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TELEMETRY AND GENETIC IDENTITY OF CHINOOK SALMON IN ALASKA: PRELIMINARY REPORT OF SATELLITE TAGS DEPLOYED IN 2020–2021

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Cover photo: Chinook salmon tagged and released with a pop-up satellite archival tag near Chignik Bay, Alaska. Research activities were conducted under the University of Alaska Fairbanks Institutional Animal Care and Use Committee assurance 495247 and State of Alaska Aquatic Resource Permits CF-20-039, CF-21-027, and CF-21-085. Photo credit, Michael Courtney.

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14. ABSTRACT
Chinook salmon (*Oncorhynchus tshawytscha*) is an iconic species found throughout the North Pacific Ocean and supports invaluable subsistence, commercial and recreational fisheries. In addition to its importance to fisheries, Chinook salmon is an important food source for many apex marine predators, including endangered southern resident killer whales (*Orcinus orca*). Currently, coast-wide changes in Chinook salmon population demographics and production have been documented from western Alaska to California, including several Evolutionarily Significant Units (ESUs) from the U.S. Pacific Northwest that are protected under the U.S. Endangered Species Act (ESA).
The U.S. Navy (Navy) conducts at-sea training in the Gulf of Alaska (GOA), including the Temporary Maritime Activities Area (TMAA). As part of the Marine Species Monitoring Program, the Navy is interested in understanding the overlap of occurrence between populations of Chinook salmon, particularly the ESUs that are listed under the ESA, and specific Navy training activities. This is challenging, as relatively little is known about the at-sea distribution and behavior of Chinook salmon, despite the fact that most individuals reside in the ocean for the majority of their lives. Therefore, an improved understanding of the distribution and behavior of Chinook salmon in the marine environment is important when addressing potential interactions between this species and specific Navy exercises within portions of the TMAA.
To qualitatively describe the spatial distribution, movement, vertical distribution, occupied habitat, and natural mortality of Chinook salmon in the GOA, we attached pop-up satellite archival tags (PSATs) to individuals near Chignik, AK (n = 20), Kodiak, AK (n = 20), and Yakutat, AK (n = 20) in 2020–2021 and collected tissue samples for genetically determining stock-of-origin of each tagged fish.

Of the 60 PSATs deployed, data were transmitted by 57 tags, providing >3,720 days of data. Reporting locations of tags were widespread across the eastern North Pacific Ocean, ranging as far west as the Bering Sea to as far east as the U.S. Pacific Northwest. Movement models suggested that the majority of tagged fish remained over the continent shelf within relatively close proximity (<500 km) to their tagging location. While occupying waters of the North Pacific Ocean, Chinook salmon occupied depths ranging from 0 to 464 m and experienced a thermal environment ranging from 1.8 to 19.0°C. Fifteen tagged Chinook salmon were inferred to have occupied the TMAA (~252 aggregated days) while at liberty (i.e., tag deployment to pop-up date). While occupying waters of the TMAA, Chinook salmon spent the majority of their time (58%) in waters over the continental shelf and spent a minority of their time over the continental slope (22%) and basin (20%). In addition to providing information on the horizontal and vertical distribution of Chinook salmon, PSATs provided evidence of mortality of tagged fish caused by endothermic fish(s) (n = 17), an ectothermic fish (n = 1), marine mammals (n = 3), and unknown (n = 6) causes. Genetic analyses suggested that all tagged Chinook salmon were from populations originating in southern Southeast Alaska, British Columbia, Washington, and Oregon.

While this study contained a small sample size, the tagged Chinook salmon were comprised of individuals from many populations extending from Southeast Alaska to the U.S. Pacific Northwest, making our results pertinent for many populations throughout North America, including stocks of concern and those listed under the ESA. The information about Chinook salmon gained in this study may be used to provide insights into important management issues in the North Pacific Ocean, including overlap between Chinook salmon and Navy training exercises in the GOA.

15. SUBJECT TERMS

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Executive Summary

Chinook salmon (*Oncorhynchus tshawytscha*) is an iconic species found throughout the North Pacific Ocean and supports invaluable subsistence, commercial and recreational fisheries. In addition to its importance to fisheries, Chinook salmon is an important food source for many apex marine predators, including endangered southern resident killer whales (*Orcinus orca*). Currently, coast-wide changes in Chinook salmon population demographics and production have been documented from western Alaska to California, including several Evolutionarily Significant Units (ESUs) from the U.S. Pacific Northwest that are protected under the U.S. Endangered Species Act (ESA).

The U.S. Navy (Navy) conducts at-sea training in the Gulf of Alaska (GOA), including the Temporary Maritime Activities Area (TMAA). As part of the Marine Species Monitoring Program, the Navy is interested in understanding the overlap of occurrence between populations of Chinook salmon, particularly the ESUs that are listed under the ESA, and specific Navy training activities. This is challenging, as relatively little is known about the at-sea distribution and behavior of Chinook salmon, despite the fact that most individuals reside in the ocean for the majority of their lives. Therefore, an improved understanding of the distribution and behavior of Chinook salmon in the marine environment is important when addressing potential interactions between this species and specific Navy exercises within portions of the TMAA.

To qualitatively describe the spatial distribution, movement, vertical distribution, occupied habitat, and natural mortality of Chinook salmon in the GOA, we attached pop-up satellite archival tags (PSATs) to individuals near Chignik, AK (n = 20), Kodiak, AK (n = 20), and Yakutat, AK (n = 20) in 2020–2021 and collected tissue samples for genetically determining stock-of-origin of each tagged fish.

Of the 60 PSATs deployed, data were transmitted by 57 tags, providing >3,720 days of data. Reporting locations of tags were widespread across the eastern North Pacific Ocean, ranging as far west as the Bering Sea to as far east as the U.S. Pacific Northwest. Movement models suggested that the majority of tagged fish remained over the continent shelf within relatively close proximity (<500 km) to their tagging location. While occupying waters of the North Pacific Ocean, Chinook salmon occupied depths ranging from 0 to 464 m and experienced a thermal environment ranging from 1.8 to 19.0°C. Fifteen tagged Chinook salmon were inferred to have occupied the TMAA (~252 aggregated days) while at liberty (i.e., tag deployment to pop-up date). While occupying waters of the TMAA, Chinook salmon spent the majority of their time (58%) in waters over the continental shelf and spent a minority of their time over the continental slope (22%) and basin (20%). In addition to providing information on the horizontal and vertical distribution of Chinook salmon, PSATs provided evidence of mortality of tagged fish caused by endothermic fish(s) (n = 17), an ectothermic fish (n = 1), marine mammals (n = 3), and unknown (n = 6) causes. Genetic analyses suggested that all tagged Chinook salmon were from populations originating in southern Southeast Alaska, British Columbia, Washington, and Oregon.

While this study contained a small sample size, the tagged Chinook salmon were comprised of individuals from many populations extending from Southeast Alaska to the U.S. Pacific Northwest, making our results pertinent for many populations throughout North America, including stocks of concern and those listed under the ESA. The information about Chinook salmon gained in this study may be used to provide insights into important management issues in

the North Pacific Ocean, including overlap between Chinook salmon and Navy training exercises in the GOA.

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Acronyms and abbreviations

CWT	Coded Wire Tag
ESU	Evolutionarily Significant Unit
ESA	U.S. Endangered Species Act
FL	Fork Length
GOA	Gulf of Alaska
HMM	Hidden Markov Model
CSSMA	Continental Shelf and Slope Mitigation Area
Navy	U.S. Navy
PSAT	Pop-up Satellite Archival Tag
TMAA	Temporary Maritime Activities Area

1. Introduction

Chinook salmon (*Oncorhynchus tshawytscha*) is an iconic species found throughout the North Pacific Ocean and supports valuable subsistence, commercial and recreational fisheries (Healey 1991; Quinn 2005; Riddell et al. 2018). In addition to fisheries, the Chinook salmon is vital to the well-being of many Indigenous communities throughout Alaska. Furthermore, Chinook salmon is an important food source for many apex marine predators, including endangered southern resident killer whales (*Orcinus orca*) (Adams et al. 2016; Chasco et al. 2017; Ford et al. 1998). Populations of anadromous (i.e., individuals that make marine feeding migrations) Chinook salmon have variable life histories. In general, Chinook salmon rear in freshwater for up to two years before they migrate to the ocean to feed for generally one to five years. After their ocean phase when they grow to adults, Chinook salmon return to their natal river to spawn once and then die.

As part of the Navy's Marine Species Monitoring Program, there is interest in understanding the overlap of occurrence between populations of Chinook salmon, particularly the ESUs that are listed under the ESA, and Navy at-sea training activities that occur in the GOA TMAA. Currently, the Navy conducts at-sea training in the GOA during the months of April to October (U.S. Navy 2020). Recently, based on results from satellite telemetry (Courtney et al. 2019; Seitz et al. 2021), in order to minimize the potential impacts to fish from Navy training exercise, the Navy has established a Continental Shelf and Slope Mitigation Area (CSSMA) within the TMAA, which prohibits explosive training activities within shelf/slope (i.e., <4,000 m bathymetry) habitats of the TMAA (U.S. Navy 2022).

While in the ocean, relatively little is known about the migration and behavior of Chinook salmon, despite the fact that individuals frequently reside in the ocean for the majority of their lives (Brodeur et al. 2000; Drenner et al. 2012; Riddell et al. 2018). Currently, based on coded wire tag (CWT) recoveries, genetic analyses, and bycatch in groundfish fisheries, there is believed to be large spatial overlap in the oceanic distributions of many populations of Chinook salmon originating from North America (Larson et al. 2013; Trudel et al. 2009; Weitkamp 2010). For example, Chinook salmon from several ESUs from the U.S. Pacific Northwest that are protected under the ESA are thought to migrate north to the GOA, extending into the Bering Sea. However, there are many details about this species that are unknown, as most of what is known about Chinook salmon occurrence in the GOA, particularly outside of State of Alaska waters (>3 nm from shore), is dependent on incidental captures in groundfish trawl fisheries, which are not conducted in a spatially and temporally uniform manner throughout the GOA. Furthermore, because Chinook salmon are designated as prohibited species and are subject to caps that may close groundfish trawl fisheries because they reach their catch quotas, Chinook salmon are actively avoided by trawl fleets. As a result, information about Chinook salmon is spatially and temporally biased and it does not exist throughout the species' entire range, which extends beyond where groundfish fisheries occur. As a result, fine-scale movements and habitat occupancy of Chinook salmon in the GOA are not well understood (Walker and Myers 2009; Walker et al. 2007).

A complementary method to bycatch records for studying the ocean ecology of Chinook salmon is PSATs (Courtney et al. 2021; Courtney et al. 2019). While attached to a fish, PSATs measure and record data, including depth, ambient temperature, and light intensity (Arnold and Dewar 2001; Musyl et al. 2011; Thorstad et al. 2013). On a user-defined date, PSATs release from the fish, float to the surface of the water and transmit data to satellites, which are then retrieved by project investigators. Because PSATs do not rely on recapture for data retrieval, they are a fisheries independent method of data collection. Therefore, PSATs are feasible method to provide an improved understanding of the spatial distribution and behaviors of Chinook salmon, independent of groundfish fisheries, which is important when addressing potential interactions between this species and Navy exercises in the TMAA.

To examine Chinook salmon ocean ecology while occupying waters of the GOA, large (>60 cm), immature Chinook salmon were captured and tagged with PSATs at three sites along the coast of Alaska. The PSATs provide information about the horizontal distribution, movement, vertical distribution, and occupied habitat of tagged Chinook salmon. To understand stock-of-origin of each tagged fish, tissue samples were collected and genetic analyses were conducted. This information can provide a more complete understanding of the biology and ecology of the oceanic phase of large, immature Chinook salmon within the GOA, which may be useful for understanding potential interactions between this species and Navy exercises in the TMAA.

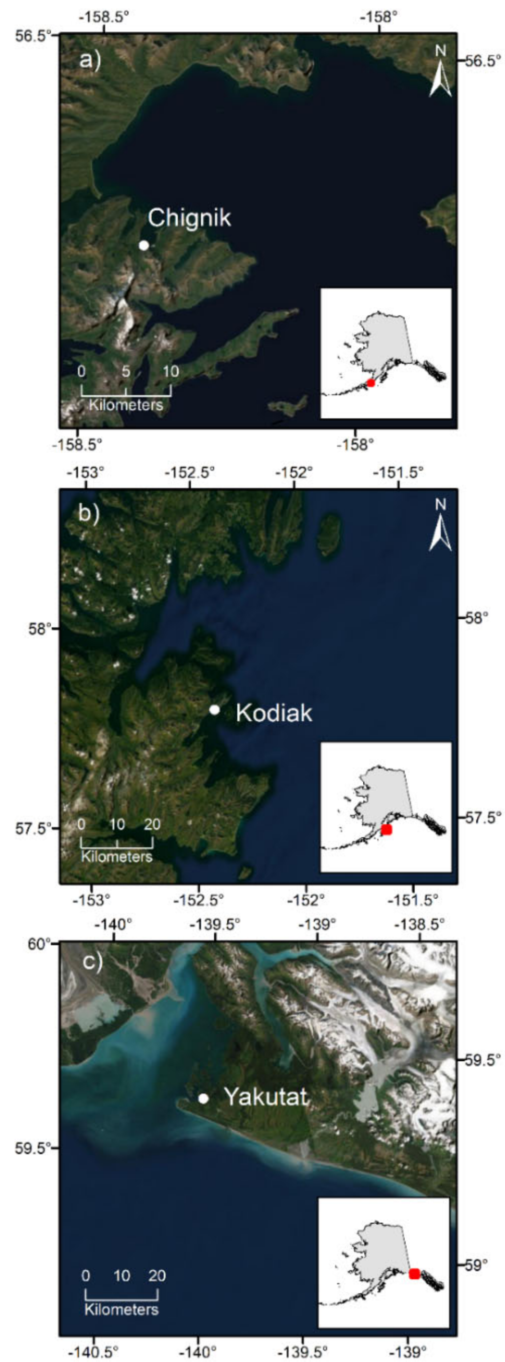

Figure 1. Study regions near Chignik, AK (a), Kodiak, AK (b), and Yakutat, AK (c), where Chinook salmon were captured and tagged with pop-up satellite archival tags in 2020 and 2021. Map insets in lower right hand corners of panels indicate extent of sampling locations within Alaska.

