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Pacific Cod Satellite Tagging Results from Gulf of Alaska Deployments: Spring 2021

K. M. Rand, C. Levy, S. McDermott, J. Nielsen, B. K. Prohaska,
R. Haehn-Tam, E. Dawson, A. Dowlin, and E. H. Markowitz

August 2026

U.S. DEPARTMENT OF COMMERCE

National Oceanic and Atmospheric
Administration
National Marine Fisheries Service
Alaska Fisheries Science Center

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Pacific Cod Satellite Tagging Results from Gulf of Alaska Deployments: Spring 2021

K. M. Rand¹, C. Levy², S. McDermott³, J. Nielsen⁴, B. K. Prohaska³, R. Haehn-Tam³, E. Dawson⁵, A. Dowlin³, and E. H. Markowitz³

¹Atka Blue LLC
516 Holly Avenue
Marshfield, WI 54449-3125

²Aleutians East Borough
Anchorage Office
3380 C St., Suite 205
Anchorage, AK 99503

³Resource Assessment and Conservation
Engineering Division
Groundfish Assessment Program
Alaska Fisheries Science Center
National Marine Fisheries Service
National Oceanic and Atmospheric Administration
7600 Sand Point Way N.E.
Seattle, WA 98115-6349

⁴Kingfisher Marine Research, LLC
1102 Wee Burn Dr.
Juneau, AK 99801

⁵Bureau of Ocean Energy Management U. S.
Department of the Interior 45600 Woodland Rd
Sterling, VA 20166

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Administration National Marine Fisheries Service
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ABSTRACT

In March 2021 the Pacific Cod Tagging Team, a collaboration among the Aleutians East Borough, Kingfisher Marine Research, and NOAA's Alaska Fisheries Science Center, conducted a Pacific cod (*Gadus macrocephalus*) research tagging cruise in the western Gulf of Alaska (GOA) (170°W to 159°W).

The scientific and vessel crews tagged and released 25 Pacific cod with Wildlife Computers miniPAT pop-up satellite tags and 960 cod with Floy conventional T-bar tags. This was the first Pacific cod satellite tagging study in the western GOA to take place. Additionally, 155 biological samples were collected from non-tagged Pacific cod that included length, weight, sex, maturity stage, otoliths for age estimation, and tissue samples for genetic analyses.

Of the 25 satellite tags deployed from the western GOA, 23 successfully transmitted data with pop-up locations from the western GOA (n=10), central GOA (defined as 159°W to 147°W) (n=1), eastern Bering Sea (n=6), northern Bering Sea (n=4), US Chukchi Sea (n=1), and Russia (n=1). This technical memorandum presents a general overview of methods, key contextual results, and each individual fish's reconstructed movement path during its time at liberty.

CONTENTS

ABSTRACT	iii
SCIENTIFIC PURPOSE	1
METHODS	2
TAGGING PROCEDURES	3
Pop-up Satellite Archival Tags (PSATs)	3
Conventional Tags (Floy T-Bar)	3
Stationary Tags	4
Pop-up Satellite Archival Tags (PSATs) Analysis	4
BIOLOGICAL SAMPLES	4
RESULTS	5
Individual Fish Tag Results (PSATs)	13
Tag 204891	14
Tag 208539	15
Tag 209230	16
Tag 208537	17
Tag 204884	18
Tag 204889	19
Tag 208534	20
Tag 204886	21
Tag 204885	22
Tag 204890	23
Tag 209231	24
Tag 204894	25
Tag 204895	26
Tag 204893	27
Tag 208538	28
Tag 209232	29
Tag 209229	30

Tag 209228	31
Tag 209234	32
Tag 204892	33
Tag 204888	34
Tag 204887	35
Tag 209233	36
DISCUSSION	37
ACKNOWLEDGMENTS	39
CITATIONS	40

SCIENTIFIC PURPOSE

Recent marine heatwaves have contributed to substantial changes in Pacific cod (*Gadus macrocephalus*) abundance in the Gulf of Alaska (GOA). These events have been linked to increased mortality, reduced recruitment, and potential summer migrations of adult fish into cooler Bering Sea (BS) waters (Barbeaux et al. 2021). Given the ecological and economic importance of Pacific cod, understanding how environmental variability influences their distribution and connectivity is critical for effective fisheries management.

Pacific cod support one of the largest groundfish fisheries in Alaska and serve an important ecological role as mid-level predators. Tracking Pacific cod is essential to ensure sustainable management because stock assessments, harvest limits, and spatial management measures depend on accurate assumptions about population structure, distribution and movement. If these fish move between the GOA and BS management regions in response to environmental conditions, current stock boundaries and assessment frameworks may not fully reflect biological reality.

During winter, Pacific cod aggregate to spawn. During this time, at least part of the population undertakes large seasonal migrations (Shimada and Kimura 1994; Rand et al. 2014). While winter spawning migrations are relatively well documented (Neidetcher et al. 2014), less is known about movements during the non-spawning period. Improved understanding of these movements is especially important because federal bottom trawl surveys occur biennially in the GOA (Siple et al. 2024) and annually in the BS (Markowitz et al. 2023) during the summer months, and survey timing may not fully capture seasonal redistribution.

Satellite telemetry studies, using pop-up satellite archival tags (PSATs), are a powerful tool for reconstructing spatial movements, seasonal habitat use, and behavioral patterns (Nielsen et al., 2023). PSATs are attached to the fish's dorsal fin and record real-time, depth, temperature, and ambient light. After a pre-programmed deployment period, the tags detach, float to the surface, and transmit data to the Argos satellite network that can be accessed remotely by researchers. Geolocation models use these data to estimate daily positions and associated uncertainties.

The primary objective of this study was to examine movement from winter and spring spawning grounds to summer feeding areas. Satellite tagging in the western GOA began in 2021 to better characterize seasonal and interannual Pacific cod movements outside the summer months and to assess connectivity between GOA and BS regions. Similar studies in the Aleutian Islands and the northern Bering Sea (Bryan et al. 2021; Nielsen et al. 2023, 2025) provided the foundation for expanding similar research into the GOA. These tag data represent the first satellite tagging study of Pacific cod movement in the GOA. This study provides critical information on seasonal migration patterns and connectivity among western GOA, central GOA, and BS cod populations; information directly relevant to stock assessment and spatial management decisions.

In addition to satellite tagging, during this study we opportunistically tagged and released 100s of Pacific cod with conventional Floy T-Bar tags across each study area. We know the release location and if the fish is recovered by fishers, a recovery location. This provides another source of information about Pacific cod movement within the GOA and BS, and significantly lower unit cost compared to satellite tagging. Conventional tag recaptures provide additional, though more coarse-scale, information about the movement of fish as well as growth, age, and other important biological information.

A secondary objective was to collect biological samples from cod across western GOA fishing locations to characterize population age structure, length distribution, genetic origin (if applicable), and spawning condition. These biological data complement movement information and help evaluate stock structure and demographic variability.

Satellite tagging and modeling methods are detailed in Nielsen et al. (2019, 2023, 2025) and Bryan et al. (2021). In this Technical Memorandum, we summarize PSAT releases conducted in the GOA in spring 2021, present key biological metrics, and provide reconstructed movement paths for individual tagged Pacific cod.

METHODS

A single Pacific cod PSAT release event took place in the western GOA between March 18 and March 26, 2021. Scientists from the Aleutians East Borough (AEB) and NOAA's Alaska Fisheries Science Center (AFSC) embarked on a research cruise to tag Pacific cod with satellite and conventional tags across the western GOA. All satellite and conventional tags were released from eight selected sites that extended across the western GOA (170°W to 159°W). This border also corresponds to the federal fishery management boundary separating the western and central GOA (Fig. 1). These eight selected sites are frequented by the commercial fishermen targeting Pacific cod during the winter months and are known as Pacific cod winter spawning areas. The tagging platform was the 58 ft. commercial pot fishing vessel FV *Decision*, chartered by the AEB for the purpose of this study.

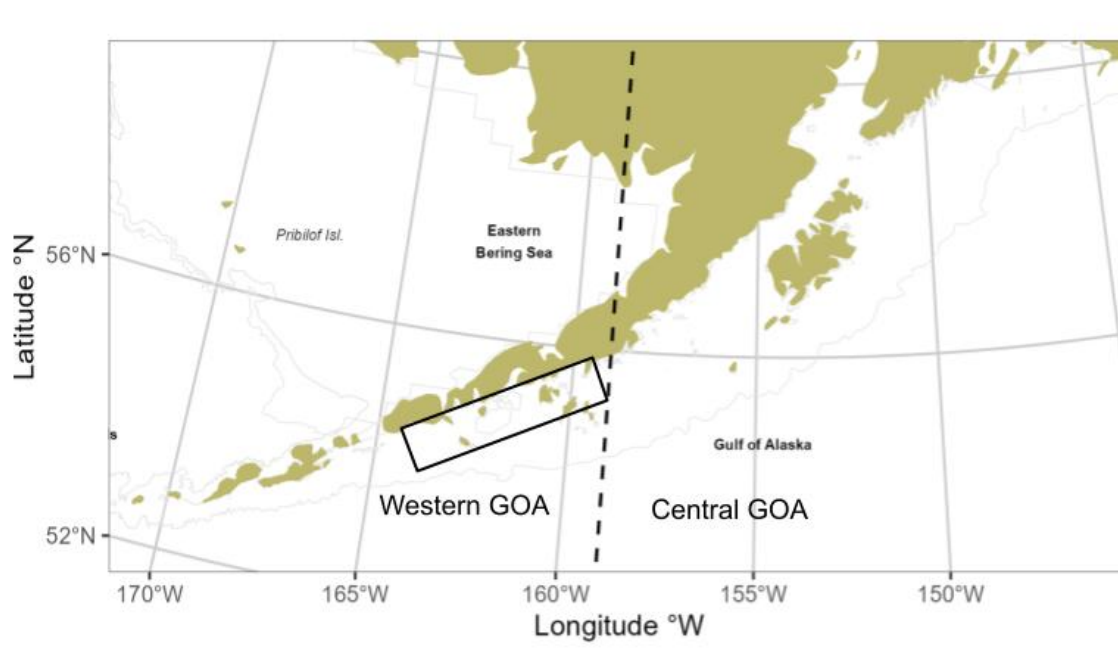


Figure 1. -- Map of Alaska water regions labeled with western GOA (Gulf of Alaska), central GOA, and eastern Bering Sea. The dashed line demarcates the federal fishery management boundary between the western and central GOA. The black box represents the general area for the eight Pacific cod tagging sites.

TAGGING PROCEDURES

All tagging procedures, including evaluations of tagging-related, natural, and fishing mortality, were described during the 2019 pilot study (Bryan et al. 2021). In general, fish were captured using baited commercial cod pot gear, with soak times ranging from 2 to 4 h. Pot retrieval methods, fish handling procedures, and release protocols are further detailed in previous studies (Bryan et al. 2021; Nielsen et al. 2023; Nielsen et al. 2025).

Although mortality estimates are not explicitly incorporated into PSAT analyses, these evaluations were used to refine handling and release methods to minimize tagging-related impacts. In particular, retrieval and release procedures were developed to reduce the effects of barotrauma associated with rapid decompression during capture from depth.

While some external signs of barotrauma, including gas release at the surface, could not be entirely avoided, tag data provided continued feedback on post-release behavior and survival, allowing assessment of fish condition following release. High tag reporting and recapture rates across years support the conclusion that the tagging approach was minimally invasive and that most tagged fish resumed normal behavior following release.

Pop-up Satellite Archival Tags (PSATs)

The PSATs used in this study were Wildlife Computer MiniPATs (<https://static.wildlifecomputers.com/MiniPAT-Product-Sheet-1.pdf>). In order to keep surface time to a minimum, only 1-2 Pacific cod per pot that looked vigorous, healthy and measured greater than 50 cm fork length were selected for Satellite tagging. After being carefully brought on board, each fish was placed in a tagging cradle and had continuous sea water circulating over its gills. Length measurements, locations, and times were recorded during the tagging process. The PSATs were attached with custom harnesses by inserting coated wire through harness pads and the pterygiophores directly under the first dorsal fin (Bryan et al. 2021). Tagging procedures and release were kept below 5 minutes to prevent further damage from barotrauma while on the surface. After the fish was tagged, a weighted descending device attached to a recreational rod and reel equipped with a line counter was clipped to the lower lip of each fish. The fish was kept in the tagging cradle and lowered into the water just below the surface to recuperate and allow for a visual confirmation that the fish was recovering. The fish was lowered to and released at 50 ft using the descending device. Images of the tagging and release procedure can be found in Markowitz et al. 2025b.

Conventional Tags (Floy T-Bar)

Pacific cod that were not used for PSAT tagging were opportunistically tagged with conventional Floy T-bar tags. The fish were brought onboard, placed in a tagging cradle, measured, and tagged with two T-bar tags. A T-bar tag was placed on each side of the first dorsal fin to accommodate the potential for tag loss. The T-bar tags are inserted with a hand-held pistol grip tagging device (<https://floytag.com/>). The fish were released back into the water near their capture point, without a descender. Conventional tagging relies entirely on recapture of the tagged fish by fishermen. If a Floy T-bar tagged fish was recaptured by a fisher(s) or fishery, information like date and time of capture, location of capture, bottom depth, and size of fish was reported.

Stationary Tags

During the western GOA research cruise, three stationary PSATs were deployed near the sea floor where the fish were released (Table 1). Stationary PSATs were used to collect data at known locations to calibrate the geolocation model. These tags were programmed to pop-off and transmit data after 365 days. The stationary tags were attached to an 8-inch plastic trawl float with 1 meter of ½-inch Blue Steel braided rope, which was attached to a weight. The stationary satellite pop-up tag recorded bottom temperature and light conditions near where the satellite-tagged Pacific cod were released.

Pop-up Satellite Archival Tags (PSATs) Analysis

There are two ways data is obtained from a PSAT: the PSAT releases successfully from a fish at a pre-programmed time and begins data transmission to satellites from the open ocean, then to Wildlife Computers (transmitted tag); PSAT is physically recovered from a fish that is captured by a fishing vessel and returned to NOAA (detailed tag). Detailed PSATs provide a rich, detailed dataset compared to transmitted PSATs, however, these account for less than 3% of PSATs with available data.

For each fish with a recovered PSAT, basic deployment information is recorded. This information includes fish length, dates and locations of release and recovery, and the number of days at liberty. For each individual PSAT tagged fish, a map of the reconstructed travel path using the geolocation hidden Markov model (HMM) is shown. The HMM model is based on light and depth data transmitted by the PSAT (Nielsen et al. 2023). Reconstructed travel paths consist of daily point location estimates generated by the Viterbi algorithm and estimated error polygons that encompass the highest 50% and 99% of the HMM posterior probability each day (Nielsen et al. 2023). Note that the reported distance traveled is the cumulative distance between successive Viterbi daily point estimates, not straight-line distances between release and recovery locations. Full details of the analytical methods are provided in Nielsen et al. (2023).

BIOLOGICAL SAMPLES

We collected biological samples from non-tagged Pacific cod across five of the eight selected sites in the western GOA (approximately 30 randomly selected specimens per site). Biological samples collected included sex, length, weight, otoliths, genetic samples, and stomach content pictures from fish with non-empty stomachs. In addition, we collected a small tissue sample (fin clip) from PSAT tagged fish for genetic processing. Genetic fin clip samples were placed in 100% ethanol. Otoliths were extracted and stored dry in plastic vials to be placed in a glycerol thymol solution in Seattle. Subsamples for maturity were placed in a small container of 10% formalin. All biological samples were analyzed at the AFSC in Seattle, WA.

RESULTS

A total of 25 Pacific cod were affixed with PSATs and released during the research cruise across eight selected sites in the western GOA (Fig. 2, Table 1). One PSAT was recovered by a fishing vessel and returned to NOAA. Of the 25 satellite tags deployed from the western GOA, 23 successfully transmitted data after they popped up to the surface from the following locations:

- Western GOA (n=10)
- Central GOA (n=1)
- eastern Bering Sea (n=6)
- northern Bering Sea (n=4)
- Chukchi Sea (US) (n=1)
- Russia (n=1)

A total of 960 Pacific cod were tagged with Floy T-bar conventional tag across five of the eight selected sites in the western GOA (Fig. 3). Of the 960 conventionally tagged Pacific cod, a total of 15 were recovered by the commercial fishery, nine from the western GOA and six from the eastern Bering Sea.

The average fork length of the PSAT tagged fish ranged from 60 to 91 cm (Fig. 4). The average fork length of the Floy T-bar tagged fish ranged from 41 to 101 cm (Fig. 4).

