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Results of the 2019 Bering Sea Tanner Crab *Chionoecetes bairdi* Tagging Study

by

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Alaska Department of Fish and Game
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Symbols and Abbreviations

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Weights and measures (metric)

centimeter	cm
deciliter	dL
gram	g
hectare	ha
kilogram	kg
kilometer	km
liter	L
meter	m
milliliter	mL
millimeter	mm

Weights and measures (English)

cubic feet per second	ft^3/s
foot	ft
gallon	gal
inch	in
mile	mi
nautical mile	nmi
ounce	oz
pound	lb
quart	qt
yard	yd

Time and temperature

day	d
degrees Celsius	°C
degrees Fahrenheit	°F
degrees kelvin	K
hour	h
minute	min
second	s

Physics and chemistry

all atomic symbols	
alternating current	AC
ampere	A
calorie	cal
direct current	DC
hertz	Hz
horsepower	hp
hydrogen ion activity (negative log of)	pH
parts per million	ppm
parts per thousand	ppt, ‰
volts	V
watts	W

General

Alaska Administrative Code	AAC
all commonly accepted abbreviations	e.g., Mr., Mrs., AM, PM, etc.
all commonly accepted professional titles	e.g., Dr., Ph.D., R.N., etc.
at	@
compass directions:	
east	E
north	N
south	S
west	W
copyright	©
corporate suffixes:	
Company	Co.
Corporation	Corp.
Incorporated	Inc.
Limited	Ltd.
District of Columbia	D.C.
et alii (and others)	et al.
et cetera (and so forth)	etc.
exempli gratia (for example)	e.g.
Federal Information Code	FIC
id est (that is)	i.e.
latitude or longitude	lat or long
monetary symbols (U.S.)	$, ¢
months (tables and figures): first three letters	Jan,...,Dec
registered trademark	®
trademark	™
United States (adjective)	U.S.
United States of America (noun)	USA
U.S.C.	United States Code
U.S. state	use two-letter abbreviations (e.g., AK, WA)

Mathematics, statistics

all standard mathematical signs, symbols and abbreviations	
alternate hypothesis	H_A
base of natural logarithm	*e*
catch per unit effort	CPUE
coefficient of variation	CV
common test statistics	(F, t, χ^2, etc.)
confidence interval	CI
correlation coefficient (multiple)	R
correlation coefficient (simple)	r
covariance	cov
degree (angular)	°
degrees of freedom	df
expected value	*E*
greater than	>
greater than or equal to	≥
harvest per unit effort	HPUE
less than	<
less than or equal to	≤
logarithm (natural)	ln
logarithm (base 10)	log
logarithm (specify base)	log_2, etc.
minute (angular)	'
not significant	NS
null hypothesis	H_O
percent	%
probability	P
probability of a type I error (rejection of the null hypothesis when true)	α
probability of a type II error (acceptance of the null hypothesis when false)	β
second (angular)	″
standard deviation	SD
standard error	SE
variance	
population	Var
sample	var

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure **Page**

LIST OF APPENDICES

Appendix **Page**

ABSTRACT

Alaska Department of Fish and Game (ADF&G) deployed 140 pop-up satellite tags and 1,441 spaghetti tags on large male Tanner crab (≥127 mm carapace width) in 5 areas near the Pribilof Islands to investigate seasonal movements relative to the Pribilof Islands blue king crab protection area (PIBKCPA). Most satellite tags (n = 132) were programed to release to the ocean surface and transmit data between December 2019 and mid-January 2020 (~3.0–4.5 months at liberty); 8 tags were programmed to release on April 1, 2020 (~7 months at liberty). Tag pop-up locations (crab end locations) and associated error ellipses were estimated using Argos satellite data derived from tag transmissions following release from the host crab. For satellite-tagged crab with the most reliable estimates of end location (n = 82), point estimates and plausible ranges were calculated for distance, rate, and direction of horizontal straight-line displacement over 90–146 days. Average (± 95% CI) straight-line horizontal movement rate of satellite-tagged crab with reliable end locations was 0.116 ± 0.027 km/d. Movement rates of new shell crab were greater than those of old shell crab (*t*-test, $P < 0.05$). Movement direction varied by deployment area, but slightly more than half of satellite-tagged crab moved in a broad southerly direction (55%; 112.5–247.5°) and most others moved in a northerly direction (29%; 292.5–67.5°). Proportions of satellite-tagged crab released along the PIBKCPA boundary that immigrated to or emigrated from the closure area were similar (15.4% and 15.8%, respectively). Spaghetti-tagged crab recovered during the 2019/20 Bering Sea snow crab fishery (n = 60) moved at an average (± 95% CI) rate of 0.075 ± 0.015 km/d over 151–218 d. Movement rates of spaghetti-tagged and satellite-tagged crab released inside the PIBKCPA southeast border were not statistically different (*t*-test, $P = 0.50$).

Keywords: Tanner crab, *Chionoecetes bairdi*, Pribilof Islands, Bering Sea, tagging, pop-up satellite tags, mrPAT, MiniPAT, satellite telemetry

INTRODUCTION

Tanner crab (*Chionoecetes bairdi*) are widely distributed throughout Alaska waters from Norton Sound to Southeast Alaska and have supported some of the state's most important crab fisheries. In the Eastern Bering Sea (EBS), highly variable Tanner crab recruitment led to a "boom or bust" cycle. First targeted by Japanese and Russian fleets in 1965, the EBS Tanner crab fishery quickly expanded in the late 1960s with a catch of 60 million lb in 1969. Directed fisheries for EBS Tanner crab by the U.S. fleet began in 1974[1] with a peak harvest of 66 million lb in 1977 followed by a population collapse in the mid-1980s and directed fishery closures in 1986 and 1987 (Nichols et al. 2019). Catches averaged 33 million lb during 1990–1993 with an average annual value of approximately U.S. $50 million but dropped sharply after 1993. The fishery was closed during 1997–2004, 2010–2012, 2016, and 2019 due to low population abundance estimates.

EBS Tanner crab is considered a single stock, but the Alaska Department of Fish and Game (ADF&G) establishes total allowable catch (TAC) in 2 areas, east and west of 166°W long (Figure 1), to spread exploitation over the stock's spatial range. Biological characteristics that suggest an east–west stock substructure include size at maturity (Somerton 1981), larval advection patterns (Richar et al. 2015), and genetic differentiation (Merkouris et al. 1998), yet it is unclear if these biological characteristics suggest a single stock with connectivity between subregions or separate discrete substocks. Regardless, existing management of EBS Tanner crab (i.e., a single stock but with separate TACs east and west of 166°W long) reflects ADF&G's current understanding of population biology and stock structure.

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[1] Foreign fishing for Tanner crab has been prohibited under the Magnuson Fisheries Conservation and Management Act since 1980.

EBS Fishery Closure Areas

Area closures in the EBS, intended to reduce bycatch mortality of red (*Paralithodes camtschaticus*) and blue (*P. platypus*) king crabs, effectively create "crab sanctuaries" for other commercially exploited species including snow (*Chionoecetes opilio*) and Tanner crabs. In 2005, ADF&G established the Pribilof Islands blue king crab protection area (PIBKCPA; Figure 1) to protect the severely depressed Pribilof blue king crab stock; the area is closed to all directed crab fishing. The PIBKCPA boundary has changed since it was first established but has remained static since the 2017/18 season. In addition to the PIBKCPA, waters east of 163°W long are closed to directed Tanner crab fishing to reduce bycatch of Bristol Bay red king crab. Area closures are easily enforceable, may conserve populations, and could hedge against resource uncertainty; however, population level effects are unknown for EBS crab stocks.