2. Methods

2.1 Fish capture and tagging

During angling field expeditions in 2020–2021, large, immature, Chinook salmon were captured, tagged, and released near Chignik, AK (n = 20; 1–4 August 2020), Kodiak, AK (n = 20; 5–28 October 2020), and Yakutat, AK (n = 20; 3–22 March 2021) (Table 1; Fig. 1). Fieldwork was also conducted near Chignik, AK, in August 2021, however no satellite tags were deployed because no Chinook salmon of adequate size for tagging (described below) were captured, and this effort is not described subsequently. After hooking, fish were retrieved quickly, brought onboard the fishing vessel in a padded net, and visually assessed for signs of stress or abnormal behavior, including external injuries, loss of scales, bleeding, loss of equilibrium, pupil dilation, abnormal coloration, frayed fins, and rapid opercular movement. Only Chinook salmon deemed to be healthy according to these metrics and >60 cm fork length (FL) were selected for tagging. Tagging Chinook salmon of this size ensured that the tag is <2% of the body weight of the fish, a commonly accepted minimum size threshold for fish tagging (Brown et al. 2010). Candidate Chinook salmon were placed in a custom-fabricated cradle and blindfolded to reduce visual stimuli that can contribute to stress and struggling (Courtney et al. 2019).

PSATs were attached to Chinook salmon while in the cradle using a tag attachment system refined for similarly sized Dolly Varden char (*Salvelinus malma*) (Courtney et al. 2016a), Atlantic salmon (*Salmo salar*) (Strøm et al. 2017), Chinook salmon (Courtney et al. 2019) and steelhead trout (*Oncorhynchus mykiss*) (Seitz et al. 2021). In short, the tag backpack system, which consists of the tag that is tethered to two padded straps, was secured with surgical-grade (0.8 mm) wire through the dorsal musculature and bony fin-ray supports of Chinook salmon (Courtney et al. 2016b). This tag attachment technique aims to minimize muscle damage and premature rejection of the tether system caused by tearing through muscle tissue due to hydrodynamic drag of the tag. After tagging, the axillary process of each fish's left pelvic fin was removed as a tissue sample for subsequent genetic analysis. After tissue sampling, Chinook salmon were identified by tag number, photographed, and released into the ocean. All fieldwork was conducted under the University of Alaska Fairbanks Institutional Animal Care and Use Committee assurance 495247 and State of Alaska Aquatic Resource Permit CF-20-039, CF-21-027, and CF-21-085.

Table 1. Deployment information for 60 PSATs attached to Chinook salmon in the GOA in 2020 and 2021.

Argos ID	Tag SN	Harness ID	Deploy date	Deploy region	Programmed attachment duration (days)	Fork length (cm)	Reporting date	Liberty (days)	Data days	Displacement (km)	Track distance (km)
202585	20P0884	2020-092	08-03-20	Chignik	220	67	09-12-20	39	35	47	278
202586	20P0889	2020-099	08-04-20	Chignik	220	70	10-25-20	82	79	224	846
202587	20P0943	2020-089	08-04-20	Chignik	200	81	12-04-20	123	120	69	1071
202588	20P0944	2020-091	08-02-20	Chignik	270	74	11-27-20	117	112	382	1292
202589	20P0945	2020-031	08-03-20	Chignik	220	67	10-12-20	70	19	22	114
202590	20P0946	2020-084	08-04-20	Chignik	220	70	02-08-21	188	116	626	1121
202591	20P0947	2020-023	08-01-20	Chignik	270	65	10-27-20	87	84	227	678
202592	20P0948	2020-038	08-03-20	Chignik	220	75	09-05-20	33	30	1251	1316
202593	20P0949	2020-040	08-02-20	Chignik	270	65	09-13-20	42	39	63	355
202594	20P0952	2020-041	08-02-20	Chignik	270	92	01-23-21	174	73	53	710
202595	20P0953	2020-086	08-04-20	Chignik	200	69	02-17-21	197	192	338	1865
202596	20P0954	2020-029	08-03-20	Chignik	220	73	11-22-20	111	106	299	789
202597	20P0955	2020-045	08-03-20	Chignik	220	72	09-25-20	53	50	52	648
202598	20P0993	2020-097	08-04-20	Chignik	200	101	09-23-20	50	50	NA	NA
202599	20P0999	2020-093	08-04-20	Chignik	220	69	10-11-20	68	62	75	781
202600	20P1002	2020-080	08-02-20	Chignik	270	83	10-17-20	76	58	1583	1764
202601	20P1029	2020-094	08-03-20	Chignik	220	62	10-08-20	66	60	89	394
202602	20P1053	2020-030	08-03-20	Chignik	220	70	10-04-20	62	57	56	497
202603	20P1055	2020-098	08-04-20	Chignik	200	71	09-07-20	34	31	305	651
202604	20P1056	2020-033	08-02-20	Chignik	270	88	NA	NA	NA	NA	NA
205398	20P1552	2020-050	10-06-20	Kodiak	240	67	11-04-20	29	26	68	145
205399	20P1565	2020-049	10-05-20	Kodiak	240	68	10-26-20	21	15	122	206
205400	20P1576	2020-027	10-08-20	Kodiak	240	74	11-26-20	49	44	189	638
205401	20P1584	2020-048	10-06-20	Kodiak	240	68	10-30-20	24	18	39	100
205402	20P1586	2020-047	10-09-20	Kodiak	240	76	10-18-20	10	7	36	36
205403	20P1588	2020-027	10-08-20	Kodiak	210	66	12-08-20	62	54	273	773
205404	20P1589	2020-090	10-11-20	Kodiak	210	69	01-02-21	83	76	246	455
205405	20P1599	2020-028	10-13-20	Kodiak	210	74	04-22-21	191	188	2282	3088
205406	20P1625	2020-043	10-11-20	Kodiak	210	66	12-13-20	63	60	463	584
205407	20P1636	2020-034	10-11-20	Kodiak	210	71	12-25-20	75	72	357	684
205408	20P1637	2020-037	10-06-20	Kodiak	180	77	11-08-20	33	28	95	305
205409	20P1649	2020-036	10-07-20	Kodiak	180	77	10-26-20	19	15	92	139
205410	20P1667	2020-039	10-09-20	Kodiak	180	69	12-03-20	55	50	201	344
205411	20P1668	NA	10-15-20	Kodiak	180	85	12-12-20	58	55	219	336
205412	20P1670	2020-026	10-06-20	Kodiak	180	69	10-24-20	18	12	78	105
205413	20P1671	2020-079	10-06-20	Kodiak	150	75	01-09-21	95	92	267	877
205414	20P1672	2020-046	10-13-20	Kodiak	150	66	NA	NA	NA	NA	NA
205415	20P1673	2020-095	10-05-20	Kodiak	150	81	02-20-21	138	135	1573	2199
205416	20P1682	2020-035	10-07-20	Kodiak	150	71	10-27-20	20	17	138	166

Argos ID	Tag SN	Harness ID	Deploy date	Deploy region	Programmed attachment duration (days)	Fork length (cm)	Reporting date	Liberty (days)	Data days	Displacement (km)	Track distance (km)
205417	20P1691	2020-078	10-07-20	Kodiak	150	64	11-12-20	36	30	142	197
210757	20P2236	2020-320	03-19-21	Yakutat	120	77	03-25-21	6	3	17	13
210758	20P2237	2020-315	03-06-21	Yakutat	120	70	06-15-21	101	98	61	953
210759	20P2238	2020-301	03-05-21	Yakutat	120	74	NA	NA	NA	NA	NA
210760	20P2239	2020-306	03-05-21	Yakutat	120	73	06-22-21	110	107	776	1493
210761*	20P2240	2020-313	03-07-21	Yakutat	90	78	06-05-21	90	89	1744	2101
210762	20P2241	2020-307	03-14-21	Yakutat	90	79	03-24-21	10	6	46	49
210763	20P2242	2020-300	03-05-21	Yakutat	90	79	06-03-21	90	90	753	1410
210764	20P2244	2020-305	03-05-21	Yakutat	90	89	06-03-21	90	90	584	977
210765	20P2246	2020-302	03-05-21	Yakutat	120	70	07-02-21	119	115	723	2535
210766	20P2247	2020-311	03-07-21	Yakutat	120	80	03-27-21	20	13	122	183
210767	20P2248	2020-308	03-05-21	Yakutat	120	74	05-21-21	77	76	757	1086
210768	20P2249	2020-321	03-20-21	Yakutat	120	82	04-24-21	35	32	88	325
210769	20P2309	2020-312	03-07-21	Yakutat	150	70	06-22-21	106	103	1196	1591
210770	20P2311	2020-322	03-22-21	Yakutat	150	74	06-25-21	94	91	454	1240
210771	20P2312	2020-310	03-07-21	Yakutat	150	72	04-24-21	48	45	429	890
210772	20P2346	2020-318	03-20-21	Yakutat	150	74	05-16-21	57	54	371	432
210773	20P2347	2020-316	03-07-21	Yakutat	180	74	07-02-21	117	108	1655	2065
210774	20P2348	2020-314	03-21-21	Yakutat	120	85	06-16-21	87	87	1800	2128
210775	20P2350	2020-309	03-07-21	Yakutat	180	70	06-05-21	90	87	337	948
210776	20P2351	2020-303	03-05-21	Yakutat	180	72	05-12-21	68	59	184	364

a) Argos ID refers to the transmitter identification number in each tag supplied by the Argos Satellite System
b) Tag SN refers to serial number of tag, provided by the tags' manufacturer
c) Harness ID refers to identification number displayed on tag harness system, which remains on the fish after the satellite tag releases
d) Liberty refers to the number of days between tagging and the first day of transmission to satellites
e) Data days refers to the total days of data provided by the tag while attached to a live, free-swimming Chinook salmon (i.e., not in the stomach of a predator)
f) Displacement refers to the minimum great arc circle distance between tagging and end locations
g) Track distance refers to curvilinear distance swam by the fish between tagging and end locations, calculated as the sum of distances between daily position estimates produced by a Hidden Markov Model
*PSAT was recaptured in a commercial fishery, near Astoria, Oregon, on 5 June 2021

2.2 Tag specifications and data acquisition

All PSATs (MiniPAT, Wildlife Computers; Redmond, WA; https://wildlifecomputers.com/our-tags/minipat/) weighed 60 g in air and were slightly buoyant in water. While attached to a Chinook salmon, the PSATs measured and archived temperature, depth, and ambient light intensity data. After releasing from the fish, the tags floated to the surface of the sea and transmitted, via satellite (Argos Satellite System), summarized temperature and depth data (resolution 5.0–10.0 min) and daily dawn and dusk times determined from light data. While transmitting, a highly accurate end location was determined (Keating 1995). If tags were recaptured from a live fish or found on shore, data were retrieved in the tags' native resolution (1–5 sec in this study). PSATs were programmed to release from tagged fish at staggered intervals between 90 and 270 days post-tagging (Table 1). This staggered pop-up scheduled was developed as a compromise between obtaining accurate end locations of tagged fish throughout the calendar year and maximizing duration of tag data records and tag-reporting rates. Additionally, tags were programmed to release and report to satellites before their scheduled pop-up date if they triggered a fail-safe mechanism by remaining at a constant depth (± 2.5 m) for three days. This release criterion was based on the assumption that live Chinook salmon in the ocean change depths frequently (Courtney et al. 2021; Courtney et al. 2019; Hinke et al. 2005; Walker and Myers 2009) and a lack of change in depth indicates mortality (e.g., tag remaining on sea floor) and/or premature release of tag (e.g., tag detached from fish and floating on sea surface).

2.3 Data analyses

To understand the horizontal movement of tagged Chinook salmon, end locations were assigned as the location of first transmission to satellites of each PSAT with an Argos location class 1–3, corresponding to an accuracy of <1.5 km and these end locations were plotted in GIS software (ArcMap 10.4; Environmental Systems Research Institute Inc., Redlands, California). In addition, the most likely movement paths of individual tagged fish were estimated by a Hidden Markov Model (HMM) provided by Wildlife Computers (Wildlife Computers 2015), similar to past comparable research (e.g., Courtney et al. 2019; Rikardsen et al. 2021; Strøm et al. 2017). To understand the depth and temperatures occupied by tagged Chinook salmon, individual depth and temperature records were visualized through scatterplots and boxplots. Mortality of tagged fish was inferred from PSAT data that departed from depth, temperature and light values typically seen while attached to live Chinook salmon, following the criteria previously published in past comparable research (Lacroix 2014; Seitz et al. 2019; Strøm et al. 2019). In short, PSATs that recorded abrupt changes in temperature and/or depth-based behavior, and low light levels indicating complete darkness, were inferred to be in the stomach of a predator that consumed the tagged Chinook salmon, including the externally attached tag. Genetic stock-of-origin assignments were conducted by the National Marine Fisheries Service Northwest Fisheries Science Center by analyzing Single Nucleotide Polymorphisms.

