/30/2014	1/30/2014	58.61556	-136.19222	3.3	213
13	DS	2/1/2014	2/1/2014	2/1/2014 **	58.58750	-136.16850	6.8	215
17	DS	2/1/2014	3/12/2014	N/A	N/A	N/A	N/A	N/A
18	DS	2/1/2014	2/15/2014	N/A	N/A	N/A	N/A	N/A
19	DS	2/1/2014	N/A	N/A	N/A	N/A	N/A	N/A
20	DS	2/1/2014	N/A	N/A	N/A	N/A	N/A	N/A
21	DS	2/1/2014	N/A	N/A	N/A	N/A	N/A	N/A
22	DS	2/1/2014	2/1/2014	2/1/2014 **	58.61950	-136.20340	4.7	214
23	DS	7/1/2014	N/A	3/9/2014	58.28200	-136.19200	48.1	250

* Represents the location of the tagged fish on this date

** 12-hour delay between first transmission and Argos location

In addition to data transmitted to satellites, one fish (#23) tagged with a Desert Star tag was recaptured in the commercial fishery in Icy Strait on March 9. This fish had moved 50 km from the release location. This fish has provided the only confirmed movement of a tagged fish to a location outside of the park. One Wildlife Computers tag (#8) was recovered floating in Glacier Bay on February 7.

Acoustic tags

Acoustic detection range varied from 200 to 500 m, depending on hydrophone configuration (v-fin vs. fine-scale), speed of vessel travel, and environmental conditions. Average estimated precision for positions obtained with the fine-scale tracking was 76 m

(s.d. 39 m). Based on a 200-m detection range with the v-fin hydrophone configuration at vessel speeds of 7 – 8 kts, transects were conducted on a 400 m grid.

The majority of acoustic-tagged fish were regularly relocated in the core study area during the 2 month period of tracking. On average, 9.5 (s.d. 5.3) positions were obtained for each fish (range 1 – 19). During each tracking trip, positions were obtained for a majority (72%) of tagged animals. The median distance between the release location and the location occupied at the time of the last telemetry observation was 823 m (range 102 m – 11.7 km). The median observation duration was 61 days (range 1 – 62). At least two animals (#24 and #16) dispersed larger distances, occupying locations that were 7 and 11 km respectively from their release locations at the time of their last observation (Figure 3).

Combining acoustic and archival tag data

There was an interesting contrast in movement inferred from acoustic tags and PSAT tags. Specifically, acoustic tag data indicated that halibut may have very small home ranges during the day, while PSAT tags indicated that their typical range of daily movement may be much larger than day-time tracking alone would indicate. For example, Fish #23 was regularly observed in the release area throughout the tracking trips and had a home range on the scale of hundreds of meters (Figure 4). However, when the detailed depth records from the PSATs are plotted, it becomes apparent that the fish occupied the shallow (30 m) home range largely during the daytime, but occupied depths of up to 250 m or more during the night. This resulted in a pattern of large differences between the maximum and minimum daily depths (Figure 5) that continued until December 21.

Migration characteristics

Based on the detailed records from fish #23, which is the only tagged fish known to leave Glacier Bay, several patterns were present in the data that may be representative of migratory behavior. After the period of hypothesized home range behavior (7/3 – 12/21) that consisted of a large range in daily depths where the minimum depth was consistently the same as that observed for the home range, the maximum and minimum daily depths began to track each other closely. In late December, the fish briefly occupied water depths shallower than the 70 m sill depth before descending to depths of 150 m again. The exit from Glacier Bay must have occurred no later than January 1, because after that time the minimum depth was never shallow enough for the fish to have crossed the sill before it was captured outside of Glacier Bay in March.

In addition to changes in daily depth patterns, changes in other recorded archival data such as temperature, acceleration, and the magnetic field also occurred in conjunction with a hypothesized switch from home range to migratory movement in late December (Figure 6). Water temperatures rose from 5 degrees to approximately 6.5 degrees C for most of January and early February. Acceleration patterns switched from a diurnal pattern of activity to a pattern of movement that was strongly associated with tide stage. Magnetic field values increased at the onset of migration, when the fish may have passed

through the magnetic anomaly area that lies between its home range and the exit from Glacier Bay.

Patterns in daily depth and temperature observed for two Wildlife Computers tags, where February end locations were inside Glacier Bay, were similar to patterns observed for fish #23, which was known to have left Glacier Bay. For these tags, a transition between a pattern of large variation in maximum and minimum daily depths to a pattern of smaller variation was observed in December (Fish #1, Figure 7A) or early January. Water temperature decreased as the fish occupied water depths that were shallower than sill depth at the entrance to Glacier Bay. Temperatures for the month of January at depths of approximately 200 m were as high as 6.5 degrees C, 1.5 degrees higher than December temperatures at similar depths. In contrast, the depth-temperature profile for a tagged fish (Fish #5) that could not have left Glacier Bay based on a minimum daily depths that were never shallower than the sill depth (Figure 8A) indicates that temperatures in January were less than 5 degrees C at depths of 200 m inside Glacier Bay (Figure 8B).