Management Considerations

A better understanding of seasonal movement patterns will improve management of EBS Tanner crab by increasing knowledge on stock structure and population level effects of area closures. The EBS crab stocks, including Tanner crab, have been surveyed annually for stock assessment by the summer National Marine Fisheries Service (NMFS) EBS bottom trawl survey since 1975 (Pereyra et al. 1978; Zacher et al. 2020). The summer bottom trawl survey is essential for establishing population estimates, yet because the survey occurs during a short temporal window (~2 months: June and July) little is known about population dynamics during the remainder of the year. The spatial distribution depicted by this summer "snapshot" may not be representative of a population's distribution during the fisheries that occur in the fall and winter. Industry-preferred size male snow crab (≥4 inches, 102 mm carapace width) undergo broad-scale seasonal and ontogenetic spatial migrations in the EBS suggesting a mismatch between the distribution depicted by the summer bottom trawl survey and that at the time of the fishery (D. Pengilly, K. A. MacTavish, and L. M. Slater, ADF&G, Kodiak, unpublished data; Nichol and Somerton 2015; Nichol et al. 2017). Similar spatiotemporal discrepancies may exist for large male Tanner crab in the EBS, thus it is important to understand how seasonal movement vectors relate to management boundaries.

The true proportion of exploitable male Tanner crab (industry-preferred size males, ≥5 inches, 127 mm carapace width, outside closed areas) could vary from that depicted by the NMFS summer trawl survey depending on seasonal immigration or emigration rates across closure area boundaries. Abundance estimates from the 2015–2019 NMFS EBS surveys suggest that during summer, approximately 50% of industry-preferred size male Tanner crab west of 166°W long have been located inside the PIBKCPA. Those crab are presumably unavailable to the fishery; however, it is unclear if that assumption is true because there is a paucity of fishery-independent data from time periods other than those covered by the NMFS summer bottom trawl surveys. ADF&G currently scales the annual TAC to the entire population including crab located inside the PIBKCPA; however, it is unknown if doing so is appropriate because it may place a higher exploitation rate on the portion of the population outside of the closure area than directed by the harvest strategy. Using data on seasonal distributions, annual TAC computations could be adjusted by applying exploitation rates to the exploitable portion of the population rather than the entire population. Furthermore, a better understanding of the extent of movement patterns could help inform EBS Tanner crab stock structure and placement of other management boundaries such as the line of demarcation between the ADF&G east and west management areas. To address the management uncertainties described above, ADF&G has developed a new tagging program with a focus on fishery-independent, pop-up satellite tags as a tool to better understand movements of EBS crabs.

Previous Tagging Efforts

Argos satellite telemetry is one of the most widely used methods to track movements of marine animals. Satellite tags record behavioral and environmental data which are archived in onboard memory. On a pre-set date, the positively-buoyant tag releases from its host animal, surfaces, and begins transmitting messages to the Argos satellite system; if a sufficient number of messages are received during a single satellite pass, an initial location and error ellipse can be estimated. The Argos system enables positioning of surfaced tags by measuring the Doppler shift in tag transmission frequency due to the relative motion between the tag and satellite, and a multiple-model Kalman filter algorithm generates estimates of locations and associated error ellipses (Lopez et al. 2013). In contrast to traditional tags (e.g., spaghetti tags), satellite tags allow researchers to track host animal movements independently of fishery effort, within closed waters, and during periods of fishery closure.

To evaluate the utility of satellite tags in tracking fishery-independent movements of Tanner crab, ADF&G conducted 2 years of pilot studies in the PIBKCPA. Details on the 2017 and 2018 pilot studies can be found in Vanek et al. (2021). Two satellite-tag models were evaluated: mrPAT and MiniPAT (Wildlife Computers Inc., Redmond, WA). After a pre-specified deployment length, both tags transmit messages used to determine tag positions at the ocean surface, associated error ellipses, and daily bottom temperatures; MiniPAT tags transmit messages encoding additional information on depth and light measurements used to inform a light-based geolocation algorithm. MiniPAT tags have been used on other benthic species, such as Pacific halibut (*Hippoglossus stenolepis*) with high rates of success (T. Loher, IPHC, Seattle, personal communication), and recent studies are exploring the utility of both tag models for tracking crab species (e.g., this study and Davidson and Hussey 2019).

Satellite tags may have some effect on crab behavior that could impact broad-scale movement patterns. The 2 types of tags deployed for this study, mrPAT and MiniPAT, are 127 mm and 124 mm in length and weigh 40 g and 60 g in air, respectively; both tags are positively buoyant (~10 g). Laboratory trials conducted in parallel to the 2017 and 2018 pilot studies compared behavior (horizontal distance traveled, acceleration, and righting response time) and energy requirements of male Tanner crab with and without satellite tags attached. Results indicate average behaviors were not statistically different, but the tagged group generally exhibited higher variability in behaviors suggesting that crab response to tag attachment may be more pronounced for some individuals. Energy requirements (calories consumed per feeding) were not statistically different between tagged and non-tagged crab. For more details on the behavior trials, see Vanek et al. (2021).

OBJECTIVES

1. Evaluate movement patterns of industry-preferred size male Tanner crab relative to PIBKCPA boundaries between late summer and early winter.
2. Quantify movement directions, distances, and rates of industry-preferred size male Tanner crab in and around the PIBKCPA.
3. Evaluate the utility of pop-up satellite tags as a tool for estimating crab movements.

METHODS

Tagging occurred from 23 August through 3 September 2019 aboard the Alaska Wildlife Troopers vessel P/V *Stimson*, a 156 ft (47.5 m) vessel previously used as a commercial crab fishing vessel. The study area was bounded by lat 56°30′N, lat 57°45′N, long 168°00′W, and long 171°30′W (Figure 2). For a complete description of project methodology, refer to Vanek et al. (2021).

TAG DEPLOYMENT

A total of 140 satellite tags (100 mrPAT and 40 MiniPAT) were deployed on industry-preferred size male Tanner crab captured in 181 of 207 pots set in 5 primary release areas: (1) near the center of the PIBKCPA; (2) approximately 10–36 km inside and (3) approximately 10–14 km outside the southeast (SE) border of the PIBKCPA boundary; (4) approximately 10 km inside and (5) approximately 10 km outside the west (W) border of the PIBKCPA boundary (Figure 2). Tags were attached to the host crab using methods outlined in Vanek et al. (2021). Each tag was programmed to release on one of 5 dates: 1 December or 16 December 2019, or 1 January, 16 January, or 1 April 2020 for an approximate time at liberty of 3.0, 3.5, 4.0, 4.5, and 7.0 months, respectively (Table 1). Both tag models collected environmental data (temperature and depth by MiniPAT and temperature by mrPAT). All tags were set to transmit once every 60 s (manufacturer's default for mrPAT is one transmission every 90 s) after reaching the ocean surface. To ground-truth movement rates of satellite-tagged crab, Floy spaghetti tags (n = 1,339) were deployed across the 5 release areas on all suitable industry-preferred size males that were not fitted with satellite tags (Figure 2). Additional spaghetti-tagged crab (n = 102) were released in a sixth area (~18.5 km to the west of area 5) to increase odds of tag recovery in the event there was no directed Tanner crab fishery in 2019/20 (Table 2). Carapace width of tagged crab was recorded as the distance across the carapace at the widest part perpendicular to the medial line, with the tips of the calipers reaching inside the lateral spines as in Jadamec et al. (1999); shell condition was assessed following guidelines in ADF&G (*unpublished*).[2]