3. Preliminary Results

3.1 Summary

Chinook salmon tagged in the GOA ranged from 62 to 101 cm FL (73.9 ± 7.4 cm, mean ± SD) (Table 1), with no significant differences in mean lengths (one-way ANOVA; p-value >0.05) among tagging regions. Of the 60 total tags deployed, 56 reported to satellites and one was recaptured in a commercial fishery near Astoria, Oregon before its programmed pop-up date

(Table 1). In sum, these tags provided approximately 3,720 days (mean 65.3 days per tag) of depth, temperature, and location data. Analyses of the depth, temperature, and light data from these 57 tags suggest that 30 tags were attached live fish on or immediately before the programmed pop-up date or at recapture, while the other 27 tagged fish experienced mortality by predation (n = 21) or unknown causes (n = 6). The remaining three tags failed to transmit any data to Argos satellites and were unaccounted for (i.e., missing without explanation). All tags that reported to satellites were used in depth, temperature, and HMM analyses, except one tag that released from a live fish tagged near Chignik, AK (Argos ID 202598) transmitted insufficient data for meaningful interpretation and was excluded from analyses.

3.2 Horizontal distribution

Reporting locations of tags (n = 57) attached to Chinook salmon were spread throughout the eastern North Pacific Ocean, extending from the eastern Bering Sea to the U.S. Pacific Northwest (Fig. 2; Fig. 3; Fig. 4; Fig. 5). Overall, reporting locations and most likely movement paths (n = 56) suggested that, regardless of time at liberty, even with tag durations up to 192 days, the majority (n = 43) of tagged Chinook salmon remained near their (<500 km displacement) tagging sites (Fig. 6). The most likely movement paths suggested non-directed or net westerly movements for the majority of fish tagged near Chignik (Fig. 3; Fig. 7), net easterly movements of fish tagged near Kodiak (Fig. 4; Fig. 8), and net southeasterly movement of fish tagged near Yakutat (Fig. 5; Fig. 9). In contrast to the majority of tags that were inferred to have remained near the tagging regions, 13 tagged Chinook salmon demonstrated extensive (>500 km) easterly movements across the GOA, while at times occupying offshore basin waters (Fig. 6; Fig. 10). Displacement (straight-line distance between tagging and pop-up locations) ranged from 22 to 1,583 km (320 ± 434 km, mean ± SD) for fish tagged near Chignik, AK, from 36 to 2,282 km (362 ± 575 km, mean ± SD) for fish tagged near Kodiak, AK, and from 17 to 1,800 km (637 ± 526 km, mean ± SD) for fish tagged near Yakutat, AK (Table 1). Curvilinear track distance determined from daily location estimates ranged from 114 to 1,865 km (843 ± 484 km, mean ± SD) for fish tagged near Chignik, AK, from 36 to 3,088 km (599 ± 776 km, mean ± SD) for fish tagged near Kodiak, AK, and from 17 to 2,535 km (1094 ± 759 km, mean ± SD), for fish tagged near Yakutat, AK (Table 1). While occupying waters of the North Pacific Ocean, tagged Chinook salmon spent the majority of their time in waters over the continental shelf (65%), and spent a minority of their time over the continental slope (22%) and basin (13%; Fig. 2).

3.3 Depth and temperature

While at liberty, tagged Chinook salmon occupied depths ranging from 0 to 464 m, with mean depths of individual fish ranging from 14 to 117 m (51 ± 24 m, grand mean ± SD) (Table 2; Fig. 11a). Depth distributions of individual tagged Chinook salmon were highly variable and dives to 100 m were common among most tagged fish (n = 55). Many tagged fish (n = 33) demonstrated dives to >200 m (Fig. 7; Fig. 8; Fig. 9; Fig. 10; Fig. 11a). In general, regardless of habitat occupied (e.g., slope, shelf, basin), tagged fish occupied shallower depths during summer months (June–September; grand mean depth = 28 m), compared to fall (September–November; grand mean depth = 53 m), winter (December–March; aggregated mean depth = 64 m), and spring (March–May; grand mean depth = 53 m) months (Fig. 12a). While at liberty, tagged Chinook salmon experienced a thermal environment ranging from 1.8 to 19.0°C with mean temperatures experienced by individual tagged fish ranging from 4.6 to 11.2°C (7.8 ± 1.7°C, grand mean ± SD) (Table 2; Fig. 11b; Fig. 12b).

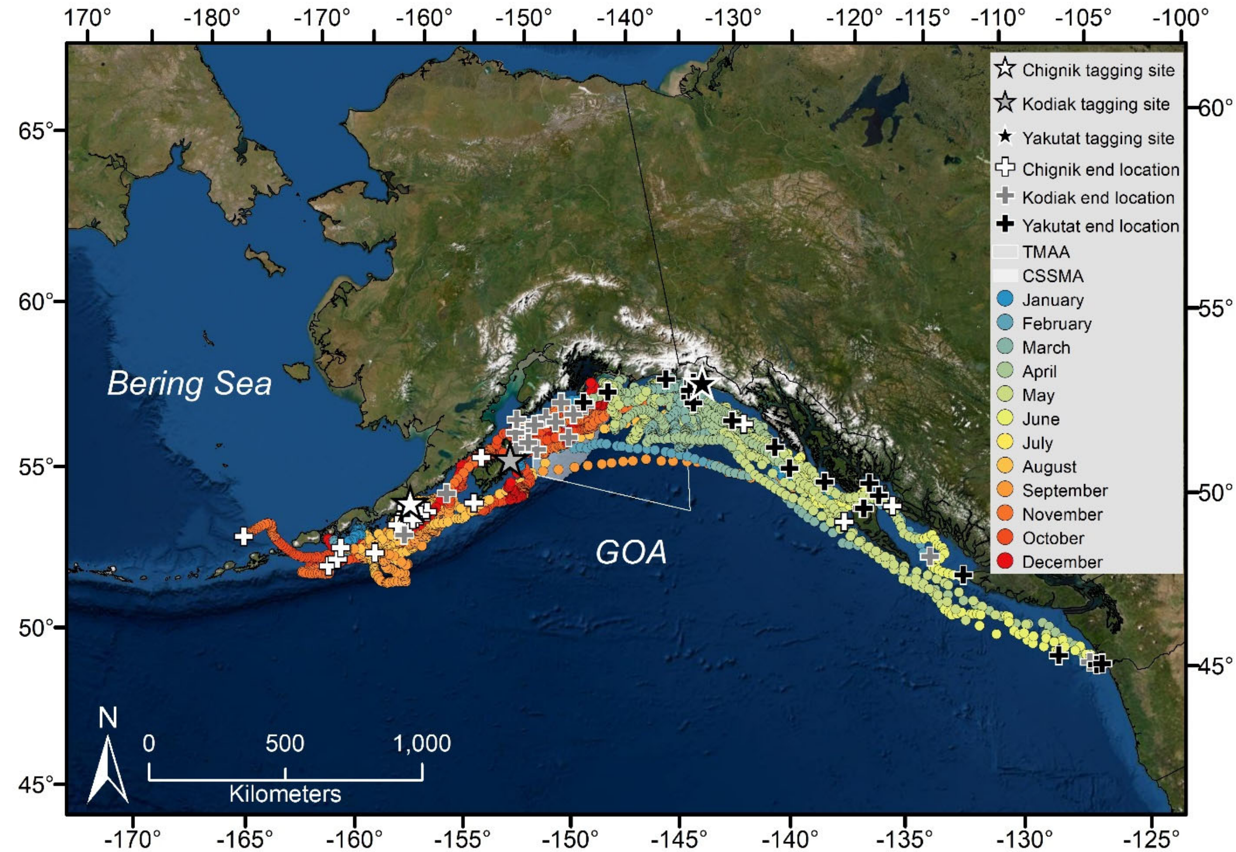

Figure 2. End locations denoted by crosses color-coded by release location (n = 57) and most likely movement paths of Chinook salmon (n = 56) tagged at three sites in the Gulf of Alaska (stars). Estimated daily locations (circles) produced by a HMM are color coded by month. The Navy GOA TMAA and CSSMA is denoted.

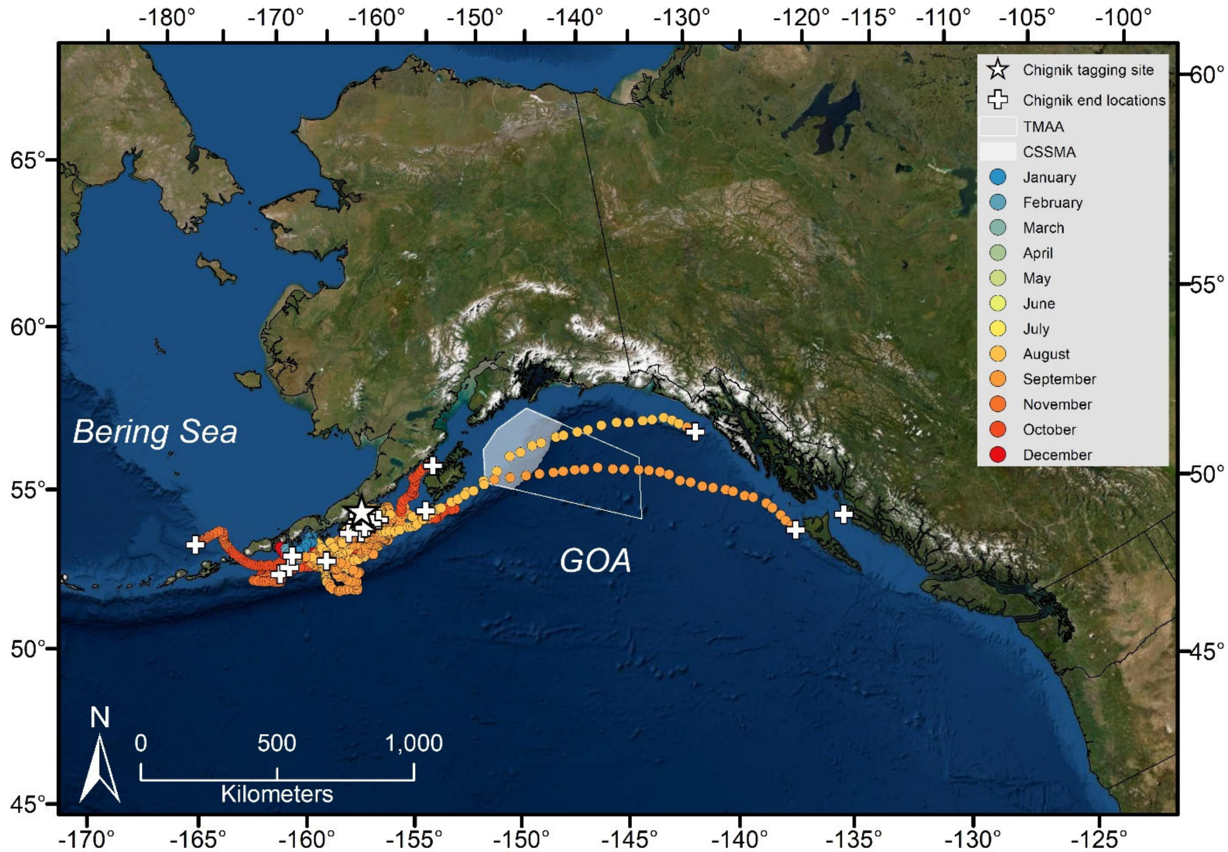

Figure 3. End locations denoted by crosses color coded by release location (n = 19) and most likely movement paths of Chinook salmon (n = 18) tagged near Chignik, AK (star). Estimated daily locations (circles) produced by a HMM are color coded by month. The Navy GOA TMAA and CSSMA is denoted.

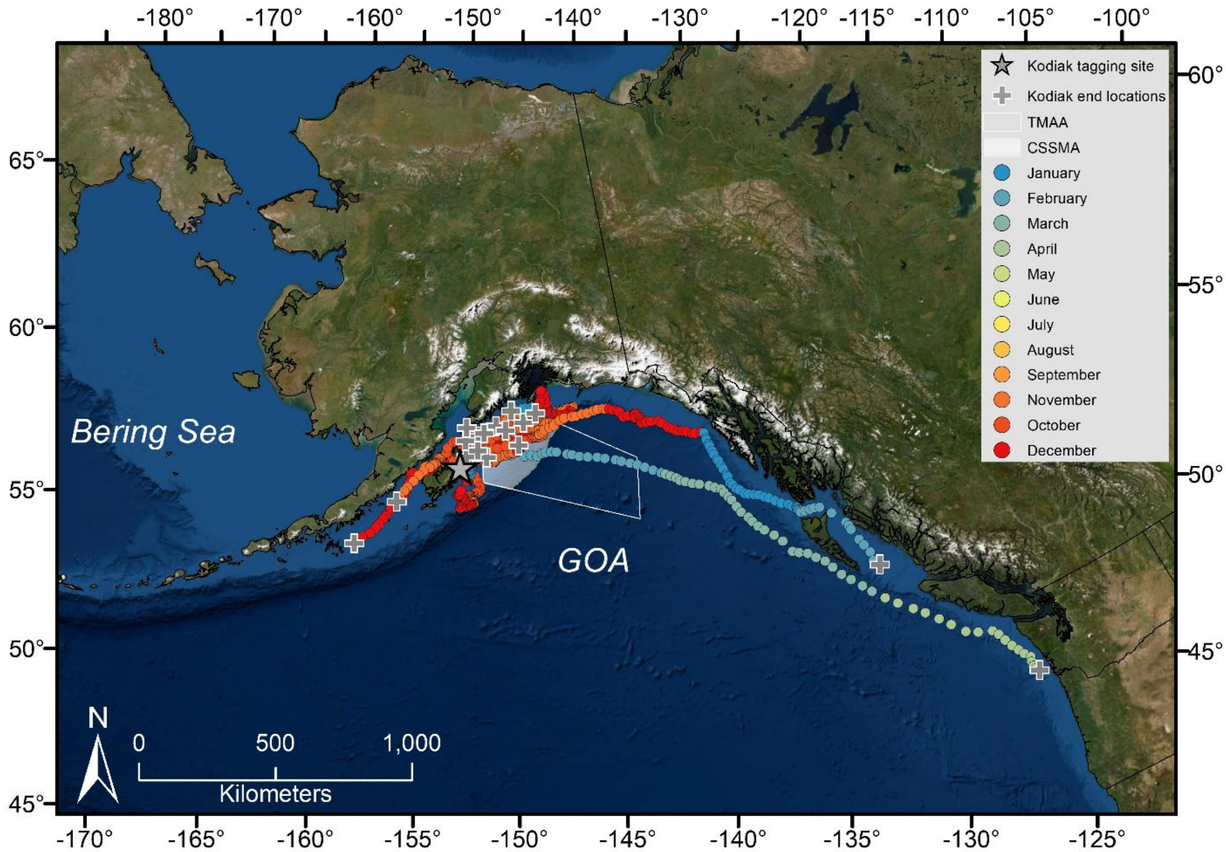

Figure 4. End locations denoted by crosses color coded by release location (n = 19) and most likely movement paths of Chinook salmon (n = 19) tagged near Kodiak, AK (star). Estimated daily locations (circles) produced by a HMM are color coded by month. The Navy GOA TMAA and CSSMA is denoted.