Preliminary discussion

Interannual site fidelity

Although data collection and analysis are currently incomplete, data collected as of mid-March 2014 indicate a strong tendency for winter residency within Glacier Bay. All ten end locations obtained from the February 1, 2014 pop-up date were inside Glacier Bay. The PSAT records for eight of these fish provide no evidence that the fish left Glacier Bay prior to February 1, and the records of two fish indicate that they may have left Glacier Bay in December or early January but had returned at the end of January.

The high degree of residency within Glacier Bay during winter suggests one of several scenarios. First, adult fish may have spawned within Glacier Bay, as has been hypothesized to occur for a closely related congener, Atlantic halibut *Hippoglossus hippoglossus*, in Norwegian fjords (Seitz et al. 2014). Alternatively, they may have skip-spawned, and thus did not undertake a spawning migration (Loher & Seitz 2008). Finally, migrations outside of the park may have occurred after the February 1 pop-up date, as adult halibut are known to return from spawning migrations as late as April (Loher 2011). To determine which of these scenarios may explain our preliminary observations of winter residency, the high-resolution data provided by tags that are physically recovered may provide evidence of spawning rises (Seitz et al. 2005), and data collected from tags programmed to pop up in the summer may provide some insight in whether or not migrations outside Glacier Bay occurred in February or March.

Observations of limited dispersion and home range behavior during the summer combined with a strong tendency toward interannual site fidelity suggest that Glacier Bay may serve as a refuge from commercial harvest for adult female halibut. The presence of such a refuge has important implications for the ability of Glacier Bay to achieve an “unfished” size structure following the phase-out of commercial fisheries. In addition, it provides some insight into the potential benefits of managing halibut harvests at smaller

spatial scales in terms of enhancement of spawning stock and addressing concerns about local depletion.

Combining acoustic and PSAT data: home range characteristics

Double-tagging fish with both archival and acoustic tags has provided important perspectives on the conclusions that might be reached from utilizing either method alone. For example, the size of home ranges determined from acoustic tracking conducted only during day may be much smaller than the actual space used by fish on a daily basis if the animal conducts regular movements to deeper waters at night. On the other hand, the ability to link patterns in archival tag records to specific movement patterns determined by acoustic telemetry (such as home range behavior) greatly aids the task of inferring and modeling large-scale movement with archival tag data. For example, based on our knowledge of home range sizes and locations for fish that were tagged with both acoustic transmitters and PSATs, it is possible to link patterns observed in the PSAT data (e.g., a large range in daily depths followed by a return to a consistent depth) to home range behavior.

Future work

Future work for this research project consists of 1) acoustic tracking during summer 2014, 2) obtaining PSAT data from the July 2014 pop-up date, 3) developing a full characterization of winter residency, migration timing, and interannual site fidelity, and 4) development of a geolocation model based on depth, light, and magnetic field information collected by the archival tags.