DATA PROCESSING

Once surfaced, satellite tags drift for a period of time prior to successfully transmitting a sufficient number of messages for an initial location to be calculated. Therefore, the first calculated location will differ from the location of tag surfacing. While the satellite tag will undergo some additional horizontal displacement during its ascent from the ocean bottom (likely <0.1 km based on ascent rate from Davidson and Hussey 2019), the location where the tag surfaced (pop-up location) provides a reasonable estimate of the tagged crab's end location. Estimation of tag pop-up location was based on the availability of suitable Argos-estimated tag drift locations: either (1) two high-quality[3] and reasonably adjacent drift locations (P_1 and P_2) of the tag in question; or (2) one high-quality and reasonably adjacent drift location (P_1) of the tag in question and two additional high-quality, spatiotemporally adjacent drift locations (P_1^* and P_2^*) of another tag (Figure 3). With P_0 denoting the pop-up location of the tag in question, let t_1 be the drift time between P_0 and P_1 (under

[2] ADF&G (Alaska Department of Fish and Game). *Unpublished*. Shell condition for *Chionoecetes* crabs. ADF&G Division of Commercial Fisheries, Western Region unpublished manuscript on shell condition standards, descriptions, and example photographs (available for ADF&G internal use only at http://kodweb.fishgame.state.ak.us/documents/guides/ChionoecetesSCPhotoGuide.pdf; accessed 10/2021).

[3] A "high-quality" location was defined as a location with the semi-major axis component of its Argos error ellipse <5.3 km as this limited the maximum estimated error of drift locations to <3% of the N–S distance across the PIBKCPA.

either scenario), let t_2 denote the drift time between P_1 and P_2, and t_2^* the drift time between P_1^* and P_2^*. The tag pop-up location was estimated either by

$$P_0 = P_1 - \left(\frac{t_1}{t_2}\right)\overrightarrow{P_1P_2} \tag{1}$$

in case (1) or by

$$P_0 = P_1 - \left(\frac{t_1}{t_2^*}\right)\overrightarrow{P_1^*P_2^*} \tag{2}$$

in case (2). These computations use an appropriately scaled version of one of the drift vectors ($\overrightarrow{P_1P_2}$ or $\overrightarrow{P_1^*P_2^*}$) as a proxy for the unknown drift vector ($\overrightarrow{P_0P_1}$) to extrapolate from the Argos-estimated tag drift location (P_1) to an estimate of tag pop-up location (P_0; Figure 3, Appendix A).

We quantified uncertainty associated with estimated pop-up location as a buffered composite error ellipse (BCEE); the BCEE combines Argos error ellipses of all tag drift locations used to estimate pop-up location with an additional buffer to account for possible underestimation of Argos-reported error (Boyd and Brightsmith 2013) and uncertainty in calculated drift rates and directions (Figure 3). Specifically, let S_M and S_m denote, respectively, the semi-major and semi-minor axes of the BCEE associated with pop-up location (P_0), where the direction of S_M is assumed to lie in the interval [0, 180°). The lengths of S_M and S_m were computed by summing the lengths of, respectively, the semi-major and semi-minor axes of the Argos error ellipses corresponding to all locations used in determining P_0, plus a buffer of one-third the estimated drift distance (d) between P_0 and P_1 $(d = \|\overrightarrow{P_0P_1}\|)$; direction of S_M was computed as the weighted average of the directions of the Argos error ellipse semi-major axes. More precisely, the length ($\|S_M\|$) and direction ($\angle S_M$) of the BCEE semi-major axis (S_M) were calculated as

$$\|S_M\| = \frac{1}{3}d + \sum_i \|S_{M_i}\| \tag{3}$$

and

$$\angle S_M = \frac{\sum_i \|S_{M_i}\| \angle S_{M_i}}{\sum_i \|S_{M_i}\|} \tag{4}$$

where the Argos error ellipse semi-major axes (S_{M_i}) corresponding to all contributing locations are chosen so that their directions are within [0, 180°), consistent with the assumed orientation of S_M. A calculation analogous to equation 3 was used to obtain the length of the BCEE semi-minor axis ($\|S_m\|$).

Estimated pop-up location was used to calculate point estimates of the overall distance (horizontal straight-line displacement), rate, and direction each host crab moved from its location at tag deployment to its end location at tag release. Plausible ranges (estimated minimum and maximum values) for each of these estimates were obtained by considering the most extreme values determined by the BCEE associated with estimated pop-up location. For distance and rate, the range of plausible values was determined using the minimum and maximum distances from the deployment location to points in the pop-up location BCEE; for direction, the range was determined by the directions of the lines from the deployment location tangent to the BCEE and reported as the minimum direction (line counterclockwise from the direction point estimate) and maximum direction (line clockwise from the direction point estimate). Tag drift time prior to first high-quality location (t_1) and length of the BCEE semi-major axis ($\|S_M\|$) were used to assess the reliability of estimated pop-up locations using the following categories: (1) t_1 < 24 h and $\|S_M\|$ < 8.35 km; (2) t_1 < 48 h and 8.35 km < $\|S_M\|$ < 16.7 km; (3) t_1 > 48 h or $\|S_M\|$ > 16.7 km; and (4) no suitable drift locations with Argos error estimates (i.e., no estimated pop-up location). Semimajor axis lengths of 8.35 and 16.7 km are ~5% and ~10% of the N–S distance across the PIBKCPA, respectively. Category 1 and 2 locations were considered the most reliable locations for data analysis. Locations classified as category 1 or 2 from tag deployments of 90–146 days were used to summarize crab movements and assess crab end locations relative to the PIBKCPA boundary.

RESULTS

SATELLITE-TAGGED CRAB

Sixty-two of 100 mrPAT tags and 23 of 40 MiniPAT tags deployed for this project yielded reliable (i.e., category 1 and 2) pop-up location estimates (Table 3, Figures 4 and 5). Average (± 95% CI) straight-line horizontal distance traveled for all satellite-tagged crab with reliable pop-up locations (n = 82) was 13.5 ± 3.1 km (range 1.4–76.0 km), while the average straight-line horizontal movement rate was 0.116 ± 0.027 km/d (range 0.013–0.682 km/d; Tables 4 and 5). Due to staggered tag release dates, time at liberty varied from 90 to 146 days and thus comparisons of absolute horizontal displacement were inappropriate. Therefore, we compared horizontal movement rate (km/d), natural log transformed data to meet assumptions of normality and equal variances for statistical comparisons and used $\alpha = 0.05$ to determine statistical significance. Because there was no difference in movement rates between the two tag models (*t*-test, $P = 0.66$), mrPAT and MiniPAT data were pooled for analysis. There was no trend in movement rate as a function of crab size (Linear Regression, $P = 0.93$; Figure 6); however, average movement rate of new shell crab (n = 14, 0.271 ± 0.129 km/d) was greater than that of old shell crab (n = 68, 0.084 ± 0.014 km/d) (*t*-test, $P < 0.05$). There was no relationship between movement rate and time at liberty.

Movement direction varied with deployment area. Overall, 55% (45 of 82) of satellite-tagged crab moved in a southerly direction (112.5–247.5°); this pattern was more pronounced for crab released at the center of the PIBKCPA (73%, 27 of 37; Figure 7). Although 41% (14 of 34) of crab released near the SE border of the PIBKCPA also moved in a southerly direction, 47% (16 of 34) moved in a northerly direction (292.5–67.5°; Figure 8). No satellite-tagged crab released near the center (area 1) moved out of the PIBKCPA by mid-January (97–146 days at liberty; Figures 4 and 5). Of satellite-tagged crab released along the PIBKCPA boundary (areas 2–5 combined), 15.8% (3 of 19) released inside the boundary moved to outside the boundary and 15.4% (4 of 26) released outside the boundary moved to inside the boundary.