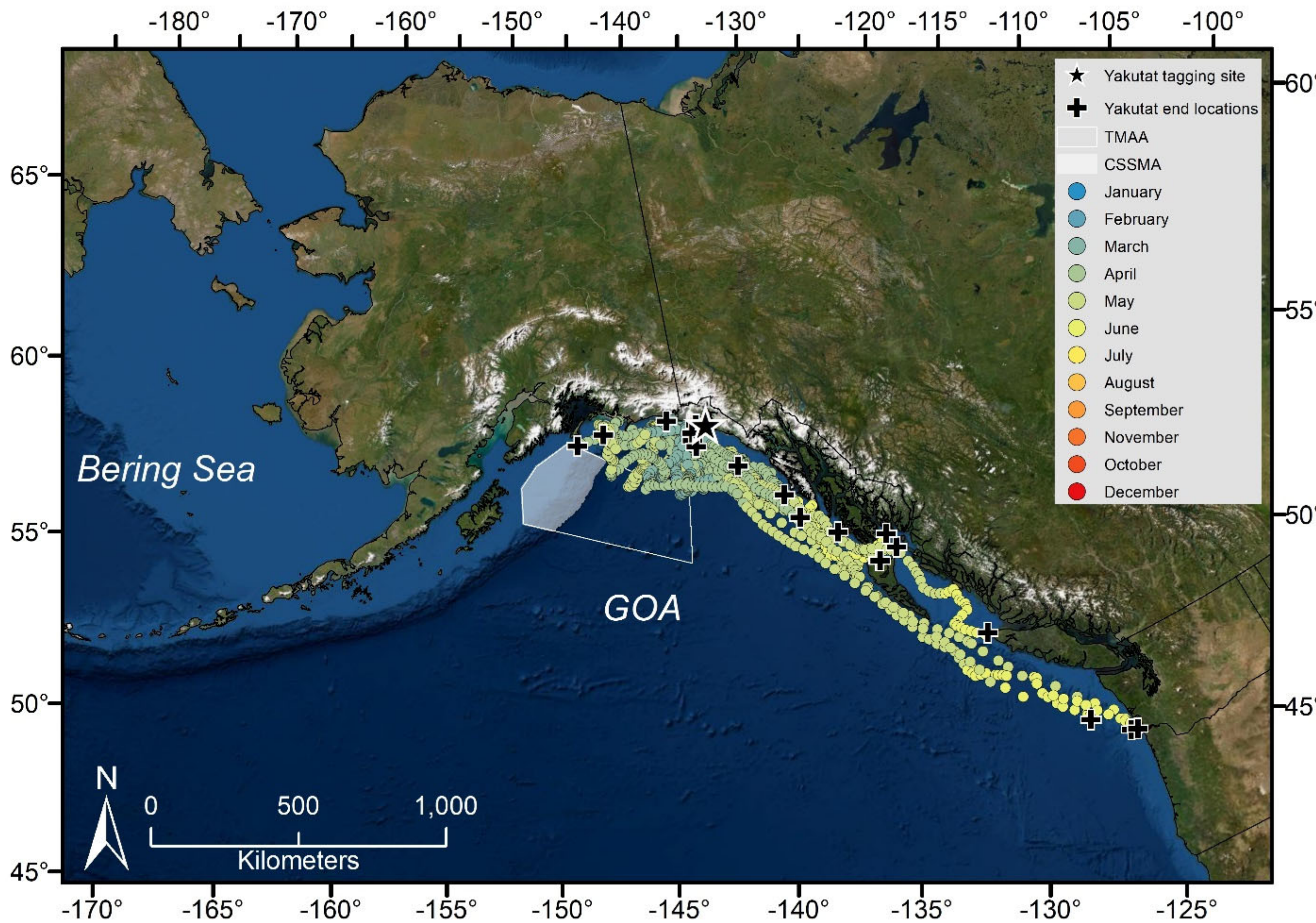

Figure 5. End locations denoted by crosses color coded by release location (n = 19) and most likely movement paths of Chinook salmon (n = 19) tagged near Yakutat, AK (star). Estimated daily locations (circles) produced by a HMM are color coded by month. The Navy GOA TMAA and CSSMA is denoted.

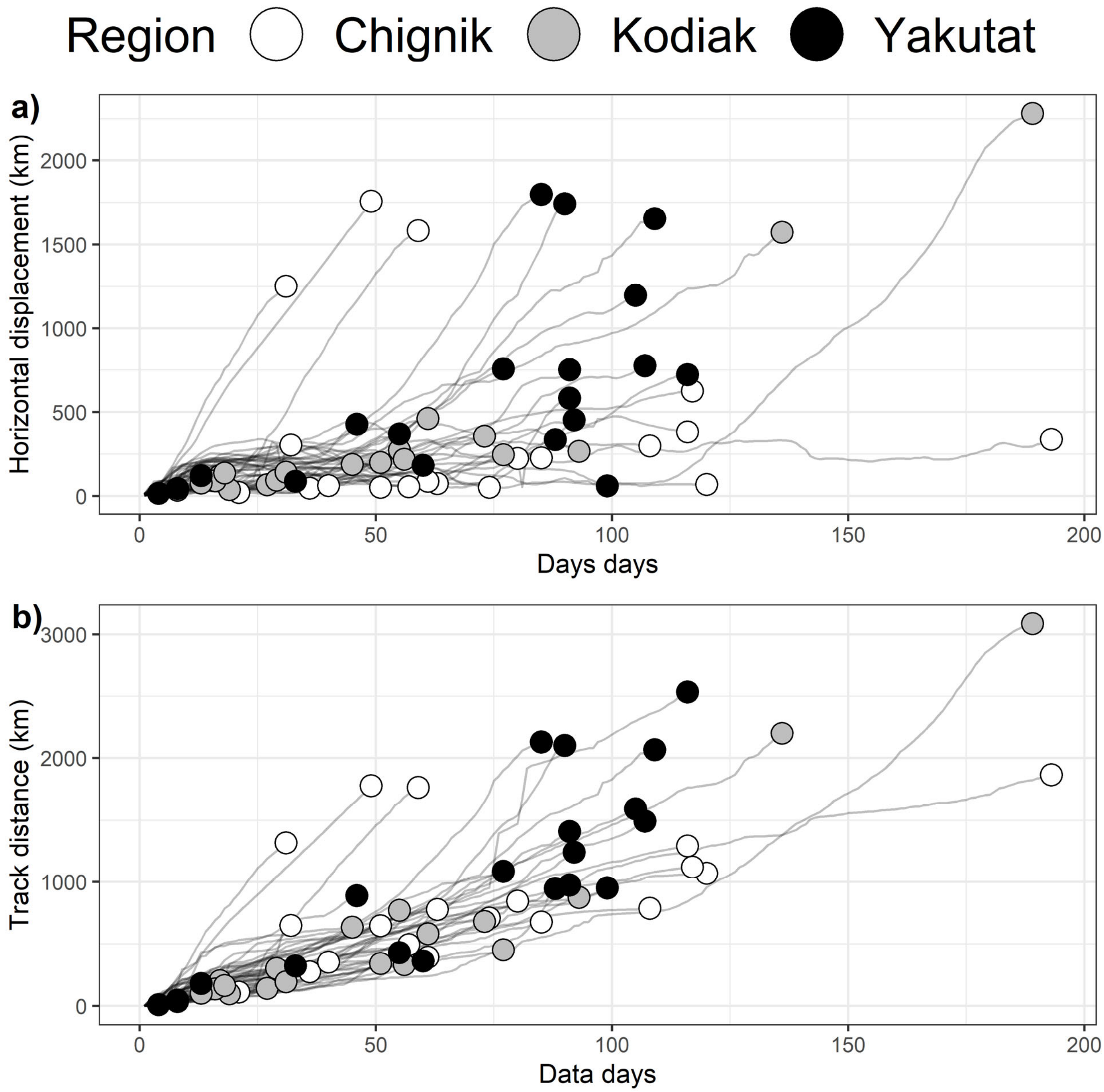

Figure 6. Relationship between the daily cumulative horizontal displacement a), daily cumulative track distance b), and data days of tagged Chinook salmon in the GOA, based on HMM results. Colors denote regions where fish were tagged.

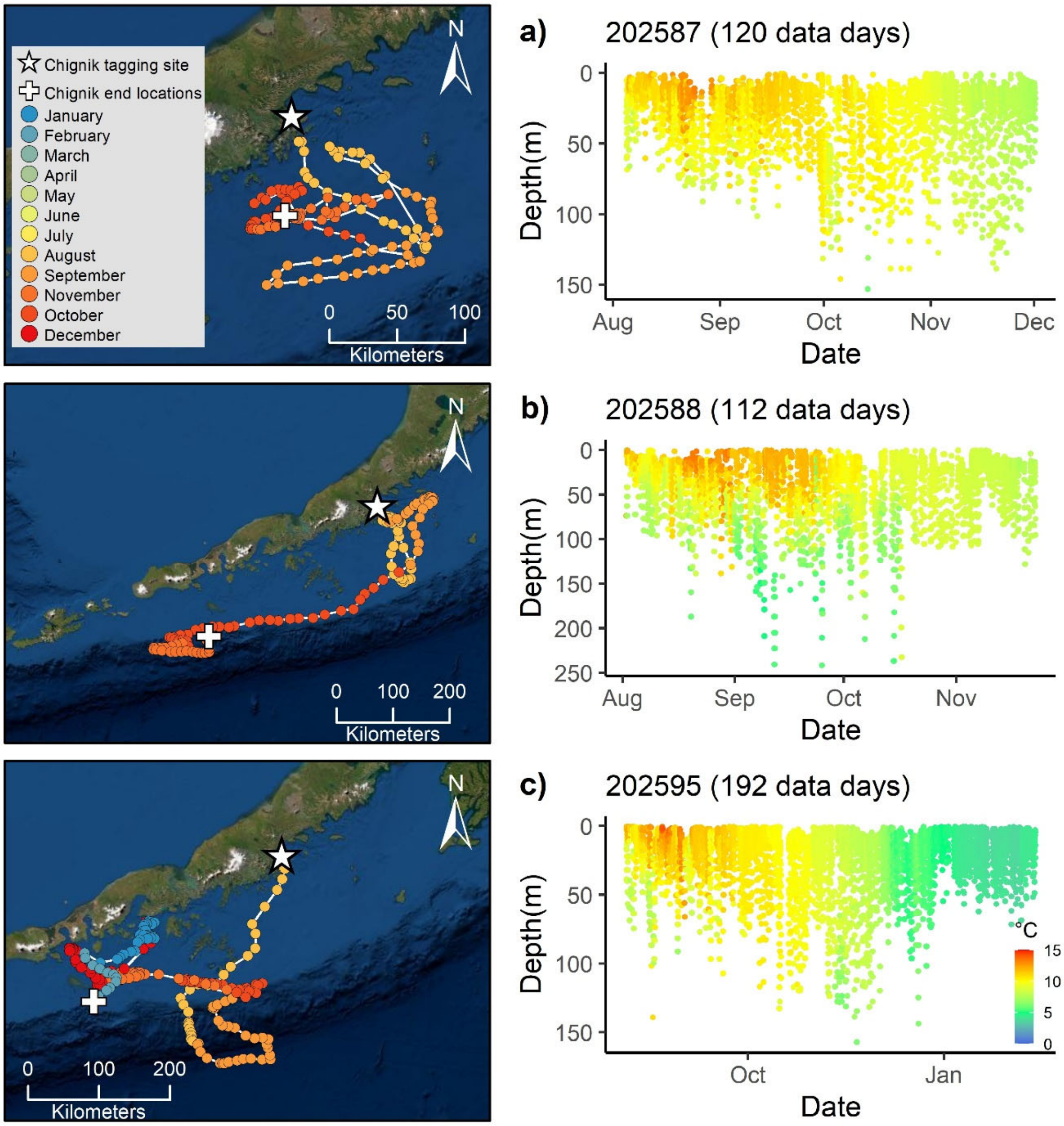

Figure 7. Most likely movement paths (left) and temperature at depth (right) of three representative Chinook salmon tagged with pop-up satellite archival tags near Chignik, AK (star) in August of 2020 that remained near the tagging site. Estimated daily locations (circles in left panels) produced by a HMM are color coded by month and crosses denote each tags' end location. Argos IDs are noted in respective panels and correspond to those given in Table 1.

