



# Characterizing Movement and Spatial Occupancy of Northern Bering Sea Pacific Halibut

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## Abstract:

Since the 1970s, the fish assemblage has been changing in the northern Bering Sea (NBS), where rising water temperatures have correlated with increases in abundance of sub-arctic fish species. One such species is the Pacific halibut (*Hippoglossus stenolepis*), an important flatfish that is a valuable resource in the NBS and may expand into the southern Chukchi Sea. To characterize the possible interactions between Pacific halibut and potential future human activities in the Bering and Chukchi seas, such as oil and gas exploration, marine mineral extraction, and renewable energy development, this species' movements and spatial dynamics must be understood. This information is currently scarce, and as such, the possible interactions between human activities and Pacific halibut are unknown. This study examined spatial dynamics of large female Pacific halibut in the NBS using pop-up satellite telemetry tags, from which reconstructed movement tracks were generated using Hidden Markov modeling (Chapter 1). Additionally, to evaluate potential halibut occupation of the Chukchi Sea, recorded thermal conditions from tagging efforts in the NBS were compared to modeled water temperatures in the Chukchi Sea to determine the spatial and temporal extent of suitable conditions within the region (Chapter 2).

Tagged individuals remained within the NBS and central Bering Sea and crossed multiple Outer Continental Shelf (OCS) lease planning area boundaries, as well as the Russian maritime border. During the winter season, Pacific halibut made long migrations to the continental shelf edge for inferred spawning purposes, with fish occupying St. George Basin and Navarin Basin planning areas, as well as coastal Russian waters along Kamchatka. Individuals returned to their tagging location the following year, which indicated inter-annual site fidelity to summer foraging areas within Norton Basin in the NBS. No Pacific halibut were tracked entering the Hope Basin planning area in the southern Chukchi Sea, despite the presence of thermal conditions that are similar to those currently occupied in the NBS. Pacific halibut primarily occupied waters from 6.0 to 8.2°C during the summer months, but were regularly found in conditions from 3.8 to 9.8°C during the summer and conditions around 0.9°C during the winter. The availability of these conditions in the Chukchi Sea was relatively limited during a recent cold year, constrained to eastern coastal waters near Alaska with maximal availability during August and September, but were 2.5 to 7.8 times more prevalent during a warm year, comprising a large portion of the Chukchi Sea from July to October.

Results indicate Pacific halibut occupy multiple OCS planning areas throughout the year, with seasonal variation in occupied areas. Pacific halibut may interact with potential resource exploration and developments across these planning areas in the Bering Sea, but at their current extent are much less likely to do so in the Chukchi Sea. However, the potential for these interactions remains, where suitable thermal habitat for Pacific halibut is currently available in the Chukchi Sea, although alternative factors such as food availability appear to be discouraging these movements.

# Chapter 1:

## *Introduction:*

The Bering Sea is a productive high latitude, sub-arctic sea that is traditionally characterized by rich benthic infauna populations and large concentrations of winter sea ice cover (Cui et al., 2012). Large sea ice extents traditionally generate a deep-water cold pool, when cold surface water made more saline by freezing and brine formation sinks to the ocean floor and persists throughout the warm summer months (Mueter and Litzow, 2008). These waters range between -2 and 2°C and may encompass a large portion of the eastern Bering Sea shelf, with cold years seeing these conditions extend from Bristol Bay to the Russian coast (Figure 1.1) (Kinney et al., 2022). This cold pool creates a thermal barrier, limiting the northward migration of more temperate species in the Bering Sea; however, in some recent years the cold pool has not formed, and as a result, bottom water temperatures have increased by several degrees Celsius (Sheffield, 2019). This rapid change has resulted in a regime shift, with the distribution of numerous species expanding northward into the northern Bering Sea (NBS) (Grebmeier et al., 2006). In particular, sub-arctic fish species traditionally found further south have been observed moving northward to exploit warming sea temperatures, expanding into these newly habitable waters (Stevenson and Lauth, 2019). Groundfishes including Pacific Cod (*Gadus microcephalus*) and Walleye Pollock (*Gadus chalcogrammus*) are among the species exhibiting these northward movements into the NBS (AFSC, 2019). Another species exhibiting these movements, and a consequential increase in abundance, is the Pacific halibut (*Hippoglossus stenolepis*) (Conners et al., 2002).

The Pacific halibut is a large, long-lived, demersal flatfish species that is distributed across the North Pacific Ocean. The Pacific halibut (hereafter referred to as “halibut”) is a highly migratory species that exhibits large-scale movements when they move between summer foraging areas in shallow continental shelf waters and deep winter spawning areas on the continental shelf edge and slope (Loher and Seitz, 2008). The species is commercially valuable and has been heavily targeted throughout its range, where in Alaska, the species also supports important recreational and subsistence fisheries throughout the Bering Sea, Aleutian Islands, and Gulf of Alaska (Figure 1.1). This is especially true in the NBS, a remote area where rural residents rely heavily on subsistence and commercial harvest opportunities. Therefore, the northward expansion and increasing abundance of halibut may have profound impacts on the food security and livelihoods of local individuals by providing new harvest opportunities in the region (Thoman Jr et al., 2020).

As their distribution expands, halibut may also interact with other human activities, such as potential resource exploration, extraction, and development in the NBS and Chukchi Sea. This area is divided into a number of Outer Continental Shelf (OCS) lease planning areas, including Hope Basin in the Chukchi Sea and Norton Basin, Navarin Basin, St. George Basin, and St. Matthew-Hall in the Bering Sea (hereafter referred to by lease planning area name). Many of these OCS lease planning areas may be explored for oil, minerals, and renewable energy suitability in the future, and as such, it is important to examine the spatial dynamics and occupied environmental conditions of halibut in these regions to provide valuable benchmark information that will aid in understanding possible interactions between this important food source and exploration activities. While halibut have been studied and comprehensively surveyed throughout much of their range, minimal research has occurred in the NBS. Currently, monitoring during an annual survey is primarily restricted to the outer shelf domain of the southern and

central Bering Sea, with limited coverage across the central shelf and no stations in the NBS (IPHC, 2023). As such, the recent expansion of halibut into the NBS has resulted in an understudied region, leaving an information gap in halibut movements and spatial dynamics. This study sought to use satellite tagging methods to assess movements and spatial occupancy of halibut in the NBS, including 1) identifying Outer Continental Shelf (OCS) planning areas in the Northern Bering Sea and potentially in the Southern Chukchi Sea that Pacific halibut currently occupy throughout the course of a year, 2) examining the timing and pathways of Pacific halibut movements among OCS planning areas, as well as the duration of occupation within a given planning area, 3) characterizing Pacific halibut spawning events to identify spawning grounds and the OCS planning areas in which they occur, and 4) characterizing the depths occupied by Pacific halibut to determine the potential exposure risk to disturbance events such as an oil spill, under the pretext that Pacific halibut are not exclusively benthic. By addressing these key knowledge gaps, this study sought to identify potential regions, and timing, where halibut may interact with potential future hydrocarbon activities.

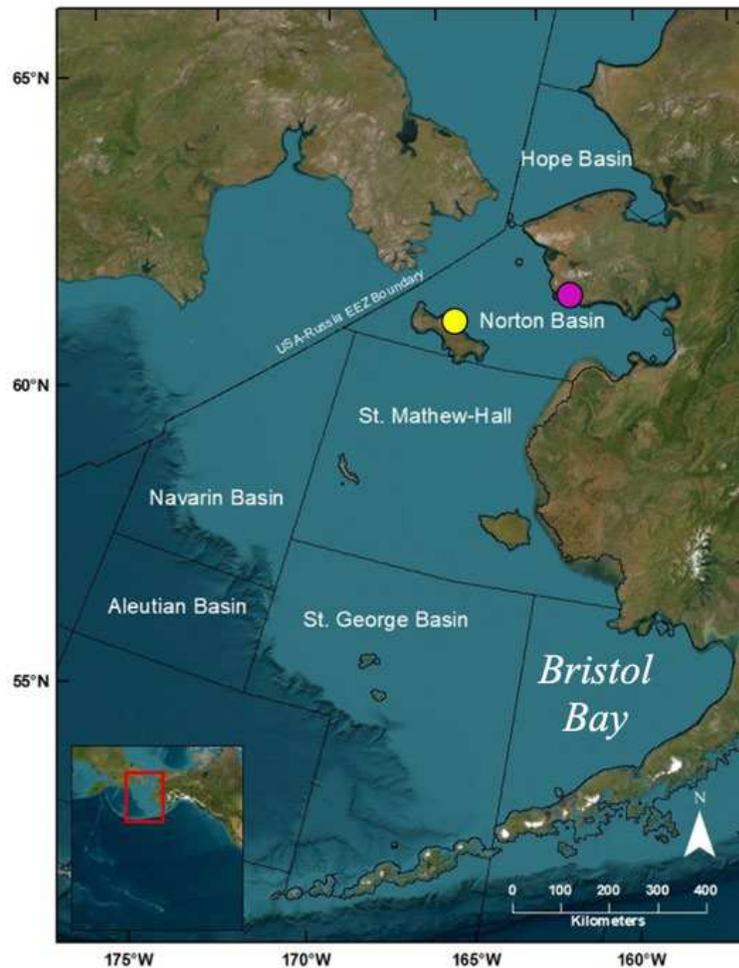


Figure 1.1: Bering Sea Outer Continental Shelf lease planning areas and Pacific halibut (*Hippoglossus stenolepis*) tagging locations, represented by the pink (Nome, AK) and yellow (Savoonga, AK) circles.

## Methods:

### Fish Capture

All halibut were captured in the northern Bering Sea in waters north of Saint Lawrence Island, Alaska, within Norton Basin (Figure 1.1), during the commercial fishing season of July, August, and September. These efforts were based out of Nome and Savoonga, Alaska (Figure 1.1). Nome (64.351 N, 166.440 W) is located on the north shore of Norton Sound and has a small commercial longline fleet. Savoonga (63.782 N, 170.406 W) lies on the north shore of Saint Lawrence Island. Savoonga is an Alaska Native village, supporting a small handline fleet that captures halibut for both commercial and subsistence purposes. During the summers of 2019, 2021, and 2022, fishing vessels were chartered out of both locations to conduct tagging efforts; in summer 2020, fishing was only conducted near Nome due to COVID-19 travel restrictions to Savoonga. Fishing gear varied across tagging vessels, but all fishing efforts were conducted using either fixed- or snap-hook longlining gear with baited (pink salmon *Oncorhynchus gorbuscha* or Pacific herring *Clupea pallasii*) circle hooks soaked for 3 to 12 hours. All halibut were brought on board by net or hand, precluding the use of a gaff.

### Tagging and Release

All captured halibut were evaluated for tagging suitability once on the boat deck. Only fish that were in good health were considered for tagging to minimize post-release mortality, and any fish that had significant injuries, poor body condition, or large numbers of parasites were excluded from consideration. For healthy fish, fork length (FL) was measured and fish >100 cm FL were selected for tagging as halibut above this threshold are likely to be sexually mature females (Loher and Stevens, 2011). Due to numerous COVID-19 complications in 2020, tagging efforts were less selective and some tags were placed on fish smaller than this size threshold.

Satellite tags were attached following previously described procedures (Seitz et al., 2003; Seitz et al., 2011). Tags were affixed to fish with a tether system that consisted of the tag, a leader, and a dart. The leader was a 13-cm length of 1.8-mm-diameter nylon monofilament and the dart a 62-mm long custom-fabricated stainless steel halibut dart. The leader was secured to the dart and the tag using 2.38-mm stainless steel crimped swage sleeves wrapped at both ends in 3:1 adhesive-lined polyolefin (4.76 mm). To insert the dart in the fish, a pilot hole was made in the dorsal surface on the eye side of the halibut, just behind the widest part of the fish. Using a dart applicator, the dart was inserted through the pilot hole and past the pterygiophores, or fin ray supports, at which point the applicator was retracted and the dart affixed under the pterygiophores. After ensuring the tag and tether were properly secured to the fish, the individual was released head first.