Some satellite tags provided useful information but were not included in the statistical comparisons described above. Data from satellite tags deemed unreliable for statistical comparisons (due to a higher level of uncertainty associated with the estimated pop-up location) still provide useful information even when considering the relatively large error ellipses (category 3 locations, n = 9; Figure 9). Of these tags, the host crab generally stayed within the PIBKCPA, and their inclusion in the analysis does not meaningfully change the proportion of crab leaving or entering the PIBKCPA. A small sample of satellite tags (n = 8) was programmed to pop-up in April 2020 to evaluate the effect of extended time at liberty on tag performance. Although half (4) of the tags transmitted location data, only 3 yielded reliable locations (Figure 9). One satellite-tagged crab released near the center of the PIBKCPA travelled 234.7 km and crossed the boundary sometime during its 219 days at liberty (rate of 1.1 km/d; Table 5).

Although all satellite tags were programmed to pop up after 3–7 months deployed, 21 tags detached from crab prematurely and surfaced prior to their scheduled release dates (i.e., "floaters"; Table 3). Reasons for early detachment are generally not discernable from transmitted data but are likely related to physical attachment failure (either in attachment harness, tether, nose cap, or burn pin), tagware errors, predation, or other mortality. Some tags that detached early (10 of 21), provided data on crab movements over 6–132 days at liberty (Table 6, Figure 10). Because most floaters surfaced independently of other tags and all required additional drift time prior to transmission to meet conditional release settings, there was greater uncertainty in estimated pop-up locations.

SPAGHETTI-TAGGED CRAB

Of the 1,441 spaghetti-tagged crab released, 62 were recaptured as bycatch in the 2019/20 snow crab fishery (60 with location data; Table 2, Figure 11). As expected, most recoveries of tagged crab occurred near the SE border of the PIBKCPA boundary due to relatively higher fishing effort in this area and all but 5 recoveries were crab released in areas 2 and 3 adjacent to the SE border. Because spaghetti-tagged crab were released both inside and outside of the PIBKCPA boundary, but recaptures can only occur outside the closure area, data indicate mostly easterly or southerly movement (60%, 36 of 60, 67.5–202.5°; Figure 12). Average (± 95% CI) straight-line horizontal distance traveled by spaghetti-tagged crab (n = 60) was 13.4 ± 2.9 km (range 0.6–70.4 km) and average horizontal movement rate was 0.075 ± 0.015 km/d (range 0.003–0.340 km/d, 151–218 days at liberty; Table 7). One crab with a spaghetti tag traveled 70.4 km straight-line distance from near the center of the PIBKCPA to outside the SE border during 207 days at liberty (Table 7, Figure 11). Because any spaghetti-tagged crab that moved into the PIBKCPA could not be recaptured and most spaghetti-tagged crab were recaptured near their release locations (particularly in area 3), horizontal displacement data is likely biased low. We compared movements of satellite-tagged crab (n = 16) and spaghetti-tagged crab (n = 16) that were released inside the PIBKCPA SE border (area 2) to evaluate the effect of tag type on crab movement (Figures 8B and 12B). Movement rate was not statistically different between tag types (*t*-test, $P = 0.50$; Figure 13).

DISCUSSION

SATELLITE TAG UTILITY

Results from this study suggest that pop-up satellite tags can be deployed on EBS Tanner crab with a reasonable rate of success (>50% reliable pop-up locations) and with spatial precision that although somewhat coarse allows for evaluation of seasonal movement patterns. Although we focused on estimated pop-up locations and report point estimates of crab movement rates (based on straight-line horizontal displacement), plausible ranges of movement rate suggest there is some level of coarseness to the data (Tables 4 and 5). Average minimum rate estimates deviated from point estimates by 30% where average maximum rate estimates deviated from point estimates by 38%. As such, estimated movement vectors should be interpreted together with corresponding buffered composite error ellipses. Although the methods used to estimate BCEEs are somewhat ad hoc in nature, they are likely conservative based on empirical data from fixed-position satellite tag deployments. Efforts are currently underway to develop an error estimation method that is more theoretically sound relative to the Kalman filter algorithm used to estimate Argos locations and error ellipses. Based on the factors described above, our confidence in estimated pop-up locations is variable but not to an extent which affected our confidence in the utility of this technology to investigate movement patterns of Bering Sea crabs. Researchers should consider the project's spatial scale and the precision needed for pop-up location estimates when considering satellite tags as a tool for addressing biological questions.

Movement vectors estimated in this study are net movements (point a to b) and despite varying uncertainty in pop-up locations, estimates likely represent coarse-scale movements of large male Tanner crab over time at liberty. We were unable, however, to estimate additional movement details, such as daily tracking intervals. MiniPAT tags can provide daily tracking information (as estimated via a light-based geolocation algorithm) for pelagic species with broad-scale (i.e., 100s to 1,000s km) migratory patterns (e.g., silky sharks; Hutchinson et al. 2019). We found the algorithm-based tracking was problematic for crab tagged in this study, probably due to insensitivity at the relatively fine spatial scale in which crab traveled. Therefore, our analysis was limited to straight-line horizontal movement directions and rates. Although straight-line rate was calculated based on distance between deployment and pop-up locations, the actual path of crab travel is probably not straight, and the relationship between time at liberty and horizontal displacement is probably not linear due to changes in movement rate associated with different behaviors and life history events (e.g., foraging, resting, mating migrations). For this reason, data from satellite tags that were programed to pop up in April were excluded from the analysis. While the tags from extended deployments or those with non-reliable pop-up location estimates (category 3) were not included in the analyses reported here, it is worth noting their results, because they confirm that (1) most crab near the center of the PIBKCPA did not cross the boundary between approximately late August and mid-January; (2) Tanner crab are capable of travelling long distances (i.e., >200 km) in extended temporal windows; and (3) satellite tags can be deployed on crab in the Bering Sea for extended periods of time (~7 months at liberty) with some success.

We acknowledge that satellite tags may have an impact on host crab behavior, and future technological advancements will probably result in reductions in tag size and thus reduce their potential behavioral impacts and expand the scope of crustacean species and sizes that can accommodate them. For example, the tags used in this study were reasonably sized for large male Tanner crab but are probably too large to deploy on smaller female Tanner crab or male snow crab. While results of the laboratory study and this study suggest satellite tags have minimal impact on host crab behavior, sample sizes in both the lab trials and spaghetti-tag comparison were small. Moreover, the comparison of movement rates between spaghetti-tagged crab and satellite-tagged crab presented here was confounded by fishery-dependence of spaghetti-tag recoveries. We acknowledge this is an imperfect comparison because spaghetti-tagged crab could only be recaptured outside of PIBKCPA, whereas satellite-tagged crab movement data was not restricted in this way. Further evaluation of the effects of satellite tags on crab behavior is needed; field studies using smaller fishery-independent tags, such as acoustic tags, may provide insight on potential tag effects.