PSAT Pacific Cod Tag Release and Recovery Locations

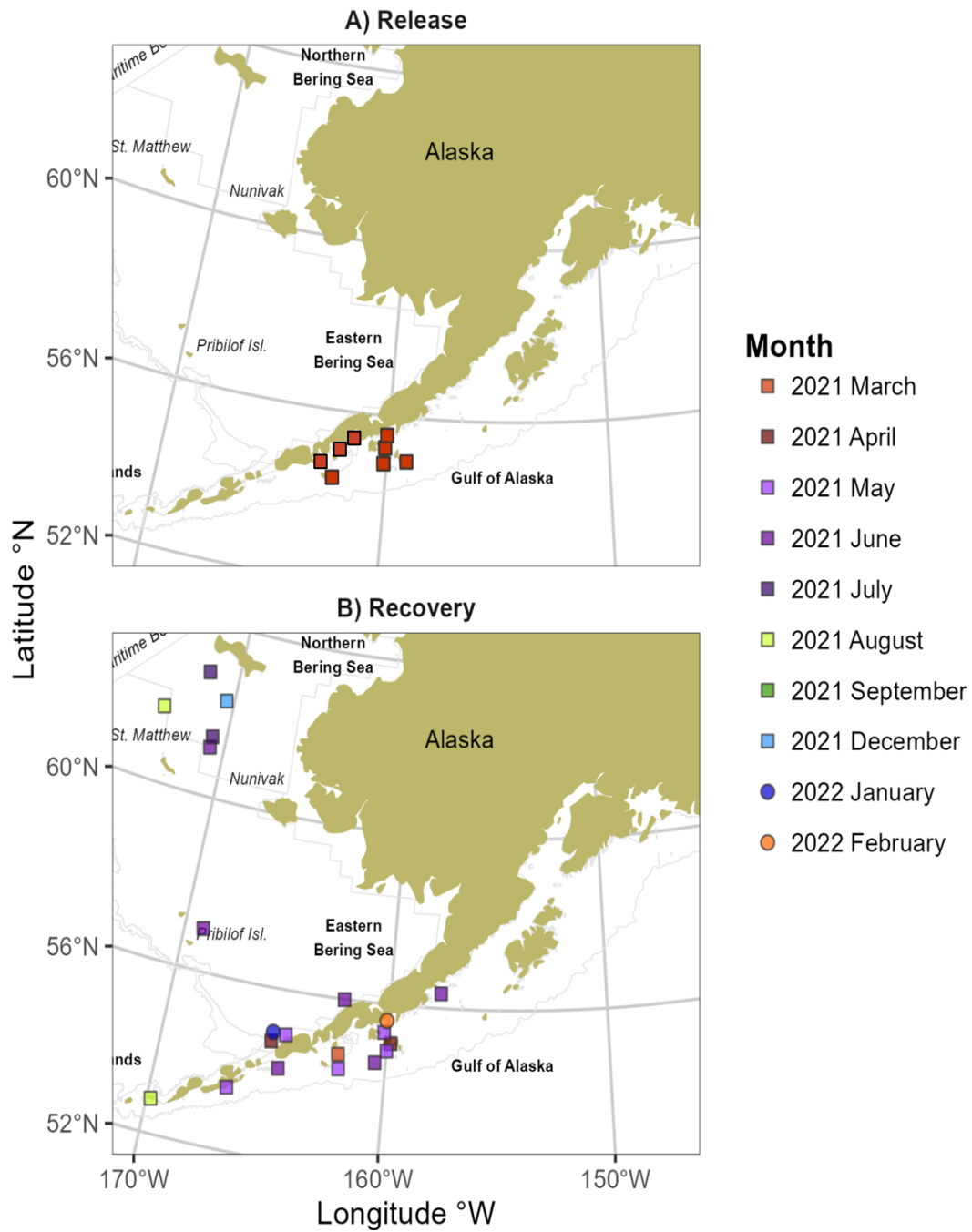


Figure 2. -- Map of where PSAT tagged Pacific cod were A) released and B) recovered, by year and month (denoted by color and shape). Colors vary by month and year of recovery. Only months where there was a PSAT recovery are shown in the legend.

Floy T-Bar Pacific Cod Tag Release and Recovery Locations

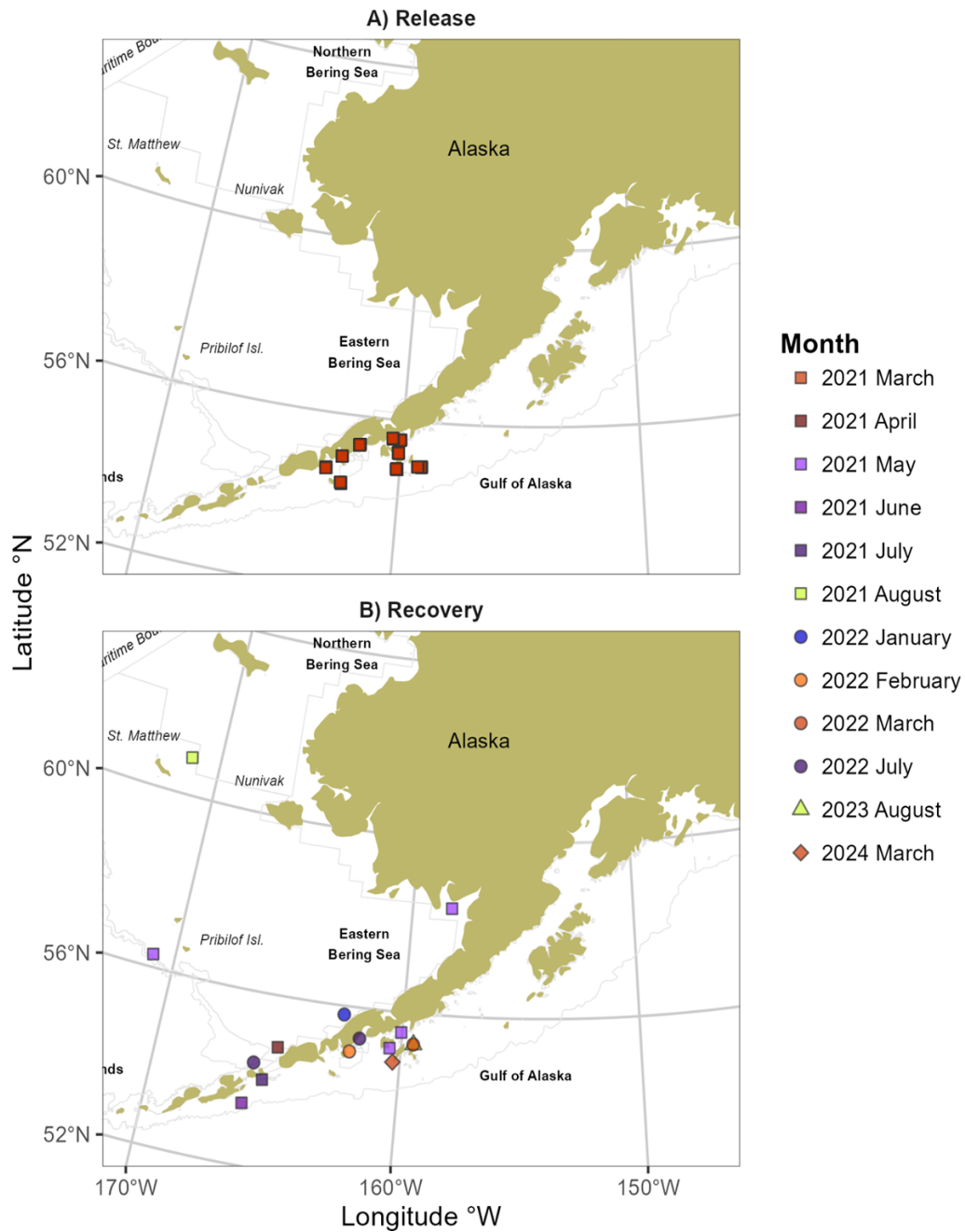


Figure 3. -- Map of where Floy T-bar tagged Pacific cod were A) released and B) recovered, by year and month (denoted by color and shape). Colors vary by month and year of recovery. Only months where there was a Floy T-bar tag recovery are shown in the legend. These recoveries are based solely on fishery capture and reporting.

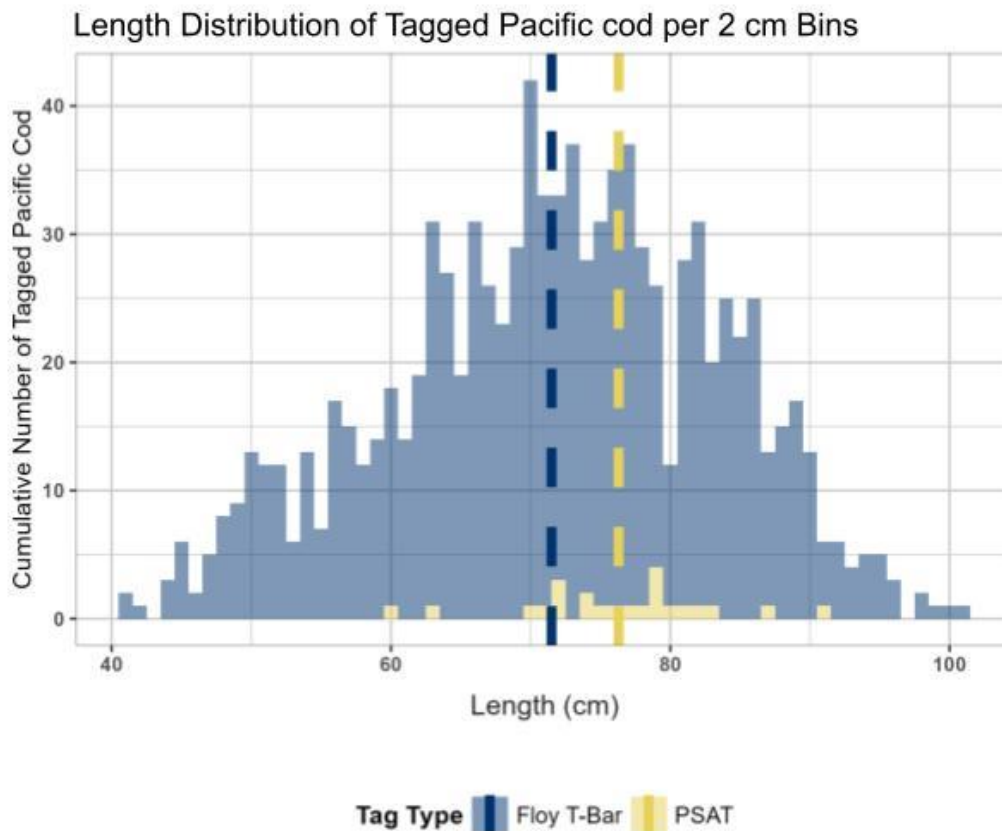


Figure 4. -- Stacked histogram of tagged Pacific cod in 2 cm bins. Twenty-three PSAT tagged Pacific cod that successfully transmitted data had average fork lengths of 76.3 cm (dashed yellow line). Nine hundred and fifty-seven Pacific cod tagged with Floy T-Bar tags had average fork lengths of 71.5 cm (dashed blue line).

A total of 155 biological samples from non-tagged Pacific cod were collected.

Pacific cod average length and weight from the biological samples are summarized as follows: female fish had an average length of 75.1 cm and average weight of 4.84 kg ($n = 82$), and male fish had an average length of 69.3 cm and average weight of 3.6 kg ($n = 73$; Fig. 5).

Pacific cod spawning stages from the biological samples are summarized as follows: for female fish, 1 developing, 3 immature, 17 pre-spawn, and 61 spent female fish. For males, there were 2 immature, 2 pre-spawn, 29 spawning, and 40 spent male fish (Fig. 6).

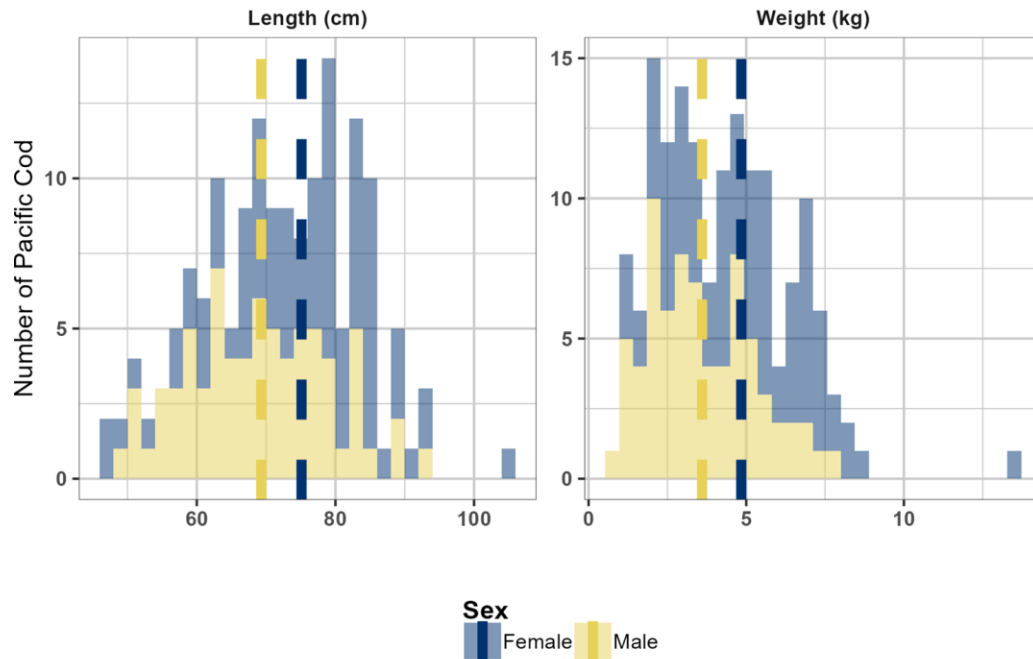


Figure 5. -- Average fork length (cm) and weight (g) by sex for 155 randomly collected non-tagged Pacific cod from the western GOA during the March 2021 tag release cruise.

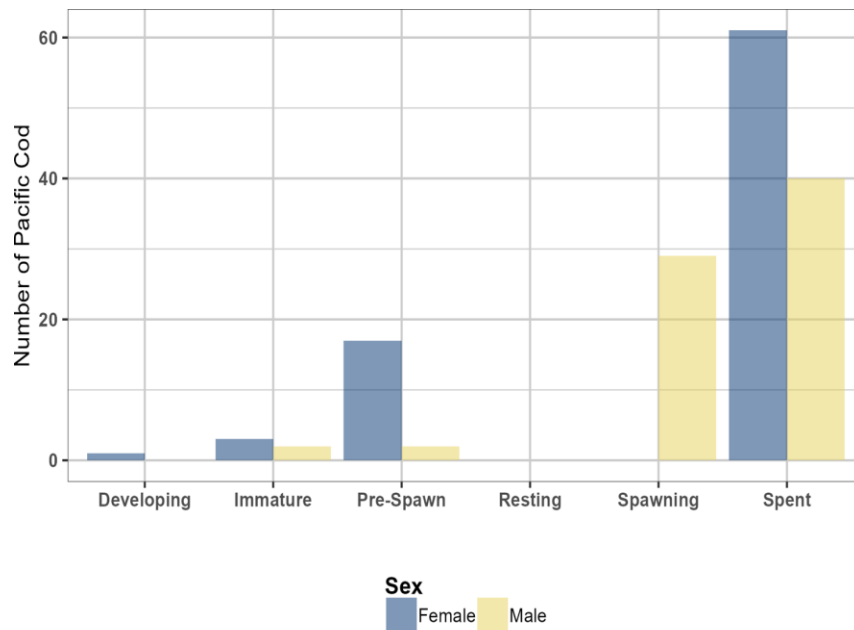


Figure 6. -- Number of male and female Pacific cod by maturity development stage from randomly collected non-tagged Pacific cod from the western GOA during the March 2021 tag release cruise.

Table 1. -- Summary of all 2021 western Gulf of Alaska Pacific cod tag releases and subsequent recoveries. If a tag is not shown, it was not recovered.