### PSAT Tag Specifications and Settings

Satellite tags were Wildlife Computers miniPATs, which weigh 60 g in air with total dimensions of 124 mm in length by 38 mm in width. These tags have a memory of up to 64 megabytes and an operating life up to two years. Each tag contains light, temperature, pressure, and wet/dry sensors. Over the course of a deployment, each tag measures and records depth (resolution 0.5 m, range 0–1700 m), temperature (resolution 0.05°C, range -20–50°C), and ambient light ( $10^{-2}$  to  $10^{-10}$  W/cm<sup>2</sup> at 440 nm) readings at 5 second intervals. These tags remain attached to the fish collecting these data until a pre-scheduled pop-up date, at which time the tag releases from the fish and floats to the surface of the ocean to transmit summarized archived data to satellites, during which time an end location is calculated.

Scheduled pop-up dates used in this study varied across tagging years, but in general tags were set to release during two time periods: winter and summer. Winter pop-ups served to identify spawning

grounds and the magnitude of annual migratory movements for NBS halibut, while summer pop-ups provided an indication of the degree of site fidelity to feeding grounds in the NBS. Winter tags were set to release between January 15<sup>th</sup> and April 1<sup>st</sup> of the year following tagging, and summer tags released approximately 1 year after deployment, from mid-July to mid-September. If a tag came free from the halibut prior to the scheduled pop-up date, the tags were set to begin transmission after 1 day at the surface, determined via the tags' pressure sensors. When transmitting, the tags' internal programming summarized archived data to minimize the number of outgoing messages. Ambient light data were condensed into sunrise and sunset light curves for each day, while depth and temperature recordings were sampled at a regular interval, providing equally spaced point readings for each day at liberty. During 2019 and 2020 these were sub-sampled at 10-minute intervals, and in the subsequent years of 2021 and 2022 at five-minute intervals. To reduce the number of messages needed for the increased temporal resolution in 2021 and 2022, temperature data were only transmitted for every third day at liberty. For tags that are physically recovered, the full data time-series can be recovered, providing occupied depth and temperature readings every 5 seconds during the tags' time at liberty.

#### *Data analysis:*

To understand the horizontal movement of tagged halibut, end locations were assigned as the location of first transmission of each tag with an Argos location class of 2 or 3, corresponding to an accuracy of <500 m and <250m, respectively. Horizontal displacement was calculated as the great circle distance between tagging and end locations. For tags that reported before their scheduled pop-up dates, only end locations from those that reported after 1 January of the year following tagging were included in horizontal displacement analyses.

Habitat occupation of halibut was characterized by determining occupied mean daily depths and temperatures for each individual. For all days during which a tag was attached to a halibut and provided time-series data, a daily mean depth and temperature was calculated from all available subsampled readings. These individual daily means were then aggregated across all individuals for each day that data were available, providing a distribution of occupied daily conditions that were summarized in monthly boxplots, providing the median, quartile, and 95% range of occupied conditions of all tagged halibut. For subsequent movement modeling, movement states were assigned for each halibut by qualitatively examining the mean daily depth data. Periods when daily means changed steadily, indicating onshore or offshore movement across the Bering Sea shelf, were assigned as a migratory state. Conversely, times when these depths did not change appreciably, indicating localized movements, were assigned as a residency state. Occupied depth and temperature conditions were also summarized (mean  $\pm$  SD) for the periods designated as the residency state, as these time periods correspond to the summer foraging and winter spawning seasons: Here, the daily depth and temperature means were aggregated across all individuals across all days in the specified time period.

For all tagged halibut for which end locations and depth time-series data were available, most likely movement paths were reconstructed using a Hidden Markov Model (HMM). HMMs are highly flexible non-parametric state space models (Pedersen, 2008) that use a movement model to predict where an individual can move within the study area and a likelihood model to identify where in the study area conditions best align with observed tag data (Nielsen and Sibert, 2007). An HMM was adapted for use on demersal fishes in the Bering Sea (Nielsen et al., 2019; Nielsen et al., 2023), in which the model framework discretized the Bering Sea into grid cells (3-km<sup>2</sup> resolution) on a daily time scale. The movement model executes a random walk to simulate fish movement using a symmetrical two-

dimensional diffusion kernel that can vary in size. Herein, the kernel varied based on movement state, with 20 km<sup>2</sup> and 100 km<sup>2</sup> being selected for the residency and migratory states, respectively: After testing multiple kernel sizes, these values were chosen as they allowed model convergence across individuals, and were consistent with values chosen to represent both residential (Nielsen et al., 2014) and migratory (J.K. Nielsen, unpublished) groundfish movements within the region. The likelihood model relies on depth and light data, which are used to generate maximum occupied depth and longitude estimates daily. Maximum daily depth was utilized following the assumption that halibut occupy the seafloor at some time each day, and therefore the maximum occupied depth for each day corresponds to ocean depth. Longitude estimates were generated via Wildlife Computer's proprietary software, Global Position Estimator 2 (GPE2), and qualitatively filtered due to previous studies documenting a high degree of variability in generated estimates (Seitz et al., 2006): Only series of consistent estimates that did not result in a daily change of >2° in longitude were retained (Teo et al., 2004). The model executes a forward filter to iteratively estimate the probability of a fish's presence across days based on the movement and likelihood models, subsequently followed by a backwards smoothing that adjusts estimated probabilities based on the end location, yielding a probability density surface for each day the fish was at liberty. Movement tracks were generated from the final smoothed probability using a Viterbi algorithm, which estimates the most likely locations for each day (Nielsen et al., 2023). The lengths of these tracks were determined for individuals and summarized (mean ± SD) for each tagging location, and one-sided independent t-tests with unequal variances were used to test for differences in track lengths for both winter and summer pop-ups between the two deployment locations.

Reconstructed movement tracks and final HMM probability density surfaces were also used to assess occupation and potential cross-boundary movements of halibut among OCS leasing areas. Each individual movement track was qualitatively examined and the proportion of halibut that emigrated into regulatory areas outside that in which they were tagged was determined for each tagging location.

For any tags that were physically recovered, depth time-series data were assessed for spawning activity. Active spawning behavior was identified as serial rises in the water column separated by approximately 65 hours (Seitz et al., 2005), when halibut make rapid ascents of 75 m or more, starting at depths >200 m, to release their gametes, followed by a steady return to depth (Loher and Seitz, 2008). For all identified spawning rises, a location was assigned from the corresponding day of the reconstructed movement track for the individual. All analyses were conducted using R version 4.3.1 (R Core Team, 2023).

### *Results:*

A total of 84 satellite tags were deployed in the NBS (Table A1) on halibut ranging in size from 89 to 175 cm in fork length ( $112.98 \pm 16.77$  cm). In total, 56 tags were deployed out of Nome and 28 out of Savoonga, AK with the deployment durations split between winter (n=52) and summer (n=32) pop-ups (Table 1.1). Of the deployed tags, 64 (76.2%) successfully communicated with satellites and transmitted data, with received messages ranging from 3 to 8,575 ( $2,401 \pm 2,167$ ) for individual tags. Three of these tags were recovered after transmitting, providing the complete data time-series from the deployment. Not all tags provided sufficient data for each analysis, and of these 64 tags, 42 were utilized in horizontal displacement, 61 in occupied habitat, and 34 in HMM modeling analyses. Tags that had insufficient data for analyses experienced premature releases (n=10), extended delays between popping up and data transmission resulting in unusable end locations (n=7), and either low numbers of or corrupted messages

that yielded extremely sparse time-series data (n=13). Additionally, 20 (23.8%) tags failed to communicate with satellites and did not provide any data.

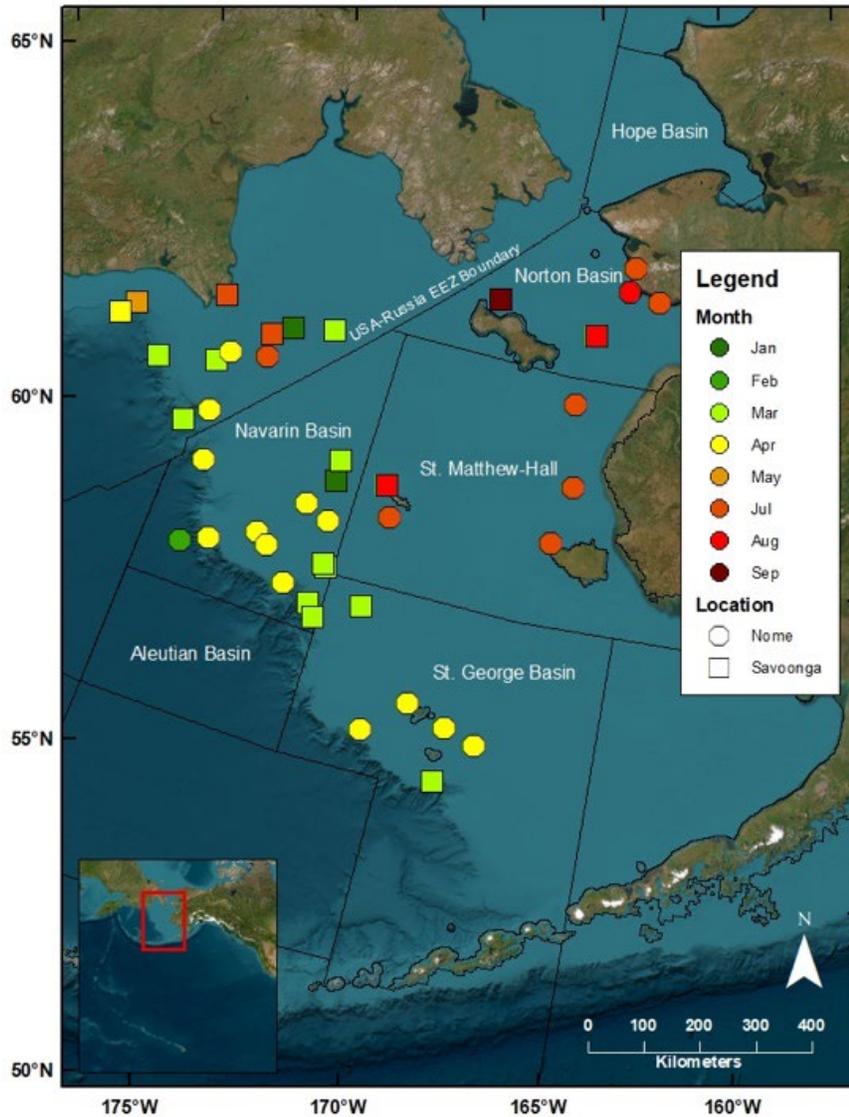
*Table 1.1:* Summary of the number of satellite tags deployed on Pacific halibut (*Hippoglossus stenolepis*) in the northern Bering Sea by tagging year, location, and pop-up schedule (when the tag is programmed to float to the surface to transmit data to satellites). For each group of tags, the number of tags used in end location, depth and temperature time-series, and Hidden Markov Model (HMM) analyses is also provided.

# OF TAGS	TAGGING YEAR	TAGGING LOCATION	POP-UP SCHEDULE	END LOCATION	TIME SERIES	HMM
5	2019	Nome	Winter	0	2	0
5	2019	Nome	Summer	0	0	0
3	2019	Savoonga	Winter	2	3	2
3	2019	Savoonga	Summer	2	3	2
15	2020	Nome	Winter	7	13	7
10	2020	Nome	Summer	4	8	4
5	2021	Nome	Winter	2	3	2
3	2021	Nome	Summer	3	3	2
6	2021	Savoonga	Winter	5	5	2
4	2021	Savoonga	Summer	3	3	3
9	2022	Nome	Winter	5	7	4
4	2022	Nome	Summer	1	1	1
8	2022	Savoonga	Winter	6	5	3
4	2022	Savoonga	Summer	2	3	2

Of the 42 tags with useful end locations (Nome n=22, Savoonga n=20), all were located in the northern and central Bering Sea (Figure 1.2). End location displacements ranged between 305 and 1022 km ( $699.3 \pm 170.7$  km) for tags that popped-up during the winter period and 14 and 675 km ( $324.8 \pm 245.9$  km) for those that popped-up during the summer. Winter end locations were located at or near the continental shelf edge, distributed from the Pribilof Islands to the Russian coast. Of the 28 tags that provided winter end locations, 8 (28%) were located in Russian waters, 14 (50%) were along the central shelf of Navarin Basin, and 6 (22%) were proximate to the Pribilof Islands in St. George Basin. Summer end locations were distributed across the continental shelf, from waters proximate to offshore winter locations to near the original release locations. Of the 14 tags that provided summer end locations, 4 (28%) were in Russian waters, 5 (36%) were in distributed across St. Matthew-Hall, and 5 (36%) were proximate to initial tagging locations in Norton Basin.