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Figures

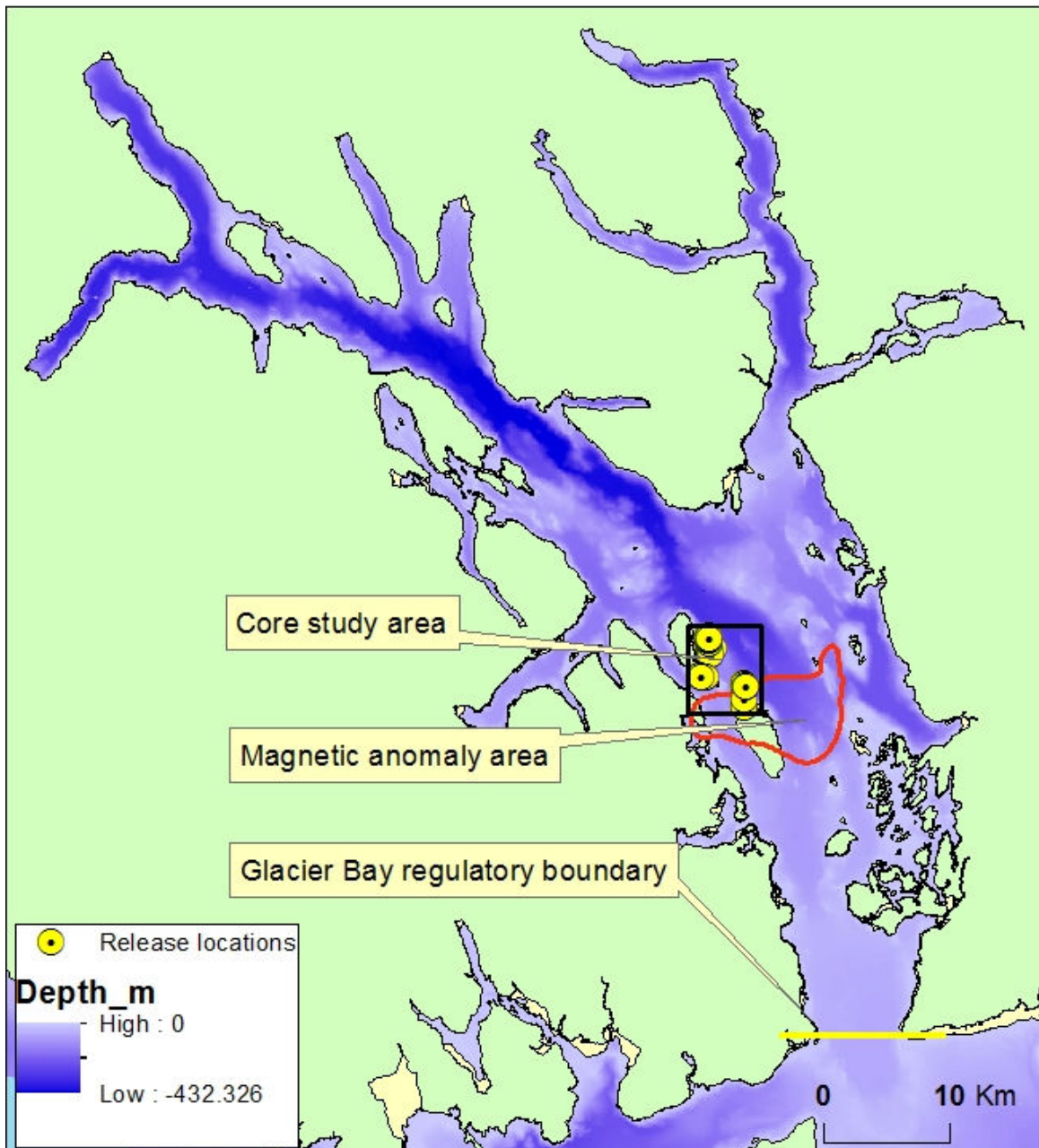


Figure 1. Fish were captured and tagged within the core study area (black rectangle; release locations are shown by yellow circles) located in the interior waters of Glacier Bay National Park. A magnetic anomaly (red polygon) is present in the central portion of the bay between the core study area and the entrance to Glacier Bay (yellow line).