Tag No.	Tag Type	Release Date (UTC)	Release Latitude (DD)	Release Longitude (DD)	Length (cm)	Recovery Date (UTC)	Recovery Latitude (DD)	Recovery Longitude (DD)	Days at Liberty
204891	PSAT	03/19/2021	55.24917	-160.1125	74	03/30/2021	54.69943	-162.1356	10
204884	PSAT	03/19/2021	55.54556	-160.0658	78	05/13/2021	55.33361	-160.1669	54
204889	PSAT	03/19/2021	55.25750	-160.1206	79	05/13/2021	54.36350	-162.0560	54
204886	PSAT	03/19/2021	55.55306	-160.0597	91	05/31/2021	53.48711	-166.7497	73
204885	PSAT	03/19/2021	55.55056	-160.0592	75	06/18/2021	56.99344	-169.1203	91
204890	PSAT	03/19/2021	55.25417	-160.1169	71	06/18/2021	55.98810	-162.1082	90
204893	PSAT	03/19/2021	55.26000	-160.1203	82	06/25/2021	61.63878	-177.2184	97
204892	PSAT	03/19/2021	55.24611	-160.1097	79	12/14/2021	62.28555	-170.4391	270
204888	PSAT	03/19/2021	55.54417	-160.0703	79	01/22/2022	54.97361	-165.1206	309
204887	PSAT	03/19/2021	55.54417	-160.0703	63	02/15/2022	55.61070	-160.0910	333
208531	Stationary	03/19/2021	55.54556	-160.0608	-	03/21/2022	55.54556	-160.0608	367
131028	Floy T-Bar	03/19/2021	55.55056	-160.0592	77	05/18/2021	55.54000	-160.0400	60
131198	Floy T-Bar	03/19/2021	55.26000	-160.1203	78	05/03/2021	55.16000	-160.4700	44
209231	PSAT	03/21/2021	54.42667	-162.3514	72	06/20/2021	54.15718	-164.6791	90
209232	PSAT	03/21/2021	54.42500	-162.3433	87	07/02/2021	61.38857	-170.7480	102
209233	PSAT	03/21/2021	54.42250	-162.3342	74	09/18/2021	69.17790	-167.1103	180
208532	Stationary	03/21/2021	54.42556	-162.3600	-	04/26/2022	54.42556	-162.3600	400

Tag No.	Tag Type	Release Date (UTC)	Release Latitude (DD)	Release Longitude (DD)	Length (cm)	Recovery Date (UTC)	Recovery Latitude (DD)	Recovery Longitude (DD)	Days at Liberty
131480	Floy T-Bar	03/21/2021	54.42500	-162.3433	91	08/11/2023	55.29000	-159.4900	872
131532	Floy T-Bar	03/21/2021	54.42500	-162.3433	76	07/19/2022	54.39000	-165.9200	484
131549	Floy T-Bar	03/21/2021	54.42250	-162.3342	65	03/20/2024	54.85000	-160.3000	1,094
131573	Floy T-Bar	03/21/2021	54.42250	-162.3342	82	06/02/2021	53.43000	-166.1200	72
209228	PSAT	03/22/2021	54.41889	-162.3294	72	08/03/2021	52.81590	-169.8282	134
209234	PSAT	03/22/2021	54.42083	-162.3375	76	08/19/2021	61.74810	-173.6699	150
131730	Floy T-Bar	03/22/2021	54.41889	-162.3294	73	05/27/2021	58.44000	-158.2300	66
131812	Floy T-Bar	03/22/2021	54.44056	-162.3578	70	04/02/2021	54.83000	-165.0500	11
131935	Floy T-Bar	03/22/2021	55.03361	-162.4208	71	07/04/2021	54.04000	-165.4700	103
137030	Floy T-Bar	03/22/2021	55.03472	-162.4117	56	02/07/2022	54.98000	-162.1100	321
137032	Floy T-Bar	03/22/2021	55.03472	-162.4117	86	01/18/2022	55.80000	-162.5000	301
137173	Floy T-Bar	03/23/2021	55.35139	-161.7297	65	07/28/2022	55.30000	-161.7500	491
208534	PSAT	03/25/2021	54.96667	-159.1175	72	05/21/2021	54.95828	-164.5438	56
204894	PSAT	03/25/2021	54.97444	-159.1022	70	06/24/2021	56.34268	-157.6818	90
204895	PSAT	03/25/2021	54.97083	-159.1147	81	06/24/2021	54.60739	-160.4778	90
208533	Stationary	03/25/2021	54.97222	-159.1361	-	03/30/2022	54.97222	-159.1361	369
208539	PSAT	03/26/2021	54.87806	-160.1242	79	04/07/2021	55.09000	-159.8360	11
209230	PSAT	03/26/2021	54.88083	-160.1450	83	04/16/2021	54.76000	-165.1467	20
208537	PSAT	03/26/2021	54.87556	-160.1097	60	05/03/2021	54.90560	-159.9991	37

Tag No.	Tag Type	Release Date (UTC)	Release Latitude (DD)	Release Longitude (DD)	Length (cm)	Recovery Date (UTC)	Recovery Latitude (DD)	Recovery Longitude (DD)	Days at Liberty
208538	PSAT	03/26/2021	54.87694	-160.1231	77	06/25/2021	61.13647	-170.7604	90
209229	PSAT	03/26/2021	54.87944	-160.1394	80	07/26/2021	62.83575	-171.6976	121
137445	Floy T-Bar	03/26/2021	54.97083	-159.1247	75	05/05/2021	56.29000	-170.9400	40
137447	Floy T-Bar	03/26/2021	54.97083	-159.1247	86	08/30/2021	60.84000	-171.4100	157
137500	Floy T-Bar	03/26/2021	54.96972	-159.2536	65	03/12/2022	55.29000	-159.5000	350

Individual Fish Tag Results (PSATs)

The following maps of individual PSAT tagged Pacific cod travel paths begin at the fish's tagging release date and end when the PSAT detached from the fish and transmitted data to the Argos satellite. For continuity between maps, all months from the first tag release event (March 2021) to the recovery of the last PSAT (January-March 2022) are shown in the legends.

When interpreting reconstructed pathways for individual fish, it is important to keep in mind that the daily point estimates are provided primarily for visualization of estimated locations over time. Because the actual location estimate provided by the model is a map of location probability in the study area for each day, the error polygons that encompass the highest 50% and 99% of the probability on each day are much more indicative of the possible location of the tagged fish compared to the daily point estimates.

Table 2. -- Colors in this report denote general Pacific cod life history behavior, including transition period months (which typically occurs in December and January) in blues, spawning months (February through April) in oranges, return migration months (May through July) in purples, and foraging months (August through November) in greens (Nielsen et al. 2025).

Month	Life History Stage
January	Transition period
February	Spawning
March	Spawning
April	Spawning
May	Return migration
June	Return migration
July	Return migration
August	Foraging
September	Foraging
October	Foraging
November	Foraging
December	Transition period

Tag 204891

The Pacific cod with tag 204891 (length: 74 cm) was released on March 19, 2021 in the Gulf of Alaska at 55.25°N latitude and -160.11°W longitude and the pop-up was on March 30, 2021 at 54.70°N latitude and -162.14°W longitude (Fig. 7; Table 1). This fish was at liberty for 11 days.

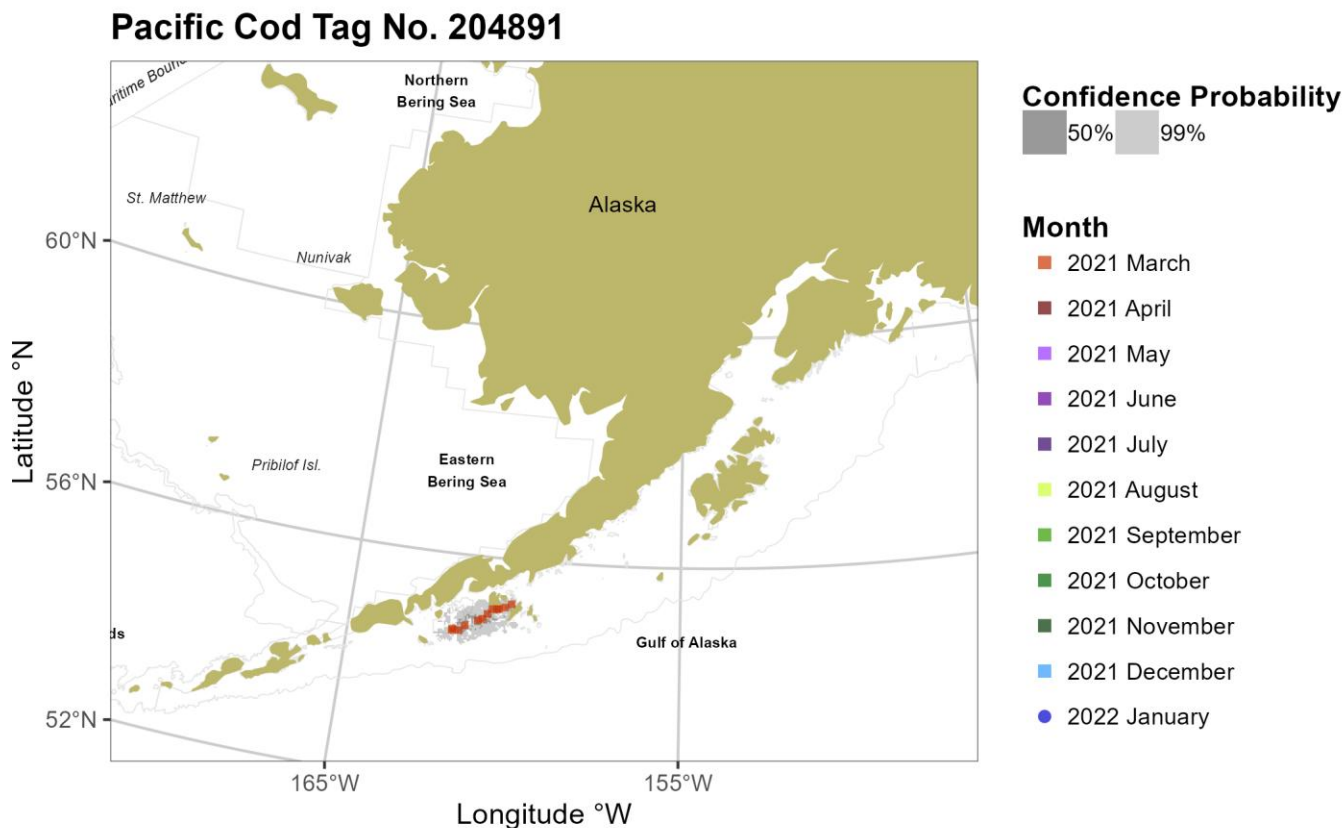


Figure 7. -- Map of Pacific cod tag 204891 with 50% (medium gray) and 99% (light gray) confidence probability shapefiles. Find color descriptions in Table 2.

Tag 208539

The Pacific cod with tag 208539 (length: 79 cm) was released on March 26, 2021 in the Gulf of Alaska at 54.88°N latitude and -160.12°W longitude and the pop-up was on April 07, 2021 at 55.09°N latitude and -159.84°W longitude (Fig. 8; Table 1). This fish was at liberty for 11 days.

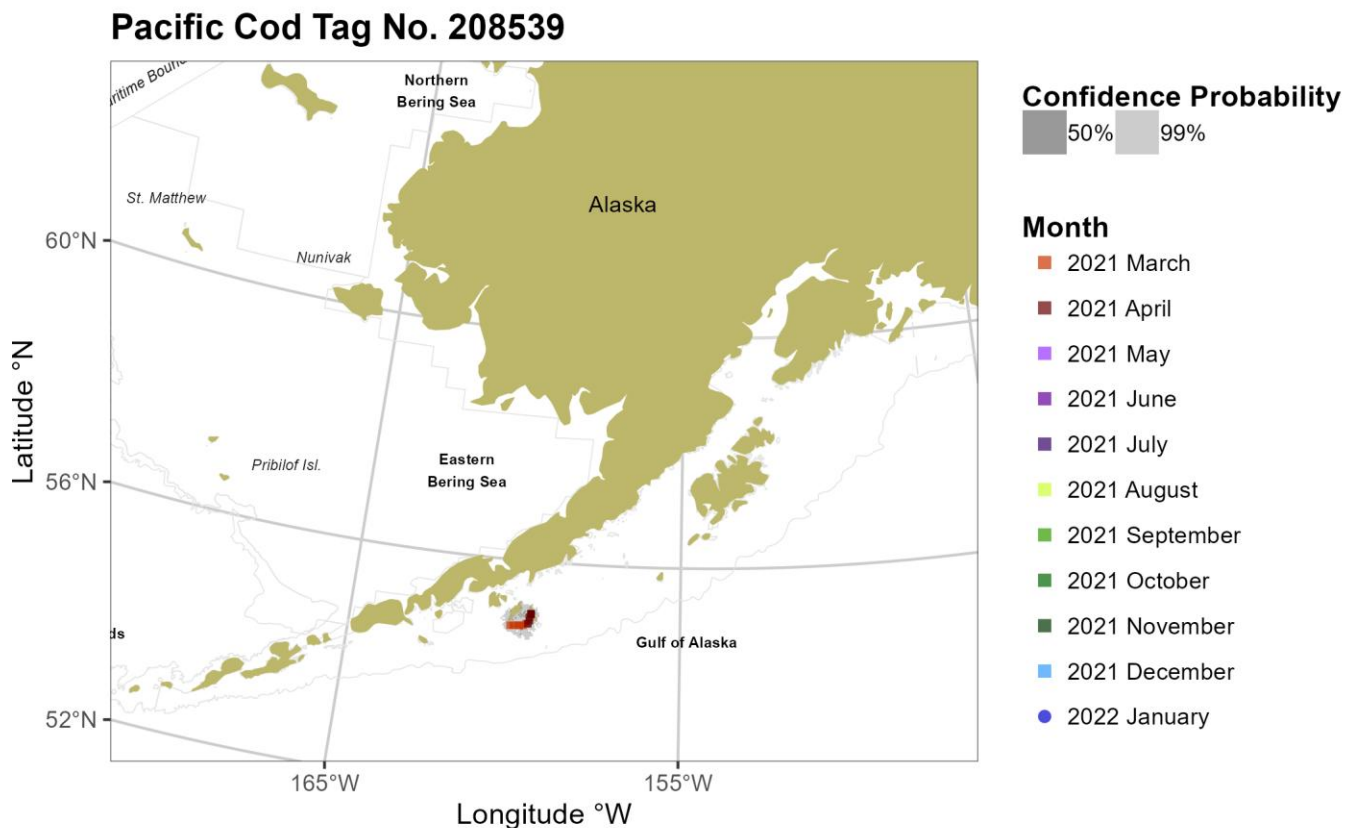


Figure 7. -- Map of Pacific cod tag 208539 with 50% (medium gray) and 99% (light gray) confidence probability shapefiles. Find color descriptions in Table 2.

Tag 209230

The Pacific cod with tag 209230 (length: 83 cm) was released on March 26, 2021 in the Gulf of Alaska at 54.88°N latitude and -160.15°W longitude and the pop-up was on April 16, 2021 at 54.76°N latitude and -165.15°W longitude (Fig. 8; Table 1). This fish was at liberty for 20 days. Within the month of tagging, the fish traveled north through Unimak Pass into the Bering Sea.

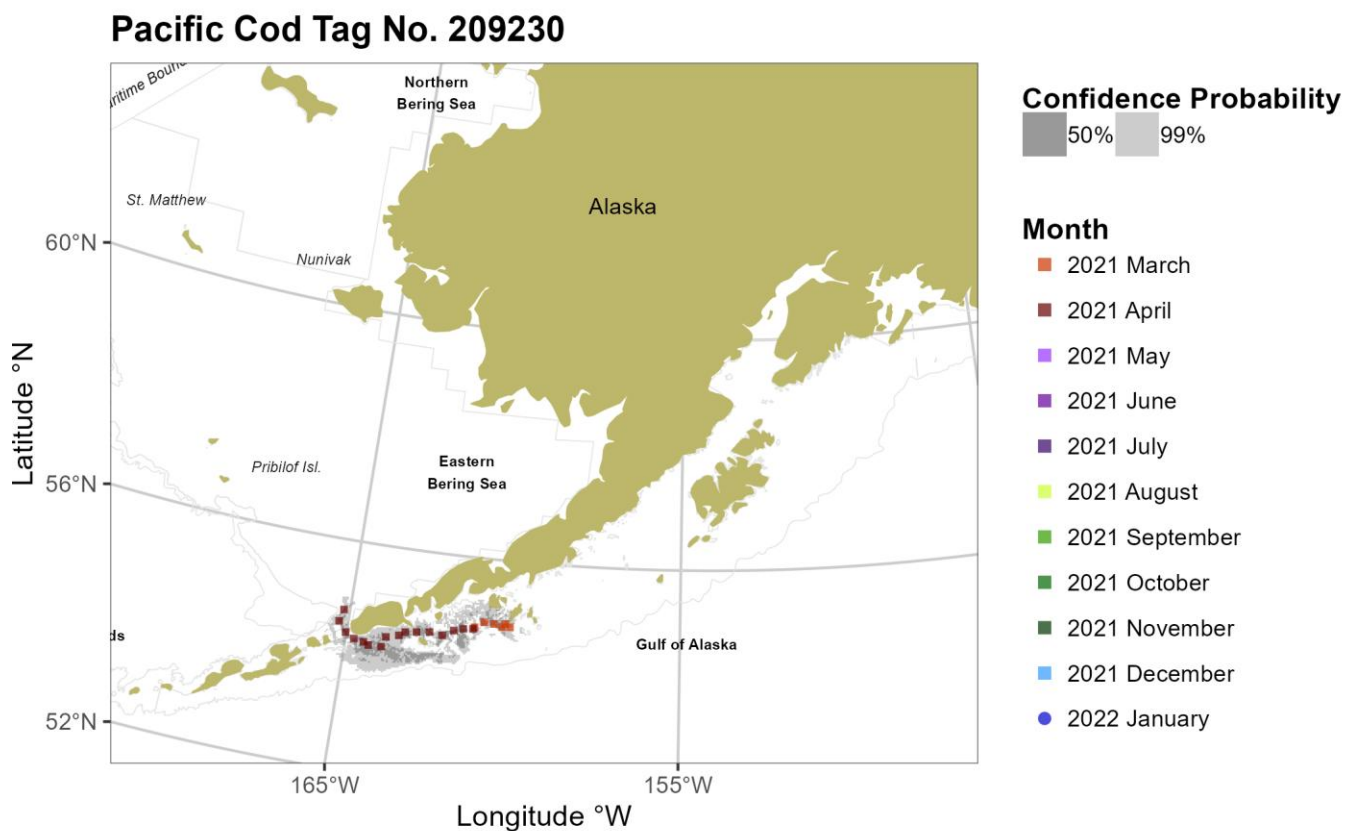


Figure 8. -- Map of Pacific cod tag 209230 with 50% (medium gray) and 99% (light gray) confidence probability shapefiles. Find color descriptions in Table 2.

Tag 208537

The Pacific cod with tag 208537 (length: 60 cm) was released on March 26, 2021 in the Gulf of Alaska at 54.88°N latitude and -160.11°W longitude and the pop-up was on May 03, 2021 at 54.91°N latitude and -160.0°W longitude (Fig. 9; Table 1). This fish was at liberty for 37 days. The fish remained in proximity to the initial release location.

