Pacific cod Satellite Tagging in the Gulf of Alaska Outreach Update - 2021 to 2025

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Overview

The Pacific Cod Tagging Team (PACT) has been working since 2019 deploying satellite archival tags on Pacific cod in Alaska to investigate their movement and migration patterns. However, we have primarily focused on tagging Pacific cod in the Western and Central Gulf of Alaska (WGOA and CGOA, respectively) since 2021. In recent years, Pacific cod distributions have changed dramatically with changing ocean conditions. In the Eastern Bering Sea (EBS), cod have moved northward into the Northern Bering Sea (NBS), and in the Gulf of Alaska (GOA), Pacific cod have experienced a large decline during the latest warm blob (2016 to 2019).

Since 2021 we have documented movement from the WGOA National Marine Fisheries Service (NMFS) Statistical Area 610 (winter spawning) to the EBS (summer foraging), which is a different Fishery Management Plan (FMP) area and managed as a separate stock. Our aim is to understand this seasonal movement to manage stocks appropriately and predict change in response to a changing climate. As of March 2025, we have released 251 satellite tags on fish in the WGOA and CGOA (Figure 1) on their winter spawning grounds (February-April). Tagging sites were selected based on known spawning locations. At each tagging site, five fish were randomly selected with pot gear following established satellite tagging methods (Bryan et. al 2020). In 2023, tagging sites were expanded into the CGOA thus reducing the number of tagging sites in the WGOA, but continuing to release five fish per site. This report summarizes preliminary key findings to date.

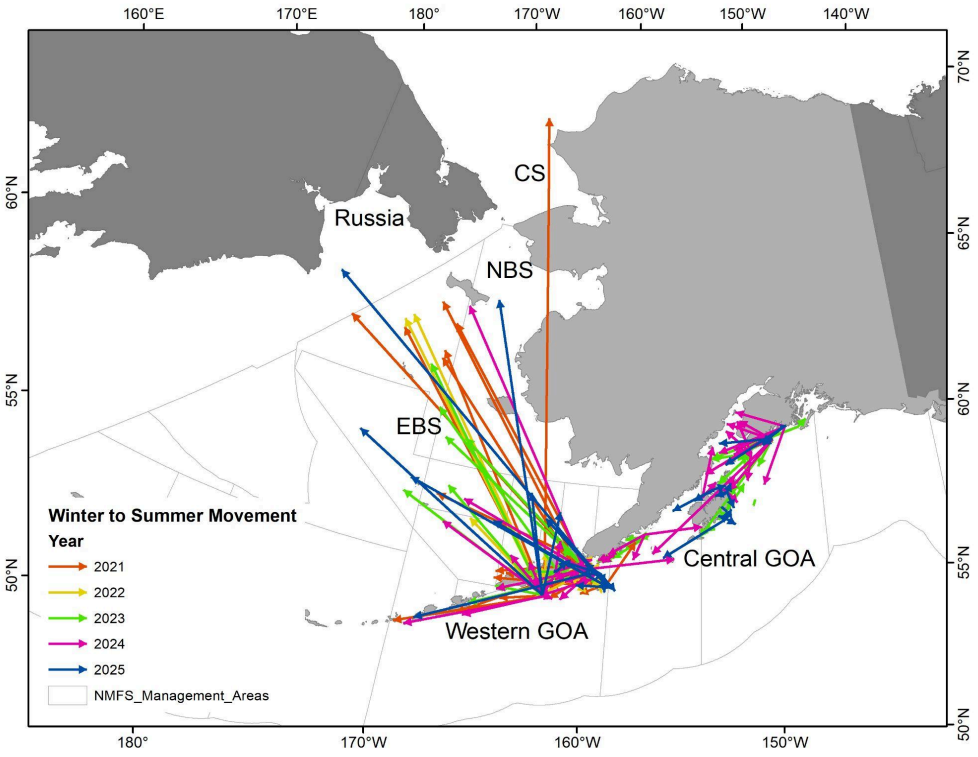

Figure 1 - Map of Pacific cod that were satellite tagged and released in the WGOA (2021-2025) and CGOA (2023-2025) during winter spawning (March). This map illustrates movement from winter to summer feeding areas (WGOA tagged fish) and little to no movement out of the CGOA.

Estimating Locations

Satellite tags record continuous depth, temperature, and light levels experienced by the tagged fish and are programmed to release from the fish on a specific date. After a satellite tag is released from the fish, it floats to the surface and transmits its data to satellites. A geolocation model (a hidden Markov model, or HMM) is used to estimate the travel path based on the release location, the pop-up location, and the data transmitted by the tag. The light level data provide information about the time of local noon (longitude) and the time of dusk and dawn (latitude). Depth data are also used in the model by linking the maximum depth of the fish each day to a depth contour in the study area.