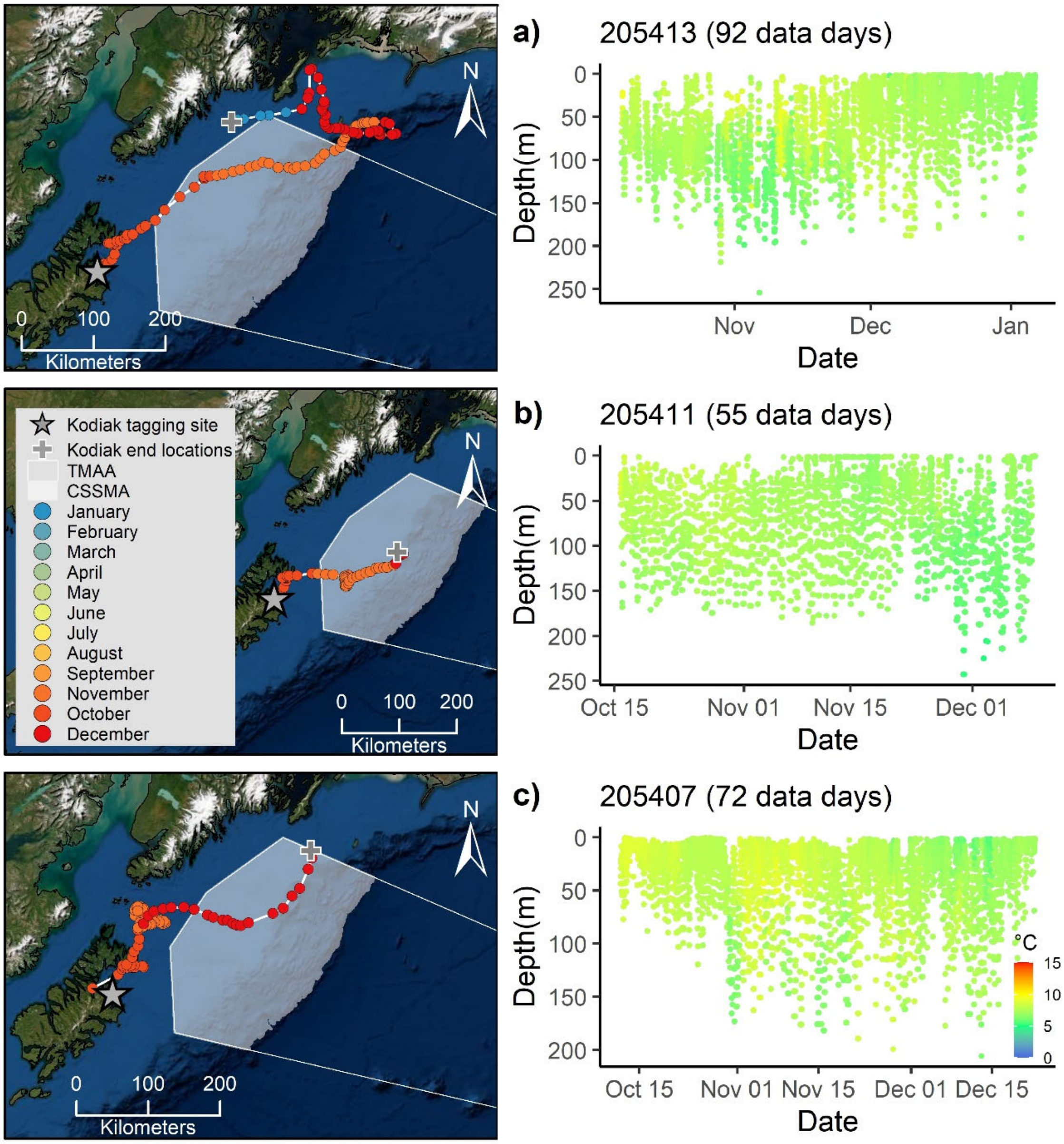

Figure 8. Most likely movement paths (left) and temperature at depth (right) of three representative Chinook salmon tagged with pop-up satellite archival tags near Kodiak, AK (star) in October of 2020 that remained near the tagging site. Estimated daily locations (circles in left panels) produced by a HMM are color coded by month and crosses denote each tags' end location. The Navy GOA TMAA and CSSMA is denoted. Argos IDs are noted in respective panels and correspond to those given in Table 1.

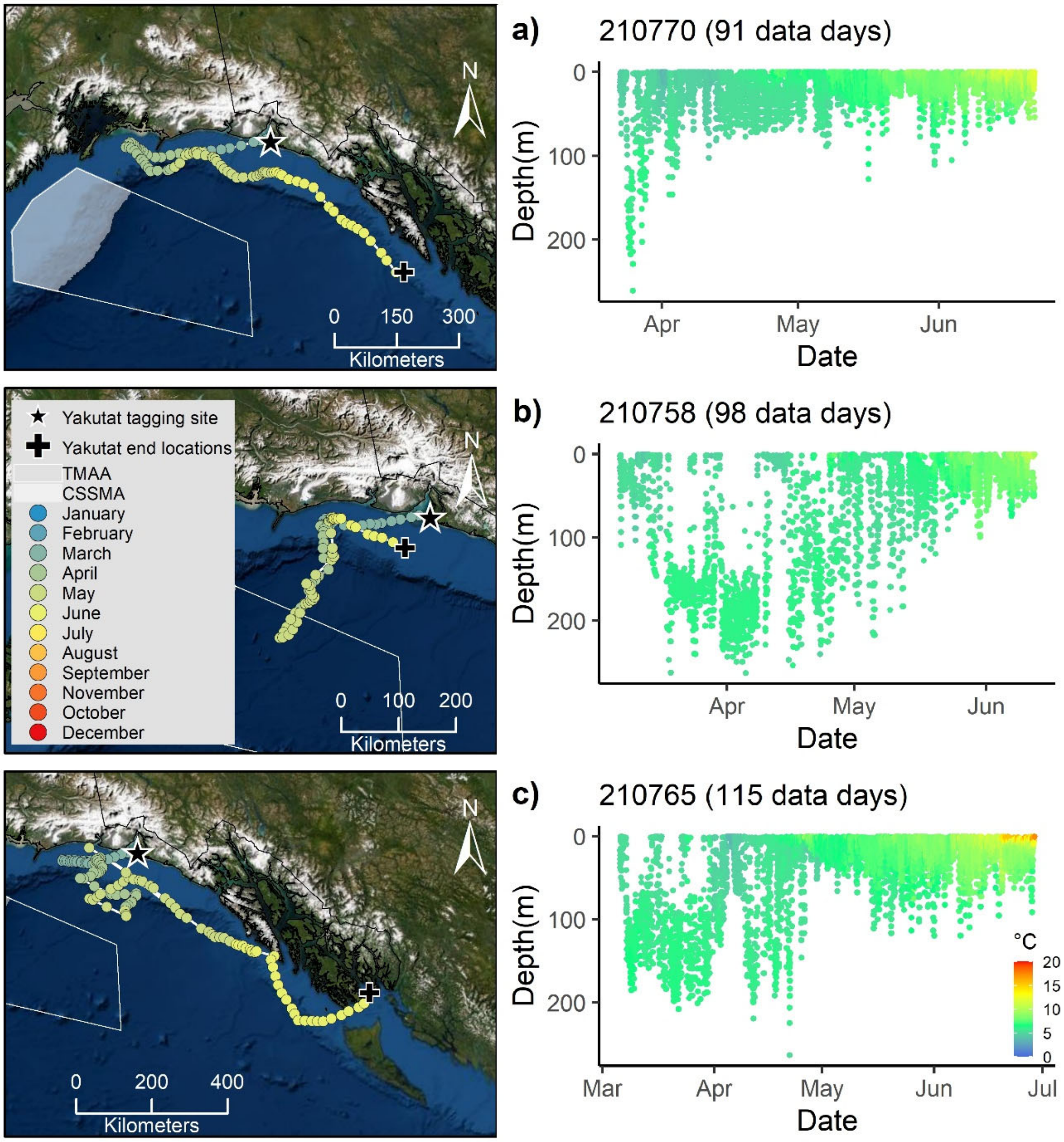

Figure 9. Most likely movement paths (left) and temperature at depth (right) of three representative Chinook salmon tagged with pop-up satellite archival tags near Yakutat, AK (star) in March 2021 that remained near the tagging site. Estimated daily locations (circles in left panels) produced by a HMM are color coded by month and crosses denote each tags' end location. The Navy GOA TMAA and CSSMA is denoted. Argos IDs are noted in respective panels and correspond to those given in Table 1.

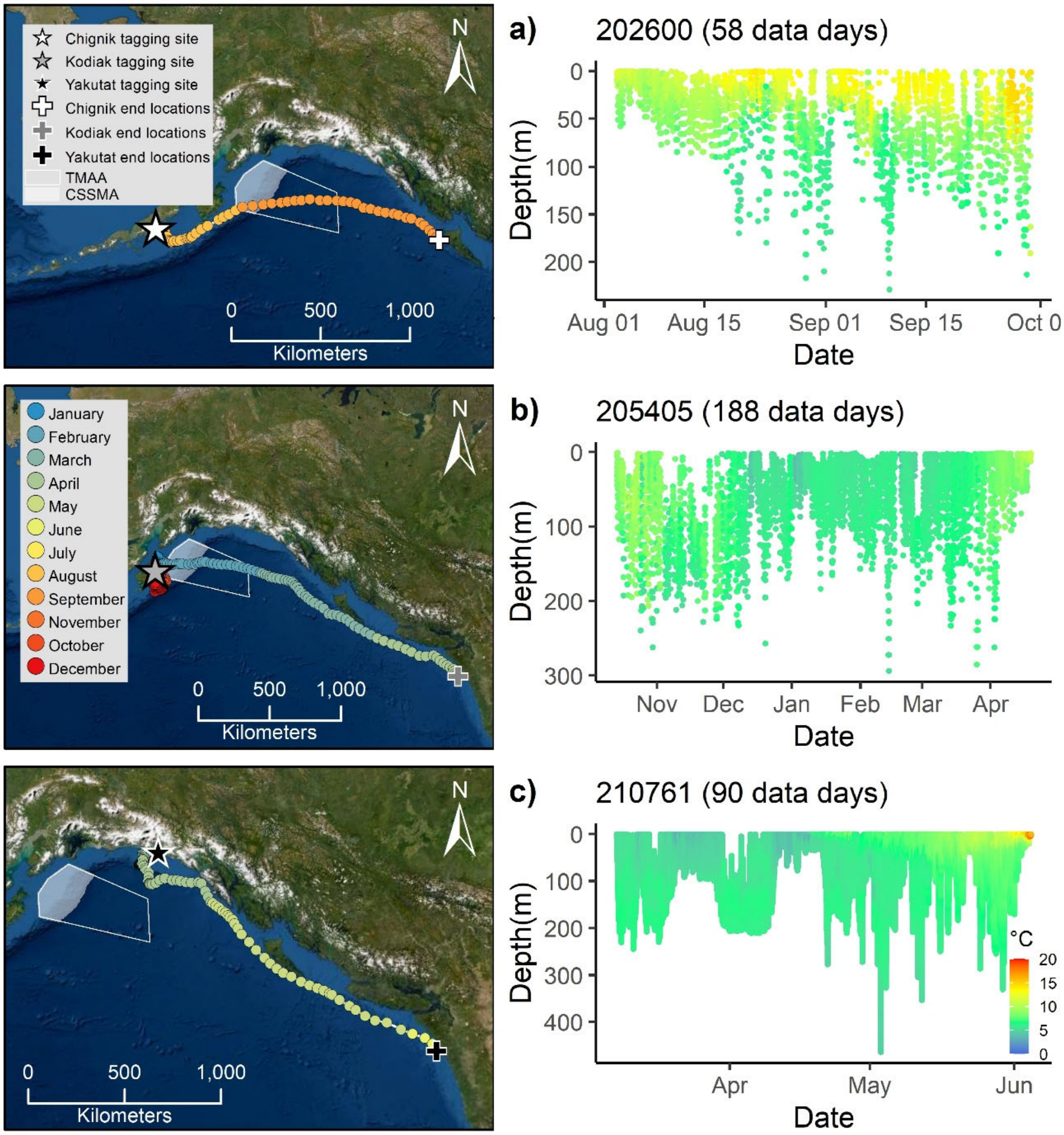

Figure 10. Most likely movement paths (left) and temperature at depth (right) of three Chinook salmon tagged with pop-up satellite archival tags that made extensive migrations from the GOA to the Pacific Northwest. Estimated daily locations (circles in left panels) produced by a HMM are color coded by month and crosses denote each tags' end location. The Navy GOA TMAA and CSSMA is denoted. Argos IDs are noted in respective panels and correspond to those given in Table 1.

Table 2. Summary of depth and temperatures occupied by Chinook salmon (n = 56) tagged in the GOA in 2020 and 2021.