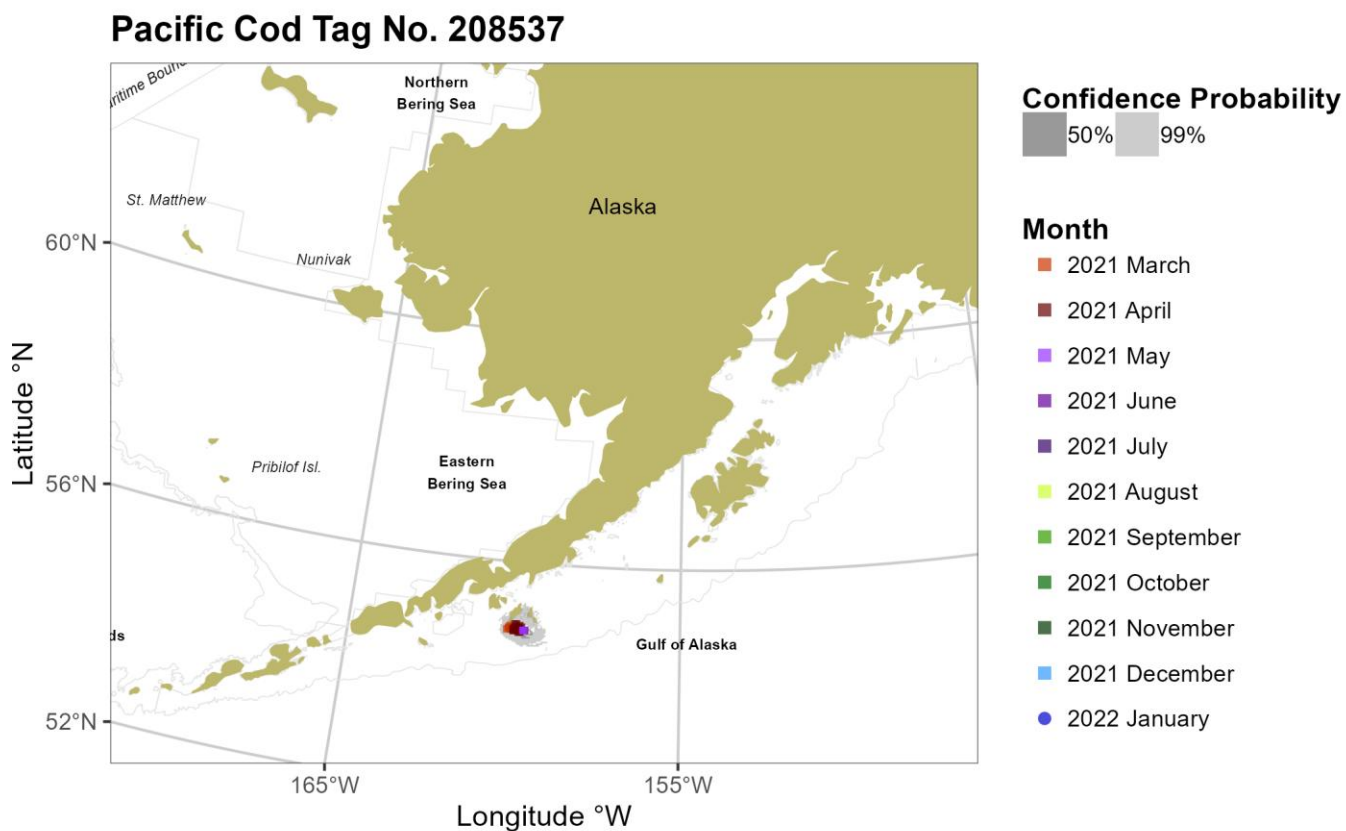


Figure 9. -- Map of Pacific cod tag 208537 with 50% (medium gray) and 99% (light gray) confidence probability shapefiles. Find color descriptions in Table 1.

Tag 204884

The Pacific cod with tag 204884 (length: 78 cm) was released on March 19, 2021 in the Gulf of Alaska at 55.55°N latitude and -160.07°W longitude and the pop-up was on May 13, 2021 at 55.33°N latitude and -160.17°W longitude (Fig. 10; Table 1). This fish was at liberty for 55 days. The fish remained in proximity to the release location.

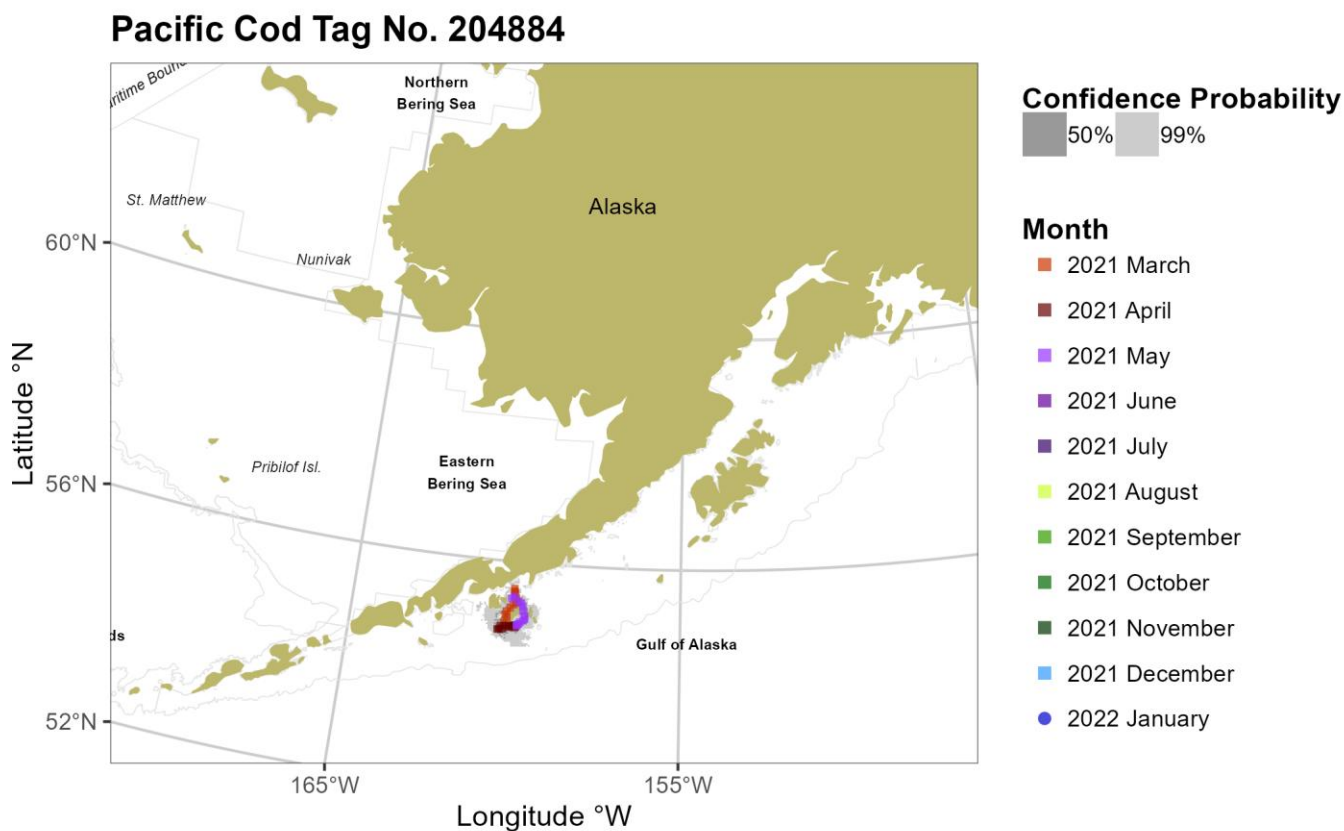


Figure 10. -- Map of Pacific cod tag 204884 with 50% (medium gray) and 99% (light gray) confidence probability shapefiles. Find color descriptions in Table 2.

Tag 204889

The Pacific cod with tag 204889 (length: 79 cm) was released on March 19, 2021 in the Gulf of Alaska at 55.26°N latitude and -160.12°W longitude and the pop-up was on May 13, 2021 at 54.36°N latitude and -162.06°W longitude (Fig. 11; Table 1). This fish was at liberty for 55 days. The fish remained in the western GOA during its time at liberty.

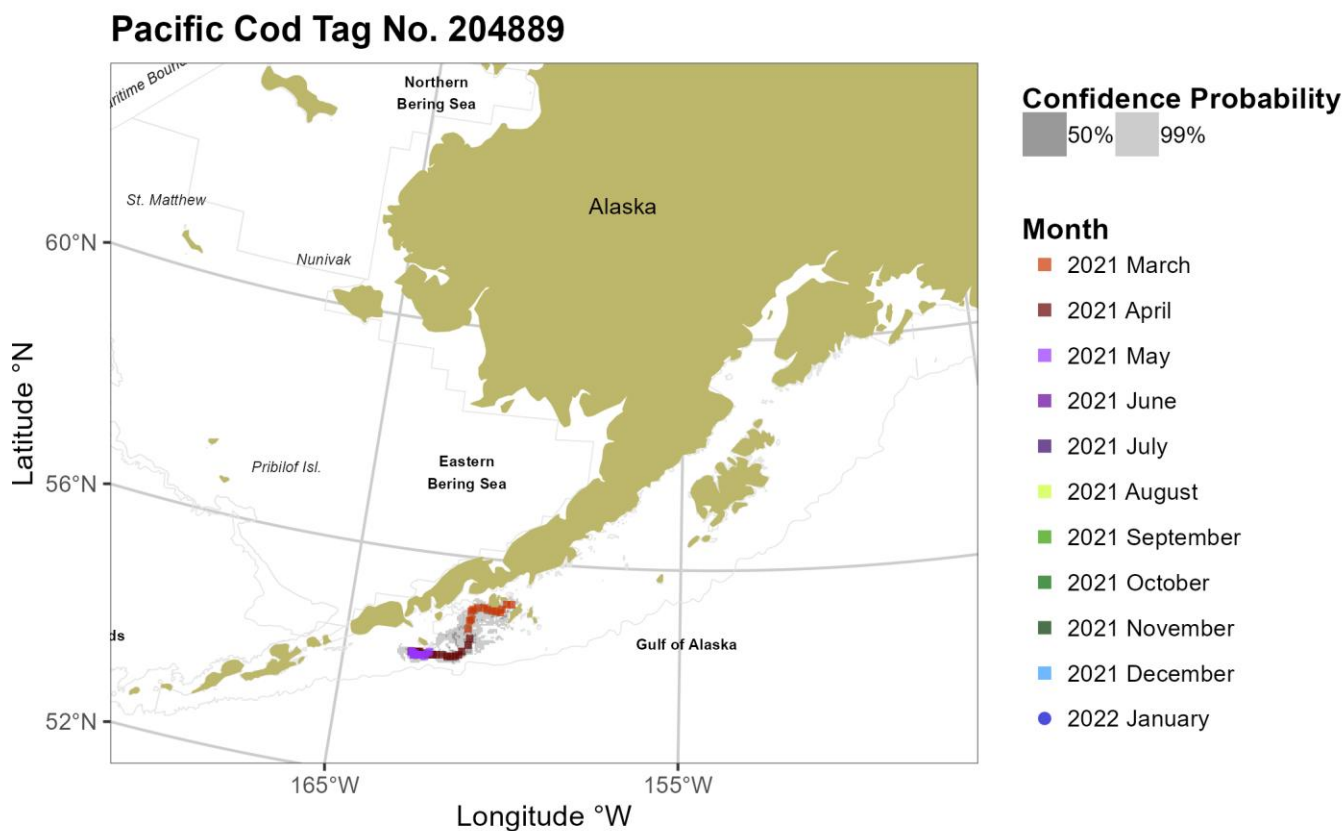


Figure 11. -- Map of Pacific cod tag 204889 with 50% (medium gray) and 99% (light gray) confidence probability shapefiles. Find color descriptions in Table 2.

Tag 208534

The Pacific cod with tag 208534 (length: 72 cm) was released on March 25, 2021 in the Gulf of Alaska at 54.97°N latitude and -159.12°W longitude and the pop-up was on May 21, 2021 at 54.96°N latitude and -164.54°W longitude (Fig. 12; Table 1). This fish was at liberty for 57 days. Within the month of tagging, the fish traveled north through Unimak Pass into the Bering Sea.

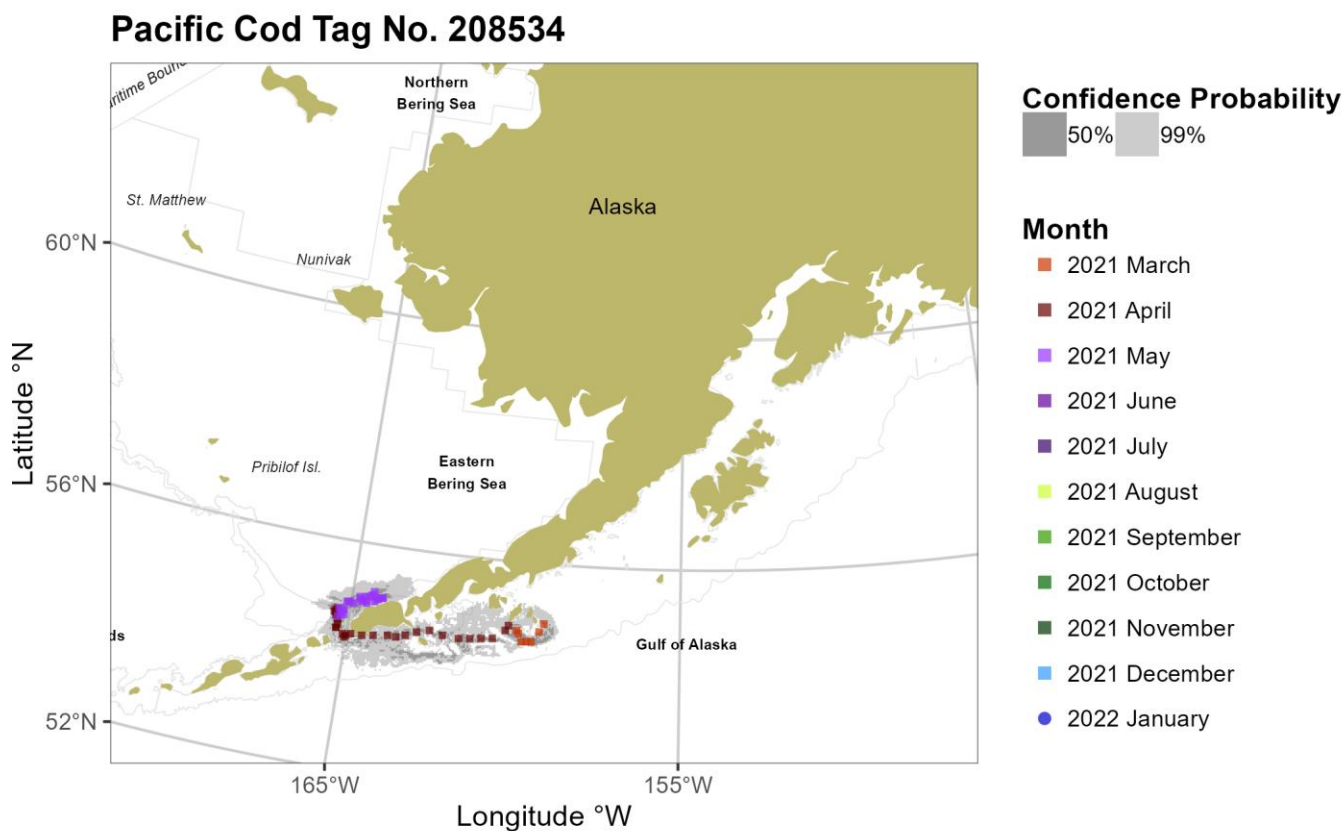


Figure 12. -- Map of Pacific cod tag 208534 with 50% (medium gray) and 99% (light gray) confidence probability shapefiles. Find color descriptions in Table 2.

Tag 204886

The Pacific cod with tag 204886 (length: 91 cm) was released on March 19, 2021 in the Gulf of Alaska at 55.55°N latitude and -160.06°W longitude and the pop-up was on May 31, 2021 at 53.49°N latitude and -166.75°W longitude (Fig. 13; Table 1). This fish was at liberty for 74 days. The fish traveled west from the release site where the pop-up occurred near Unimak Pass in May.

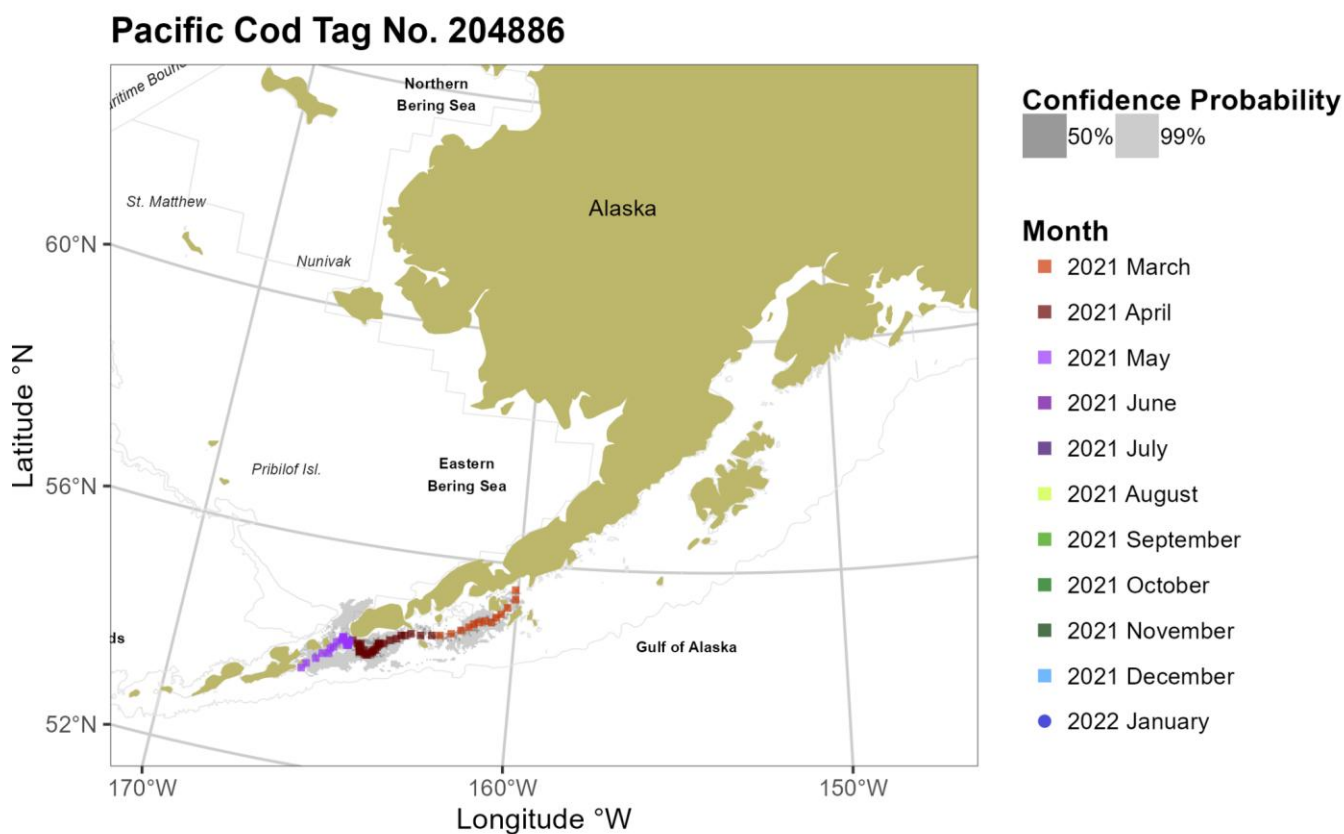


Figure 13. -- Map of Pacific cod tag 204886 with 50% (medium gray) and 99% (light gray) confidence probability shapefiles. Find color descriptions in Table 2.