Temperatures occupied by halibut ranged from -1.9 to 13.0°C (Figure 1.3B), while occupied depths ranged from 0.5 to 696.5 m (Figure 1.3A). While halibut predominantly occupied waters near the seafloor, they were seen occupying shallow waters (Figure 1.3A) and making ascents into the water column (Figure 1.5A), when they often approached or reached the ocean's surface. Tagged fish remained in shallow waters throughout the months of August, September, and October, when occupied depths ( $30.8 \pm 12.3$  m) and temperatures ( $6.1 \pm 2.2$ °C) were relatively consistent across individuals. All individuals then made an offshore migration towards the continental shelf edge and slope during the months of

November, December, and January. The halibut remained in deeper waters for the months of February, March, and April when occupied depths ( $196.5 \pm 148.8$  m) were relatively deep (maximum 696.5 m) and thermal conditions displayed little variability ( $2.2 \pm 1.3^\circ\text{C}$ ). Following the winter deep-water occupation, halibut returned to shallow waters during the months of May, June, and July.



*Figure 1.2:* Pop-up locations for all satellite tags attached to Pacific halibut (*Hippoglossus stenolepis*) in the northern Bering Sea that remained affixed until at least January 1st of the following year and successfully transmitted a location (n=42). Pop-up locations are color-coded by the month the tag detached from the fish. Symbol shape corresponds to tagging location, with octagons representing tags attached to Pacific halibut near Nome, AK and squares near Savoonga, AK. Outer Continental Shelf lease planning areas are overlaid.

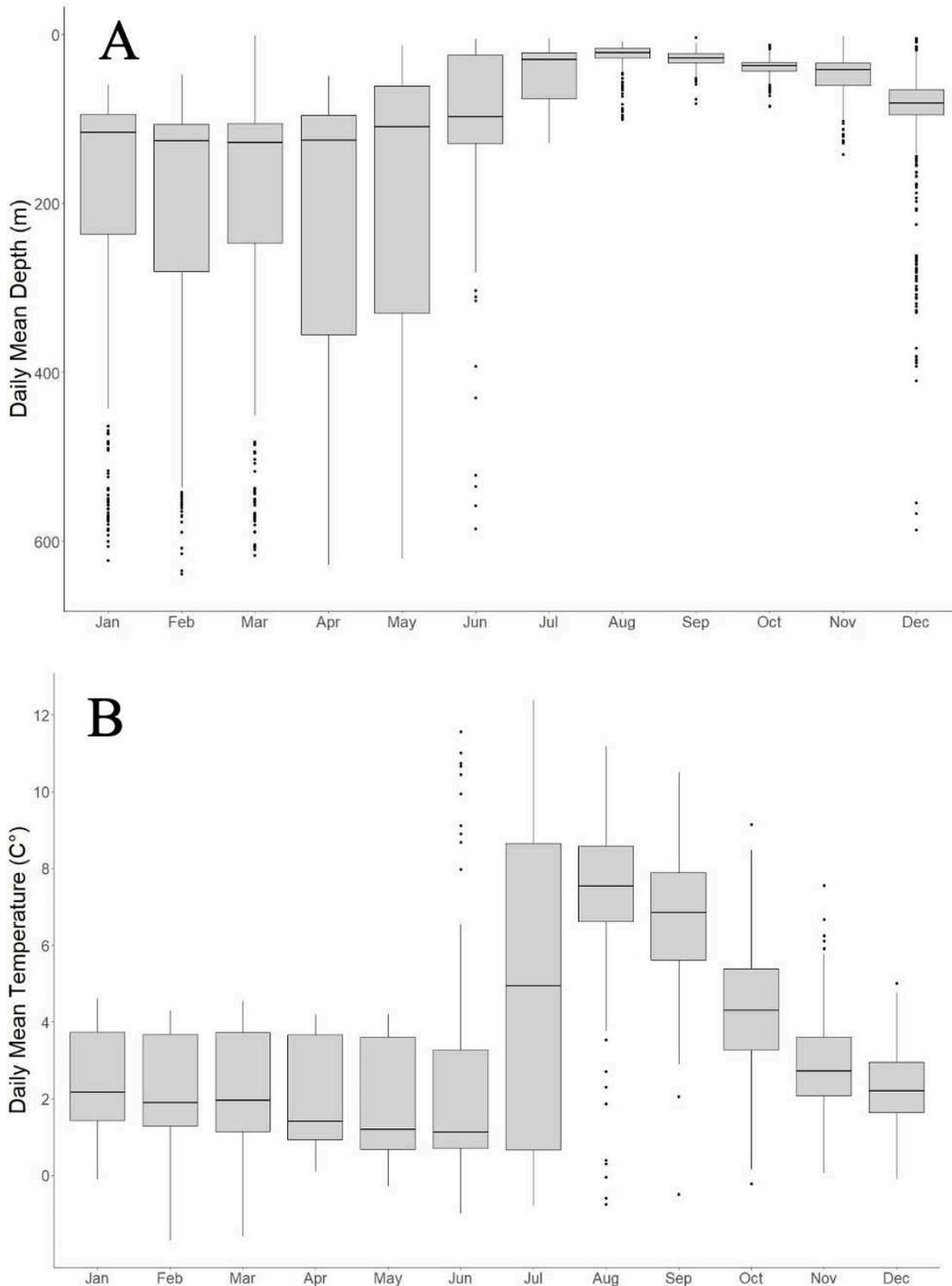


Figure 1.3: Monthly occupied depths (A) and temperatures (B) of Pacific halibut (*Hippoglossus stenolepis*) satellite tagged in the northern Bering Sea whose tags transmitted time-series data (n=61). Boxes represent the first and third quartiles, while the horizontal line is the median; whiskers extend out to the minimum and maximum values, except for any values that lie farther than 1.5 times the interquartile distance from the box, which are represented as points.

Reconstructed movement tracks (Figure 1.4) were generated for fish tagged near both Nome (n=20) and Savoonga (n=14). For fish tagged near Nome with winter pop-ups (n=13), winter track lengths (range 961 to 1354 m, mean  $\pm$  SD 1163.8  $\pm$  121.5 km) were significantly longer than for halibut (n=10) tagged near Savoonga (range 571 to 1356 km, mean  $\pm$  SD 911.7  $\pm$  241.9 km;  $t(12) = 3.015$ ,  $p = 0.005$ ). This was not the case for halibut with summer pop-ups, as fish tagged near Nome (n=7) had summer track lengths (range 1285 to 2430 km, mean  $\pm$  SD 1938.4  $\pm$  377.6 km) that were not significantly longer than for halibut (n=4) tagged near Savoonga (range 1199 to 2111 km, mean  $\pm$  SD 1586.8  $\pm$  384.1 km;  $t(6) = 1.470$ ,  $p = 0.096$ ).

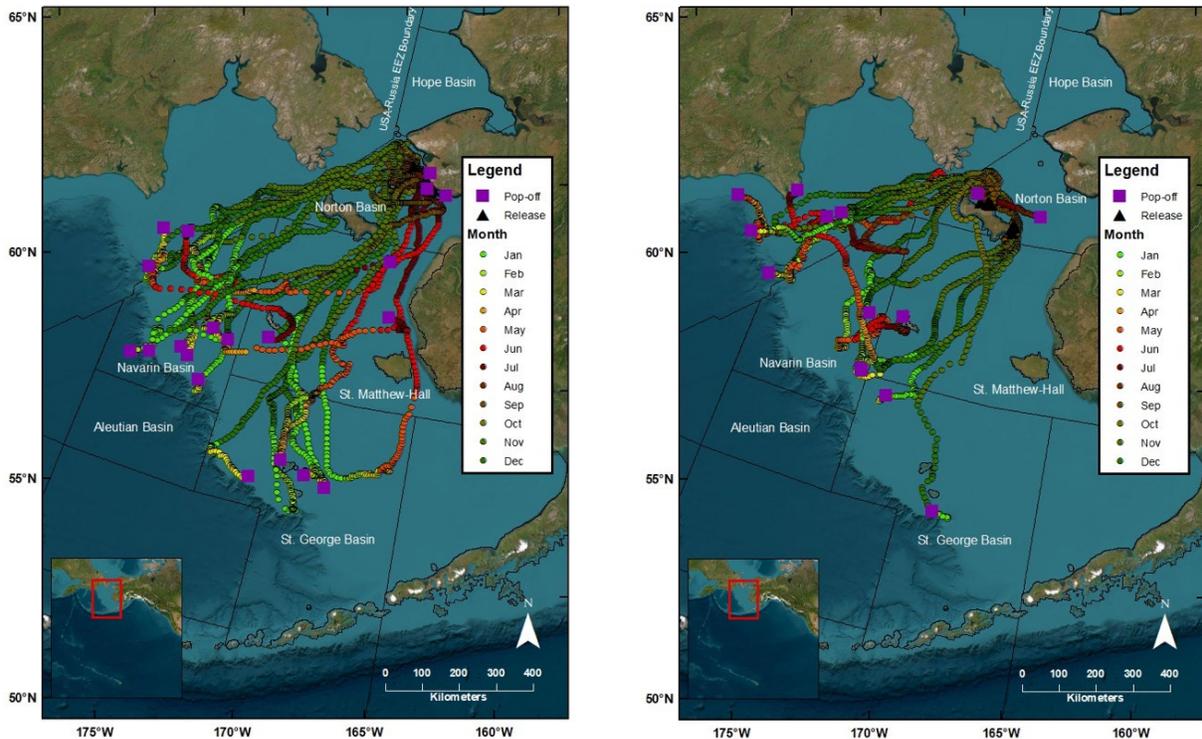


Figure 1.4: Most likely movement paths for Pacific halibut (*Hippoglossus stenolepis*) satellite tagged near Nome, AK (Left, n=14) and Savoonga, AK (Right, n=20). Circles, color coded by month, are estimated daily locations generated from the Hidden Markov Model probability surface using a Viterbi algorithm. The black triangles represent Pacific halibut tag and release locations, while the purple squares are tag pop-up locations. Outer Continental Shelf lease planning areas are overlaid.

Pacific halibut moved across multiple OCS leasing area boundaries during their tag deployments (Figure 1.4). All reconstructed movement tracks crossed OCS leasing area boundaries, with many individuals tagged near Nome crossing into St. Matthew-Hall on their way to the continental shelf edge, with 6 (30%) then entering St. George Basin, 10 (50%) entering Navarin Basin, and 4 (20%) crossing into Russian waters. Fish tagged near Savoonga exhibited similar movements among planning areas, with 2 (14%) entering St. George Basin, 4 (29%) moving into Navarin Basin, and 8 (57%) leaving US waters and residing across the Russian maritime border. For both tagging regions, the occupation of Norton Basin was predominantly during the late-summer and early-fall months (August, September, October) prior to offshore movements across St. Matthew Hall and into Navarin Basin, St. George Basin, and

Russian waters during the late-fall and early-winter (November, December, January). The occupation of the offshore planning areas (Navarin Basin and St. George Basin) and Russian waters persisted through the late-winter and early-spring (February, March, April) before fish again crossed St. Matthew-Hall during the late-spring and early-summer (May, June, July) and returned to Norton Basin.