Argos ID	Tagging region	Mean (±SD) depth (m)	Depth range (m)	Mean (±SD) temperature (°C)	Temperature range (°C)	Data days
202585	Chignik	39.5±33.2	0–168	9.9±2.5	4.7–13.4	35
202586	Chignik	33.1±28.4	0–164	10.0±1.2	5.3–13.9	79
202587	Chignik	35.1±28.8	0–153	9.9±1.3	5.9–13.6	120
202588	Chignik	52.9±40.0	0–242	9.2±1.7	4.8–13.7	112
202589	Chignik	29.3±21.9	0–116	10.4±1.5	6.7–12.9	19
202590	Chignik	43.2±36.7	0–153	8.7±1.8	1.8–12.5	116
202591	Chignik	26.2±31.4	0–247	10.7±1.5	5.1–13.8	84
202592	Chignik	48.9±45.3	0–206	10.1±2.7	5.6–14.6	30
202593	Chignik	21.5±18.8	0–116	11.2±1.3	6.8–14.1	39
202594	Chignik	40.1±23.0	0–86	10.2±0.9	6.5–13.8	73
202595	Chignik	26.9±27.7	0–157	8.3±2.8	3.7–14.4	192
202596	Chignik	39.1±32.7	0–270	9.6±1.7	5.1–13.4	106
202597	Chignik	28.7±24.8	0–179	10.6±1.2	7.0–13.6	50
202599	Chignik	22.9±25.3	0–184	10.9±0.9	7.1–13.8	62
202600	Chignik	52.6±41.1	0–228	9.7±2.3	4.6–14.7	58
202601	Chignik	31.5±28.4	0–112	10.3±1.7	5.9–13.9	60
202602	Chignik	31.9±24.3	0–138	10.3±1.3	5.3–14.1	57
202603	Chignik	34.0±33.7	0–157	10.0±1.8	5.8–13.6	31
205398	Kodiak	60.5±46.0	0–204	7.7±0.4	6.6–9.5	26
205399	Kodiak	86.8±59.9	0–206	7.8±1.5	6.0–10.6	15
205400	Kodiak	89.8±57.0	0–420	7.4±0.9	4.6–9.7	44
205401	Kodiak	76.7±42.1	0–188	7.7±0.6	6.6–9.9	18
205402	Kodiak	49.9±28.1	0–172	7.6±0.6	6.4–9.7	7
205403	Kodiak	105.6±37.3	0–242	7.5±1.4	5.6–11.0	54
205404	Kodiak	59.9±50.2	0–202	7.3±1.0	5.4–10.9	76
205405	Kodiak	75.9±55.4	0–294	6.6±1.2	3.6–11.0	188
205406	Kodiak	50.0±38.4	0–202	7.5±0.8	5.5–9.3	60
205407	Kodiak	46.6±43.1	0–206	7.8±0.7	5.4–9.5	72
205408	Kodiak	73.6±45.1	0–202	8.0±1.1	5.6–10.0	28
205409	Kodiak	43.9±41.7	0–187	8.0±0.7	6.2–9.7	15
205410	Kodiak	63.0±44.0	0–209	7.5±1.1	4.4–9.8	50
205411	Kodiak	92.1±43.3	0–242	7.0±0.6	5.1–9.0	55
205412	Kodiak	55.3±39.3	0–194	8.0±0.9	6.4–9.6	12
205413	Kodiak	69.4±46.2	0–254	7.2±0.7	5.2–10.0	92
205415	Kodiak	117.3±65.0	0–336	7.5±0.8	4.9–10.3	135
205416	Kodiak	50.4±41.6	0–187	8.9±1.1	5.9–10.8	17
205417	Kodiak	60.4±42.3	0–198	8.0±0.8	6.1–10.1	30
210757	Yakutat	14.2±13.3	0–68	4.6±0.2	4.1–5.2	3
210758	Yakutat	82.0±78.1	0–262	6.3±1.1	4.1–10.8	98
210760	Yakutat	34.6±44.8	0–224	6.7±2.2	2.9–13.9	107
210761*	Yakutat	70.5±67.7	0–464	6.6±2.0	3.2–19.0	89
210762	Yakutat	86.3±40.8	0–161	6.0±0.6	3.9–6.6	6
210763	Yakutat	56.6±50.3	0–238	5.8±1.5	2.3–9.5	90
210764	Yakutat	22.9±19.7	0–317	6.1±1.4	3.8–9.5	90
210765	Yakutat	43.3±54.2	0–263	7.3±1.9	3.3–17.4	115
210766	Yakutat	19.7±21.2	0–138	4.8±0.4	2.9–6.3	13
210767	Yakutat	22.9±28.6	0–254	5.7±1.5	1.9–10.0	76
210768	Yakutat	44.2±22.3	0–132	4.6±0.4	2.2–6.3	32
210769	Yakutat	55.9±56.8	0–286	7.1±1.8	2.9–13.1	103
210770	Yakutat	21.9±31.0	0–260	6.8±1.9	3.2–13.3	91
210771	Yakutat	56.1±57.7	0–262	5.3±0.7	3.7–7.7	45
210772	Yakutat	57.9±42.0	0–426	6.1±0.9	4.0–9.8	54
210773	Yakutat	45.6±48.3	0–232	7.3±2.2	3.4–14.9	108
210774	Yakutat	29.5±34.2	0–269	7.5±3.1	3.2–16.8	87
210775	Yakutat	52.9±54.4	0–254	6.3±1.1	3.8–10.9	87
210776	Yakutat	93.8±63.4	0–269	6.1±0.5	4.6–7.9	59

a) Argos ID refers to the transmitter identification number of each tag supplied by the Argos Satellite System

b) Data days refers to the total days of data provided by the tag while attached to a live, free-swimming Chinook salmon (i.e., not in the stomach of a predator)

*PSAT was recaptured in a commercial fishery, near Astoria, Oregon, on 5 June 2021.

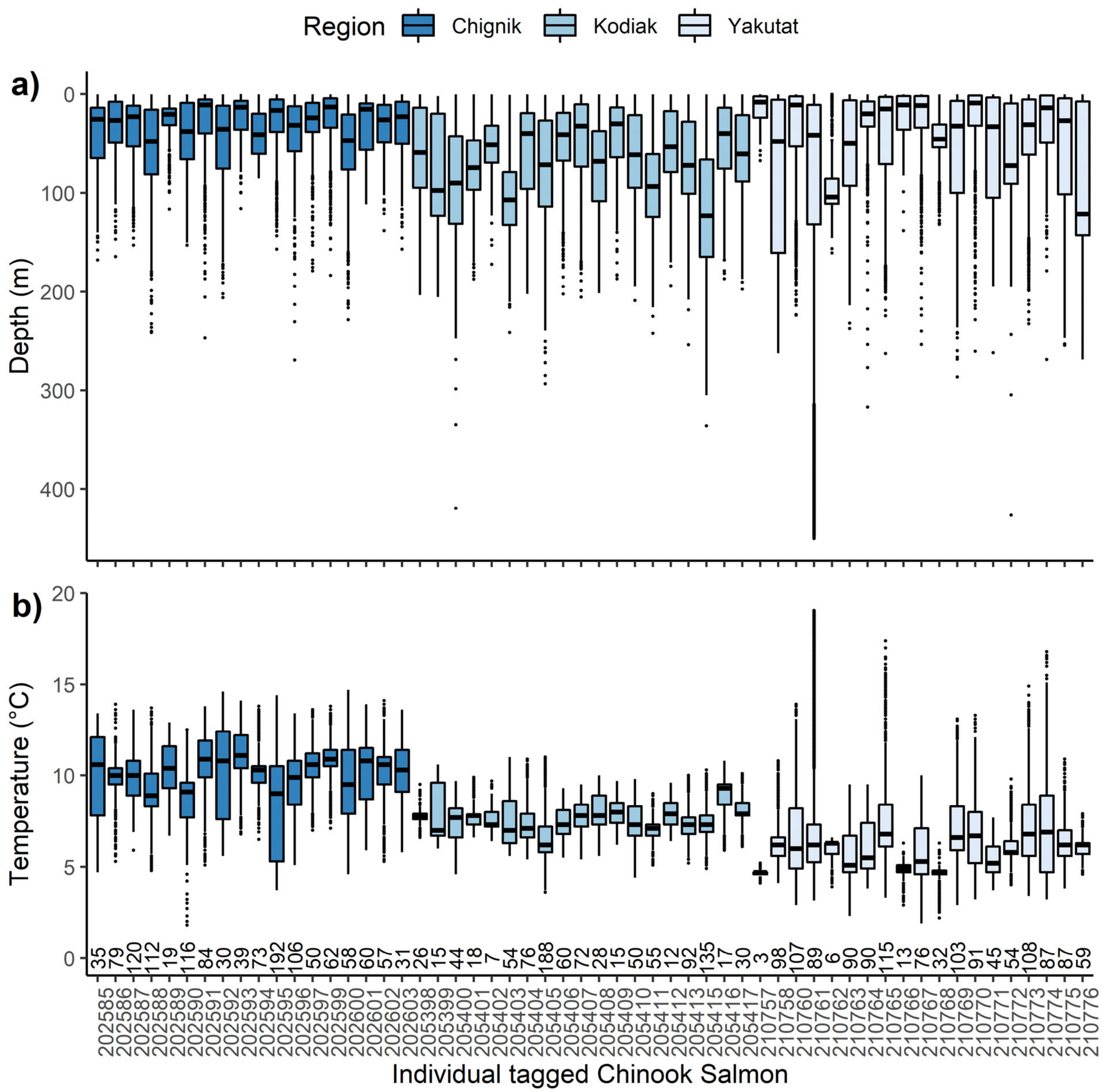

Figure 11. Box and whisker plots of depths (a) and temperatures (b) recorded by pop-up satellite archival tags attached to individual Chinook salmon tagged near Chignik, Kodiak, and Yakutat AK in 2020 and 2021. Argos IDs on the horizontal axis correspond to those given in Table 1. Data days for each tag are noted above Argos ID numbers in panel b. For boxplots, median diving depths are solid lines, and boxes represent the first and third quartiles. Whiskers represent the largest observation less than or equal to the box, plus or minus 1.5 times the interquartile range, and black dots represent outliers.

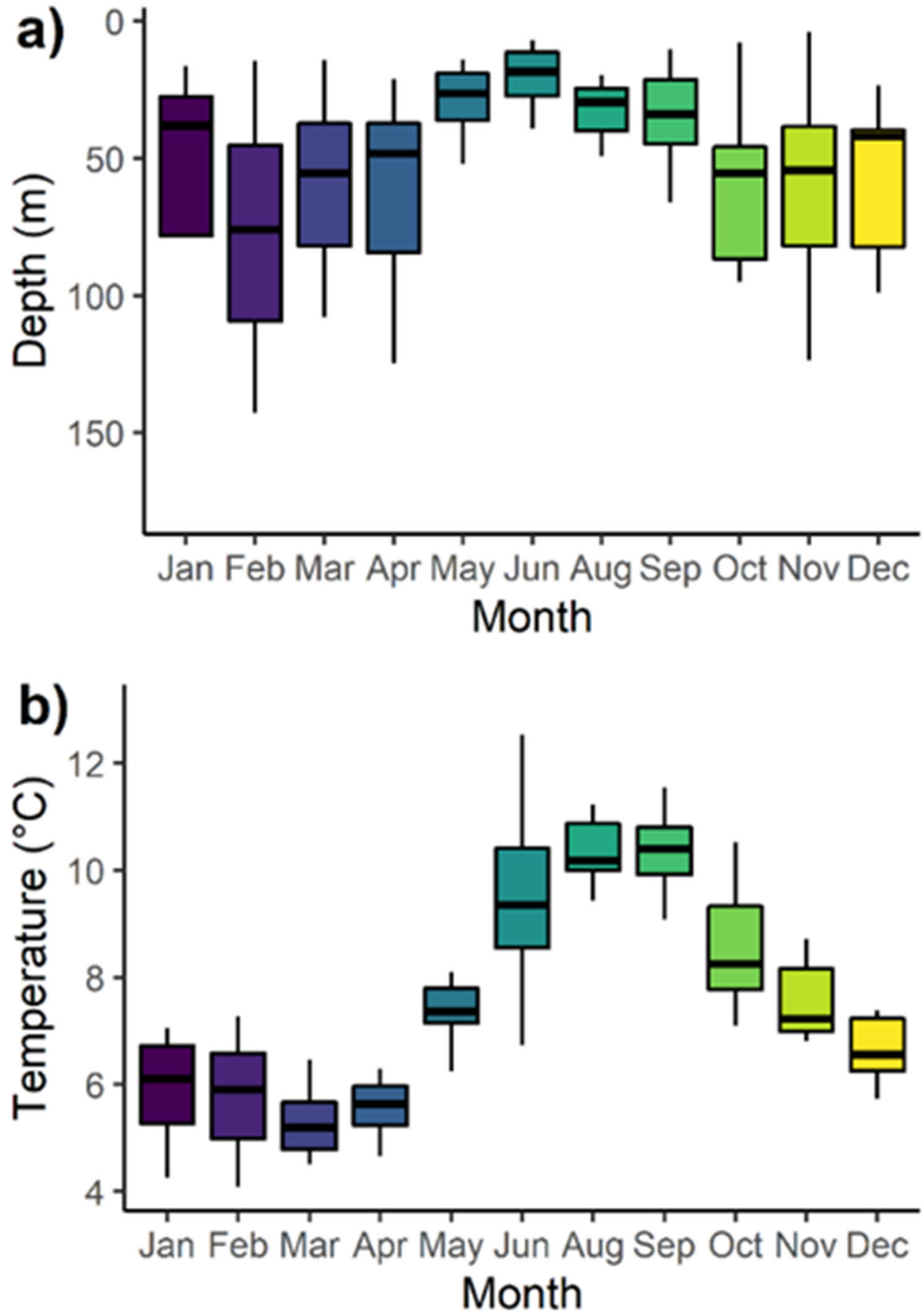

Figure 122. Monthly depth a) and temperature b) distributions experienced by all tagged Chinook salmon. For boxplots, median diving depths are solid lines, and boxes represent the first and third quartiles. Whiskers represent the largest observation less than or equal to the box, plus or minus 1.5 times the interquartile range, and black dots represent outliers.

3.4 Mortality

Twenty-seven tags provided evidence that Chinook salmon (71.3 ± 4.8 cm, mean ± SD) experienced mortality (Table 3; Fig. 13). Of these 27 tags, 17 provided evidence of predation on Chinook salmon (69.6 ± 4.2 cm, mean ± SD) by endothermic fish(es) with internal temperatures of ~25ºC, 12–192 days after tagging. Based on known visceral temperatures and species distribution, these endothermic fish predation events are likely attributed to salmon sharks (*Lamna ditropis*) (Anderson and Goldman 2001; Goldman et al. 2004) (Table 3; Fig. 13a). Three other tags provided evidence of predation on tagged Chinook salmon (73.3 ± 4.0 cm, mean ± SD) by marine mammals with stomach temperatures of ~36–38ºC, 3–76 days after tagging (Fig. 13b). Based on the location of the inferred predation event, the occupation of 0 m for up to 8 hrs, and short dive bouts (~10 min) while in the stomach of the predator, we speculate that one event was likely caused by a species of pinniped, such as a Steller sea lion (*Eumetopias jubatus*) (Call et al. 2007; Lander et al. 2011; Trites and Porter 2002). In the other two cases of inferred predation by a marine mammal, based on frequent dives >50 m, it is probable that predation occurred by a toothed whale, such as a resident killer whale (*Orcinus orca*) (Ford and Ellis 2006; Kasting et al. 1989; Whittow et al. 1974). Another tag provided evidence of predation on a Chinook salmon (83 cm FL) by an unknown species of ectothermic fish approximately 58 days after tagging (Fig. 13c). In addition to predation of tagged Chinook salmon, six tagged fish were inferred to have succumbed to unknown mortality and died and sank to the seafloor 13–115 days after release (Fig. 13d). Reporting locations of tags suggest that mortality of tagged Chinook salmon was geographically widespread (Fig. 14).