Aside from information on crab movements, this study provided insight to other aspects of satellite tags including spatial and temporal differences in successful data transmission. Satellite tags deployed on crab adjacent to the SE border of the PIBKCPA (areas 2 and 3) produced a higher proportion of category 1 locations than tags deployed near the center of the PIBKCPA (area 1) or adjacent to the W border of the PIBKCPA (areas 4 and 5). Area-specific physical conditions (substrate rugosity and composition, ocean corrosivity) and/or biological factors (biofouling, crab activity levels, competitive interactions, predation) could explain differences in tag performance between areas. The aforementioned variables may cause damage to tags that inhibit message transmission thereby decreasing the rate of efficient and high-quality location estimates among the affected tags. Reliability of pop-up location estimates also varied with time at liberty as satellite tags that surfaced in December produced more category 1 locations than those which surfaced in January. Aside from potential effects of deployment length (chemical and physical impacts to tags), differences in ocean conditions at the time of tag surfacing may explain some of the difference in tag performance; forecasted wind speeds and wave heights were generally greater for January pop-up dates than for December pop-up dates. Average (± 95% CI) drift rate of surfaced satellite tags was 1.4 ± 0.2 km/h (range 0.2–2.7 km/h) for January dates and was 0.8 ± 0.1 km/h (range 0.1–1.9 km/h) for December dates, suggesting that differences in drift rates mirrored forecasted ocean conditions. It is possible that temporal differences in wind speed, wave height, and surface current can impact tag performance by affecting whether tags can transmit sufficient messages for a location estimate to be determined in a timely manner. Further research should consider area-specific variables that might affect tag performance and bracketing pop-up dates around a target date is advised to hedge against all tags encountering unfavorable ocean conditions.

We consider the mrPAT tag nonstandard repetition rate of 1 transmission every 60 s to have improved timely acquisition of high-quality locations relative to the default rate of 1 transmission every 90 s. An even higher rate (30 or 45 s) may result in further improvements with the tradeoff of a shorter overall transmission duration at the surface. Future studies should consider transmission rate for optimizing success. In addition to transmitting messages used in positioning and error estimation, satellite tags record and transmit data on environmental conditions encountered by host animals. However, complete sets of environmental data were not transmitted successfully by tags used in this study and resulting datasets are patchy with respect to time and of limited value in correlating crab movements with changes in environmental conditions (Appendix B). Future research with the aim of correlating crab movement distances or rates with environmental variables should attempt to limit the total number of daily messages that satellite tags report to allow complete sets of data to be transmitted.

MANAGEMENT UTILITY

The similar migration rate of industry-preferred size male Tanner crab entering or leaving the PIBKCPA between approximately late August and mid-January implies that the spatial distribution of industry-preferred males during the summer NMFS EBS bottom trawl survey is a reasonable representation of their distribution at the time of the fishery. However, these findings should be viewed within the context of a single tagging effort in time and space and do not inform interannual variability in movement patterns. Directional data from this study suggest no overall coordination of movements of industry-preferred male Tanner crab during the fall through early winter. While satellite-tagged crab released near the center of the PIBKCPA generally moved in a broad southerly direction, those released inside and outside the SE border exhibited a bidirectional movement pattern either toward or away from the closure area. Spaghetti tags cannot inform coordination of Tanner crab movements relative to the PIBKCPA because they rely on recapture during fisheries which cannot occur inside the PIBKCPA; however, data from spaghetti-tagged crab confirmed that movement across the boundary from inside the PIBKCPA occurs. Results from 1 spaghetti-tagged crab and 1 satellite-tagged crab suggest that some crab near the PIBKCPA center move out of the PIBKCPA over longer temporal periods (~7 months). However, this study cannot quantify crab moving into the PIBKCPA from distant locations during a similar time period and only confirms that individual crab are capable of traveling the distance to do so. Further studies are necessary to determine whether sufficient data can be recovered from satellite tags deployed on Tanner crab over extended time periods to investigate coordination and seasonality of movements relative to the PIBKCPA. Additionally, repeated studies could inform interannual variability in crab movements, possibly associated with fluctuating environmental conditions, which could have direct implications on the proportion of crab that cross the PIBKCPA boundary during a given management cycle.

The magnitudes of estimated horizontal displacements in this study suggest Tanner crab can move at rates necessary to enter or leave the PIBKCPA between the summer survey and fall-winter fishery periods. Although we demonstrate that broad-scale movements are possible by individual crab, estimates of proportions expected to move such distances are needed to evaluate population-level effects. Although results suggest that immigration approximates emigration during the period from late summer to early winter for crab along the SE and W borders of the PIBKCPA, only 7 of 45 satellite-tagged crab released near the borders crossed the boundary after 97–146 days at liberty, a period that encompasses recent fishery effort; additionally, 0 of 37 satellite-tagged crab released near the center of the PIBKCPA crossed the boundary over this same period, suggesting that seasonal site fidelity may occur in areas inside and outside the PIBKCPA. Overall, few crab (5 satellite-tagged and 3 spaghetti-tagged) exhibited horizontal displacements >35 km, which is far less than the distance from the center of the PIBKCPA to the boundary (>80 km), but ability of crab to enter or leave the PIBKCPA depends in part on their late summer spatial distribution. Recent (2015–2019) NMFS EBS bottom trawl survey pooled abundance estimates indicate that 74% of industry-preferred males inside the PIBKCPA were located at stations with at least one border <35 km from the closure boundary, suggesting a net transfer of fishery-targeted males out of (or into) the PIBKCPA could occur between the summer survey and fall-winter fishery periods with coordinated migration behavior. While this study implies a minimal net transfer for 2019, we cannot assume this applies to all years, as 2019 was an exceptionally warm year with little to no summer cold pool in the EBS. A more southerly cold pool extent would create a more pronounced horizontal gradient in bottom temperatures in areas that overlap with the EBS Tanner crab population. Such shifting environmental conditions could lead to changes in broad-scale movements, thus reinforcing the need to evaluate interannual differences.

Because annual TAC is based on the entire EBS Tanner crab population and crab in the PIBKCPA are inaccessible to fishing, harvest rates outside the PIBKCPA can be higher than intended by the harvest strategy which could have population-level consequences. While the closure area protects part of the population, localized depletion of large males could occur outside the boundary. As a result, the availability of large, competitively dominant males for mating may be reduced in some areas which could increase mating opportunities for smaller mature males (Ennis et al. 1988), facilitate gene flow that may promote slower growth and earlier terminal molt (Kruse 1993; Zheng 2008), and/or reduce genetic diversity. However, genetic consequences of fishing behavior are complex and difficult to measure in previously exploited populations. Implications of high harvest rates may be more predictable from a population demographic standpoint. Recent survey trends show an aging cohort in the mature size classes with limited near-term recruitment (Zacher et al. 2020). Because movement rates may vary with shell condition (as suggested by this study: old shell crab tend to move slower), the likelihood of large males emigrating from the PIBKCPA to the fishery grounds (or vice versa) may be reduced. Thus, high harvest rates outside the PIBKCPA could exacerbate population declines if migration of large, mature males from adjacent areas is low and Allee effects occur in portions of the population. Further, localized depletion of competitively dominant males could impact mating dynamics, especially when mature females are in low abundance. Although reproductive failure has not been demonstrated to date for EBS Tanner crab, female Tanner crab stored sperm cell counts are negatively correlated with fishery exploitation rates in southeast Alaska (Webb and Bednarski 2010), signaling that male-only harvest may decrease levels of stored sperm available for fertilization of subsequent clutches. Further, variation in operational sex ratios affects sperm reserves in Canadian snow crab stocks (Sainte-Marie et al. 2008), suggesting the potential for instability of reproductive potential with shifting population mating dynamics.

CONCLUSIONS

This study provides information on fishery-independent movements of large male Tanner crab in the EBS that suggests (1) no large net movement of industry-preferred size males in or out of the PIBKCPA occurs between survey and fishery periods, although more information is needed to evaluate inter-annual patterns; (2) movements of industry-preferred size male Tanner crab located in and around the PIBKCPA are variable and can cover large distances in relatively short times; and (3) pop-up satellite tags can be used to answer biological questions pertaining to crab population dynamics. Overall, we mark this study as a successful first exploration in tracking movements of EBS Tanner crab with pop-up satellite tags and are optimistic that future studies employing similar tag technology will benefit from methods and ideas described herein.