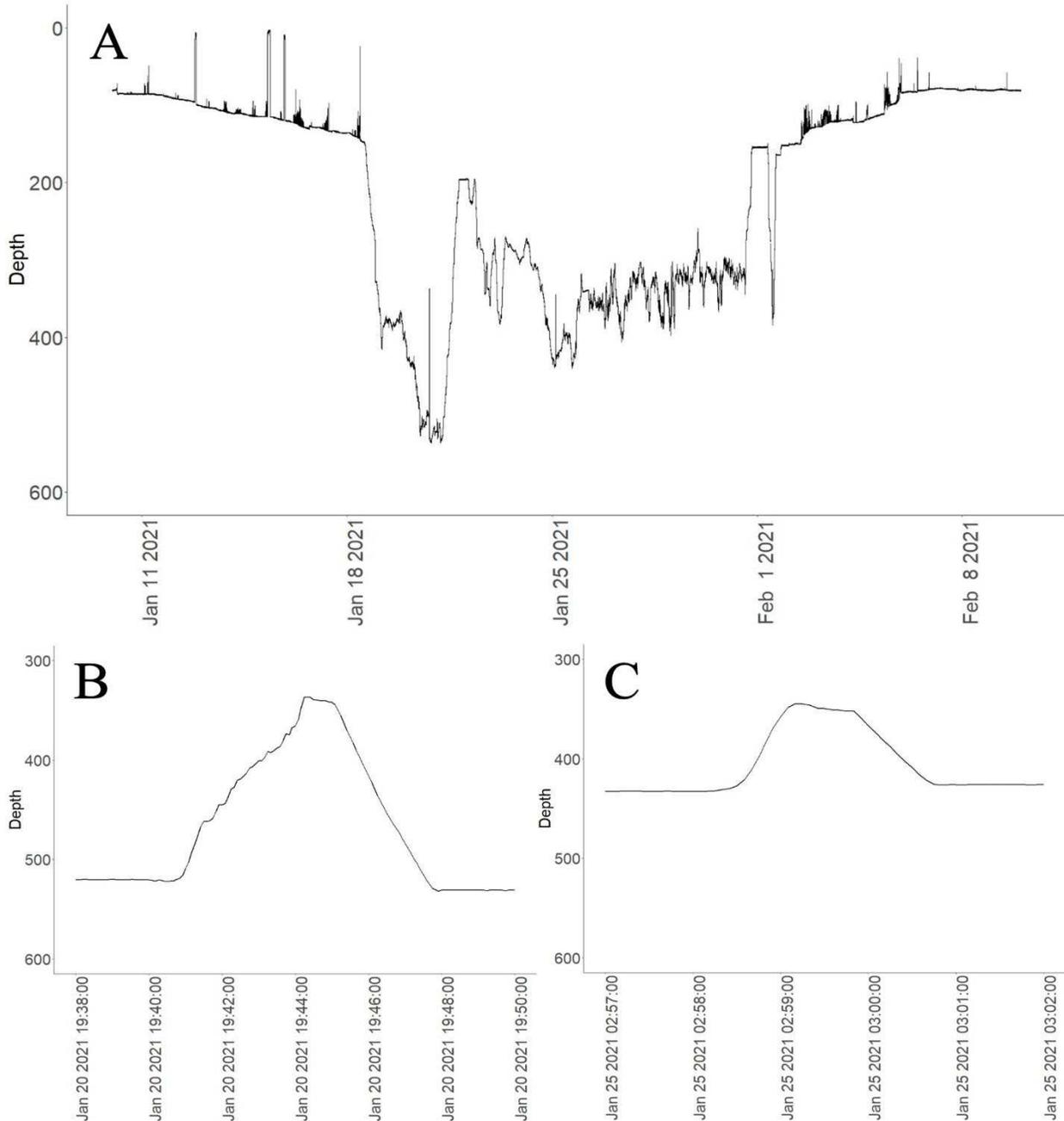


Figure 1.5: Depth time-series data (A) from a recovered satellite tag that was attached to a Pacific halibut (*Hippoglossus stenolepis*) near Nome, AK, that exhibited spawning rises. Data are at a 5-second resolution and plotted as a continuous line. The two rises occurred while the halibut was >200 m, with the first rise (B) occurring on 20 January and the second (C) on 25 January, lasting approximately 7 and 3 minutes, respectively.

Spawning rises were identified in the depth time-series of one of the recovered tags. This halibut (ID 202305) occupied waters >200 m from 18 January to 31 January, during which time it conducted two spawning rises, both in St. George Basin. The first was ~150 m in magnitude and occurred on 20 January, while the second was ~75 m in magnitude and occurred on 25 January (Figure 1.5). Spawning rises were not evident in the depth time-series of the other two recovered tags.

*Discussion:*

Halibut in the NBS appear to exhibit a similar annual migratory cycle as individuals from farther south in the species' range. Occupation of shallow continental shelf waters in Norton Basin is likely for foraging purposes, where these fish are predominantly present in the region during the warm months (August, September, and October) when halibut are thought to be primarily foraging (Best, 1979). Various prey species of halibut, such as Pacific Cod and Walleye Pollock, have also been observed inhabiting this region during this time (Mecklenburg et al., 2018; Stevenson and Lauth, 2019). Following the summer feeding period, halibut made large-scale offshore movements, migrating hundreds of kilometers. Unlike in other regions, where some halibut are observed occupying shallow coastal habitat throughout the year (Loher and Seitz, 2006; Nielsen and Seitz, 2017), all fish tagged in the present study undertook this migration. This is likely a result of thermal conditions in the NBS being inhospitable to halibut over long periods of time, when the onset of sea ice results in bottom waters being colder (<0°C) than deeper and more southerly waters in the Bering Sea (Mueter and Litzow, 2008). Halibut were seen moving to both the west and south, presumably to reach these more favorable thermal conditions. It is also possible that winter emigration from the NBS continental shelf is due to the disappearance of available prey, as species such as the Pacific cod have been observed making similar southward movements (Nielsen et al., unpublished).

In addition to escaping the unfavorable NBS winter conditions, the fall migratory movements of halibut are also likely for reproductive purposes. The tagged individuals traveled hundreds of kilometers offshore to deep continental slope waters for the winter months, conditions that correspond to previously inferred halibut spawning depths (Seitz et al., 2005) and spawning season (Loher and Seitz, 2008). Past studies have documented halibut moving large distances to reach winter spawning grounds that ranged from the Gulf of Alaska (Loher and Seitz, 2008) to Pribilof and Middle canyons along the central Bering Sea continental shelf edge (Seitz et al., 2011). In the present study, halibut were observed migrating as far south as Pribilof Canyon in St. George Basin, and as far north as Navarin Basin and the Russian coast. One of the individuals occupying St. George Basin conducted two inferred spawning rises (Figure 1.5), further evidence that these movements and occupation of this region are for spawning purposes. These observations corroborate previous inference on the existence of spawning grounds in the Central Bering Sea that are also thought to be utilized by halibut tagged further south in the Bering Sea (Seitz et al., 2011). Additionally, these observations provide the first evidence of inferred spawning activity in Russian waters by halibut that are commercially targeted within US waters.

Following their winter occupation of offshore habitat, some halibut returned to shallow inshore waters proximate to their initial tagging location. This is an indication of site fidelity to foraging habitat in Norton Basin, where individuals were seen within 14 km of their tagging location after migrating as far as 2400 km during their 1-year at liberty. Fidelity to foraging habitat has been observed in the past in halibut tagged in the Gulf of Alaska (Loher, 2008) and Glacier Bay, Alaska (Nielsen and Seitz, 2017). In contrast, many individuals tagged in the NBS were still hundreds of kilometers away when their scheduled pop-off date was reached, but many of these release locations appear to have occurred while

the fish were still in transit to their summer feeding locations. This is likely due to interannual variability of tagging procedure and ocean conditions in the NBS. When this project was initiated, the NBS was extremely warm (Stabeno and Bell, 2019) and halibut were captured and tagged in July, resulting in their tags being set to release in the following July. In contrast, the following years saw colder conditions, with satellite tag pop-up locations occurring in shelf waters south of the NBS and the NBS fleet reporting limited catches up until mid- to late-August. This suggests that halibut migration occurred later than in warm conditions, with their arrival to the region being delayed due to colder waters. As such, tagging efforts and summer pop-off schedules were instead set to occur in August in the final year of tagging. This yielded summer displacements of 14, 78, and 371 km from initial release locations, supporting the presence of fidelity to NBS foraging habitat.

Despite being primarily a demersal fish species, tagged halibut were also seen utilizing the water column throughout the year. Regardless of where potential human activities and development occur, there is potential for interaction with halibut throughout the entire water column. However, occupation of surface waters was short-term and irregular, predominantly occurring outside of the halibut's spawning season. As such, the probability of interactions between halibut and human activities in surface waters is greatly reduced relative to pelagic species that regularly occupy surface waters, such as the Dolly Varden charr (*Salvelinus malma*) (Seitz et al., 2014), and surface-based human activities are not likely to impact halibut spawning behavior.

While satellite tagging experiments on halibut in the Bering Sea had high success rates in past studies (Seitz et al., 2011; Loher, 2022), the lower success rate seen in this study is likely due to several factors. Poor data transmission occurred due to batteries dying prematurely, resulting in no (n= 20) or a low number of transmissions (n=13). This appears to be a result of faulty batteries from the manufacturer and from tags being deployed at below optimum voltage levels due to long term storage resulting from tagging complications in previous tagging seasons (D. Short, Wildlife Computers Redmond, USA, personal communication). In addition, there were many tags that succeeded in transmitting archived data but did not reach their full deployment length. The anchor for some tags appears to have become dislodged from the fish after a short period at sea as the tag reported prematurely with the release pin intact (n=17); two of these individuals appeared to have been consumed by marine mammals, as several days prior to transmission the tags reported temperatures reflective of mammal viscera (~ 36°C) and repeated rises to the surface, presumably for the animal to breathe (*sensu* Seitz et al., 2019). Furthermore, the programming used to direct the tag to transmit upon reaching the surface (i.e., "premature release detection") failed for seven of these tags, resulting in them floating until their pre-scheduled pop-off date, at which point they began data transmission. The reasons behind this are undetermined.

This study provides the first look at the spatial dynamics of halibut at the northern extreme of their range, providing valuable benchmark information for future assessment of potential interactions with hydrocarbon exploration activities. Halibut were seen seasonally occupying four OCS lease planning areas, which comprise most of the eastern Bering Sea shelf, but were not observed entering Hope Basin in the Chukchi Sea. This suggests that halibut may interact with oil and gas exploration while foraging, spawning, and migrating in the Bering Sea, but not in the Chukchi Sea. While it does not appear as though halibut currently occupy the Chukchi Sea at this juncture, the potential for further northward expansion of halibut into this region in the future remains (Chapter 2). Additionally, predominantly adult females were evaluated herein, and as such this study mainly represents findings from sexually mature individuals from a small portion of the Bering Sea sub-population. With satellite tagging studies having focused on adult individuals, the movements of juvenile halibut remain largely unstudied, and have only

been theorized in the NBS based on larval drift analyses (Sadorus et al., 2020). Additional tagging and monitoring efforts may enable some of these questions to be answered.

## Chapter 2:

### *Introduction:*

Climate change, and associated increases in ocean temperatures, have large-scale impacts on the spatial dynamics of fish species across the globe. As conditions warm, the ranges of fishes expand and contract, resulting in shifts in the spatial extent of fish assemblages (Mueter and Litzow, 2008). This phenomenon is particularly drastic at northern latitudes, where it is resulting in a process known as borealization, in which Arctic specialists are replaced by more boreal, sub-arctic species as they exhibit northward range expansions (von Biela et al., 2022). This has been observed in continental shelf waters throughout the northern hemisphere, including the Barents Sea in the northern Atlantic Ocean and the Bering and Chukchi seas in the northern Pacific Ocean (Mueter et al., 2021). Changes have been particularly drastic in the Pacific Ocean, where the recent disappearance of the Bering Sea deep-water cold pool (Stabeno and Bell, 2019), and transport of warm Pacific water into the Chukchi Sea (Yang and Bai, 2020), have allowed the abundance and range of sub-arctic fish species to increase dramatically (Thoman Jr et al., 2020).