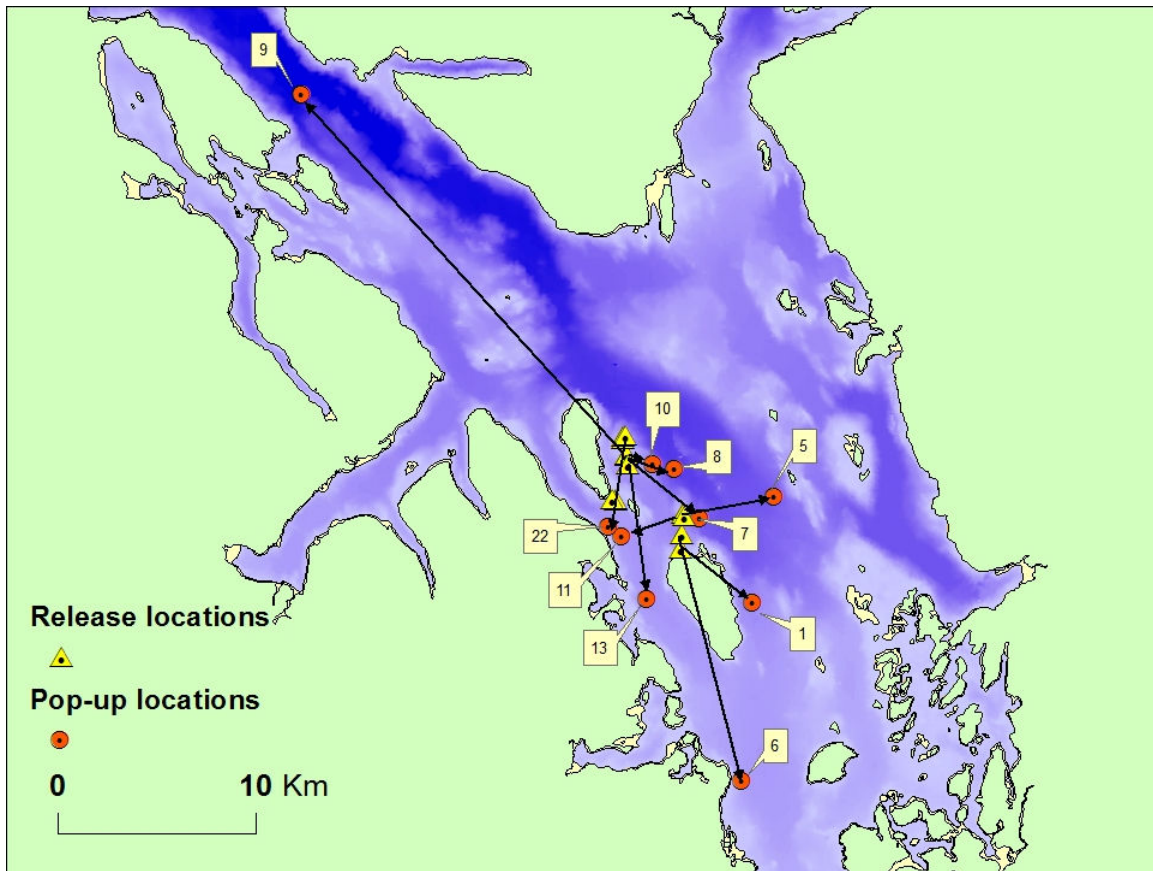


Figure 2. Release locations (yellow triangles) and pop-up locations (orange circles, labeled with Fish ID) of PSATs programmed to release from fish on February 1.

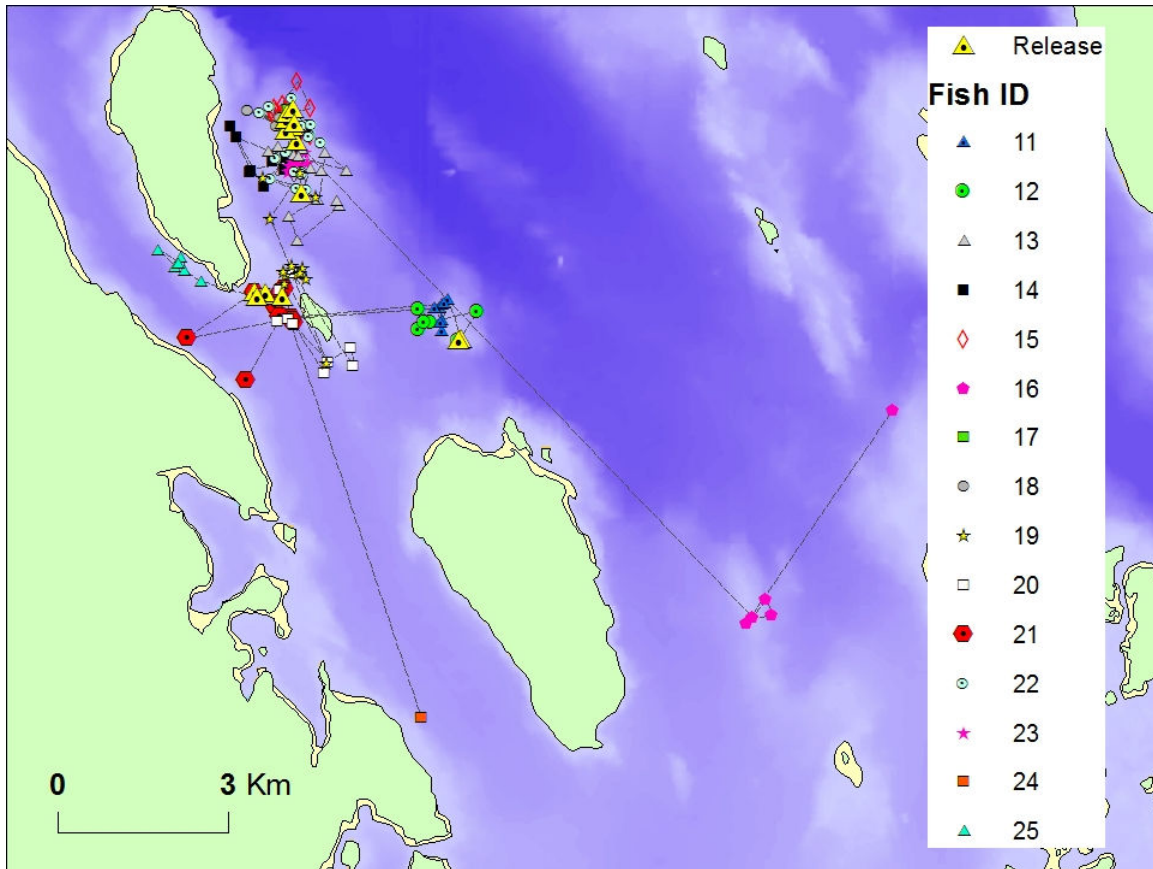


Figure 3. Release locations (yellow triangles) and acoustic telemetry position estimates for 15 acoustic-tagged halibut between July 1, 2013 and September 2, 2013.