The study area is divided into a 3 x 3 km grid, and each grid cell contains the probability that the fish was present in that grid cell each day based on the estimated latitude and longitude and maximum daily depth. Daily point estimates are the center of the most probable grid cell occupied on each day. Additionally, the model creates error polygons that encompass the highest 50% and 99% of the HMM posterior probability for each day. Full methods for the analyses are in Nielsen et al. (2023; https://doi.org/10.1186/s40317-023-00340-3).

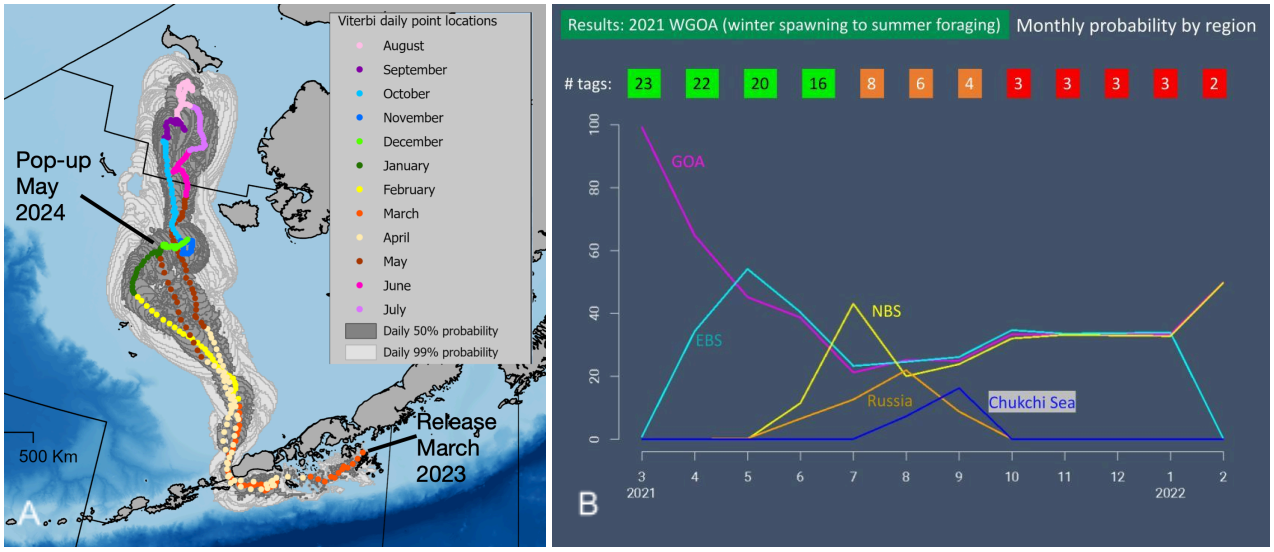

Figure 2. (A) Movement pathway of a cod released in the WGOA during winter 2023 that moved to the NBS during the summer of 2023, returned to the WGOA the winter of 2024, and moved back to the EBS the summer of 2024. Daily point estimates are color coded by month; 99% error polygons (light grey) and 50% error polygons (dark grey) provide information on uncertainty of daily point estimates. (B) Example of aggregated monthly location probability by region (for GOA, NBS, EBS, Russia and the Chukchi Sea) for tags released in the WGOA in 2021. The number of tags contributing to the probability each month is listed, and decreases as tags pop-up.

Using the geolocation results, we are able to map a movement pathway that shows daily location point estimates color coded by month, along with 50% and 99% location probabilities (Figure 2A). We have produced these pathways for each individual tagged fish, and are in the

process of aggregating the pathways to estimate the probability that a cod will be in a given region during a given month.

The example in 2021 (Figure 2B) shows a 100% probability that WGOA fish are in the WGOA in March because that is where they were tagged and released. But by April, the probability of being in the WGOA decreased to roughly 65% and increased to 35% in the EBS. This will be an important result for management, because it helps stock assessment authors understand if, and to what degree (in space and time), a cod is available to a fishery and the bottom trawl survey.

Key Takeaway #1: Western Gulf of Alaska tagged cod demonstrate consistent seasonal movements northward into the Bering Sea, crossing management boundaries.