Recent studies have observed gadids exhibiting these northwards shifts, particularly Pacific Cod (*Gadus macrocephalus*) and Walleye Pollock (*Gadus chalcogrammus*). Pacific Cod have displayed a significant increase in abundance in the northern Bering Sea (NBS) (Stevenson and Lauth, 2019), and were observed in the southern Chukchi Sea (SCS) for the first time in 2018 (Cooper et al., 2023). Walleye Pollock juveniles and adults have been observed in the NBS and SCS in insignificant numbers for decades (Mecklenburg et al., 2018), but adults have recently been documented in numbers that may be capable of supporting a commercial fishery (Orlov et al., 2021). The increase of these species has coincided with a decrease in abundance and distribution in the NBS and SCS of Arctic gadids such as Polar (*Boreogadus saida*) and Saffron cods (*Eleginus gracilis*) (Baker, 2021; Kuznetsov et al., 2023). Shifts in available species, and their relative abundance, may have profound impacts on the food security and livelihoods of residents in this region, as they rely heavily on both subsistence and commercial fish harvests. While the ability to harvest traditional Arctic species may decrease, the increasing abundance of sub-arctic species provides new opportunities for residents in the region (Thoman Jr et al., 2020). Additionally, range expansion of sub-arctic fish species may expose them to potential future human activities, such as hydrocarbon exploration, marine resource extraction, and renewable energy development. As such, characterizing and predicting these ongoing shifts in species distributions is critical for both maximizing harvest opportunities and understanding possible interactions with potential future human activities. With continued environmental change, additional fish species may exhibit similar northward movements, such as the Pacific halibut (*Hippoglossus stenolepis*).

The Pacific halibut is a wide ranging and commercially valuable boreal demersal fish species found in Gulf of Alaska and Bering Sea waters (NOAA, 2019). During the winter months, Pacific halibut are known to inhabit deep offshore waters along the continental slope, where they are presumed to spawn (Loher and Seitz, 2008). During the summer months, Pacific halibut migrate into shallow continental shelf waters to forage (Flanigan et al., Chapter 1; Loher, 2008). In the Bering Sea, these foraging areas were thought to occur primarily in the southern portion and the outer shelf domain, but as conditions have warmed, Pacific halibut have expanded into the NBS (Connors et al., 2002), where they are currently targeted by commercial and subsistence fisheries based in Northwestern Alaska, including Nome and Savoonga. Despite this, Pacific halibut still do not occur in sufficient abundance to be targeted in fisheries

north of the Bering Strait in the SCS, although local knowledge suggests that these fish occasionally move this far north. However, Pacific halibut co-occur with and prey on Pacific Cod and Walleye Pollock, both of which have an increasing presence in the SCS (Stevenson and Lauth, 2019). As water temperatures continue to rise, the spatial and temporal extent of thermally suitable habitat in the SCS will increase. This may allow Pacific halibut to utilize the SCS for summer foraging opportunities in the coming years, providing a potentially valuable resource for local residents while concurrently exposing this species to potential future human activities such as hydrocarbon exploration and development. To assess the potential for Pacific halibut to expand into the SCS, this study sought to characterize the thermal environment currently occupied by Pacific halibut in the NBS and compare it to existing bottom temperatures in the SCS to infer potential for range expansion northward.

#### *Methods:*

##### *Data:*

This study compared thermal occupancy data of Pacific halibut collected by electronic tags (Flanigan et al., Chapter 1) to model-generated bottom water temperatures of the Chukchi Sea (Danielson et al., 2020). Thermal time series data were available from 53 pop-up satellite tags attached to Pacific halibut in the northern Bering Sea during 2019–2022. Tags were deployed near Nome and Savoonga, Alaska, during July, August, and September. Wildlife Computers miniPATs (resolution 0.05°C, range -20–50°C) recorded temperature readings at 5-second intervals while affixed to the fish. These data were binned and averaged at 10-minute intervals for every other or every third day of the deployment (Flanigan et al., unpublished) and transmitted to satellites after the tags released from the fish and floated to the ocean's surface.

Chukchi Sea thermal conditions were modeled using the three-dimensional physical Regional Ocean Modeling System (ROMS), a free-surface, hydrostatic primitive equation and finite volume (Arakawa C-grid) ocean circulation model (Shchepetkin and McWilliams, 2005). In particular, the Pan-Arctic ROMS (PAROMS) model was selected (Danielson et al., 2020), which was developed for use in northern latitudes by coupling ROMS with a sea-ice model (Hunke and Dukowicz, 1997; Hunke, 2001; Mellor and Kantha, 1989). The model uses a telescoping grid that extends from south of the Aleutian Islands (50°N) to Iceland (65°N), covering the entire Bering Sea, Arctic Ocean, and Canadian Archipelago. Model resolution varies spatially but is highest for the Chukchi and Beaufort Seas, where it varies from 5–6.5 km (Vestfals et al., 2021). Resolution also varies with depth, with this model containing 50 vertical depth levels that are terrain following, leading to increased resolution in shallower waters and in the depth layers near the ocean bottom and surface. Given the benthic nature of Pacific halibut, temperature output from the bottom layer was selected for this study. Specifically, the mean bottom-water temperature was obtained for each month from June to November, corresponding to the Pacific halibut NBS foraging season and the immediately adjacent months.

##### *Data Analysis:*

###### *Thermal Occupation:*

Thermal occupancy of all tagged Pacific halibut was assessed by aggregating and summarizing transmitted temperature data. For all individuals, the average daily occupied temperature was determined for each day at liberty by averaging across all 10-minute intervals for which temperature recordings were

received. These were then pooled across individuals for each day of the year when data were available, providing a distribution of average daily occupied temperatures for Pacific halibut in the NBS.

To characterize Pacific halibut cold-water tolerance, and hence maximum potential extent of geographic range, the pooled temperature time series were evaluated during May and June when they were occupying continental shelf waters < 200 m, as this corresponds to the time of year and conditions when these fish occupy thermal minimum conditions (Flanigan et al., unpublished). From this period, the 50<sup>th</sup> percentile of pooled average daily temperatures was taken as the cold-water tolerance threshold; this was assumed to provide a conservative functional lower limit for the thermal conditions that Pacific halibut can occupy for an extended period of time, or what is thermally tolerable.

To characterize Pacific halibut thermal conditions, and hence potential geographic range under typical conditions, the thermal time series data were evaluated during August and September, as this corresponds to the peak Pacific halibut summer foraging period in the NBS and the period they are most likely to expand into the SCS. Two thermal ranges were identified during this time: the 50% core range (hereafter referred to as core range) of summer foraging temperatures, which was found by identifying the 25<sup>th</sup> and 75<sup>th</sup> percentiles of occupied thermal conditions, and the 95% range of summer foraging temperatures, which was similarly found by identifying the 2.5 and 97.5 percentiles of occupied thermal conditions.

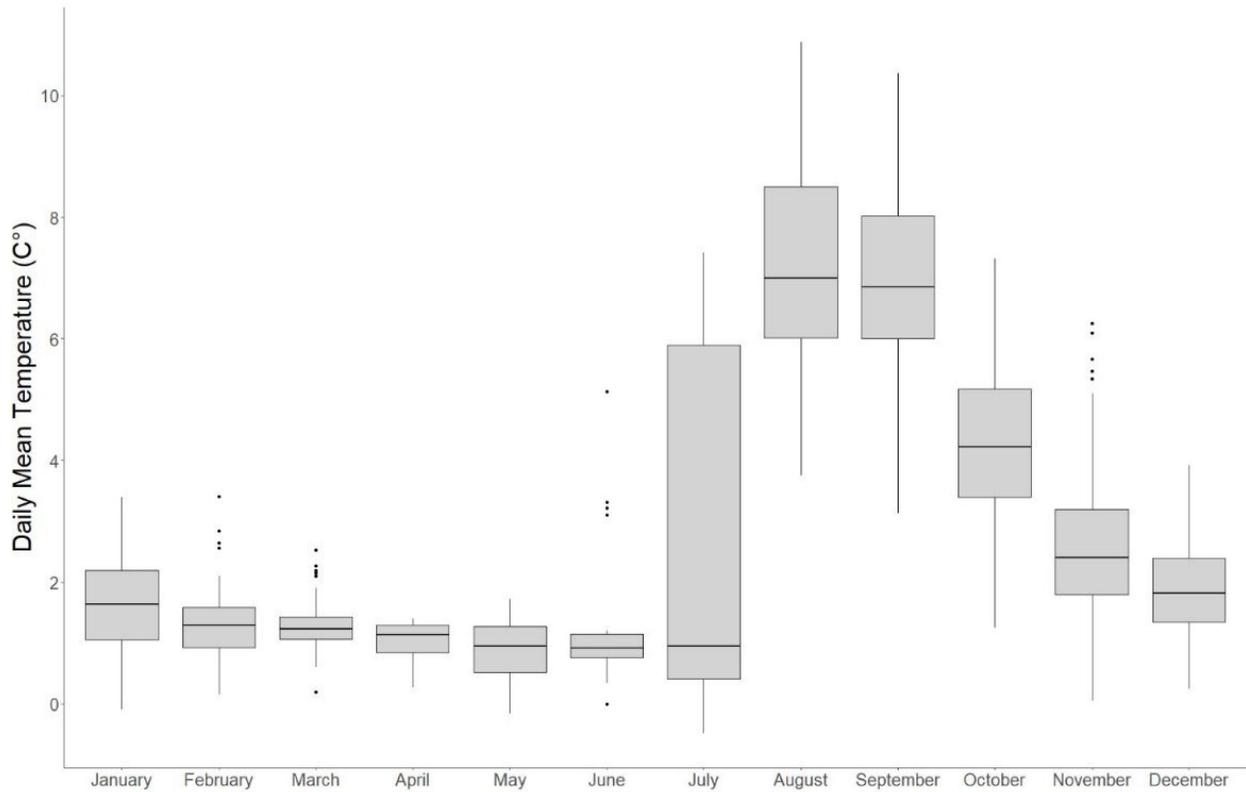
#### *Ocean Conditions:*

The spatial extent of suitable thermal habitat available to Pacific halibut in the SCS during the summer foraging period was inferred in two ways. First, the greatest hypothetical extent of thermal habitat for Pacific halibut was determined by finding all waters that exceeded the cold-water tolerance threshold. Second, the extent of thermal habitat within the core and 95% range of summer foraging conditions in the NBS was determined. These analyses generated three polygons for each month depicting: 1) bottom waters with temperatures within the core range of summer occupancy 2) bottom waters with temperatures within the 95% range of summer occupancy and 3) bottom waters with temperatures below those of summer occupancy, but greater than the cold-water thermal tolerance threshold. To quantify the spatial extent of these conditions, the area (km<sup>2</sup>) of each polygon north of the Bering Strait was calculated.

To understand the impacts of climatic variability on available thermal habitat for Pacific halibut in the SCS, the extent of potential habitat during a recent cold (2012) and warm-water (2019) year were compared. Conditions are known to vary significantly from year to year in this region, with cold-years being characterized by extensive sea ice formation and an expansive deep-water cold pool, while warm-years consist of limited sea ice and reduced cold pool extent (Mueter and Litzow, 2008). This variability in temperature across years in the SCS could have large impacts on the ability, or lack thereof, of Pacific halibut to occupy the region. As such, the impact of thermal variation in the Chukchi sea on the extent of suitable thermal habitat was quantified by comparing the relative change in area of the generated polygons between years, specifically the magnitude of increase in the area of waters within the 95% summer occupancy range between 2012 and 2019.

*Results:*

The Pacific halibut cold-water thermal tolerance threshold was 0.95°C, while the 50% core summer foraging temperatures ranged from 6.00 to 8.2°C and the 95% summer foraging temperature ranged from 3.79 to 9.77°C (Figure 2.1).



*Figure 2.1:* Distribution of mean daily temperatures occupied by individual Pacific halibut (*Hippoglossus stenolepis*) in the northern Bering Sea. Boxplot summaries represent the first and third quartiles, the center bar is the mean and whiskers extend to the 95% level. All observations outside of this range are outliers and represented as points.

In the cold year of 2012, the temporal and spatial extent of summer foraging conditions in the Chukchi Sea was relatively limited (Table 2.1). Suitable thermal foraging conditions were not widely available until August and were completely absent by November. During the period that these conditions were available, they were almost exclusively near the coast of Alaska in the eastern Chukchi Sea (Figure 2.2), with the 95% range covering 70,909 km<sup>2</sup> at their greatest extent during the month of September, with a core ranges of 30,122 km<sup>2</sup>. Waters above the thermal tolerance threshold added an additional 89,940 km<sup>2</sup> of habitat in the central Chukchi Sea during this time, providing a total of 160,849 km<sup>2</sup> of available habitat.