Tag 204885

The Pacific cod with tag 204885 (length: 75 cm) was released on March 19, 2021 in the Gulf of Alaska at 55.55°N latitude and -160.06°W longitude and the pop-up was on June 18, 2021 at 56.99°N latitude and -169.12°W longitude (Fig. 14; Table 1). This fish was at liberty for 91 days. The PSAT pop-up occurred as programmed. Within a month of tagging the fish traveled into the Bering Sea and remained on the Bering Sea shelf until the pop-up.

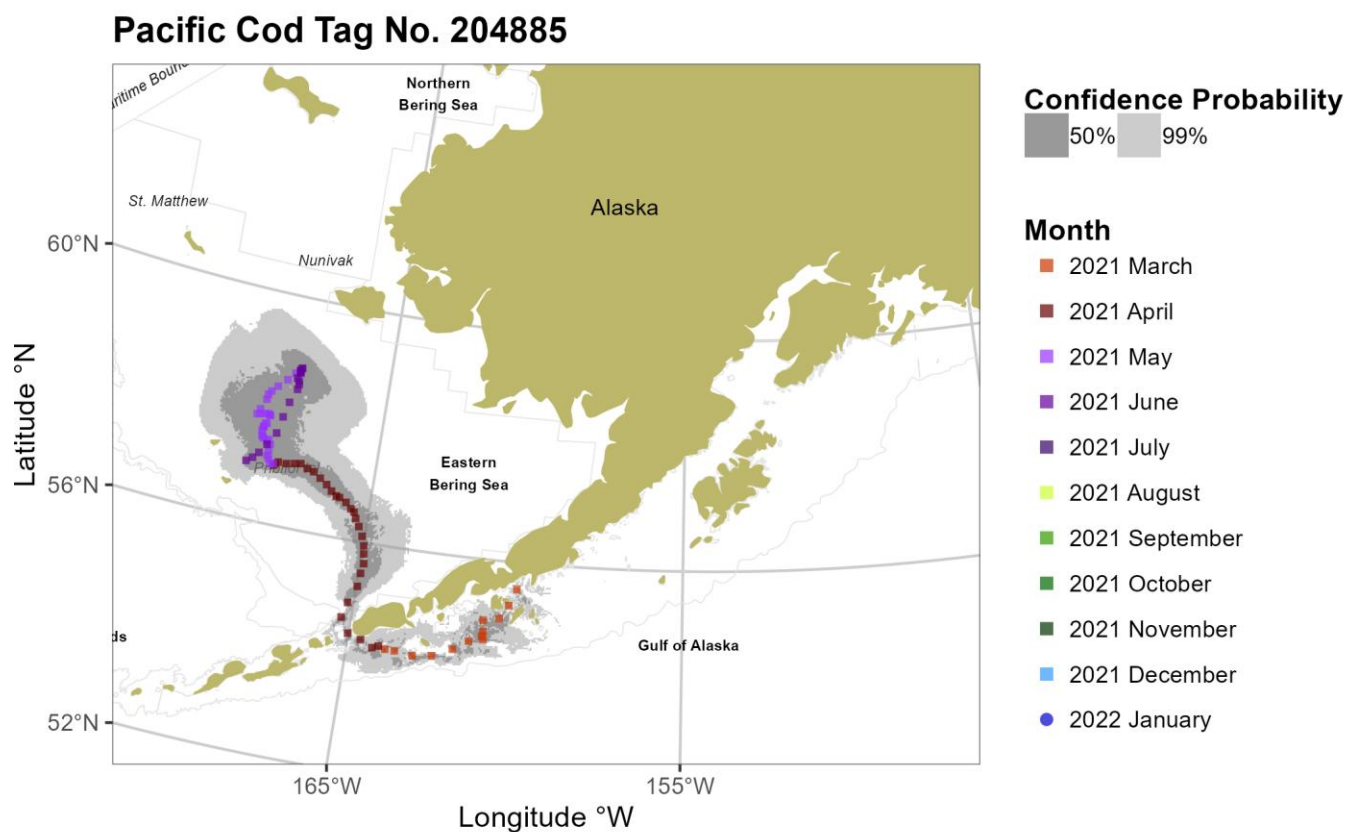


Figure 14. -- Map of Pacific cod tag 204885 with 50% (medium gray) and 99% (light gray) confidence probability shapefiles. Find color descriptions in Table 2.

Tag 204890

The Pacific cod with tag 204890 (length: 71 cm) was released on March 19, 2021 in the Gulf of Alaska at 55.25°N latitude and -160.12°W longitude and the pop-up was on June 18, 2021 at 55.99°N latitude and -162.11°W longitude (Fig. 15; Table 1). This fish was at liberty for 91 days. Within a month of tagging the fish traveled into the Bering Sea and remained just north of the peninsula.

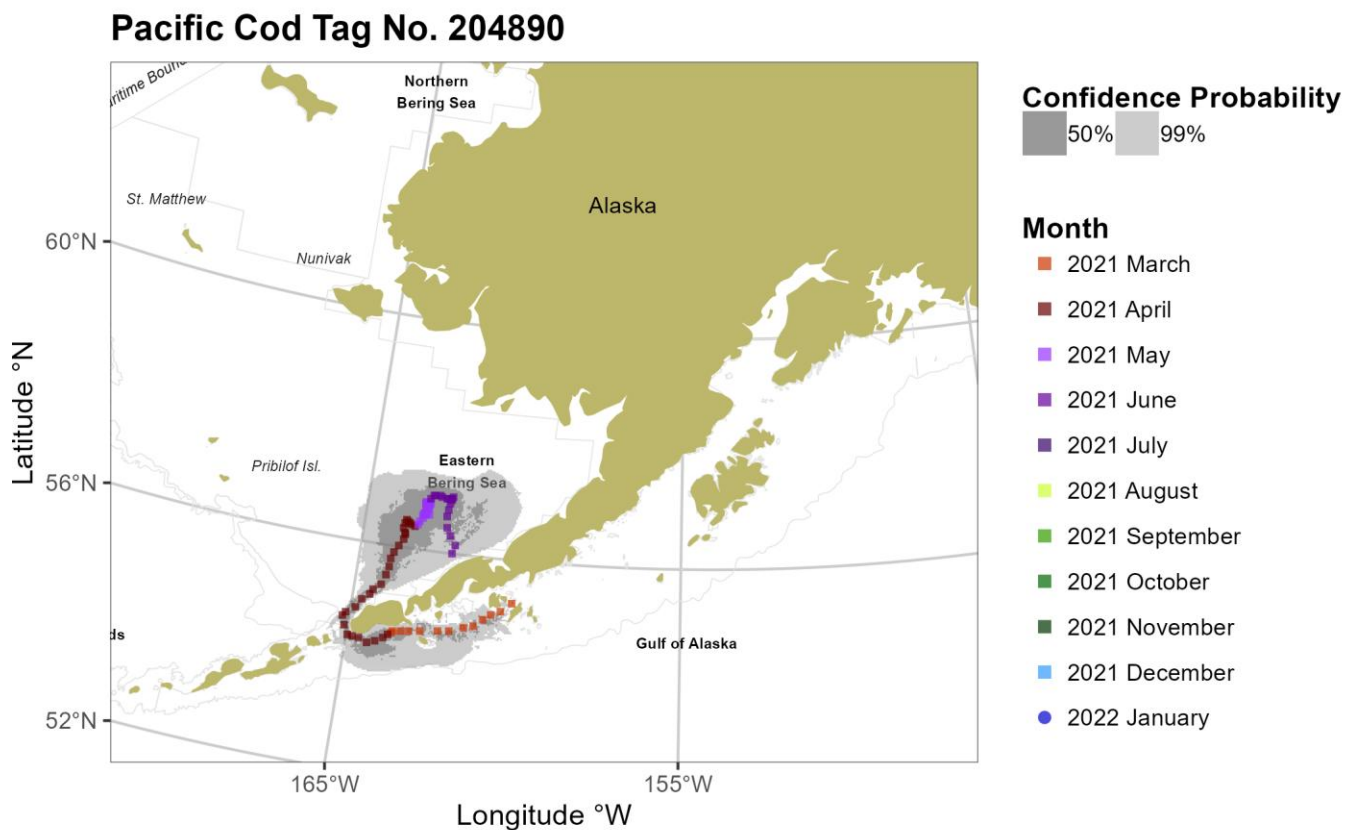


Figure 15. -- Map of Pacific cod tag 204890 with 50% (medium gray) and 99% (light gray) confidence probability shapefiles. Find color descriptions in Table 2.

Tag 209231

The Pacific cod with tag 209231 (length: 72 cm) was released on March 21, 2021 in the Gulf of Alaska at 54.43°N latitude and -162.35°W longitude and the pop-up was on June 20, 2021 at 54.16°N latitude and -164.68°W longitude (Fig. 16; Table 1). This fish was at liberty for 90 days. This fish stayed in the western Gulf of Alaska during its time at liberty, spending most of its time just south of Unimak Pass.

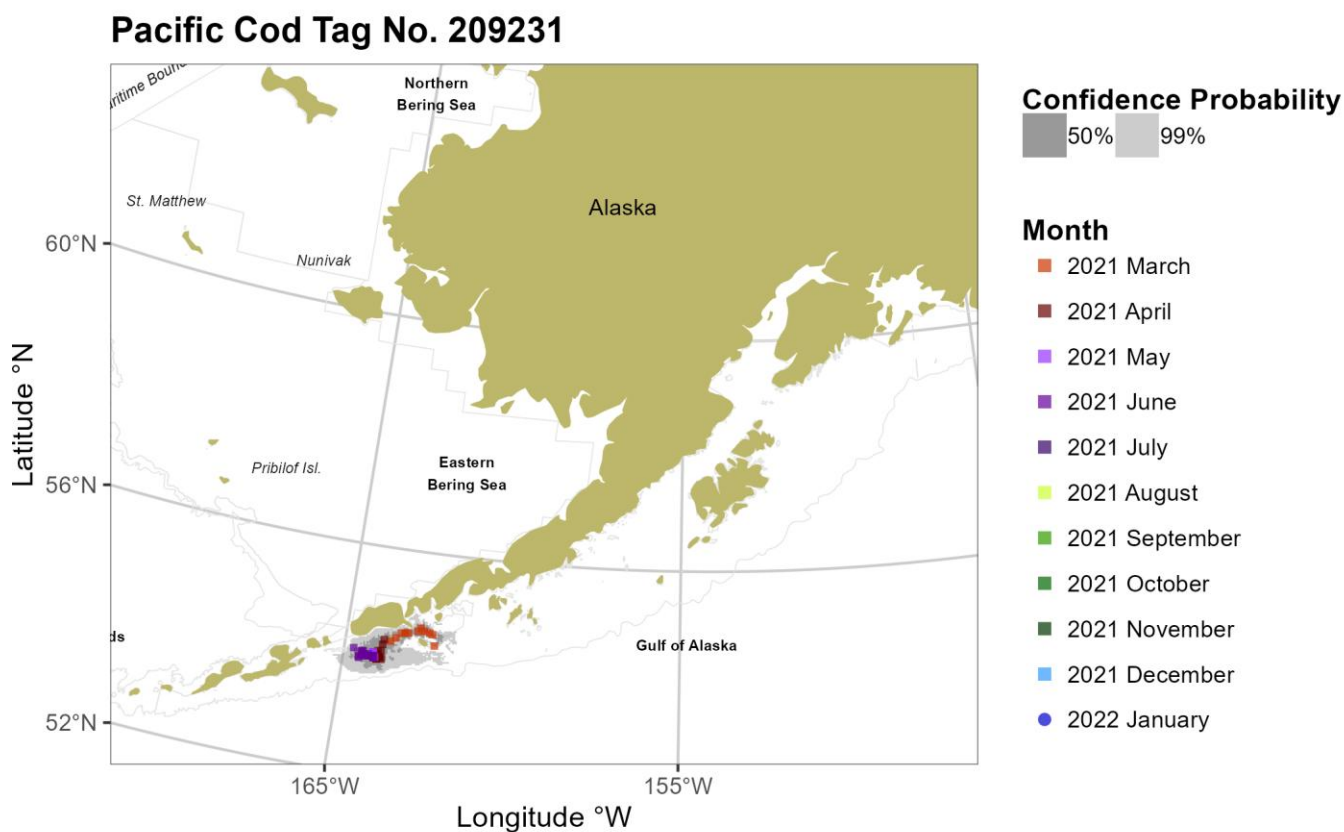


Figure 16. -- Map of Pacific cod tag 209231 with 50% (medium gray) and 99% (light gray) confidence probability shapefiles. Find color descriptions in Table 2.

Tag 204894

The Pacific cod with tag 204894 (length: 70 cm) was released on March 25, 2021 in the Gulf of Alaska at 54.97°N latitude and -159.1°W longitude and the pop-up was on June 24, 2021 at 56.34°N latitude and -157.68°W longitude (Fig. 17; Table 1). This fish was at liberty for 90 days. This fish is one of the few fish released in March 2021 that traveled east toward the central Gulf of Alaska while at liberty.

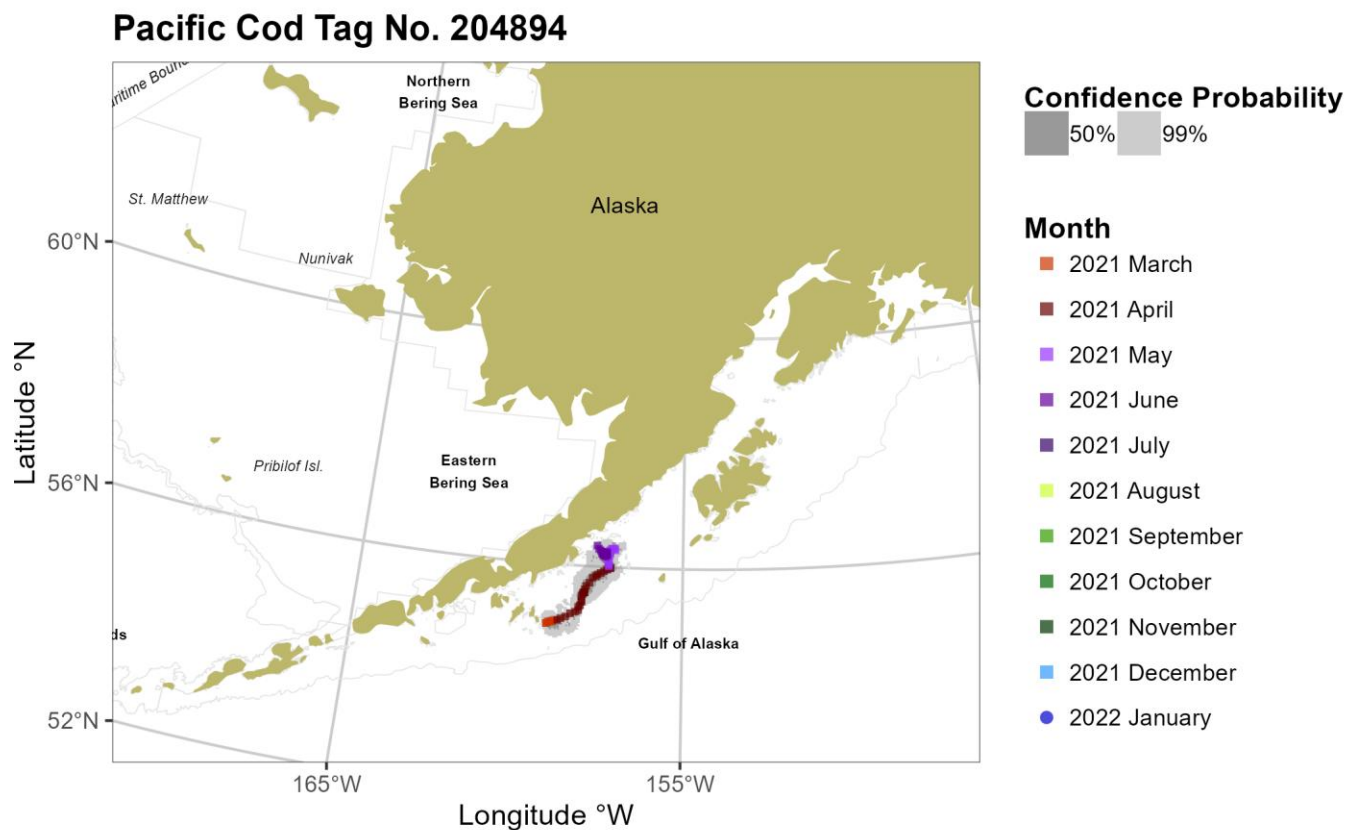


Figure 17. -- Map of Pacific cod tag 204894 with 50% (medium gray) and 99% (light gray) confidence probability shapefiles. Find color descriptions in Table 2.