On average between 2021-2025, of fish with known migration, approximately 43% of satellite tagged Pacific cod from the WGOA moved north into the EBS/NBS shortly after tagging during winter spawning (Table 1). These migratory fish then remain in the Bering Sea regions throughout the summer months, presumably to feed. There was consistent migration every year, although years 2022 and 2025 saw a lower proportion of migration. In 2022, field work was delayed several weeks because the air temperature was too cold to tag without risk of damaging fish. In 2025, water temperatures were notably high despite field work occurring during the usual period. In both cases, we suspect the timing of field work may have “missed” migratory fish as our tag data show that migratory fish tended to leave quickly after spawning.

To summarize movement by release year between the WGOA Region and the Bering Sea, we used the following assumptions to create a table of movement for **WGOA tagged fish only**:

- We define migratory Pacific cod based on any fish whose satellite tag pops up in the EBS/NBS, Russia or the Chukchi Sea (aggregated in the BS column).
- Migratory Pacific cod are then considered either available to the EBS/NBS annual summer bottom trawl survey or at least not available to the GOA survey (i.e. Russia and Chukchi).
- A fish whose tag pops-up in the CGOA is presumed to be part of the population available to be assessed in the biennial GOA summer bottom trawl survey during the same year.
- A fish whose tag pops up in the WGOA on schedule (or after) or pops up during/after May, is presumed to be part of the population available to be assessed in the biennial GOA summer bottom trawl survey during the same year.
- Early pop-up tags in the WGOA before May, are designated "Unknown" as these fish could have still migrated into the BS, but there was not enough tag data or days at liberty to define the fish as migratory.
- Any fish with a satellite tag that pops up in an FMP area by May is considered a resident of that area for the duration of summer.
- The “Minimum % Migrated” is a conservative estimate of tagged Pacific cod migration.

Table 1. Pop-up satellite tags released in the Western Gulf of Alaska only during winter spawning, for tags where we received data. Minimum % migrated is calculated as the number of fish in the Eastern/Northern Bering Sea, divided by the sum of all known fish. BS = Eastern/Northern Bering Sea, GOA = Gulf of Alaska, pop-up = pop-up for satellite tag.

Release Year	BS	GOA (pop-up>= May)	Unknown (pop-up < May)	Total WGOA Releases (BS+GOA)	Minimum % Migrated
2021	12	8	4	24	60%
2022	5	21	0	26	19%
2023	10	8	1	19	56%
2024	8	6	5	19	57%
2025	8	15	3	26	35%
Total Average	**43**	**58**	**13**	**114**	**43%**

Key Takeaway #2: Central Gulf of Alaska tagged cod demonstrate year around movement within the Central Gulf of Alaska management region.

More than 93% of tagged Pacific cod in the CGOA did not move into the WGOA; the remaining 7% were tagged and recovered close to the management boundary. We are further exploring movement within the CGOA, in particular, regions where fish move very little (10s of km) vs. those that move across the CGOA management area from the tag release site (but not into the WGOA).

Key Takeaway #3: Satellite tagging limitations and new research

Over the course of our research we have discovered several limitations in using satellite tags. Although they are very effective at determining movement from winter to summer locations, problems with transmission in the winter limit our ability to detect movement back to winter grounds. Additionally, satellite tags are expensive and the sample sizes are small but provide highly detailed data that has shown consistent and substantial seasonal movement between management areas. Therefore it has become apparent that alternative technologies such as acoustic telemetry are needed to provide information on year-round movement of fish tagged in the WGOA during the winter and boost sample sizes to allow population-level inference of movement between management areas.

In early 2025 we were awarded a grant from North Pacific Research Board (NPRB) to conduct a pilot study to examine the effectiveness of deploying acoustic moorings in Unimak Pass. The acoustic moorings would be capable of picking up Pacific cod with surgically implanted transmitters. In October 2025, we deployed 3 sets of acoustic moorings directly in Unimak Pass

and surgically implanted 20 Pacific cod with transmitters. The moorings will remain deployed until spring 2026, at which time we will retrieve them and analyze the data. The data will help us determine the effective detection radius of our moorings, which will be used when determining how far apart to deploy acoustic receivers in the future to ensure we don't miss any tagged fish moving through the pass. This is the first step in the process of establishing a "gate" of acoustic receivers across Unimak Pass to determine Pacific cod movement into the EBS/NBS on a much larger scale over a longer period of time.

Biological Data Collections

In addition to tagging Pacific cod with satellite tags, we also measure and collect biological data associated with fish captured over the duration of the tagging cruise. Therefore, most of our collected biological data is from March/April of that year. We also measure each Pacific cod that is satellite tagged to the nearest centimeter (cm) (Figure 3). Preliminary assessment of demographics show that the difference in length between WGOA and CGOA tagged cod varies between years (Figure 3A). However when looking only at WGOA tagged cod, migratory fish are consistently larger than resident fish (Figure 3B). For the purposes of this report, resident is defined as fish that did not leave the GOA FMP area. Our next step is to compare length-at-age to look for differences in growth rate that help us understand if resident vs. migrant fish are behaviorally distinct populations, or alternatively, a single population that exhibits ontogenetic behavior where fish that reach a certain age/size/condition become migratory.