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TABLES AND FIGURES

Table 1.–Number of satellite tags deployed during the 2019 Bering Sea Tanner crab tagging study by pop-up date, area, and tag model.

		Number of tags		
Pop-up date	Area	MiniPAT	mrPAT	Total
Dec 1	1	5	12	17
Dec 1	2	2	4	6
Dec 1	3	2	4	6
Dec 1	4	1	2	3
Dec 1	5	1	2	3
Dec 1 total	1–5	11	24	35
Dec 16	1	4	12	16
Dec 16	2	1	4	5
Dec 16	3	1	4	5
Dec 16	4	0	2	2
Dec 16	5	0	2	2
Dec 16 total	1–5	6	24	30
Jan 1	1	5	12	17
Jan 1	2	2	4	6
Jan 1	3	2	4	6
Jan 1	4	1	2	3
Jan 1	5	1	2	3
Jan 1 total	1–5	11	24	35
Jan 16	1	4	12	16
Jan 16	2	1	4	5
Jan 16	3	1	4	5
Jan 16	4	1	2	3
Jan 16	5	1	2	3
Jan 16 total	1–5	8	24	32
Apr 1	1	4	4	8
All dates	1–5	40	100	140

Table 2.–Number of spaghetti tags deployed during the 2019 Bering Sea Tanner crab tagging study and number of tagged crab recovered as bycatch in the 2019/20 Bering Sea snow crab fishery by area of release.

Release area	Area	Number of tags released	Number of tagged crab recovered		
			With location	No location	Total
CENTER					
Inside	1	527	1	0	1
SOUTHEAST (SE)					
Inside	2	309	16	0	16
Outside	3	182	41	0	41
All SE	2–3	491	57	0	57
WEST (W)					
Inside	4	243	0	0	0
Outside	5	78	1	0	1
Outside	6[a]	102	1	2	3
All W	4–6[a]	423	2	2	4
All areas	1–5	1,339	59	0	59
	1–6[a]	1,441	60	2	62

Note: Inside and Outside refer to the portion of a release area either inside or outside the PIBKCPA boundary.

[a] Only spaghetti-tagged crab were released in area 6.

Table 3.–Satellite tag performance by tag model.

	Number of tags							
	Location category							
Tag model	Cat 1	Cat 2	Cat 3	Cat 4	Floater	No loc.	Silent	Total
mrPAT	40	22	6	7	17	6	2	100
MiniPAT	20	3	4	4	4	5	0	40
All tags	60	25	10	11	21	11	2	140

Note: Location and other categories are defined as:

1) tag with surface drift prior to first high-quality location (t_1) < 24 h and semi-major axis length of buffered composite error ellipse ($\|S_M\|$) < 8.35 km

2) t_1 < 48 h and 8.35 km < $\|S_M\|$< 16.7 km

3) t_1 > 48 h or $\|S_M\|$ > 16.7 km

4) no suitable drift locations with Argos error estimates; no estimated pop-up location

Floater: tag that surfaced prior to its programmed release date

No loc.: tag that transmitted at the surface, but no Argos locations were estimated

Silent: tag was not detected by satellites (no transmissions)

Table 4.–Movement information on Tanner crab tagged with mrPAT satellite tags with category 1 or 2 pop-up locations.

	Deployment information						Location	Distance (km)[a]			Rate (km/d)[a]			Direction (°)[a]		
Tag	Area	Deployed	Tag surfaced	Days	CW (mm)	Shell	category	Min	Est	Max	Min	Est	Max	Min	Est	Max
93	1	08/26/2019	12/02/2019	97	138	Old	1	13.2	15.0	17.3	0.135	0.154	0.178	319	335	354
82	1	08/26/2019	12/02/2019	98	131	Old	1	5.2	8.9	12.7	0.054	0.091	0.130	222	237	245
76	1	08/26/2019	12/02/2019	98	142	Old	1	7.0	9.6	13.8	0.072	0.098	0.142	154	199	236
62	1	08/25/2019	12/02/2019	98	136	Old	1	1.5	4.1	7.5	0.015	0.042	0.076	169	228	243
70	1	08/25/2019	12/02/2019	99	151	Old	2	0.4	4.7	9.0	0.004	0.047	0.092	108	174	250
43	1	08/24/2019	12/02/2019	99	135	Old	1	9.7	11.3	13.4	0.098	0.113	0.135	302	316	333
26	1	08/24/2019	12/02/2019	100	135	New	1	57.1	57.9	58.8	0.574	0.581	0.590	147	147	148
96	1	08/26/2019	12/17/2019	112	128	Old	2	0.0	1.4	9.4	0.000	0.013	0.084	0	176	359
77	1	08/26/2019	12/16/2019	113	139	Old	1	4.6	10.1	16.2	0.041	0.090	0.144	301	334	21
84	1	08/26/2019	12/17/2019	113	141	Old	1	0.0	5.3	11.7	0.000	0.047	0.104	0	286	359
71	1	08/25/2019	12/17/2019	113	126	New	1	12.7	16.7	21.1	0.112	0.147	0.186	196	216	232
44	1	08/24/2019	12/17/2019	114	132	Old	2	0.6	5.3	13.2	0.005	0.046	0.115	128	243	277
27	1	08/24/2019	12/17/2019	115	125	Old	1	0.1	2.5	5.6	0.001	0.022	0.049	84	144	242
85	1	08/26/2019	01/02/2020	129	139	Old	2	9.0	13.7	20.1	0.070	0.106	0.156	184	225	251
78	1	08/26/2019	01/02/2020	129	127	Old	1	4.3	9.3	14.3	0.034	0.072	0.111	144	185	228
72	1	08/25/2019	01/02/2020	129	136	Old	2	4.2	11.1	18.8	0.033	0.086	0.145	154	210	252
67	1	08/25/2019	01/02/2020	129	136	Old	2	3.4	10.8	19.4	0.026	0.083	0.150	170	231	260
55	1	08/25/2019	01/02/2020	130	138	Old	2	0.0	7.7	19.0	0.000	0.060	0.147	0	184	359
60	1	08/25/2019	01/02/2020	130	141	Old	1	0.0	2.1	6.9	0.000	0.016	0.053	0	249	359
45	1	08/24/2019	01/02/2020	130	142	Old	2	0.0	5.7	16.2	0.000	0.044	0.125	0	221	359
35	1	08/24/2019	01/02/2020	131	133	Old	2	0.0	6.9	16.6	0.000	0.053	0.127	0	300	359
29	1	08/24/2019	01/02/2020	131	130	Old	2	14.8	24.8	35.0	0.113	0.190	0.268	257	272	288
98	1	08/26/2019	01/17/2020	143	137	Old	2	8.5	15.9	25.5	0.059	0.111	0.178	180	225	249
79	1	08/26/2019	01/17/2020	144	131	Old	1	8.3	14.3	20.5	0.058	0.099	0.142	207	234	256
68	1	08/25/2019	01/17/2020	144	135	Old	1	4.8	7.9	13.0	0.033	0.055	0.090	108	137	190

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Table 4.–Page 2 of 3.