Tag 204895

The Pacific cod with tag 204895 (length: 81 cm) was released on March 25, 2021 in the Gulf of Alaska at 54.97°N latitude and -159.11°W longitude and the pop-up was on June 24, 2021 at 54.61°N latitude and -160.48°W longitude (Fig. 18; Table 1). This fish was at liberty for 90 days. This fish remained in the western GOA in proximity to the release location.

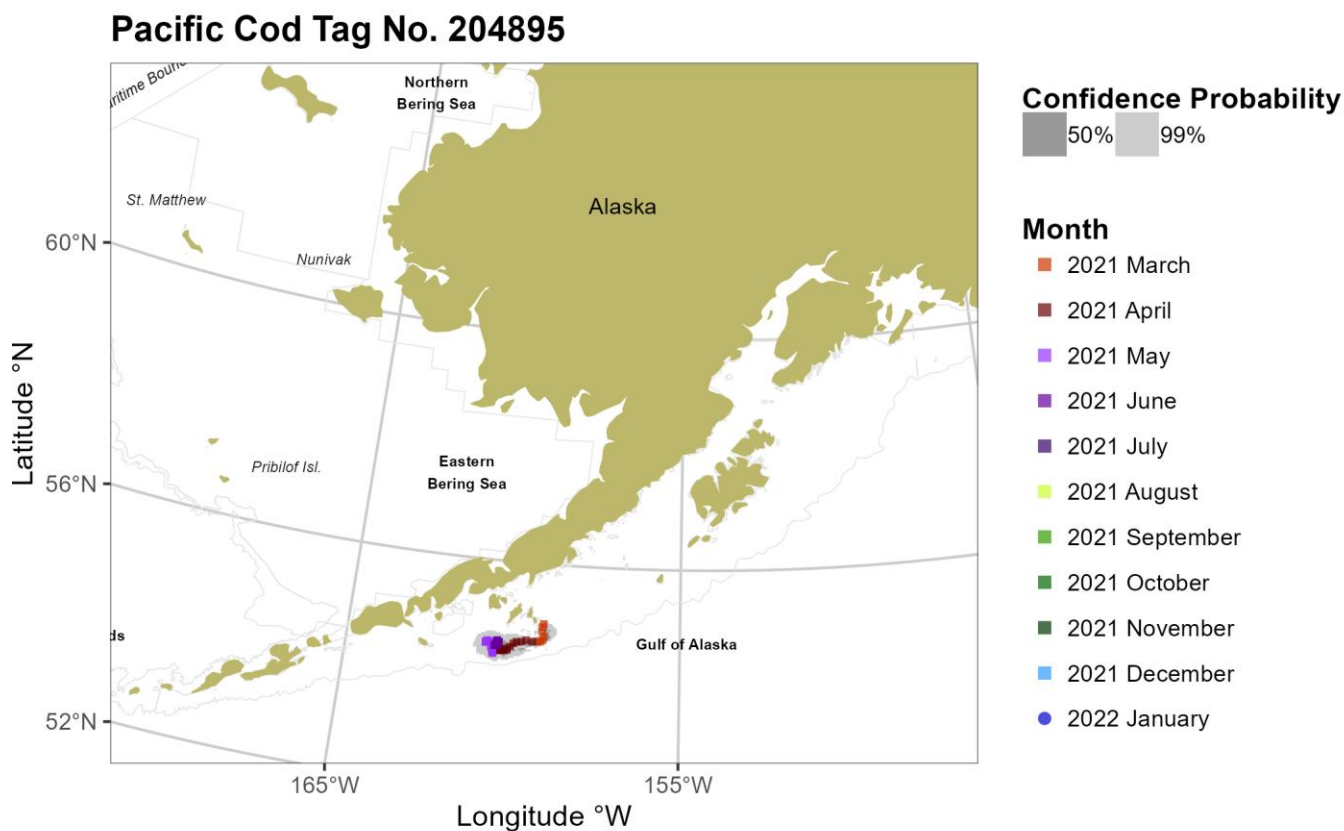


Figure 18. -- Map of Pacific cod tag 204895 with 50% (medium gray) and 99% (light gray) confidence probability shapefiles. Find color descriptions in Table 2.

Tag 204893

The Pacific cod with tag 204893 (length: 82 cm) was released on March 19, 2021 in the Gulf of Alaska at 55.26°N latitude and -160.12°W longitude and the pop-up was on June 24, 2021 at 61.64°N latitude and -177.22°W longitude (Fig. 19; Table 1). This fish was at liberty for 98 days. This fish traveled within a month from the release location into the Bering Sea and continuously headed northwest during April to July for over 1000 km with a pop-up location probability at or near the U.S. and Russia Maritime Boundary.

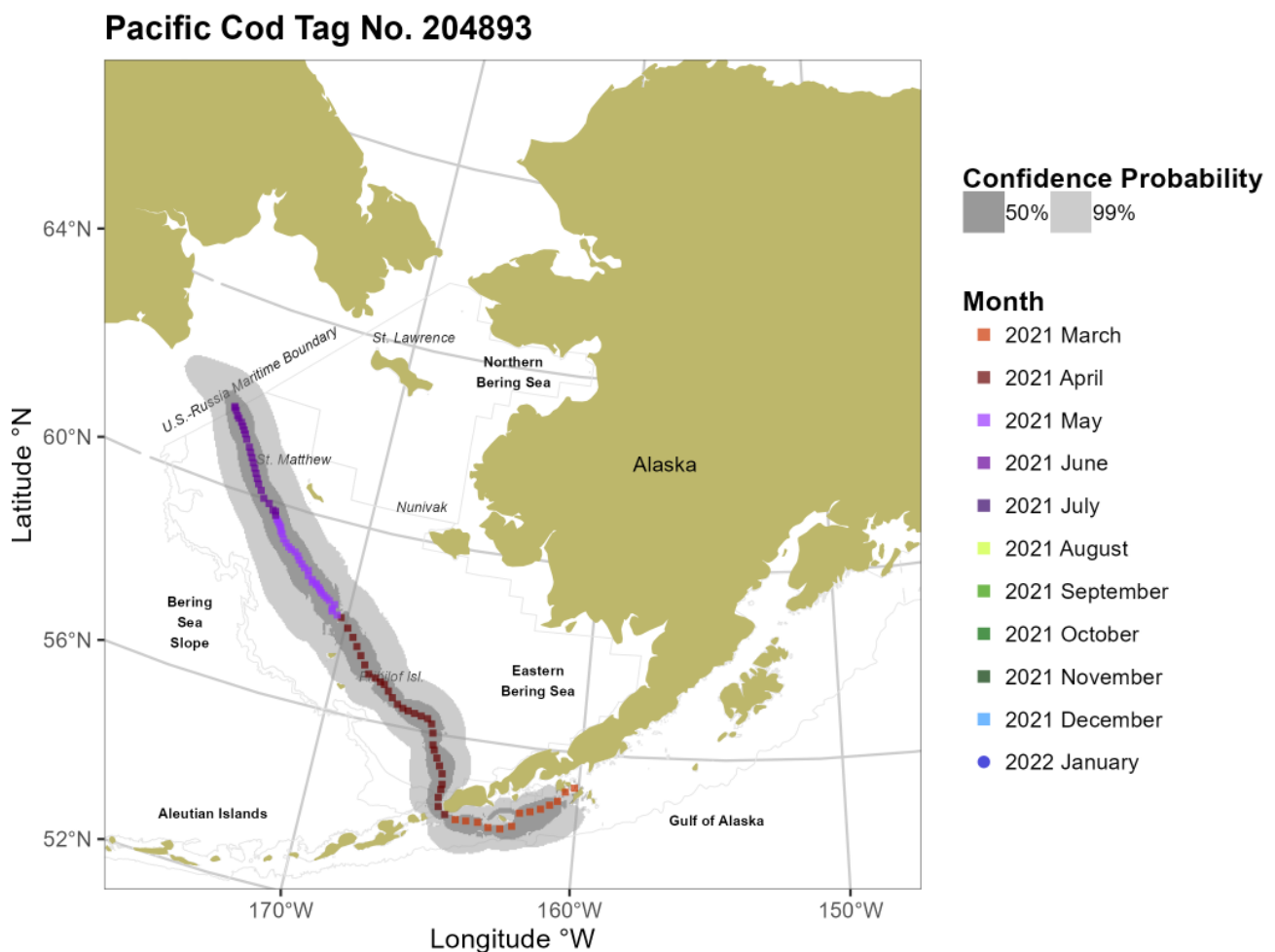


Figure 19. -- Map of Pacific cod tag 204893 with 50% (medium gray) and 99% (light gray) confidence probability shapefiles. Find color descriptions in Table 2.

Tag 208538

The Pacific cod with tag 208538 (length: 77 cm) was released on March 26, 2021 in the Gulf of Alaska at 54.88°N latitude and -160.12°W longitude and the pop-up was on June 25, 2021 at 61.14°N latitude and -170.76°W longitude (Fig. 20; Table 1). This fish was at liberty for 91 days. This fish moved from the release location within a month, through Unimak Pass and traveled continuously north into the Bering Sea with a pop-up location just east of St. Matthew Island.

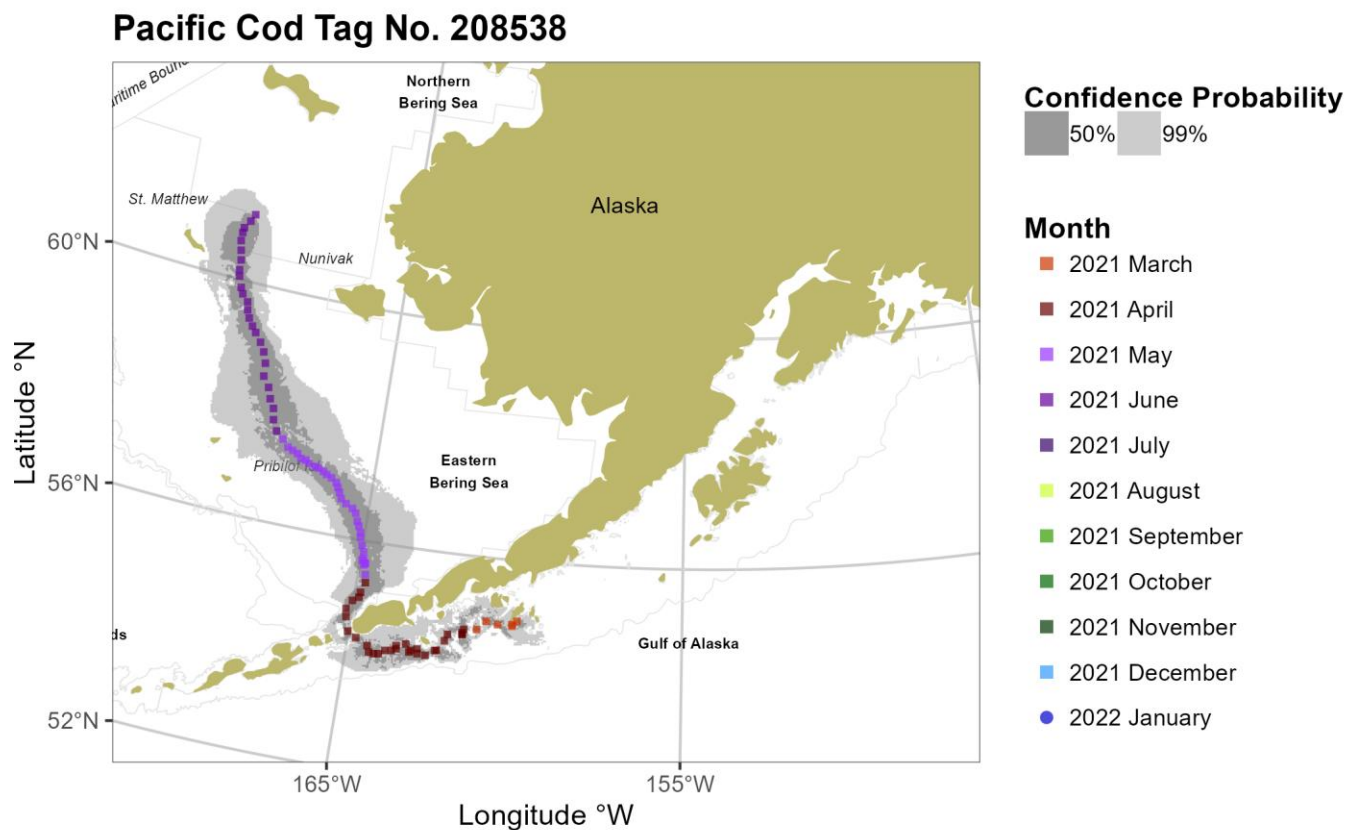


Figure 20. -- Map of Pacific cod tag 208538 with 50% (medium gray) and 99% (light gray) confidence probability shapefiles. Find color descriptions in Table 2.

Tag 209232

The Pacific cod with tag 209232 (length: 87 cm) was released on March 21, 2021 in the Gulf of Alaska at 54.42°N latitude and -162.34°W longitude and the pop-up was on July 02, 2021 at 61.39°N latitude and -170.75°W longitude (Fig. 21; Table 1). This fish was at liberty for 103 days. This fish moved from the release location through Unimak Pass during April and headed north into the Bering Sea with a pop-up location northeast of St. Matthew Island.

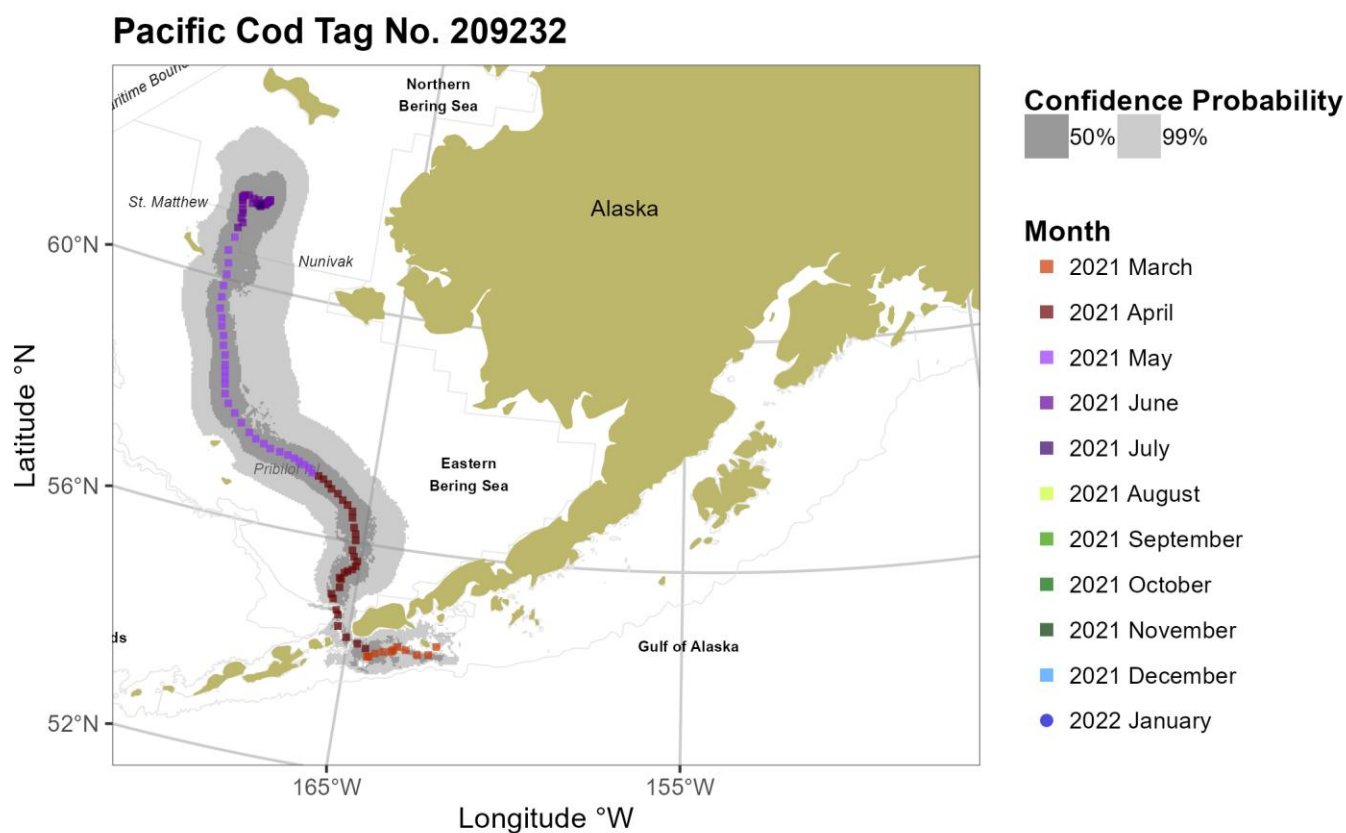


Figure 21. -- Map of Pacific cod tag 209232 with 50% (medium gray) and 99% (light gray) confidence probability shapefiles. Find color descriptions in Table 2.