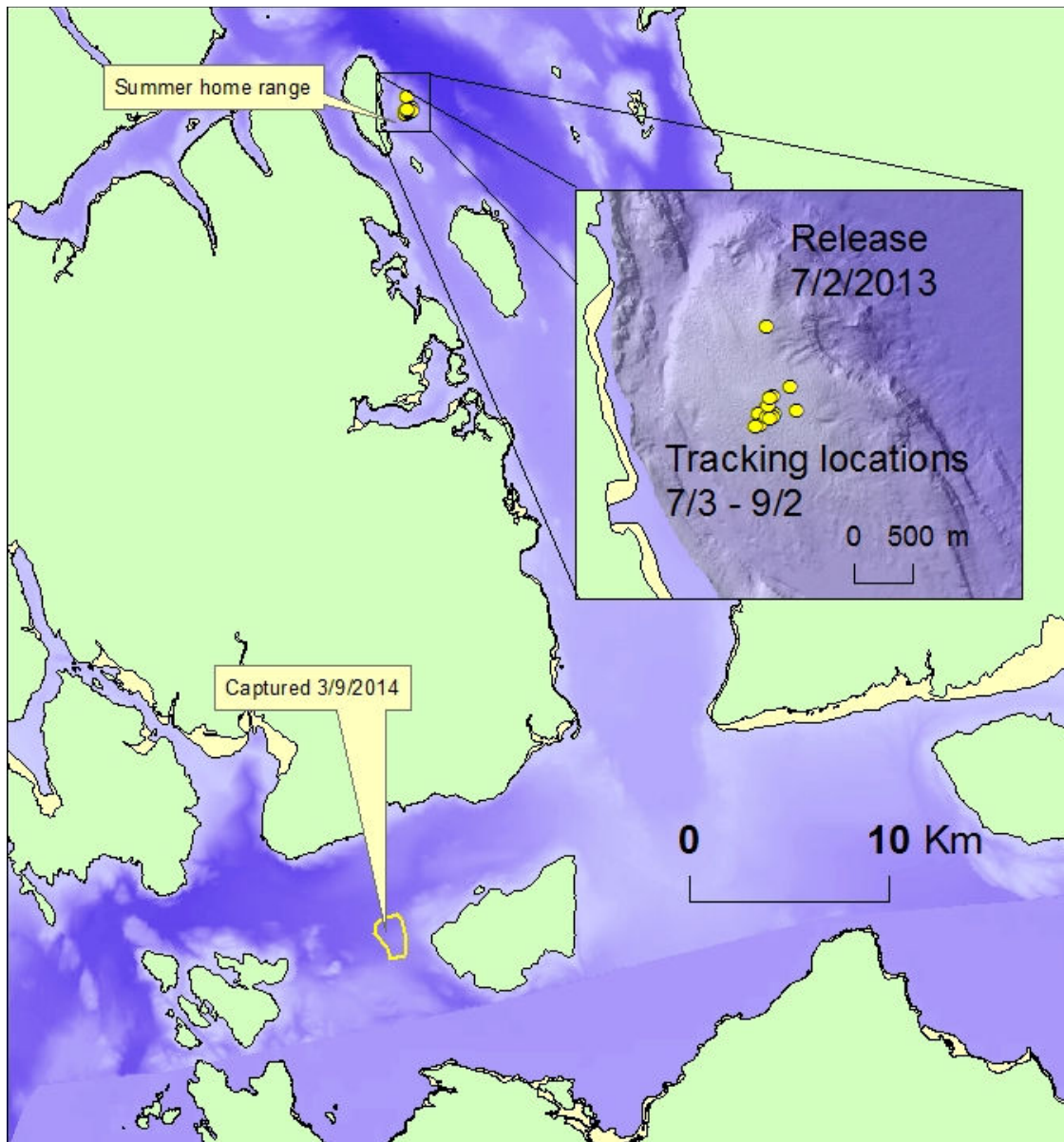


Figure 4. Acoustic telemetry locations for Fish #23, recaptured in the commercial fishery March 9, 2014. Inset shows zoomed-in view of home range area located on a 30-m deep mound.