Table 3. Information on the inferred fates of Chinook salmon tagged in the GOA in 2020 and 2021.

Inferred fate of tagged fish	Sample size (n)	Fork length (cm; mean±SD, range)	Chinook salmon data days (mean±SD, range)
Pelagic ectothermic fish predation	1	83	58
Endothermic fish predation	17	69.6±4.2 (62–77)	55.0±46.6 (12–192)
Marine mammal predation	3	73.3±4.0 (69–77)	43.0±37.0 (3–76)
Unknown mortality	6	73.0±3.7 (70–80)	73.8±41.1 (13–115)
Missing	3	76.0±11.1 (66–88)	NA
Alive	30	76.0±8.3 (65–101)	71.8±40.5 (6–188)
Total	60	73.9±7.4 (62–101)	65.3±41.9 (3–192)

a) Chinook salmon data days refers to the total days of data provided by the tag while attached to a live, free-swimming Chinook salmon (i.e., not in the stomach of a predator).

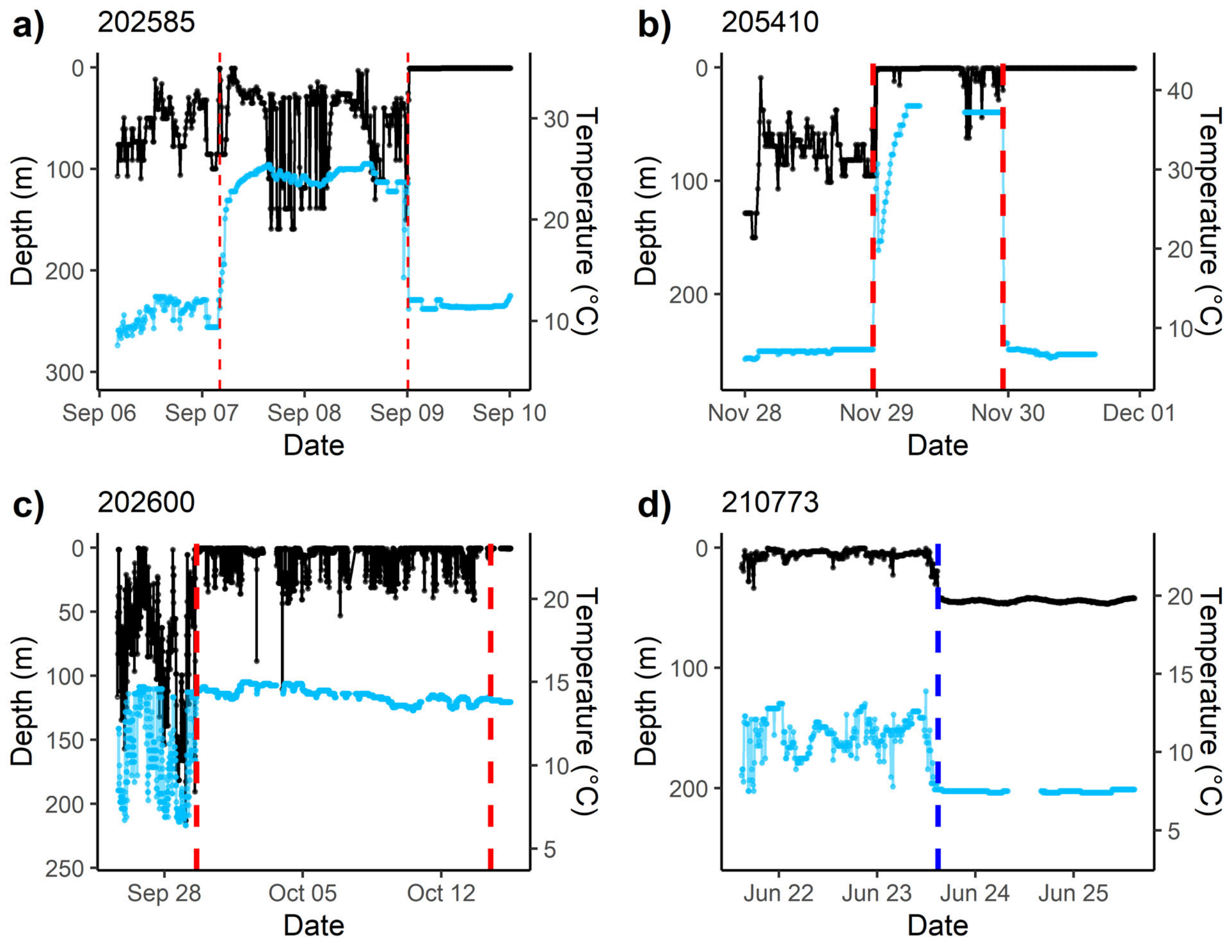

Figure 13. Examples of inferred predation of tagged Chinook salmon, by salmon shark a), marine mammal b), ectothermic fish c), and unknown mortality d). Black circles and lines denote depth (m) while blue circles and lines denote temperature (°C). Red dashed lines in panels a), b), and c), denote estimated times of consumption of tagged Chinook salmon, and subsequent expulsion of the satellite tag. The blue dashed line in panel d denotes the estimated time of unknown mortality. Argos IDs are denoted in upper left hand corner of each figure for reference purposes, and correspond to those given in Table 1.

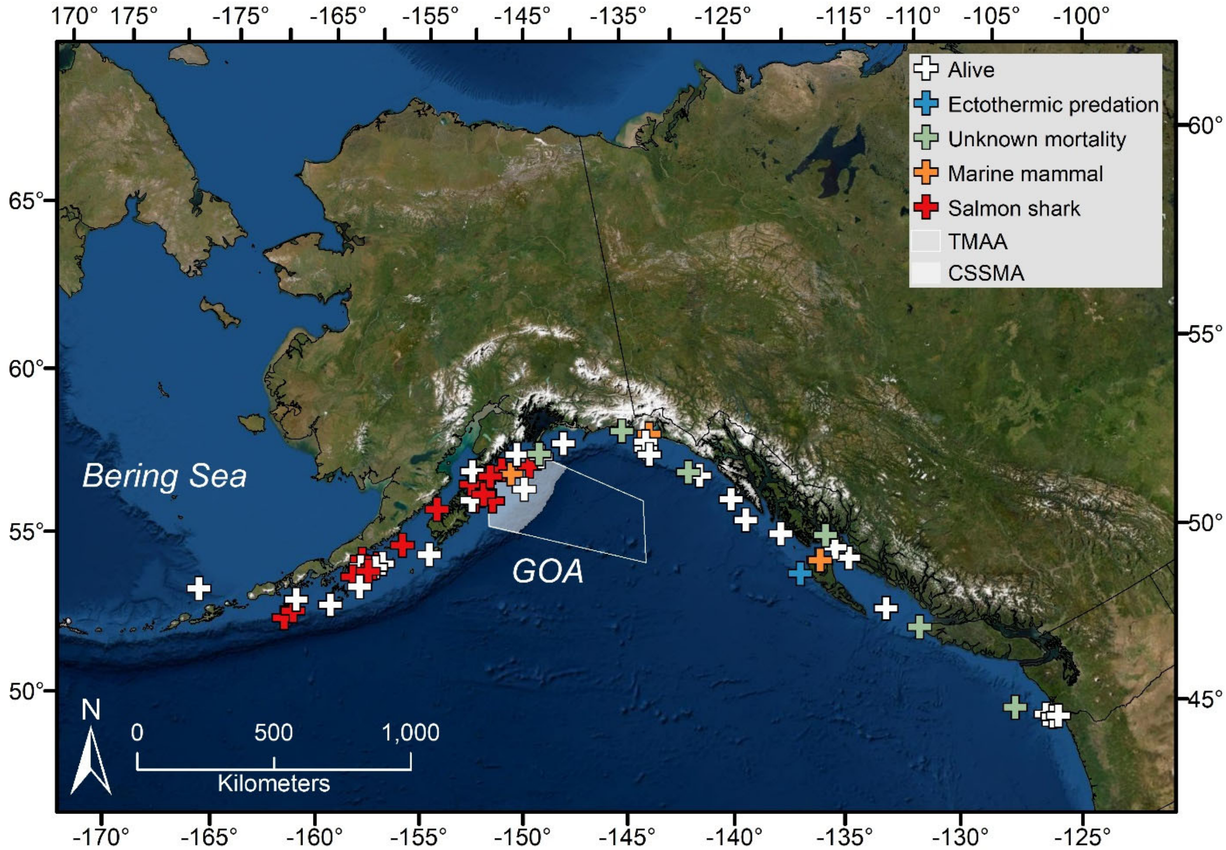

Figure 14. End locations (crosses) of pop-up satellite archival tags attached to Chinook salmon, color coded by inferred fates. The Navy GOA TMAA and CSSMA is denoted.

3.5 TMAA occupancy

Based on end locations and estimated daily locations, 15 tagged Chinook salmon occupied the TMAA for an aggregated total of 252 days (Fig.15a). While occupying waters of the TMAA, Chinook salmon mostly occupied the northern portion of the TMAA while over the continental shelf (Fig. 2; Fig. 15a). Specifically, 58% of the aggregated days (146/252 days) occurred over the continental shelf, compared to 22% (56/252 days) over the continental slope and 20% (50/252 days) over the basin. Mean individual occupied depths in the TMAA ranged from 19 to 110 m (70 ± 27 m; grand mean ± SD) (Fig. 15b). While the data on the timing and duration of occupation of the TMAA are biased by the timing and locations of tag deployment, tagged Chinook salmon were documented to occupy waters of the TMAA across the calendar year (Fig. 15a). While inferably occupying basin waters of the TMAA, fish occupied waters ranging from 0 to 293 m, with individual mean depths ranging from 20 to 82 m (53 ± 23 m; grand mean ± SD). During the months of the U.S. Navy conducts at-sea training in the GOA TMMA (April to October), 10 tagged Chinook salmon occupied the TMAA for an aggregated total of 92 days. Of these 92 days, 35 were inferred to occur over the basin, whereas 57 days were inferred to occur over the CSSMA of the TMAA.

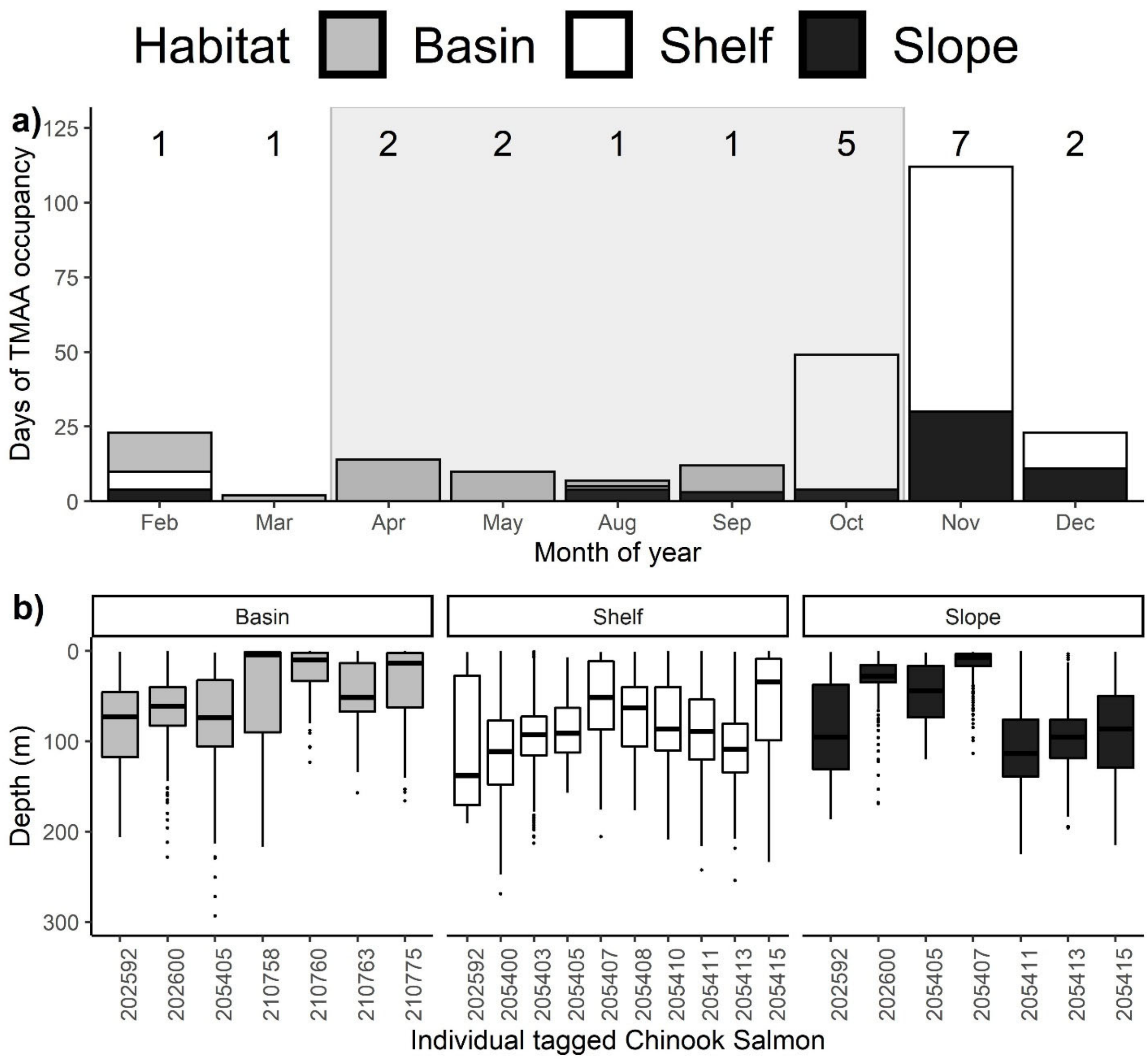

Figure 15. The aggregated number of days the TMAA were occupied by habitat and month of year, by all tagged fish a), and depth distributions of individual tagged Chinook salmon when estimated to be occupying the Navy GOA TMAA b). The number of tagged fish for each of the month, are noted in panel a. Gray transparent box in panel a, denote months in which the U.S. Navy conducts at-sea training in the TMAA. Note shelf and slope habitats in panel a and b, denote the CSSMA of the TMAA. For boxplots, median diving depths are solid lines, and boxes represent the first and third quartiles. Whiskers represent the largest observation less than or equal to the box, plus or minus 1.5 times the interquartile range, and black dots represent outliers.