Tag 209229

The Pacific cod with tag 209229 (length: 80 cm) was released on March 26, 2021 in the Gulf of Alaska at 54.88°N latitude and -160.14°W longitude and the pop-up was on July 26, 2021 at 62.84°N latitude and -171.70°W longitude (Fig. 22; Table 1). This fish was at liberty for 121 days. This fish moved from the release location through Unimak Pass during April and headed north into the Bering Sea with a pop-up location just south of St. Lawrence Island. The pop-up location is considered to be in the northern Bering Sea.

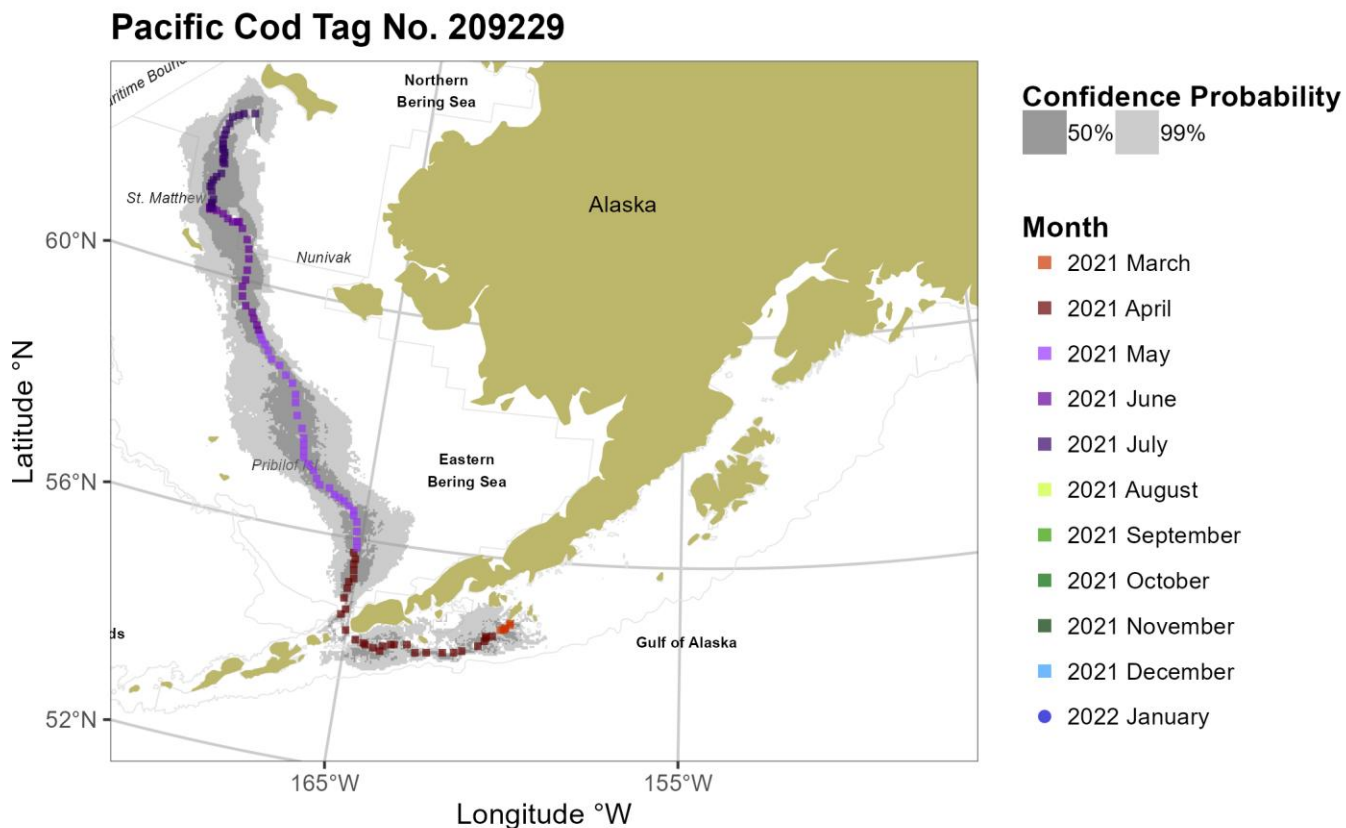


Figure 22. -- Map of Pacific cod tag 209229 with 50% (medium gray) and 99% (light gray) confidence probability shapefiles. Find color descriptions in Table 2.

Tag 209228

The Pacific cod with tag 209228 (length: 72 cm) was released on March 22, 2021 in the Gulf of Alaska at 54.42°N latitude and -162.33°W longitude and the pop-up was on August 03, 2021 at 52.81°N latitude and -169.82°W longitude (Fig. 23; Table 1). This fish was at liberty for 135 days. This fish migrated straight west from its release location, traveling along the southern coast of the Aleutian Island chain and popped up just West of Umnak Island in August.

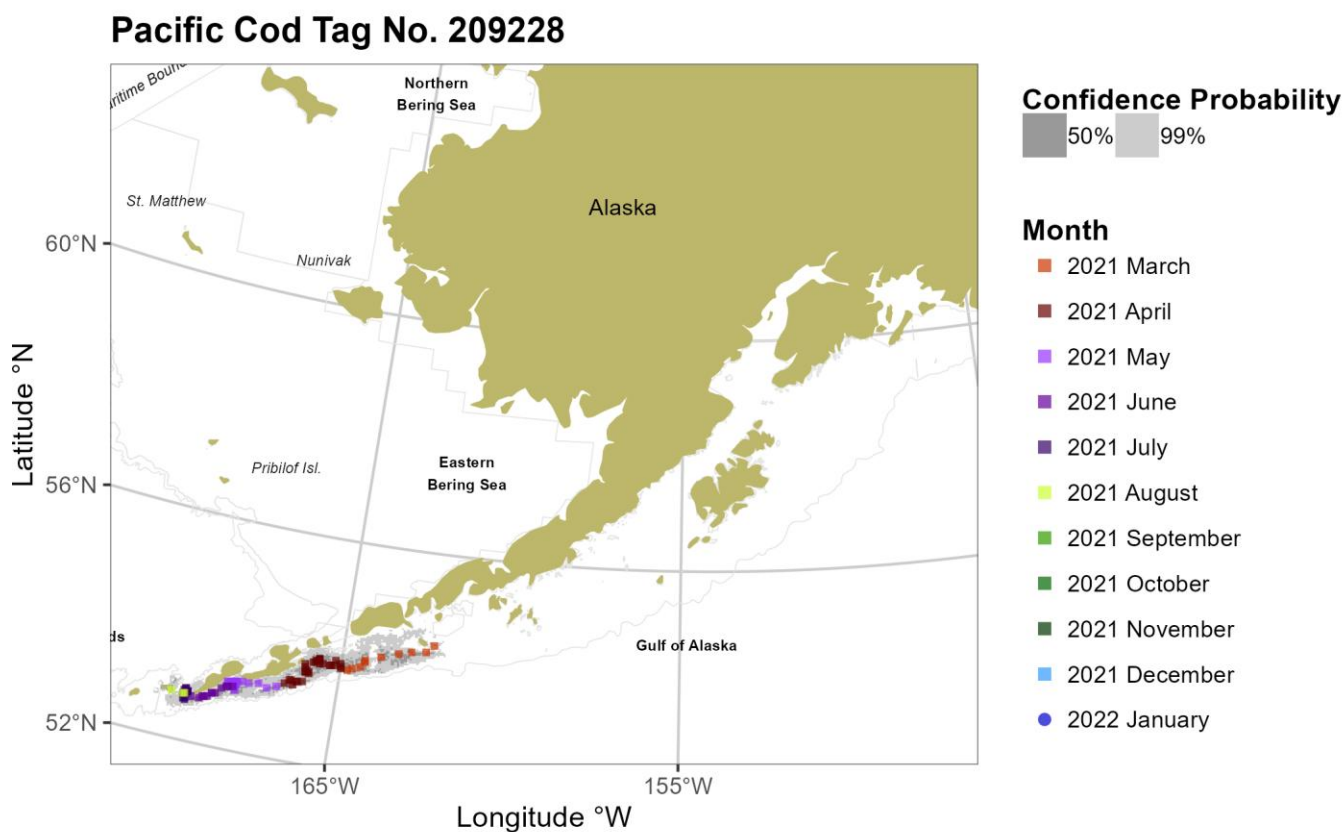


Figure 23. -- Map of Pacific cod tag 209228 with 50% (medium gray) and 99% (light gray) confidence probability shapefiles. Find color descriptions in Table 2.

Tag 209234

The Pacific cod with tag 209234 (length: 76 cm) was released on March 22, 2021 in the Gulf of Alaska at 54.42°N latitude and -162.34°W longitude and the pop-up was on August 19, 2021 at 61.75°N latitude and -173.67°W longitude (Fig. 24; Table 1). This fish was at liberty for 150 days. This fish traveled quickly from the release location into the Bering Sea and further north with a pop-up location probability inside Russian waters.

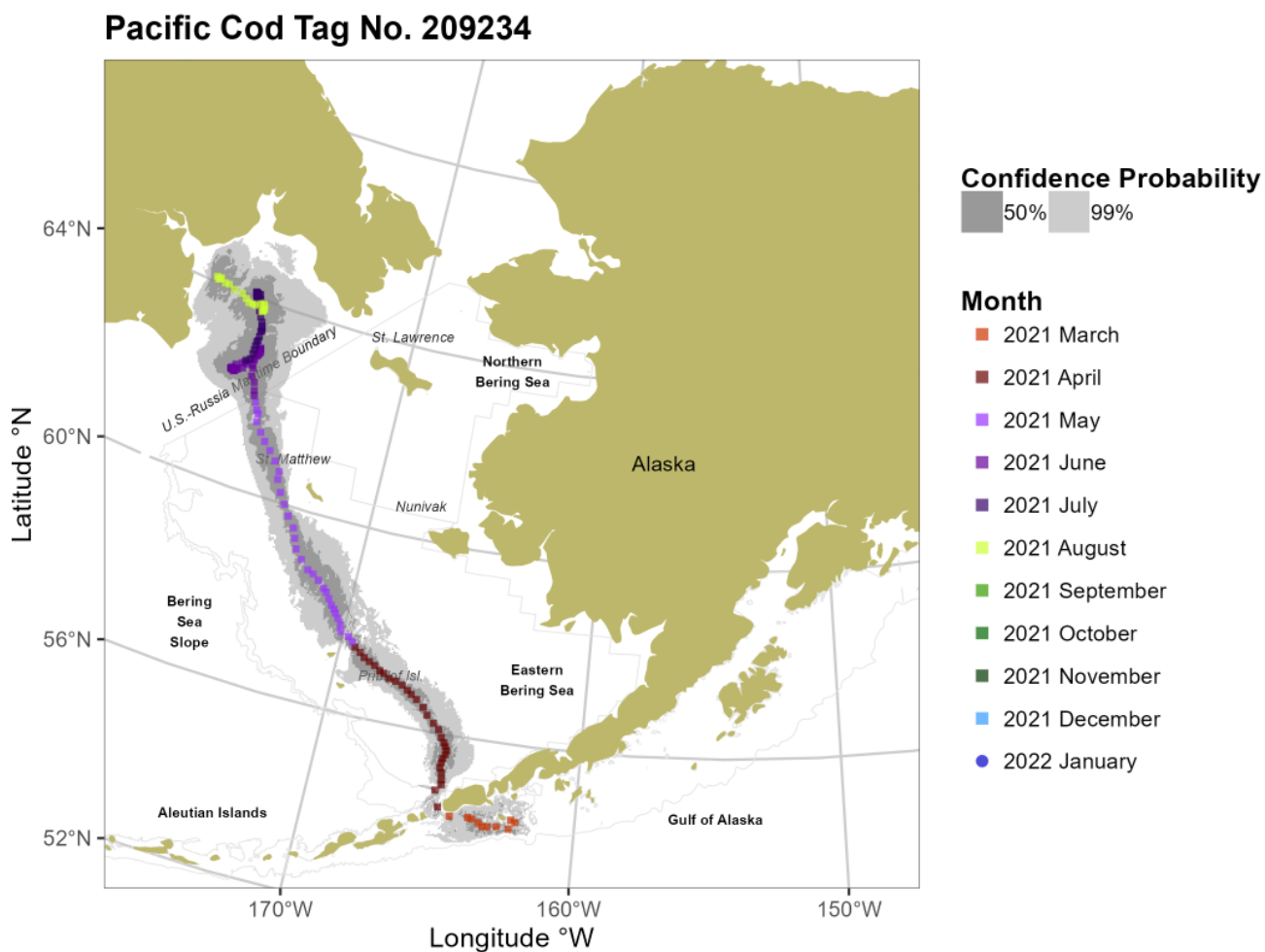


Figure 24. -- Map of Pacific cod tag 209234 with 50% (medium gray) and 99% (light gray) confidence probability shapefiles. Find color descriptions in Table 2.

Tag 204892

The Pacific cod with tag 204892 (length: 79 cm) was released on March 19, 2021 in the Gulf of Alaska at 55.25°N latitude and -160.11°W longitude and the pop-up was on December 14, 2021 at 62.28°N latitude and -170.44°W longitude (Fig. 25; Table 1). This fish was at liberty for 270 days. This fish moved quickly from the release location, through Unimak Pass and into the Bering Sea where it popped-up just south of St. Lawrence Island in the northern Bering Sea in December.

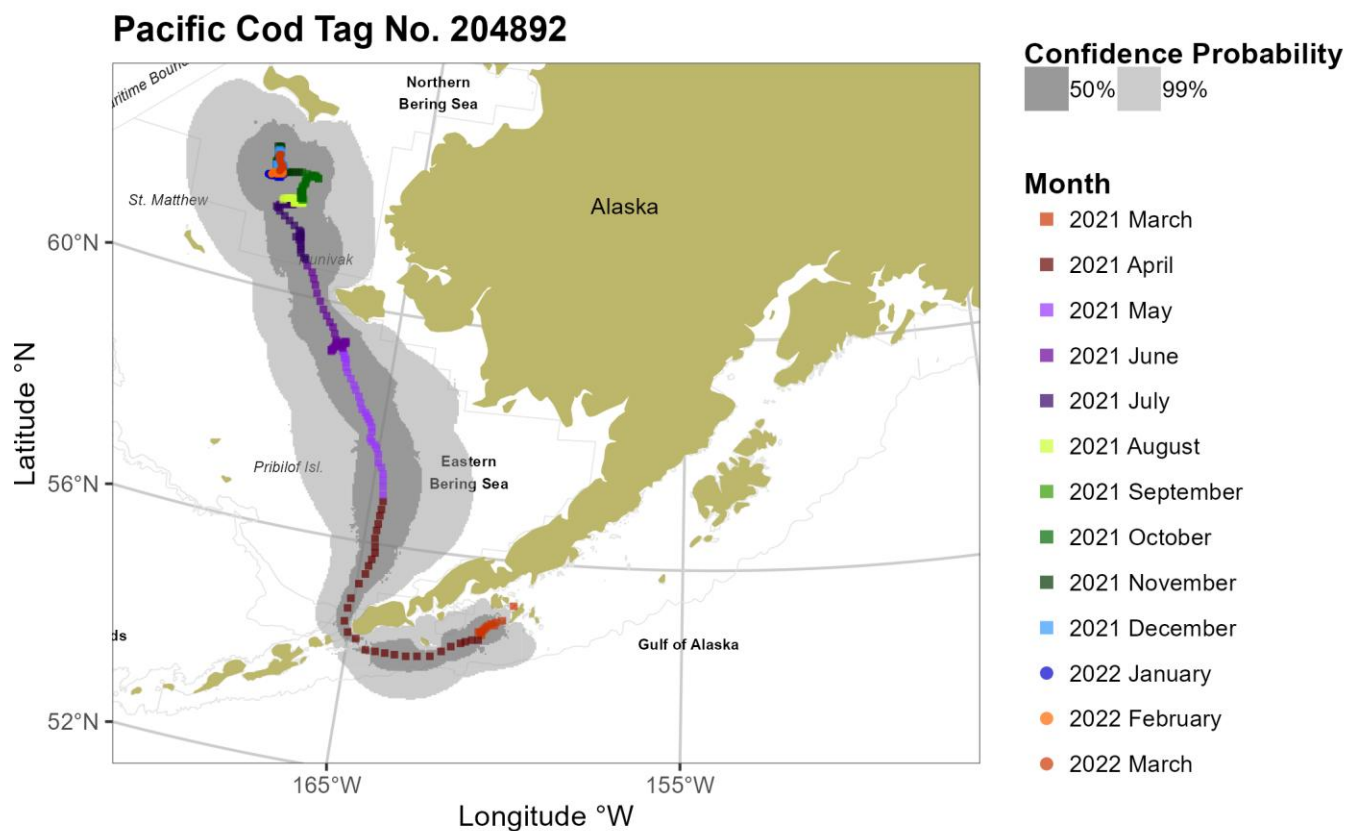


Figure 25. -- Map of Pacific cod tag 204892 with 50% (medium gray) and 99% (light gray) confidence probability shapefiles. Find color descriptions in Table 2.

Tag 204888

The Pacific cod with tag 204888 (length: 79 cm) was released on March 19, 2021 in the Gulf of Alaska at 55.54°N latitude and -160.07°W longitude and the pop-up was on January 22, 2022 at 54.97°N latitude and -165.12°W longitude (Fig. 26; Table 1). This fish was at liberty for 310 days. This fish traveled from its release location through Unimak Pass into the Bering Sea, by July. The rest of its time was spent just north of Unimak Pass in the Bering Sea.