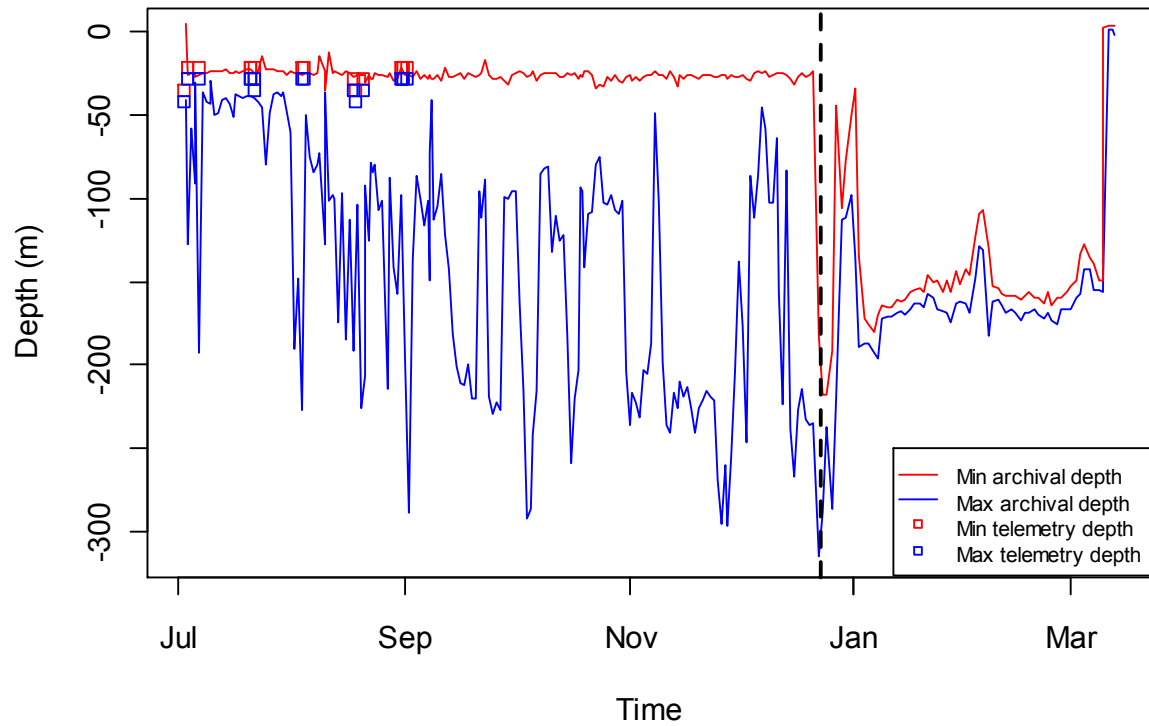


Figure 5. Maximum (blue) and minimum (red) daily depths from the archival tag record from Fish #23 (lines) and the depths transmitted by acoustic tags during active tracking (squares). Dotted line at December 21, 2013 denotes a possible switch from a home range to a mobile movement pattern.