Table 2.1: Extent of suitable thermal habitat (km<sup>2</sup>) for Pacific halibut (*Hippoglossus stenolepis*) in the Chukchi Sea by month in the cold year of 2012. The total habitat represents the sum of the 95% summer and the thermally tolerable waters.

Month	Thermally Tolerable	95% Summer Foraging	Core Summer Foraging	Total Habitat
June	4,483	3,064	1,250	7,547
July	26,041	11,360	3,182	37,401
August	67,885	56,953	19,259	124,838
September	89,940	70,909	30,122	160,849
October	128,879	32,533	0	161,412
November	119,937	0	0	119,937

Table 2.2: Extent of suitable thermal habitat (km<sup>2</sup>) for Pacific halibut (*Hippoglossus stenolepis*) in the Chukchi Sea by month in the warm year of 2019. The total habitat represents the sum of the 95% summer and the thermally tolerable waters. The increase multiplier is the magnitude of increase in available habitat between the 95% summer occupation ranges of 2012 and 2019.

Month	Thermally Tolerable	95% Summer Foraging	Core Summer Foraging	Total Habitat	Increase Multiplier
June	77,578	14,720	1,900	92,298	4.8
July	101,060	86,320	27,706	187,380	7.6
August	98,383	140,265	38,285	238,648	2.5
September	70,493	200,393	43,079	270,886	2.8
October	81,678	254,934	98,665	336,612	7.8
November	253,145	35,348	0	288,493	NA

In the warm year of 2019, the spatial and temporal availability of suitable thermal habitat was far greater than in the cold year, with suitable foraging temperatures in the Chukchi Sea lasting from June to November (Table 2.2). These conditions extended to the western Chukchi Sea, and even excluded the coastal eastern Chukchi Sea during August and September due to conditions being warmer than those currently occupied by Pacific halibut in the NBS (Figure 2.3). Much of the central shelf in the Chukchi Sea warmed to suitable foraging conditions, with September and October providing the greatest spatial extent of suitable habitat, with 200,393 and 254,934 km<sup>2</sup> falling within the 95% range and 43,079 and 98,665 km<sup>2</sup> within the core range, respectively. For months when suitable foraging conditions were available in both years, the warm year provided an average of 5.1 times (range 2.5 to 7.8 times) more thermal habitat within the 95% range of summer occupation than the cold year. Additionally, when combined with thermally tolerable waters during October, the month with the greatest extent of available thermal habitat, a total of 336,612 km<sup>2</sup> was available to Pacific halibut in the Chukchi Sea.

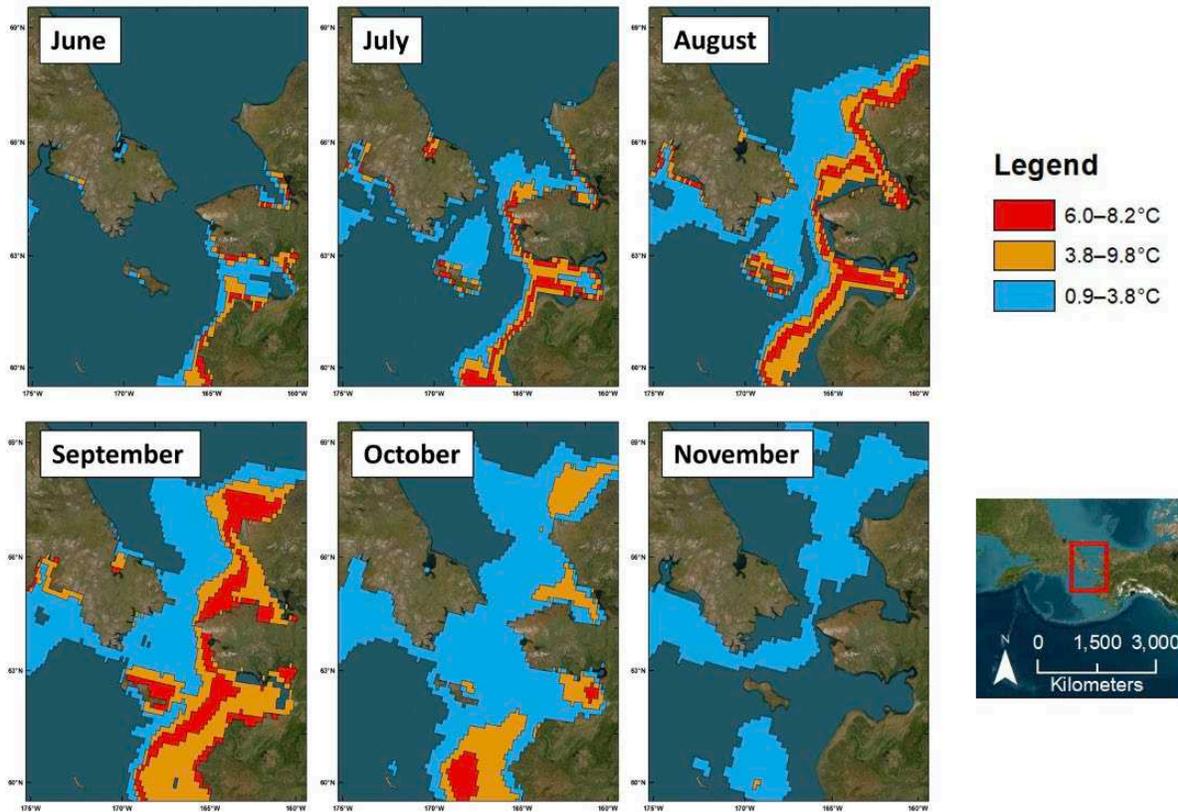
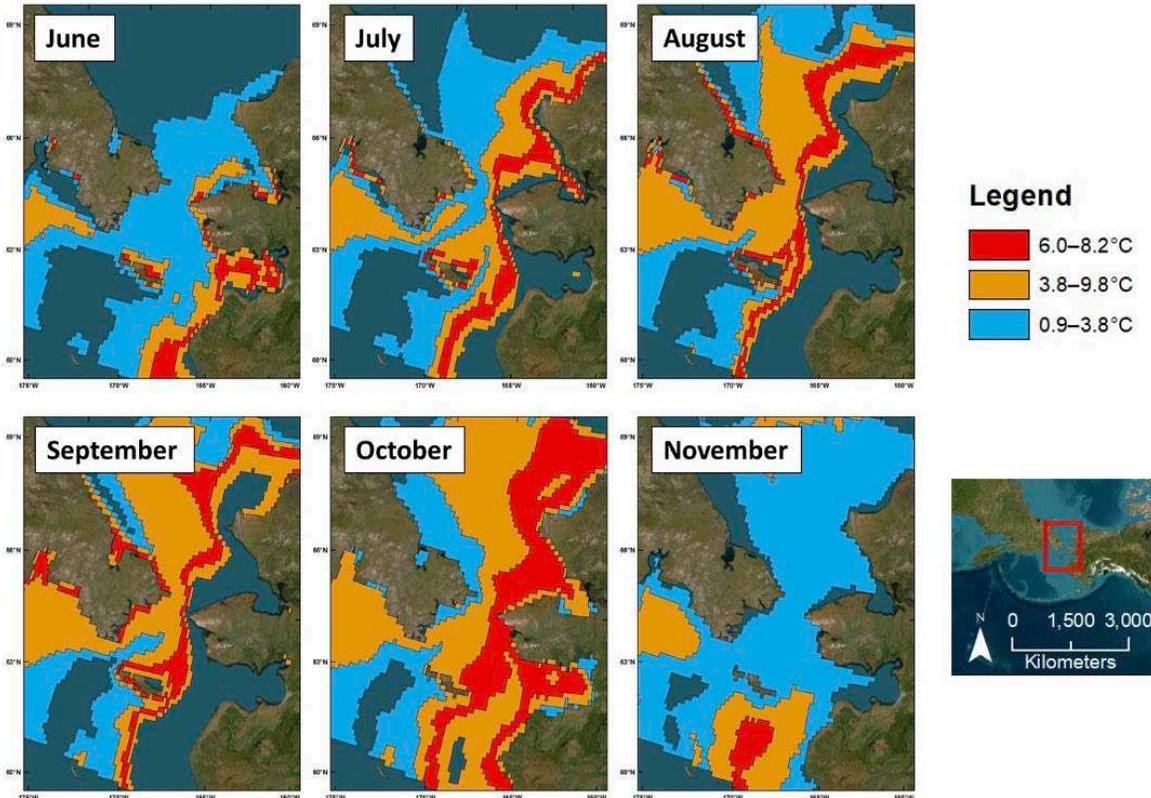


Figure 2.2: Extent of potentially suitable thermal habitat of Pacific halibut (*Hippoglossus stenolepis*) based on monthly mean bottom water temperatures from the pan-arctic Regional Ocean Modeling System output for the Bering and Chukchi seas in 2012. Polygons represent thermal conditions within the 50% core (red) and 95% (orange) thermal occupation range of Pacific halibut, as well as conditions below the lower end of the 95% thermal range and above the thermal minima threshold (blue).

#### Discussion:

A comparison of occupied thermal conditions of Pacific halibut in the NBS with available temperatures in the SCS revealed that the Chukchi Sea portion of the Arctic Ocean contains suitable thermal habitat for this fish species in the summer months, suggesting the potential for this species to move into the region in the coming years. Despite the current availability of suitable thermal habitat and the apparent potential for Pacific halibut to move into the SCS, these fish are not currently encountered in survey efforts, or targeted in directed fisheries, within the region due to their extremely low abundance. As such, other factors may be limiting their expansion into this habitat. One potential explanation for the apparent lack of Pacific halibut occupation in the Chukchi Sea is substrate type. Pacific halibut are known to prefer bottoms composed of gravel and sand, enabling them to settle into the substrate and ambush prey (Bishop et al., 1993; Carlson et al., 2005). The minority of the Chukchi Sea bottom has a high prevalence of mud and clay substrates (Mecklenburg et al., 2007), which may limit the amount of suitable habitat for Pacific halibut. However, the majority of the bottom of the SCS is predominantly gravelly and sandy substrates (Feder et al, 2004), and as the most proximate region to the currently occupied NBS, would be the area Pacific halibut expand into first. As such, it is likely that another factor is responsible for their lack of occupation, such as food availability. Pacific halibut movements into the

NBS are thought to be associated with foraging (Flanigan et al., Chapter 1), where the region apparently supports sufficient opportunities to merit individuals migrating hundreds of kilometers from their overwintering and spawning habitats along the Bering Sea shelf edge. While the abundances of prey fish species have been increasing in the SCS (Baker et al., 2023), the prevalence of these fishes may not yet be sufficient to motivate additional movements into SCS waters, with the energetic cost of reaching the SCS outweighing any potential additional foraging success. This may change in coming years if waters continue to warm and the availability of these prey species continues to increase, similar to what was observed in the Gulf of Alaska in the late 20<sup>th</sup> century (Anderson and Piatt, 1999). Such changes in potential foraging success will increase the likelihood that Pacific halibut expand into this habitat.



*Figure 2.3:* Extent of potentially suitable thermal habitat of Pacific halibut (*Hippoglossus stenolepis*) based on monthly mean bottom water temperatures from the pan-arctic Regional Ocean Modeling System output for the Bering and Chukchi seas in 2019. Polygons represent thermal conditions within the 50% core (red) and 95% (orange) thermal occupation range of Pacific halibut, as well as conditions below the lower end of the 95% thermal range and above the thermal minima threshold (blue).

If Pacific halibut expand into the SCS, there is a potential for the species to become a valuable harvest opportunity for local residents and for possible interactions with potential future human activities such as hydrocarbon exploration. However, the extent of potential occupation of Pacific halibut in the Chukchi Sea in the future is likely highly dependent on whether it is a warm- or cold-water year, as the availability of suitable habitat is correlated with the Pacific Decadal Oscillation and atmospheric blocking in the Bering Sea, both of which have significant impacts on sea ice formation and ocean temperatures (Kodaira et al., 2020). As a result, the distribution and abundance of Pacific halibut may differ greatly across years. Consequently, if Pacific halibut are to be targeted in the SCS in the future, this potential

fishery may be subject to large-scale fluctuations from year to year and may not provide consistent harvest opportunity for local residents. Further, these annual fluctuations will result in varied exposure to hydrocarbon exploration activities among years. This suggests that while Pacific halibut may provide a valuable harvest opportunity when present, and potentially interact with oil and gas explorations, fluctuations in the availability of suitable thermal habitat may change the degree to which these occur from year to year.