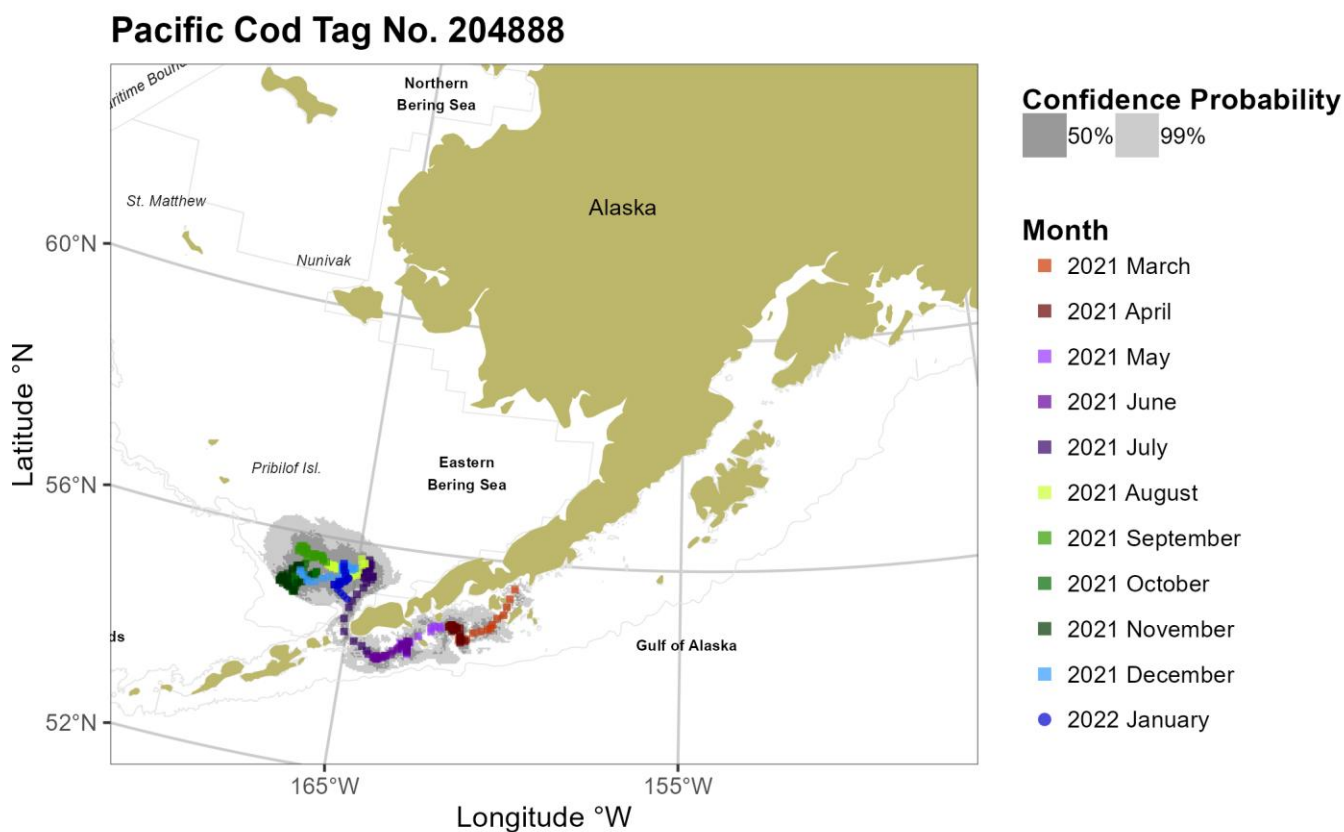


Figure 26. -- Map of Pacific cod tag 204888 with 50% (medium gray) and 99% (light gray) confidence probability shapefiles. Find color descriptions in Table 2.

Tag 204887

The Pacific cod with tag 204887 (length: 63 cm) was released on March 19, 2021 in the Gulf of Alaska at 55.54°N latitude and -160.07°W longitude and the pop-up was on February 15, 2022 at 55.61°N latitude and -160.09°W longitude (Fig. 27; Table 1). This fish was at liberty for 334 days. This fish was at liberty for almost a year and remained close to the release location in the western Gulf of Alaska.

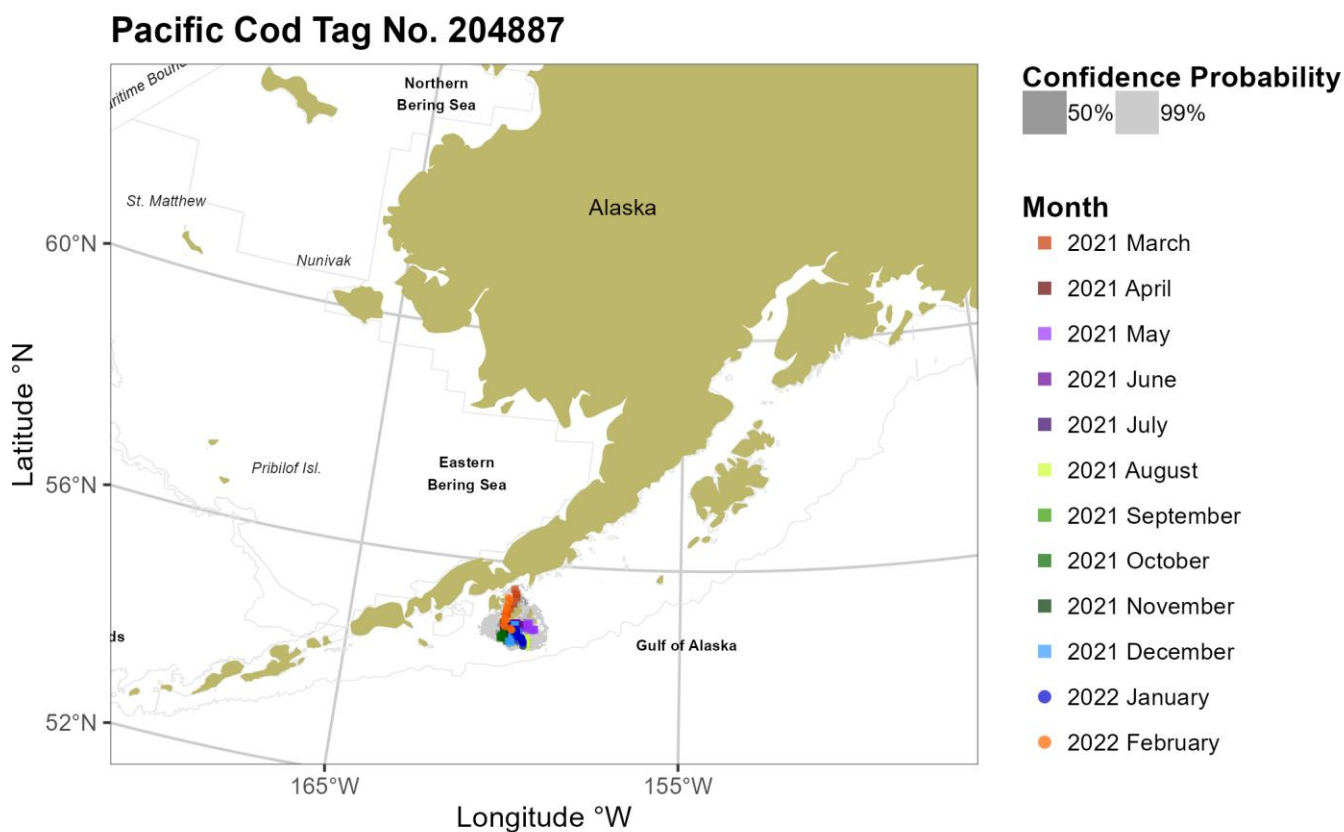


Figure 27. -- Map of Pacific cod tag 204887 with 50% (medium gray) and 99% (light gray) confidence probability shapefiles. Find color descriptions in Table 2.

Tag 209233

The Pacific cod with tag 209233 (length: 74 cm) was released on March 21, 2021 in the Gulf of Alaska at 54.42°N latitude and -162.33°W longitude and the pop-up was on September 18, 2021 at 69.1779°N latitude and -167.1103°W longitude (Fig. 28; Table 1). This fish was at liberty for 180 days. This fish traveled steadily northward from the western Gulf of Alaska to the Chukchi Sea where the tag popped-up in September.

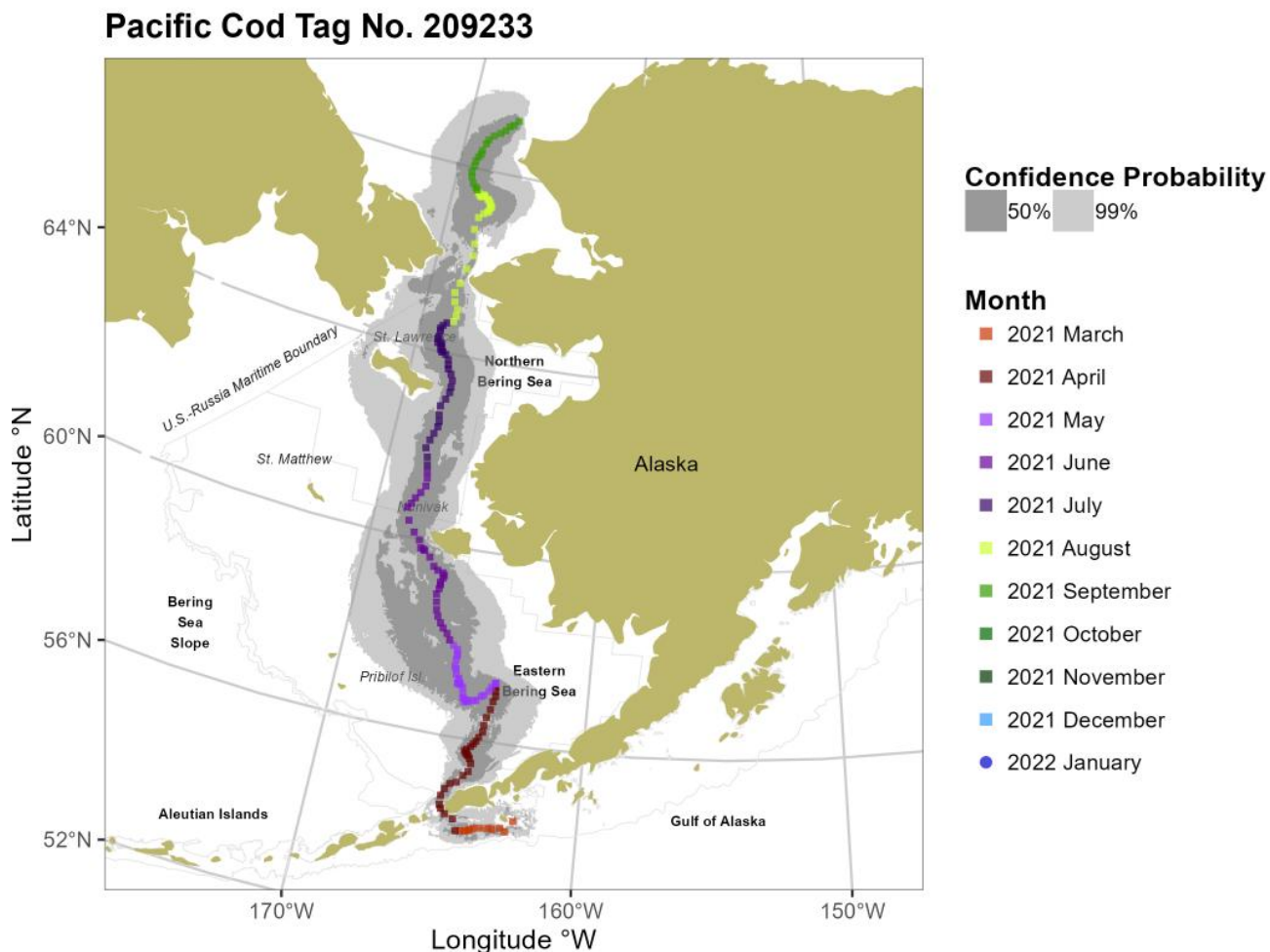


Figure 28. -- Map of Pacific cod tag 209233 with 50% (medium gray) and 99% (light gray) confidence probability shapefiles. Find color descriptions in Table 2.

DISCUSSION

This report is one of five Alaska Fisheries Science Center (AFSC) Technical Memorandums summarizing results from PSAT-tagged Pacific cod, including reconstructed individual movement paths, for release years 2019 (Markowitz et al. 2025), 2021, 2022, 2023, and 2024. With the exception of 2019, all tag releases from 2021–2024 occurred in the western and/or central GOA.

Pacific cod stocks are presently managed separately in the GOA and BS which is why it is so important to understand how much movement of Pacific cod there is between the GOA and the BS. To summarize coarse interannual movement patterns, we calculated migration rates by release year, focusing on movements from the western GOA into the BS, including the eastern and northern Bering Sea, Chukchi Sea, and Russian waters. A summary table of these movements is included in each subsequent AFSC Technical Memorandum (2021–2024). The following assumptions were applied to generate the movement summary table (western GOA releases only):

- Pacific cod were classified as “migratory” if their satellite tag popped up outside of the western GOA in northern waters, which includes the eastern or northern Bering Sea, Russian waters, or the Chukchi Sea (aggregated within the BS column, Table 3).
- Fish with tags that popped up in the western GOA after May 1 were presumed residents of the GOA for the remainder of their time (if applicable) at liberty, according to their programmed pop-off time.
- Early pop-up tags in the western GOA (before May 1) were designated as “unknown”, as these fish may have subsequently migrated into the BS but lacked sufficient days at liberty to confirm migration (Table 3, “Pre-May 1 Pop-Up”).
- The “% Migrated (minimum)” represents a conservative estimate of tagged Pacific cod migration.

Table 3. -- Movement summary table for pop-up satellite tags (PSATs) released during winter spawning in the western Gulf of Alaska (GOA), restricted to PSATs from which a pop-up recovery location was available. “Migrated North” are fish with pop-up locations north of the GOA (BS, CS, Rus). “In GOA May 1” are fish that have a pop-up location in the GOA sometime after May 1. “Total Known” is the total of “Migrated North” and “In GOA May 1”. The “% Migrated (minimum)” represents the number of fish that “Migrated North (BS, CS, or Rus)” divided by the “Total Known May 1”. The “Pre-May 1 Pop-Up” column is the number of tags that surfaced in the GOA before May 1. Because the ultimate fate of these fish is unknown, they are excluded from the migration calculation. BS = eastern and northern Bering Sea, CS = Chukchi Sea, Rus = Russia.

Year	Migrated North (BS, CS, Rus)	In GOA May 1	Total Known May 1	% Migrated (minimum)	Pre-May 1 Pop-Up
2021	12	9	21	57%	2
2022	5	21	26	19%	0
2023	11	7	18	61%	1
2024	8	6	14	57%	5

In 2021, a conservative estimate indicated that 57% of Pacific cod migrated from the western GOA release area into the Bering Sea and, in some cases, further north (Fig. 2). Once Pacific cod migrated northward, they generally remained in the northern regions throughout the summer months, presumably to forage.

According to the Gulf of Alaska Ecosystem Status Report (Ferris and Zador 2021), summer 2021 (June–August) represented the second consecutive non-marine heatwave year in the western GOA, with sea surface and subsurface temperatures near average. This suggests that temperature anomalies associated with the 2019 GOA marine heatwave had dissipated prior to the March 2021 PSAT release cruise.

In contrast, the Bering Sea experienced its seventh consecutive year of above-average bottom temperatures (Markowitz et al. 2021), potentially providing favorable thermal conditions for northward migration if Pacific cod. Pacific cod are known to avoid the coldest bottom temperatures, such as those associated with the Bering Sea cold pool (bottom temperatures $\leq 2^{\circ}\text{C}$) and warmer conditions may therefore facilitate expanded distribution into northern regions (Stevenson and Lauth, 2018).

Collectively, these results demonstrate substantial interannual variability in migration rates and highlight the importance of accounting for cross-regional movement in stock assessment and survey interpretation, because the bottom trawl surveys only occur in the summer months (Markowitz et al. 2021; Siple et al. 2024). Continued tagging and movement analyses will be critical for improving our understanding of Pacific cod spatial dynamics and for informing management decisions across the GOA and BS management areas.

ACKNOWLEDGMENTS

Recognition and appreciation are extended to the captain and crew of the FV *Decision* which provided the platform to tag and release Pacific cod. Without their extensive knowledge of western Gulf of Alaska fishing areas, terrain and limitations, this study would not have been possible. In particular, we'd like to thank the vessel crew, Kiley Thompson (Captain), Kevin Gunderson (crew), Chris Yetchmeneff (crew), and Sergio Porcinola (crew) for their hard work on deck and assisting with all the tagging operations.

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Finally, we thank reviewers Steve Barbeaux, Ingrid Spies, and Ned Laman for their efforts and timely feedback to improve this report.

Aleutians East Borough's work is conducted in the waters and along the coastlines of Alaska, which include the traditional homelands and waters of the Inupiat, Yupiit, Siberian Yupiit, Unangax, Alutiiq/Sugpiaq, Eyak, Dena'ina Athabascan, Tlingit, Haida, and Tsimshian who have stewarded their lands and waters since time immemorial. We are indebted to these peoples for their wisdom and knowledge of their lands and waters.

This document was prepared in the greater Seattle area, which is located on the traditional lands of the Coast Salish people, including the Duwamish people, past and present and Juneau, Alaska, which is located on the on the unceded territory of the Áak'w K̓wáan on Lingít Aaní, also known as Juneau and Douglas, Alaska, which also houses neighboring X̱aadas and Ts'msyen peoples. We are grateful for their continued sharing of vision, wisdom, values, and leadership.

Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

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