3.6 Stock-origin

Stock origin could be determined for 47 of the 60 fish tagged (Table 4). Of these 47 fish, 11 originated from Southeast Alaska, 23 from western Vancouver Island, two from the Thompson River, British Columbia, two from east Vancouver Island, British Columbia, four from the Columbia River in Washington, one from the Oregon coast, and four from the Willamette River, Oregon (Table 4). The stock-origins of tagged fish that occupied the TMAA (that could be determined) were from North/Mid Oregon Coast (n = 1), Willamette River spring run (n = 1), Upper Columbia River summer/fall run (n = 1), West Vancouver Island (n = 7), South Thompson River (n = 1), and South Southeast Alaska (n = 2).

Table 4. Genetic stock-origin of Chinook salmon tagged in the Gulf of Alaska in 2020–2021.

Argos ID	Tagging region	Stock origin region	Stock origin best reporting group
202585	Chignik	NA	NA
202586	Chignik	Northern	South Southeast Alaska
202587	Chignik	NA	NA
202588	Chignik	NA	NA
202589	Chignik	Northern	South Southeast Alaska
202590	Chignik	Northern	South Southeast Alaska
202591	Chignik	NA	NA
202592	Chignik	NA	NA
202593	Chignik	NA	NA
202594	Chignik	NA	NA
202595	Chignik	Northern	East Vancouver Island
202596	Chignik	NA	NA
202597	Chignik	Northern	South Southeast Alaska
202598	Chignik	NA	NA
202599	Chignik	Northern	West Vancouver Island
202600	Chignik	NA	NA
202601	Chignik	Northern	West Vancouver Island
202602	Chignik	NA	NA
202603	Chignik	Northern	South Southeast Alaska
202604	Chignik	NA	NA
205398	Kodiak	Northern	West Vancouver Island
205399	Kodiak	Northern	South Thompson River
205400	Kodiak	Southern	North / Mid Oregon Coast
205401	Kodiak	Northern	West Vancouver Island
205402	Kodiak	Northern	South Southeast Alaska
205403	Kodiak	Northern	West Vancouver Island
205404	Kodiak	Northern	West Vancouver Island
205405	Kodiak	Columbia	Willamette River spring run**
205406	Kodiak	Columbia	Upper Columbia River summer/fall run
205407	Kodiak	Northern	West Vancouver Island
205408	Kodiak	Northern	West Vancouver Island
205409	Kodiak	Northern	West Vancouver Island
205410	Kodiak	Northern	South Thompson River
205411	Kodiak	Northern	South Southeast Alaska
205412	Kodiak	Northern	West Vancouver Island
205413	Kodiak	Northern	West Vancouver Island
205414	Kodiak	NA	NA
205415	Kodiak	Columbia	Upper Columbia River summer/fall run
205416	Kodiak	Northern	West Vancouver Island
205417	Kodiak	Northern	West Vancouver Island
210757	Yakutat	Northern	South Southeast Alaska
210758	Yakutat	Northern	West Vancouver Island
210759	Yakutat	Columbia	West Cascade fall run
210760	Yakutat	Northern	West Vancouver Island
*210761	Yakutat	Columbia	Willamette River spring run**
210762	Yakutat	Northern	South Southeast Alaska
210763	Yakutat	Northern	South Southeast Alaska
210764	Yakutat	Northern	East Vancouver Island
210765	Yakutat	Northern	West Vancouver Island
210766	Yakutat	Northern	West Vancouver Island
210767	Yakutat	Northern	West Vancouver Island
210768	Yakutat	Columbia	Upper Columbia River summer/fall run
210769	Yakutat	Northern	West Vancouver Island
210770	Yakutat	Northern	West Vancouver Island
210771	Yakutat	Northern	West Vancouver Island
210772	Yakutat	Northern	West Vancouver Island
210773	Yakutat	Columbia	Willamette River spring run**
210774	Yakutat	Columbia	Willamette River spring run**

Argos ID	Tagging region	Stock origin region	Stock origin best reporting group
210775	Yakutat	Northern	West Vancouver Island
210776	Yakutat	Northern	South Southeast Alaska

a) "NA" denotes tagged fish from which no stock-origin could be determined
*PSAT was recaptured in a commercial fishery, near Astoria, Oregon, on 5 June 2021.
**Willamette River spring run Chinook is an ESA-listed Threatened ESU

4. Discussion

Satellite tags provided detailed insights into the movements, behaviors, and thermal environment of individual Chinook salmon originating from many populations, including Southeast Alaska, British Columbia, and the U.S. Pacific Northwest, while occupying waters of the GOA and beyond. Insights into the spatial and vertical distribution of tagged Chinook salmon provide valuable information that may be used to address important conservation issues in the North Pacific Ocean including understanding interactions of Chinook salmon and Navy training exercises conducted in the GOA. Furthermore, this study provides valuable information on the location and timing of natural mortality of Chinook salmon caused by apex predators throughout the North Pacific Ocean.

Stock-origins of tagged fish in this study were all from populations south of central Alaska, similar to stock composition estimates of Chinook salmon incidentally captured in groundfish fisheries in the GOA, which are predominately comprised of British Columbia, U.S. Pacific Northwest, and coastal Southeast Alaska populations (Balsiger 2021; Guthrie et al. 2020; Masuda 2019). Capturing Chinook salmon exclusively from these populations, which have both hatchery and natural origins relatively far from their respective tagging locations, is not surprising as these populations have much higher abundances than Chinook salmon with natural origins in the GOA closer to the tagging sites (Healey 1991; Riddell et al. 2018).

Differences in dispersal and behaviors of tagged fish in this study are likely due to many factors including the stock-origin of tagged fish (A.O. et al. 2019; Tucker et al. 2011; Weitkamp 2010), and the variable range of age-at-maturity in Chinook salmon populations (Healey 1991; Riddell et al. 2018). The tendency of many tagged fish to demonstrate fidelity to the region in which they were tagged is likely representative of tagging immature Chinook salmon that still have an additional year or more of feeding at sea before swimming back to their natal origins to spawn. In contrast, based on the direction of travel and genetic assignments, Chinook salmon that were observed to make extensive southeasterly migrations to the Pacific Northwest were likely maturing fish returning to their natal rivers to spawn.

During this study there was a tendency for tagged fish to occupy the continental shelf from roughly 165–130°W during all months for which we have data. These results highlight the importance of this coastal shelf region in the GOA for Chinook salmon growth. Occupation of this region by tagged Chinook salmon corroborates past research that suggests that this species is more coastally-oriented than other species of Pacific salmon such as pink salmon (*O. gorbuscha*), sockeye salmon (*O. nerka*), and chum salmon (*O. keta*), and are largely concentrated on the continental shelf while inhabiting the GOA (Healey 1991; Quinn 2018; Riddell et al. 2018). The importance of continental shelf habitat for Chinook salmon populations throughout North America is reinforced by incidental catches of this species in many large commercial fisheries that occur in this area (Fissel et al. 2016; Guthrie et al. 2020; Masuda 2019; Turner et al. 2017). The biological importance of the continental shelf is additionally supported by the high abundances of zooplankton, forage fishes, marine mammals and sea birds (Byrd et al. 2005;

Heifetz et al. 2005; Logerwell et al. 2005), based on productivity arising from westerly transport of well-mixed nutrient-rich waters (Hunt and Stabeno 2005; Stabeno et al. 2005).

Insights into the horizontal distribution of Chinook salmon from this study may be used to address important management issues in the North Pacific Ocean, including understanding this species' potential exposure to Navy training exercises conducted in the GOA. Although the end locations and movement patterns observed in this study are biased by the locations of capture/tagging, these results do suggest that tagged Chinook salmon primarily reside over the continental shelf while occupying the GOA, including while in the TMAA. These findings are corroborated by previous CWT recoveries and satellite tagging research in the GOA, all of which suggest that Navy training activities that occur over basin waters of the TMAA are less likely to co-occur with this species, compared to other areas of the TMAA (e.g., shelf). This information was used recently to assist the Navy in developing the CSSMA that would move specific Navy training activities with the potential to impact Chinook salmon to TMAA basin waters >4,000 m depth, thereby minimizing overlap between this species and specific training activities (U.S. Navy 2020).

Chinook salmon occupied a broad range of depths, with a tendency to occupy deeper and more isothermal waters during the fall and winter, compared to the shallower and more stratified waters during the spring and summer months. These seasonal patterns in depth and temperature occupancy are corroborated by previous electronic tagging studies in the Bering Sea, GOA, Puget Sound, and off the coast of Oregon and California. These depth and temperature occupation patterns are thought to arise from seasonal changes in stratification of the water column, and the distribution and abundance of prey that occur throughout each region (Courtney et al. 2019; Hinke et al. 2005; Smith et al. 2015; Walker and Myers 2009). Changes in the stratification of the water column have also been suggested to shape the foraging behavior of other pelagic fish species, such as Atlantic salmon (Hedger et al. 2017a; Strøm et al. 2017; Strøm et al. 2018) and Atlantic bluefin tuna (*Thunnus thynnus*) (Walli et al. 2009).

In addition to providing information on the horizontal distribution, satellite tags provided valuable information about the vertical distribution and diving behavior of Chinook salmon, while occupying the GOA and the TMAA. While occupying the TMAA, tagged Chinook salmon occupied a wide range of depths, similar to past electronic tagging research in the GOA, which documented Chinook salmon occupying depths from 0 to 538 m (Courtney et al. 2021; Courtney et al. 2019). The results from this study, combined with additional deployments of PSATs on Chinook salmon would likely lead to a better understanding of trends in daily depth occupation of individual Chinook salmon, and may further aid management strategies to minimize interactions between Navy training exercises and Chinook salmon in the GOA.

Predation of tagged Chinook salmon in this study suggests that consumption by salmon sharks is common across the western and central GOA throughout the calendar year. These results corroborate previous research that documented intense late-stage mortality of Chinook salmon by salmon sharks near the Aleutian Islands and Bering Sea (Seitz et al. 2019). Furthermore, the common occurrence of salmon shark predation on Chinook salmon is supported by previous estimates that salmon sharks have the capacity to consume a considerable proportion of Pacific salmon (*Oncorhynchus* spp.) residing in the North Pacific Ocean each year (Nagasawa 1998), and have the ability to alter their population demographics through top-down control (Manishin et al. 2021).

In this study, all salmon shark predation events were inferred to have occurred west of 145°W, similar to inferred results from recent satellite tagging research on Chinook salmon in the Bering Sea and Aleutian Islands (Seitz et al. 2019). When the current results are considered with previous satellite tagging research in the Bering Sea (Seitz et al. 2019) and GOA (Courtney et al. 2021), along with other research examining removals of Chinook salmon by a variety of marine mammals (Adams et al. 2016; Chasco et al. 2017; Ohlberger et al. 2019), there appear to be regional differences in mortality and its agents. Increases in abundance of Chinook salmon predators throughout the North Pacific Ocean may partly explain recent declines in Chinook salmon production (Adams et al. 2016; Chasco et al. 2017; Manishin et al. 2021; Ohlberger et al. 2019; Okey et al. 2007; Seitz et al. 2019), including some ESUs that are protected under the ESA.

It is important to acknowledge that the methods used in this study likely introduces some bias to the results of this study. For example, PSATs could alter the swimming performance of tagged Chinook salmon (e.g., Methling et al. 2011), and/or increase their susceptibility to predation (e.g., Cosgrove et al. 2015). While the effects of towing PSATs on the swimming performance and survival of Chinook salmon is currently poorly understood, it has been qualitatively examined for adult Atlantic salmon and suggests that PSATs have minimal effects on its marine behavior and survival (Hedger et al. 2017b). Future laboratory studies on Chinook salmon towing PSATs would be valuable to understand the possible changes in behavior or increased metabolic costs associated with this research tool.

The tagged Chinook salmon in this study were comprised of individuals from many populations extending from Southeast Alaska to the U.S. Pacific Northwest, likely making these results pertinent to other populations throughout North America. Currently, several ESUs from the Pacific Northwest are listed under the ESA, and coast-wide changes in Chinook salmon population demographics and production has been documented from Western Alaska to California (ADF&G 2013; Lewis et al. 2015; Ohlberger et al. 2018; Schindler et al. 2013; Welch et al. 2021), highlighting the importance of understanding this species' marine ecology. This information has not only basic application for trying to unravel many questions about changing demographics, but it also has applied application for inferring and reducing impacts of human activities on this species, such as Navy training exercises conducted in the GOA TMAA. Currently, the sample size of tags is insufficient to quantitatively draw conclusions about Chinook salmon distribution and behavior. To provide additional information on Chinook salmon ocean ecology, additional PSATs will be deployed on Chinook salmon near Sitka, AK (n = 20), and Craig, AK (n = 20) in the spring/summer of 2022. Results from all tag deployments will be integrated to provide a more holistic understanding of this species' ecology in the North Pacific Ocean.

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