Future efforts are needed to monitor these ongoing changes within this region. Currently, models such as PAROMS are suitable for constructing past ocean conditions, but have reduced efficacy projecting these conditions into the future (Haidvogel et al., 2008). As such, diligent survey efforts are needed to quantify ongoing shifts in stock presence and abundance, as well as in ocean conditions. With waters hypothesized to continue warming (Hermann et al., 2021), the number and degree of shifts in fish stocks will likely increase as fish assemblages reorganize. The method presented herein provides a tool to assess the possibility of these shifts, where it can be applied to many sub-arctic fish species with the potential for future range expansion.

## Acknowledgments:

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## Study Products:

Flanigan, A.F., Wehde, D., Loher, T., Seitz, A.C. 2022. Understanding Pacific Halibut (*Hippoglossus stenolepis*) Spatial Dynamics in the Northern Bering Sea. Alaska Marine Science Symposium. Virtual. January 2022. (Poster)

Flanigan, A.F., Wehde, D., Loher, T., Seitz, A.C. 2022. Understanding Pacific Halibut (*Hippoglossus stenolepis*) Spatial Dynamics in the Northern Bering Sea. American Fisheries Society Alaska Chapter. Virtual. March 2022. (Oral)

Flanigan, A.F., Wehde, D., Loher, T., Seitz, A.C. 2022. Understanding Pacific Halibut (*Hippoglossus stenolepis*) Spatial Dynamics in the Northern Bering Sea. American Fisheries Society University of Alaska Fairbanks Student Sub-unit Symposium. Fairbanks, AK. March 2022. (Oral)

Flanigan, A.F., Wehde, D., Loher, T., Seitz, A.C. 2022. Understanding Pacific Halibut (*Hippoglossus stenolepis*) Spatial Dynamics in the Northern Bering Sea. Ecosystem Studies of Subarctic and Arctic Seas. Seattle, WA. June 2022. (Oral)

Flanigan, A.F., Wehde, D., Loher, T., Seitz, A.C. 2022. Understanding Pacific Halibut (*Hippoglossus stenolepis*) Spatial Dynamics in the Northern Bering Sea. PICES. Busan, South Korea. September 2022. (Oral)

Flanigan, A.J., Wehde, D., Loher, T., Seitz, A.C. 2023. Assessing spawning behavior at the northern extreme of Pacific halibut. Alaska Marine Science Symposium. Anchorage, AK, January 2023. (Oral)

Flanigan, A.J., Wehde, D., Loher, T., Seitz, A.C. 2023. Assessing spawning behavior at the northern extreme of Pacific halibut. American Fisheries Society. Fairbanks, AK, March 2023. (Oral)

Flanigan, A.J., Wehde, D., Loher, T., Seitz, A.C. 2023. Assessing spawning behavior at the northern extreme of Pacific halibut. American Fisheries Society Alaska Chapter Student Sub-Unit Symposium. Fairbanks, AK, March 2023. (Oral)

Flanigan, A.J., Wehde, D., Loher, T., Seitz, A.C. 2023. Assessing spawning behavior at the northern extreme of Pacific halibut. Western Groundfish Conference. Juneau, AK, April 2023. (Oral)

Flanigan, A.J., Wehde, D., Loher, T., Seitz, A.C. 2023. Assessing spawning behavior at the northern extreme of Pacific halibut. ICES Annual Meeting. Bilbao, Spain. September 2023. (Oral)

Flanigan, A.J., Wehde, D., Loher, T., Seitz, A.C. 2023. Characterizing the scale of Pacific halibut distribution in the Bering Sea. ICES Annual Meeting. Bilbao, Spain. September 2023. (Poster)

## References:

- Anderson, P.J., Piatt, J.F. 1999. Community reorganization in the Gulf of Alaska following ocean climate regime shift. *Marine Ecology Progress Series*. 189: 117–123
- Baker, M.R. 2021. Contrast of warm and cold phases in the Bering Sea to understand spatial distributions of Arctic and sub-Arctic gadids. *Polar Biology*. 44: 1083–1105
- Baker, M.R., Farley, E.V., Danielson, S.L., Mordy, C., Stafford, K.M., Dickson, D.M.S. 2023. Integrated research in the Arctic-ecosystem linkages and shifts in the northern Bering Sea and eastern and western Chukchi Sea. *Deep Sea Research Part II: Topical Studies in Oceanography*. 208: 1–11
- Best, E.A. 1979. Halibut ecology. *Fisheries Oceanography-Eastern Bering Sea shelf: Northwest and Alaska Fisheries Center Processed Report 79-20*: 127–165
- Bishop, G.H., Hooge, P.N., Taggart, S.J. 1993. Habitat correlates of Pacific halibut and other groundfish species in Glacier Bay National Park. *Proceedings of the Third Glacier Bay Science Symposium*. 1: 215–220
- Carlson, P.R., Hooge, P.N., Cochrane, G.R. 2005. Discovery of 100–160-year-old iceberg gouges and their relation to halibut habitat in Glacier Bay, Alaska. *American Fisheries Society Symposium*. 41: 235–243
- Connors, M.E., Hollowed, A.B., Brown, E. 2002. Retrospective analysis of Bering Sea bottom trawl surveys: regime shift and ecosystem reorganization. *Progress in Oceanography*. 55(1–2): 209–222
- Cooper, D.W., Cieciel, K., Copeman, L., Emelin, P.O., Logerwell, E., Ferm, N., Lamb, J., Levine, R., Axler, K., Woodgate, R.A., Britt, L., Lauth, R., Laurel, B., Orlov, A.M. 2023. Pacific cod or tikhookceanskaya treska (*Gadus macrocephalus*) in the Chukchi Sea during recent warm years: Distribution by life stage and age-0 diet and condition. *Deep Sea Research Part II: Topical Studies in Oceanography*. 208: 105241
- Cui, X., Grebmeier, J.M., Cooper, L.W. 2012. Feeding ecology of dominant groundfish in the northern Bering Sea. *Polar Biology*. 35: 1407–1419
- Danielson, S.L., Hennon, T.D., Hedstrom, K.S., Pnyushkov, A.V., Polyakov, I.V., Carmack, E., Filchuk, K., Janout, M., Makhotin, M., Williams, W.J., Padman, L. 2020. Oceanic routing of wind-sourced energy along the Arctic continental shelves. *Frontiers in Marine Science*. 7: 509
- Feder, H.M., Jewett, S.C., Blanchard, A. 2005. Southeastern Chukchi Sea (Alaska) epibenthos. *Polar Biology*. 28: 402–421

- Grebmeier, J.M., Overland, J.E., Moore, S.E., Farley, E.V., Carmack, E.C., Cooper, L.W., Frey, K.E., Helle, J.H., McLaughlin, F.A., McNutt, S.L. 2006. A major ecosystem shift in the northern Bering Sea. *Science*. 311(5766): 1461–1464
- Haidvogel, D.B., Arango, H., Budgell, W.P., Cornuelle, B.D., Curchitser, E., Di Lorenzo, E., Fennel, K., Geyer, W.R., Hermann, A.J., Lanerolle, L., Levin, J., McWilliams, J.C., Miller, A.J., Moore, A.M., Powell, T.M., Shchepetkin, A.F., Sherwood, C.R., Signell, R.P., Warner, J.C., Wilkin, J. 2008. Ocean forecasting in terrain-following coordinates: Formulation and skill assessment of the Regional Ocean Modeling System. *Journal of Computational Physics*. 227: 3595–3624
- Hermann, A.J., Kearney, K., Cheng, W., Pilcher, D., Aydin, K., Holsman, K.K., Hollowed, A.B. 2021. Coupled modes of projected regional change in the Bering Sea from a dynamically downscaling model under CMIP6 forcing. *Deep-Sea Research Part II*. 194: 1–27
- Hunke, E.C. 2001. Viscous-plastic sea ice dynamics with the EVP model: Linearization issues. *Journal of Computational Physics*. 170(1): 18–38
- Hunke, E.C., Dukowicz, J.K. 1997. An elastic-viscous-plastic model for sea ice dynamics. *American Meteorological Society*. 27(9): 1849–1867
- IPHC. 2023. International Pacific Halibut Commission fishery regulations. Seattle, Washington: International Pacific Halibut Commission. IPHC-2023-FISHR23
- Kinney, J.C., Maslowski, W., Osinski, R., Lee, Y.J., Goethel, C., Frey, K., Craig, A. 2022. On the variability of the Bering Sea cold pool and implications for the biophysical environment. *PLoS One*. 17(4): e0266180
- Kokkairi, T., Waseda, T., Nose, T., Inoue, J. 2020. Record high Pacific Arctic seawater temperatures and delayed sea ice advance in response to episodic atmospheric blocking. *Scientific Reports*. 10: 1–12
- Kuznetsov, M.Yu., Polyanichko, V.I., Syrovatkin, E.V. 2022. Acoustic researches of arctic cod (*Boreogadus saida*) (Gadidae) in the southwestern Chukchi Sea in 2003–2020. *Известия ТИНРО*. 202(3): 580–600
- Loher, T., Seitz, A.C. 2006. Seasonal migration and environmental conditions of Pacific halibut *Hippoglossus stenolepis*, elucidated from pop-up archival transmitting (PAT) tags. *Marine Ecology Progress Series*. 317: 259–271
- 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. *Fisheries Research*. 92(2008): 63–69

- Loher, T., Seitz, A.C. 2008. Characterization of active spawning season and depth for eastern Pacific halibut (*Hippoglossus stenolepis*), and evidence of probable skipped spawning. *Journal of Northwest Atlantic Fishery Science*. 41: 23–36
- Loher, T. & S.M. Stephens. 2011. Use of veterinary ultrasound to identify sex and assess female maturity of Pacific Halibut in nonspawning condition. *North American Journal of Fisheries Management*. 31: 1034–1042
- Mecklenburg, C.W., Stein, D.L., Sheiko, B.A., Chernova, N.V., Mecklenbur, A.T., Holladay, B.A. 2007. Russian-American long-term census of the Arctic: Benthic fishes trawled in the Chukchi Sea and Bering Strait, August 2004. *Northwestern Naturalist*. 88(3): 166–187
- Mecklenburg, C.W., Lynghammar, A., Johannesen, E., Byrkjedal, I., Christiansen, J.S., Dolgov, A.V., Karamushko, O.V., Møller, P.R., Steinke, D., Wienerroither, R.M. 2018. Marine fishes of the Arctic region Volume 2. Conservation of Arctic Flora and Fauna Monitoring Series 28, Norwegian Ministry of Foreign Affairs.
- Mellor, G.L., Kantha, L. 1989. An ice-ocean coupled model. *Journal of Geophysical Research*. 94(C8): 10937–10954
- Mueter, F.J., Planque, B., Hunt Jr, G.G., Alabia, I.D., Hirawake, T., Eisner, L., Dalpadado, P., Chierici, M., Drinkwater, K.F., Harada, N., Arneber, P., Saitoh, S. 2021. Possible future scenarios in the gateways to the Arctic for Subarctic and Arctic marine systems: II. Prey resources, food webs, fish, and fisheries. *ICES Journal of Marine Science*. 78(9): 3017–3045
- Meuter, F.J., Litzow, M.A. 2008. Sea ice retreat alters the biogeography of the Bering Sea continental shelf. *Ecological Applications*. 18(2): 309–320
- NOAA. 2023. Pacific Halibut. [Internet]. [cited 2023 May 16]. Available from: <https://www.fisheries.noaa.gov/species/pacifichalibut>
- Nielsen, A., Sibert, J.R. 2007. State-space model for light-based tracking of marine animals. *Canadian Journal of Fisheries and Aquatic Science*. 64(8): 1055–1068
- Nielsen, J.K., Seitz, A.C. 2017. Interannual site fidelity of Pacific halibut: Potential utility of protected areas for management of a migratory demersal fish. *ICES Journal of Marine Science*. 74(8): 2120–2134
- Nielsen, J.K., Mueter, F.J., Adkison, M.D., Loher, T., McDermott, S.F., Seitz, A.C. 2019. Effect of study area bathymetric heterogeneity on parameterization and performance of a depth-based geolocation model for demersal fishes. *Ecological Modelling*. 402: 18–34