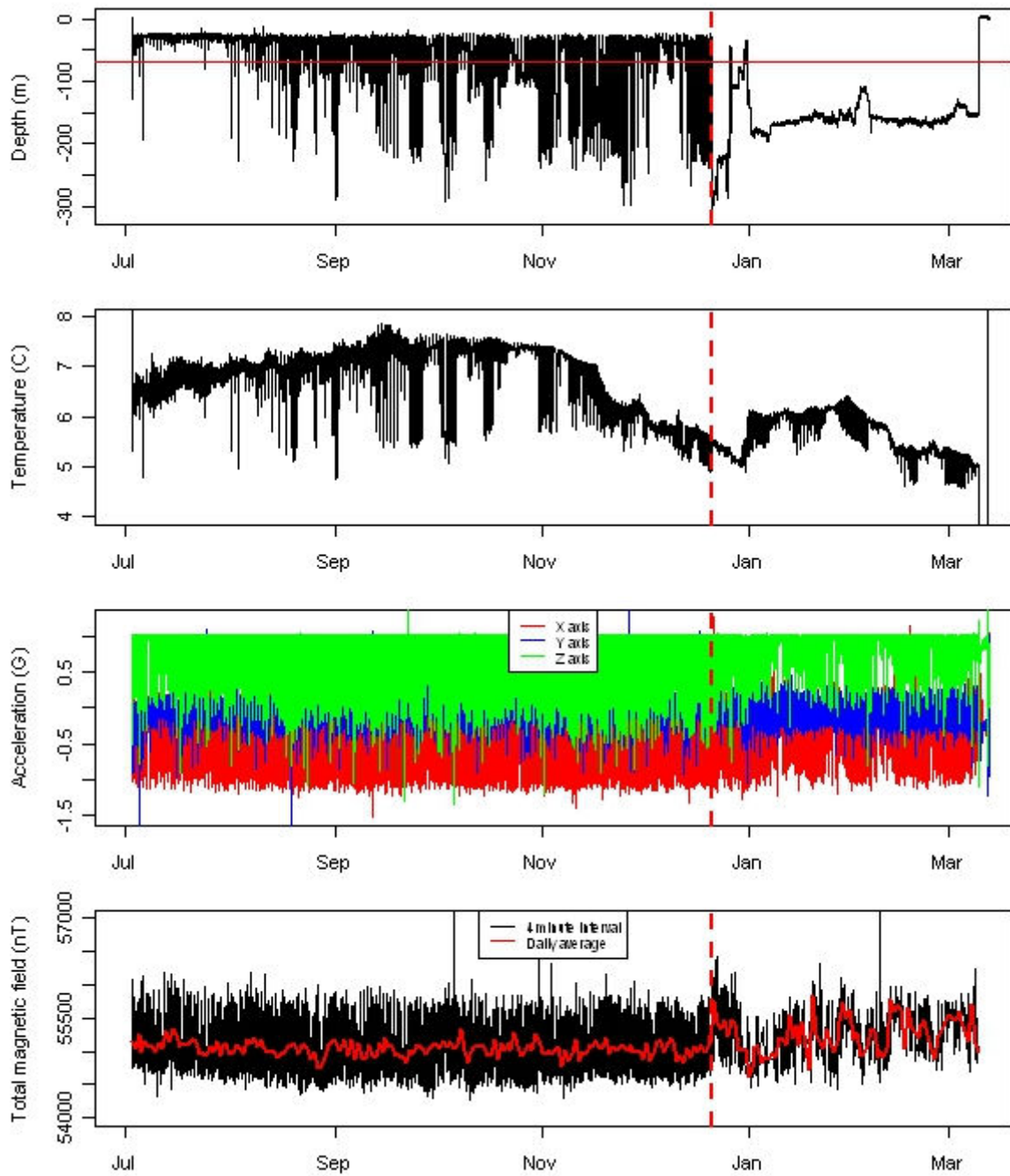


Figure 6. Detailed (4-minute measurement interval) data from Fish #23 including depth (sill depth depicted by the solid red line at 70 m), temperature, acceleration, and the magnetic field (measurements restricted to one tag orientation of $Z = 1$, $X = 0$, $Y = 0$ for consistency in comparisons during different movement patterns). Dashed red line at December 21 depicts hypothesized transition between home range behavior and migratory behavior.

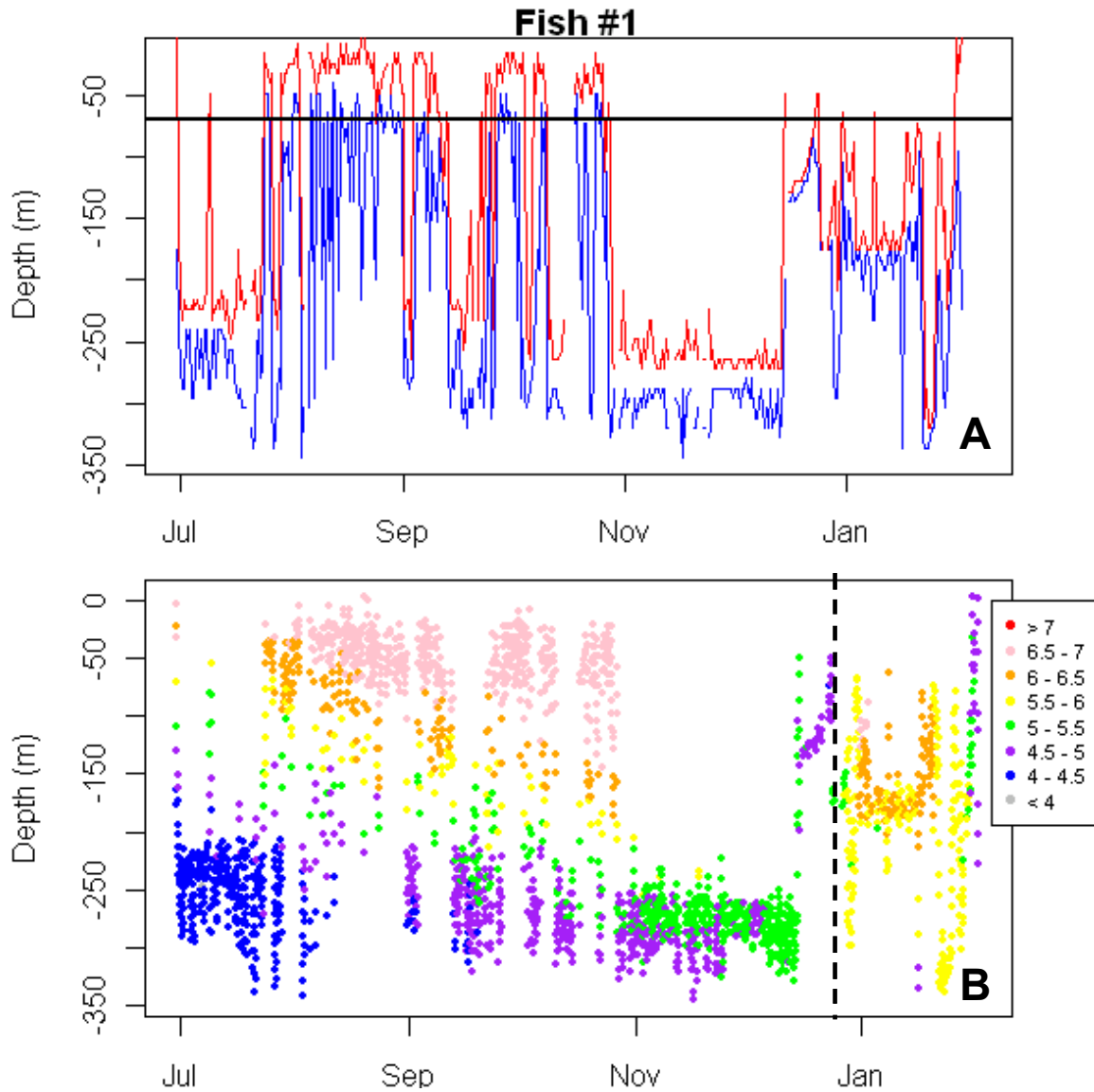


Figure 7. Daily depth (A) and temperature (B) records for a fish (# 1) that putatively left Glacier Bay based on a change in pattern observed in maximum and minimum daily depths and January temperatures of up to 6.5 degrees C. Vertical dashed line in late December denotes the possible timing for the exit from Glacier Bay. Minimum depths were shallow enough for the fish to have crossed the sill and re-entered Glacier Bay on January 31.