	Deployment information						Location	Distance (km)[a]			Rate (km/d)[a]			Direction (°)[a]		
Tag	Area	Deployed	Tag surfaced	Days	CW (mm)	Shell	category	Min	Est	Max	Min	Est	Max	Min	Est	Max
48	1	08/25/2019	01/17/2020	145	138	Old	2	0.0	9.4	22.4	0.000	0.065	0.155	0	222	359
59	1	08/25/2019	01/17/2020	145	133	Old	1	4.6	7.2	9.9	0.032	0.049	0.068	95	101	114
30	1	08/24/2019	01/17/2020	146	133	Old	2	0.0	5.1	12.9	0.000	0.035	0.088	0	197	359
61	1	08/25/2019	01/18/2020	146	137	Old	2	0.0	4.2	10.7	0.000	0.029	0.073	0	248	359
64[b]	1	08/25/2019	04/02/2020	221	136	Old	1	16.4	21.0	25.8	0.074	0.095	0.117	303	313	323
37[b]	1	08/24/2019	04/02/2020	222	135	Old	1	20.2	22.8	25.5	0.091	0.103	0.115	324	333	343
118	2	08/28/2019	12/02/2019	95	145	Old	2	6.7	16.2	25.8	0.071	0.170	0.270	10	32	51
106	2	08/27/2019	12/02/2019	96	137	Old	1	2.3	4.1	6.9	0.024	0.043	0.071	285	304	355
99	2	08/27/2019	12/02/2019	97	140	Old	1	21.5	22.9	24.5	0.222	0.236	0.253	314	318	323
119	2	08/28/2019	12/17/2019	110	145	Old	1	22.5	26.0	29.5	0.204	0.235	0.267	176	188	199
111	2	08/28/2019	12/17/2019	111	163	Old	1	13.7	16.9	20.2	0.124	0.153	0.183	323	336	351
107	2	08/27/2019	12/17/2019	111	133	New	1	72.9	76.0	79.4	0.654	0.682	0.713	151	154	157
100	2	08/27/2019	12/17/2019	112	135	Old	1	0.6	4.6	8.8	0.005	0.041	0.079	103	159	232
115	2	08/28/2019	01/02/2020	126	140	New	2	37.1	43.2	50.1	0.293	0.341	0.396	310	319	330
102	2	08/27/2019	01/02/2020	127	127	Old	2	2.8	12.4	22.3	0.022	0.098	0.175	113	169	231
120	2	08/28/2019	01/17/2020	141	130	Old	1	0.0	3.4	7.2	0.000	0.024	0.051	0	155	359
114	2	08/28/2019	01/17/2020	142	141	New	1	5.4	8.6	12.3	0.038	0.061	0.087	288	316	353
139	3	08/30/2019	12/02/2019	94	138	Old	1	0.1	1.8	5.7	0.002	0.019	0.061	78	215	242
134	3	08/29/2019	12/02/2019	94	151	Old	1	3.8	6.5	9.4	0.040	0.069	0.099	66	84	93
121	3	08/29/2019	12/03/2019	96	133	Old	1	12.3	14.3	16.7	0.128	0.149	0.173	359	12	22
140	3	08/30/2019	12/17/2019	109	146	Old	1	2.8	6.2	9.8	0.026	0.057	0.090	218	249	273
132	3	08/29/2019	12/17/2019	109	148	Old	1	9.4	13.0	16.7	0.086	0.119	0.152	354	17	39
127	3	08/29/2019	12/17/2019	110	130	Old	1	5.1	8.5	12.1	0.046	0.078	0.110	218	241	260
137	3	08/30/2019	01/02/2020	125	139	Old	2	24.3	32.4	41.2	0.195	0.260	0.331	323	337	355
129	3	08/29/2019	01/02/2020	125	141	Old	1	11.7	14.0	17.0	0.093	0.112	0.135	285	302	323

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Table 4.–Page 3 of 3.

	Deployment information						Location	Distance (km)[a]			Rate (km/d)[a]			Direction (°)[a]		
Tag	Area	Deployed	Tag surfaced	Days	CW (mm)	Shell	category	Min	Est	Max	Min	Est	Max	Min	Est	Max
124	3	08/29/2019	01/02/2020	126	132	Old	1	0.0	2.2	5.6	0.000	0.018	0.044	0	351	359
141	3	08/30/2019	01/17/2020	140	143	New	1	62.6	67.6	73.0	0.448	0.484	0.522	127	131	135
125	3	08/29/2019	01/17/2020	140	149	Old	1	7.3	9.9	13.1	0.052	0.071	0.093	312	347	24
136	3	08/29/2019	01/17/2020	141	135	New	1	21.2	24.9	28.7	0.151	0.177	0.204	177	188	200
152	4	09/01/2019	12/02/2019	91	135	Old	2	0.0	5.1	12.3	0.000	0.056	0.135	0	191	359
148	4	09/01/2019	12/17/2019	107	134	Old	1	6.8	10.1	13.5	0.063	0.095	0.127	281	294	310
161	5	09/02/2019	12/02/2019	91	136	New	1	0.0	3.1	9.9	0.000	0.034	0.110	0	262	359
163	5	09/02/2019	12/17/2019	105	146	Very-old	1	0.0	2.1	5.4	0.000	0.020	0.051	0	74	359
155	5	09/02/2019	12/17/2019	106	140	Old	1	0.3	3.4	7.0	0.003	0.032	0.066	156	247	286
159	5	09/02/2019	01/02/2020	122	140	Old	2	7.9	13.6	19.5	0.065	0.112	0.161	328	10	53
156	5	09/02/2019	01/17/2020	137	139	New	2	9.5	14.8	24.6	0.070	0.108	0.180	147	202	245
158	5	09/02/2019	01/17/2020	137	135	New	2	10.7	14.6	21.5	0.078	0.107	0.157	334	17	46

Note: CW = carapace width.

Note: Location categories are defined as:

1) tag with surface drift prior to first high-quality location (t_1) < 24 h and semi-major axis length of buffered composite error ellipse ($\|S_M\|$) < 8.35 km

2) t_1 < 48 h and 8.35 km < $\|S_M\|$ < 16.7 km

[a] Min and max refer to the most extreme values of a plausible range determined by the buffered composite error ellipse associated with estimated pop-up location.

[b] Data for crab not included in analysis of movement rates and directions.

Table 5.–Movement information on Tanner crab tagged with MiniPAT satellite tags with category 1 or 2 pop-up locations.