- Nielsen, J.K., Bryan, D.R., Rand, K.M., Arostegui, M.C., Braun, C.D., Galuardi, K., McDermott, S.F. 2023. Geolocation of a demersal fish (Pacific cod) in a high-latitude island chain (Aleutian Islands, Alaska). *Animal Biotelemetry*. 11(29): 1–22
- Orlov, A.M., Rybakov, M.O., Vedishcheva, E.V., Volkov, A.A., Orlova, S.Y. 2021. Walleye pollock *Gadus chalcogrammus*, a species with continuous range from the Norwegian Sea to Korea, Japan, and California: New records from the Siberian Arctic. *Journal of Marine Science and Engineering*. 9: 1141
- Pederson, M.W., Righton, D., Thygesen, U.H., Andersen, K.H., Madsen, H. 2008. Geolocation of North Sea cod (*Gadus morhua*) using hidden Markov models and behavioral switching. *Canadian Journal of Fisheries and Aquatic Sciences*. 65(11): 2367–2377
- Peterson, M.J., Mueter, F., Criddle, K., Haynie, A.C. 2014. Killer whale depredation and associated costs to Alaskan sablefish, Pacific halibut, and Greenland turbot longliners. *PLoS One*. 9(2): e88906
- Shchepetkin, A.F., McWilliams, J.C. The regional oceanic modeling system (ROMS): A split explicit, free-surface, topography-following-coordinate oceanic model. *Ocean Modelling*. 9(4): 347–404
- Seitz, A.C., Wilson, D., Norcross, B.L., 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 Fishery Research Bulletin*. 10(2): 124–136
- Seitz, A.C., Norcross, B.L., Wilson, D., Nielsen, J.L. 2006. Evaluating light-based geolocation for estimating demersal fish movements in high latitudes. *Fish bulletin*. 104(4): 571–578
- Seitz, A.C., Loher, T., Norcross, B.L., Nielsen, J.L. 2011. Dispersal and behavior of Pacific halibut *Hippoglossus stenolepis* in the Bering Sea and Aleutian Islands region. *Aquatic Biology*. 12: 225–239
- Seitz, A.C., Courtney, M.B., Scanlon, B. 2014. Dispersal patterns and summer ocean distribution of adult Dolly varden from the Wulik River, Alaska, evaluated using satellite telemetry. Coastal Marine Institute Final Report for OCS Study BOEM 2014-663.
- Seitz, A.C., Farrugia, T.J., Norcross, B.L., Loher, T., Nielsen, J.L. 2017. Basin-scale reproductive segregation of Pacific halibut (*Hippoglossus stenolepis*). *Fisheries Management and Ecology*. 24: 339–34
- Seitz, A.C., Courtney, M.B., Evans, M.D., Manishin, K. 2019. Pop-up satellite archival tags reveal evidence of intense predation on large immature Chinook salmon (*Oncorhynchus tshawytscha*) in the North Pacific Ocean. *Canadian Journal of Fisheries and Aquatic Sciences*. 76(9): 1608–1615

- Stabeno, P.J., Bell, S.W. 2019. Extreme conditions in the Bering Sea (2017–2018): Record breaking low sea-ice extent. *Geophysical Research Letters*. 46: 8952–8959
- Stevenson, D.E., Lauth, R.R. 2019. Bottom trawl surveys in the northern Bering Sea indicate recent shifts in the distribution of marine species. *Polar Biology*. 42: 407–421
- Teo, S.L.H., Boustany, A., Blackwell, S., Walli, A., Weng, K.C., Block, B.A. 2004. Validation of geolocation estimates based on light level and sea surface temperature from electronic tags. *Marine Ecology Progress Series*. 283: 81–98
- Thoman Jr, R.L., Bhatt, U.S., Bieniek, P.A., Brettschneider, B.R., Brubaker, M., Danielson, S.L., Labe, Z., Lader, R., Meier, W.N., Sheffield, G., Walsh, J.E. 2020. The record low Bering Sea ice extent in 2018: Context, impacts, and an assessment of the role of anthropogenic climate change. *American Meteorological Society*. 101(1): S17–S22
- Vestfals, C.D., Mueter, F.J., Hedstrom, K.S., Laurel, B.J., Petrik, C.M., Duffy-Anderson, J.T., Danielson, S.L. 2021. Modeling the dispersal of Polar cod (*Boreogadus saida*) and Saffron cod (*Eleginus gracilis*) early life stages in the Pacific Arctic using a biophysical transport model. *Progress in Oceanography*. 196: 102571
- von Biela, V.R., Laske, S.M., Stanek, A.E., Brown, R.J., Dunton, K.H. 2022. Borealization of nearshore fishes on an interior Arctic shelf over multiple decades. *Global Change Biology*. 29: 1822–1838
- Yang, Y., Bai, X. 2020. Summer changes in water mass characteristics and vertical thermohaline structure in the eastern Chukchi Sea, 1974–2017. *Water*. 12 (5): 1434

## Appendix:

Table A1: Deployment information for pop-up satellite archival tags attached to 84 Pacific halibut (*Hippoglossus stenolepis*) in the northern Bering Sea. For tags that successfully transmitted, the date the tag began transmitting data, and the number of messages sent to satellites, is provided. Additionally, when the tag provided a useful end location, the horizontal displacement (km) of the tag from its tagging location is provided.

TAG ID	FORK LENGTH	RELEASE DATE	TAGGING REGION	DEPLOYMENT OUTCOME <sup>A</sup>	POP-UP DATE	HORIZONTAL DISPLACEMENT	MESSAGES
182704	102	7/19/19	Nome	No Report			
182705	103	7/17/19	Nome	No Report			
182706	130	7/19/19	Nome	No Report			
182707	132	7/17/19	Nome	Floater	3/20/20		313
182708	141	7/19/19	Nome	No Report			
182709	118	7/19/19	Nome	Premature	8/15/19		6042
182710	113	7/17/19	Nome	No Report			
182711	104	7/17/19	Nome	No Report			
182712	124	7/17/19	Nome	No Report			
182713	120	7/17/19	Nome	No Report			
182715	89	9/9/19	Savoonga	Good	1/15/20	437	2846
182716	108	9/9/19	Savoonga	Good	1/15/20	401	1235
182718	108	9/9/19	Savoonga	Premature	9/9/19		3301
182720	126	9/8/19	Savoonga	Good	3/5/20	644	2185
182721	112	9/8/19	Savoonga	Floater	9/8/20		4174
182722	97	9/9/19	Savoonga	Good	9/8/20	41	5127
202294	95	7/30/20	Nome	Premature	9/24/20		4945
202295	112	7/30/20	Nome	Floater	4/1/21		2220
202296	94	7/30/20	Nome	Good	2/18/21	927	2261
202297	100	7/30/20	Nome	Good	4/2/21	677	1793
202298	90	7/30/20	Nome	Floater	9/29/20		3662
202299	113	7/30/20	Nome	Good	4/2/21	916	2237
202300	92	7/30/20	Nome	Good	7/21/21	596	3708
202301	98	7/30/20	Nome	Good	4/18/21	836	1826
202302	94	7/30/20	Nome	Good	7/21/21	365	8575
202303	90	7/30/20	Nome	Floater	12/29/20		4334
202304	91	7/30/20	Nome	Premature	10/5/20		5080
202305	115	7/30/20	Nome	Good	7/22/21	40	1264
202318	147	7/30/20	Nome	Premature	10/13/20		7720
202319	101	7/30/20	Nome	Premature	9/17/20		1741
202320	121	7/30/20	Nome	No Report			
202321	91	7/30/20	Nome	Good	3/2/21	871	2118
202322	89	7/30/20	Nome	Floater	7/20/21		5232
202323	95	7/30/20	Nome	Premature	9/10/20		7386
202324	131	7/31/20	Nome	Good	7/21/21	54	2663
202325	96	7/31/20	Nome	Premature	9/3/20		7575
202339	116	7/30/20	Nome	No Report			
202340	160	7/30/20	Nome	No Report			
202341	103	7/30/20	Nome	Good	3/16/21	845	2154
202342	92	7/30/20	Nome	Good	3/16/21	815	2145
202343	120	7/30/20	Nome	Floater	3/15/21		3443
202336	112	8/18/21	Nome	Good	7/5/22	660	5490
202337	136	8/1/21	Nome	Good	7/16/22	225	2971

TAG ID	FORK LENGTH	RELEASE DATE	TAGGING REGION	DEPLOYMENT OUTCOME <sup>A</sup>	POP-UP DATE	HORIZONTAL DISPLACEMENT	MESSAGES
202338	106	8/3/21	Nome	Poor Data	7/16/22	469	29
220912	129	9/9/21	Nome	Good	3/20/22	791	3298
220915	100	8/18/21	Nome	No Report			
220918	116	8/1/21	Nome	Premature	11/3/21		1608
220922	116	8/4/21	Nome	No Report			
220923	110	8/3/21	Nome	Good	3/20/22	799	1923
202306	108	7/23/21	Savoonga	Good	7/16/22	515	2067
202307	130	8/31/21	Savoonga	Good	7/16/22	444	6224
202311	121	7/23/21	Savoonga	Good	5/13/22	675	1179
202313	100	8/31/21	Savoonga	No Report			
202314	102	8/31/21	Savoonga	Good	3/16/22	565	2171
202316	105	8/31/21	Savoonga	Poor Data	3/16/22	636	609
202326	128	7/19/21	Savoonga	Poor Data	3/22/22	530	15
202331	103	8/31/21	Savoonga	Premature	10/19/21		2245
202333	116	8/31/21	Savoonga	Poor Data	4/19/22	717	19
202334	101	8/31/21	Savoonga	Good	3/17/22	620	1120
220913	118	8/18/22	Nome	Good	3/16/23	765	402
220914	107	8/19/22	Nome	Good	3/16/23	1022	1484
220916	111	8/19/22	Nome	Poor Data	3/22/23		18
220917	107	8/19/22	Nome	No Data	3/26/23		3
220919	129	8/19/22	Nome	Good	3/16/23	695	585
220920	120	8/19/22	Nome	Poor Data	3/26/23		52
220921	128	8/18/22	Nome	Good	3/19/23	696	848
220924	108	8/19/22	Nome	Poor Data	3/16/23		36
220925	105	8/19/22	Nome	Poor Data	3/16/23	816	145
220926	108	8/19/22	Nome	No Report			
220927	120	8/19/22	Nome	No Report			
220928	114	8/19/22	Nome	No Report			
220929	106	8/19/22	Nome	Good	8/16/23	14	2380
202308	103	8/26/22	Savoonga	Poor Data	6/7/23		147
202309	111	8/26/22	Savoonga	No Report			
202310	101	8/23/22	Savoonga	Good	8/16/23	371	2333
202312	139	8/26/22	Savoonga	Good	8/16/23	78	585
202315	175	8/26/22	Savoonga	No Report			
202317	107	8/26/22	Savoonga	Good	3/16/23	547	1350
202327	116	8/23/22	Savoonga	Poor Data	3/16/23	639	1064
202328	154	8/26/22	Savoonga	Good	3/16/23	804	966
202329	113	8/23/22	Savoonga	Poor Data	3/26/23	305	21
202330	107	8/26/22	Savoonga	Good	3/16/23	569	927
202332	127	8/24/22	Savoonga	No Report			
202335	144	8/24/22	Savoonga	Poor Data	3/22/23	390	45

<sup>A</sup> “Good Data” refers to tags that released from fish after 1 January and transmitted both robust time-series data and a viable end location. “Poor Data” refers to tags that released from fish after 1 January and either failed to provide a viable end location or only transmitted time-series data for a small number of days. “No Data” refers to tags that communicated with satellites but failed to transmit any usable data. “Premature” refers to tags that reached the surface and began data transmission prior to 1 January. “Floater” refers to tags detached from the fish prematurely but did not begin transmission until the scheduled pop-up date. “Missing” refers to tags that failed to transmit to satellites and were unaccounted for.

Supplementary Study Photos:



























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