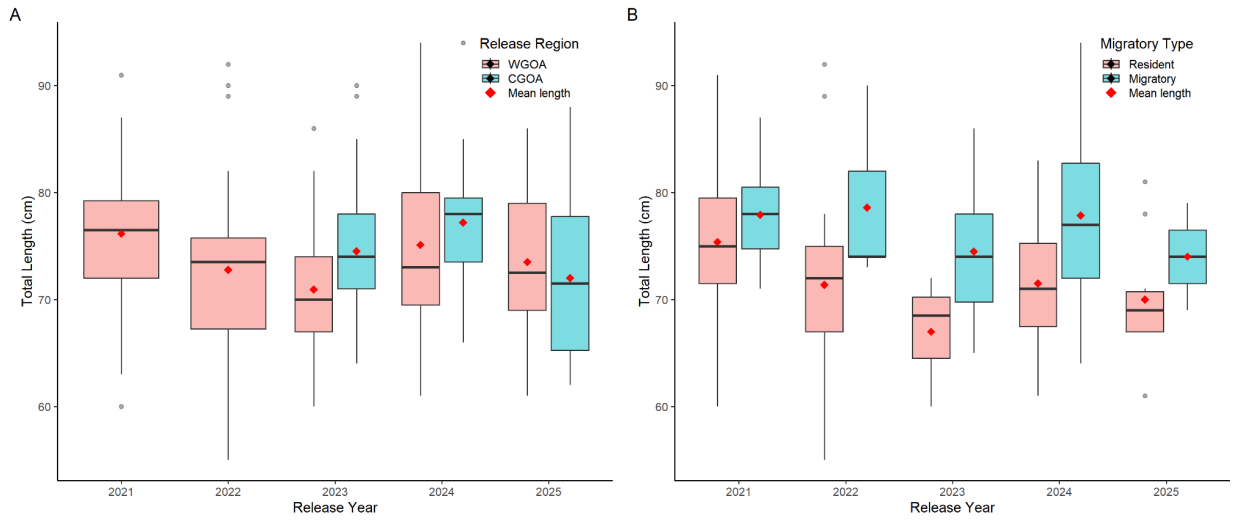

Figure 3. Mean length of Pacific cod tagged in the WGOA and CGOA by region (A) and migratory type (B) (WGOA only).

Contributions to Stock Assessment

Each year, our team provides a summary of results to date to Pacific cod stock assessment authors. There have been ongoing discussions on how to best incorporate tagging results into stock assessment and management. GOA stock assessment author Pete Hulson recently gave

a presentation on this topic at the September 2025 Plan Team meeting. The full presentation can can be found at this link, and summarized here:

"Combining all Western and Central Gulf of Alaska tagging data to date, the Western Gulf of Alaska has the largest amount of movement out of the region when compared to the Eastern Bering Sea and Central Gulf of Alaska. There is a strong seasonal component, where the bulk of movement from Western Gulf of Alaska to the Eastern/Northern Bering Sea and Central Gulf of Alaska occurs prior to April [each year]. Recent tagging has less movement to the Eastern/Northern Bering Sea (~37%) as compared to historical tagging data (~54%) prior to April [2025]. Eastern/Northern Bering Sea movement to the Western Gulf of Alaska is consistent across month/season, and hovers ~6%. The Central Gulf of Alaska has limited movement to the Western Gulf of Alaska and none recorded to the Eastern/Northern Bering Sea."

Next Steps

- Peer-review publications: estimated movement pathways and satellite tag data in NOAA Technical Memorandum for all GOA tags; comprehensive GOA movement and behavior manuscripts for peer-review.
- Continue collaboration with stock assessment scientists to develop methods to incorporate both the timing and magnitude of movement from the Western Gulf of Alaska to the Eastern/Northern Bering Sea. We will also include results from satellite tagged fish from the Central Gulf of Alaska, which tend to stay within the Central Gulf of Alaska area.
- Analyze temperature and depth data with geneticists to understand the influence of stock structure on migratory and other behavioral patterns in Pacific cod that may be affected by ocean temperatures.
- Field effort to retrieve Unimak pass acoustic receivers in Spring 2026. Data retrieved from receivers will be used to analyze signal detection to complete pilot study. Results will be used to design a full-scale array, and the tagging sampling design with input from stock assessment to achieve population-level movement.