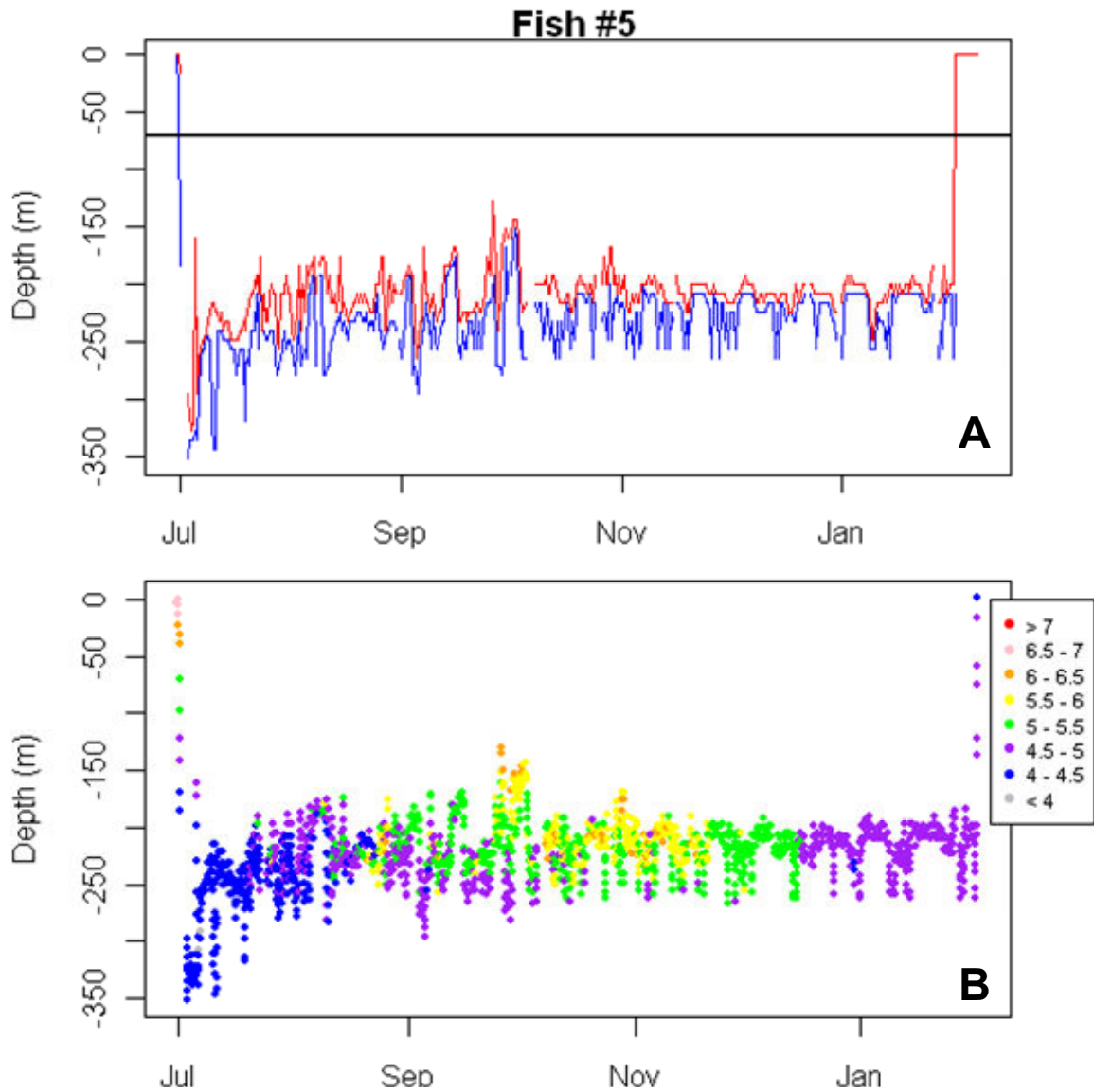


Figure 8. Daily depth (A) and temperature (B) records for a fish (#5) that could not have left Glacier Bay based on a known end location inside Glacier Bay and minimum daily depths that were never shallower than the sill depth at the entrance prior to the pop-up date on February 1.