Deployment information							Location	Distance (km)[a]			Rate (km/d)[a]			Direction (°)[a]		
Tag	Area	Deployed	Tag surfaced	Days	CW (mm)	Shell	category	Min	Est	Max	Min	Est	Max	Min	Est	Max
95	1	08/26/2019	12/01/2019	97	144	Old	1	3.6	5.7	8.9	0.037	0.058	0.092	160	208	235
75	1	08/26/2019	12/01/2019	97	156	Old	2	0.0	5.1	15.4	0.000	0.052	0.158	0	94	359
58	1	08/25/2019	12/01/2019	98	147	Old	1	6.8	9.2	12.3	0.070	0.094	0.125	136	166	202
49	1	08/25/2019	12/01/2019	98	140	Old	1	0.3	3.5	8.6	0.003	0.035	0.087	94	150	249
83	1	08/26/2019	12/16/2019	112	133	Old	2	17.6	26.4	35.4	0.157	0.235	0.316	117	134	152
66	1	08/25/2019	12/16/2019	113	137	Old	1	10.5	12.1	13.7	0.093	0.107	0.121	186	197	208
52	1	08/25/2019	12/16/2019	113	145	Old	1	4.1	6.5	9.1	0.036	0.057	0.080	230	247	257
28	1	08/24/2019	12/16/2019	114	144	Old	1	3.0	4.9	7.0	0.026	0.043	0.061	202	229	248
81[b]	1	08/26/2019	04/01/2020	219	130	New	1	228.9	234.7	242.2	1.044	1.071	1.105	84	84	85
116	2	08/28/2019	12/01/2019	95	140	New	1	21.1	23.0	25.0	0.222	0.242	0.263	308	313	317
103	2	08/27/2019	12/16/2019	111	159	Old	1	13.7	15.1	16.5	0.123	0.136	0.149	148	155	163
117	2	08/28/2019	01/01/2020	126	173	Old	1	0.0	2.9	8.5	0.000	0.023	0.067	0	23	359
112	2	08/28/2019	01/01/2020	126	163	Old	1	10.3	15.2	20.8	0.082	0.121	0.165	320	341	9
105	2	08/27/2019	01/16/2020	142	137	Old	1	15.2	20.4	26.3	0.107	0.144	0.185	123	136	154
142	3	08/30/2019	12/01/2019	93	152	Old	1	12.8	15.5	18.8	0.138	0.166	0.202	147	162	180
123	3	08/29/2019	12/01/2019	94	147	Old	1	0.2	2.6	6.4	0.002	0.027	0.068	130	250	286
131	3	08/29/2019	12/16/2019	109	134	New	1	61.8	64.8	68.0	0.567	0.594	0.624	340	343	347
138	3	08/30/2019	01/01/2020	124	150	Very-old	1	2.9	5.1	7.4	0.023	0.041	0.059	146	190	234
128	3	08/29/2019	01/01/2020	125	146	Old	1	0.6	6.9	13.6	0.005	0.055	0.109	179	260	305
133	3	08/29/2019	01/16/2020	140	141	New	1	10.9	13.8	17.0	0.078	0.099	0.121	175	185	198
149	4	09/01/2019	01/01/2020	122	143	New	1	9.6	16.7	23.9	0.078	0.137	0.196	297	321	349
162	5	09/02/2019	12/01/2019	90	137	Old	1	2.0	3.4	4.9	0.023	0.038	0.054	101	121	149
164	5	09/02/2019	01/16/2020	136	146	Very-old	2	3.3	15.3	28.8	0.024	0.112	0.212	81	107	173

Note: CW = carapace width.

Note: Location categories are defined as:

1) tag with surface drift prior to first high-quality location (t_1) < 24 h and semi-major axis length of buffered composite error ellipse ($\|S_M\|$) < 8.35 km

2) $t_1 < 48$ h and 8.35 km < $\|S_M\|$ < 16.7 km

[a] Min and max refer to the most extreme values of a plausible range determined by the buffered composite error ellipse associated with estimated pop-up location.

[b] Data for crab not included in analysis of movement rates and directions.

Table 6.–Movement information on Tanner crab tagged with mrPAT satellite tags that surfaced prior to their programmed release dates.

	Deployment information						Location				Buffered composite ellipse axes (km)	
Tag	Area	Deployed	Tag surfaced	Days	CW (mm)	Shell	category	Distance (km)	Rate (km/d)	Direction (°)	Semi-major	Semi-minor
51	1	08/25/2019	09/23/2019	29	150	Old	1	1.7	0.060	128	2.9	1.4
80	1	08/26/2019	10/15/2019	50	133	Old	3	28.8	0.572	190	25.3	21.9
65	1	08/25/2019	11/22/2019	89	142	Old	2	16.3	0.184	303	10.6	5.6
36	1	08/24/2019	01/03/2020	132	139	Old	3	30.1	0.229	305	15.7	9.6
109	2	08/27/2019	10/13/2019	47	137	Old	2	21.9	0.463	216	16.1	11.6
108	2	08/27/2019	10/14/2019	48	148	Old	1	2.2	0.046	220	8.2	6.5
110	2	08/28/2019	10/20/2019	53	143	Old	2	18.3	0.344	118	9.4	8.4
130	3	08/29/2019	09/04/2019	6	129	New	1	1.8	0.287	347	4.2	2.8
135	3	08/29/2019	09/12/2019	13	153	Old	1	3.7	0.274	115	2.5	1.6
146	4	09/01/2019	11/26/2019	85	161	Old	2	11.7	0.137	293	9.8	8.0

Note: CW = carapace width.

Note: Location categories are defined as:

1) tag with surface drift prior to first high-quality location (t_1) < 24 h and semi-major axis length of buffered composite error ellipse ($||S_M||$) < 8.35 km

2) t_1 < 48 h and 8.35 km < $||S_M||$ < 16.7 km

3) t_1 > 48 h or $||S_M||$ > 16.7 km

Table 7.–Movement information on Tanner crab tagged with spaghetti tags.

	Deployment information						Release location			Recovery location			Distance	Rate	Direction
Tag	Area	Deployed	Recovered	Days	CW (mm)	Shell	Lat	Long	Depth (m)	Lat	Long	Depth (m)	(km)	(km/d)	(°)
1987	1	08/26/2019	03/20/2020	207	128	Old	57.12	-169.34	69	56.75	-168.39	99	70.4	0.340	125
2124	2	08/28/2019	02/03/2020	159	140	Old	56.70	-168.83	100	56.41	-168.51	ND	37.8	0.238	148
2293	2	08/28/2019	02/17/2020	173	136	Old	56.75	-168.72	99	56.69	-168.57	102	11.5	0.067	125
2198	2	08/28/2019	02/18/2020	174	140	Old	56.75	-168.72	99	56.67	-168.64	106	10.2	0.059	150
2237	2	08/28/2019	02/28/2020	184	146	Old	56.81	-168.61	96	56.66	-168.68	110	17.0	0.092	194
2189	2	08/28/2019	02/28/2020	184	142	Very-old	56.74	-168.74	99	56.62	-168.68	110	13.9	0.075	164
2250	2	08/28/2019	03/01/2020	186	137	Old	56.81	-168.61	96	56.68	-168.63	104	14.6	0.078	183
2053	2	08/28/2019	03/02/2020	187	139	Old	56.66	-168.90	99	56.68	-168.60	106	18.2	0.097	86
2178	2	08/28/2019	03/02/2020	187	128	Old	56.73	-168.77	99	56.72	-168.58	106	11.5	0.061	97
2247	2	08/28/2019	03/05/2020	190	138	Old	56.81	-168.61	96	56.70	-168.60	106	12.0	0.063	175
2244	2	08/28/2019	03/10/2020	195	140	Old	56.81	-168.61	96	56.67	-168.47	106	18.1	0.093	150
2296	2	08/28/2019	03/14/2020	199	139	Old	56.75	-168.72	99	56.74	-168.49	99	14.1	0.071	98
2055	2	08/28/2019	03/20/2020	205	136	Old	56.66	-168.90	99	56.59	-168.48	110	27.0	0.132	108
2245	2	08/28/2019	03/20/2020	205	146	Old	56.81	-168.61	96	56.78	-168.12	99	30.3	0.148	96
2076	2	08/28/2019	04/02/2020	218	131	Old	56.66	-168.90	99	56.75	-168.22	101	42.8	0.196	77
2151	2	08/28/2019	04/02/2020	218	132	Old	56.71	-168.81	100	56.75	-168.27	101	33.5	0.154	82
2265	2	08/28/2019	04/02/2020	218	131	Old	56.79	-168.66	97	56.75	-168.38	99	17.5	0.080	102
2473	3	08/30/2019	01/28/2020	151	144	Old	56.54	-168.62	109	56.64	-168.53	ND	12.7	0.084	28
2422	3	08/30/2019	01/30/2020	153	149	Old	56.65	-168.40	106	56.63	-168.51	110	6.9	0.045	254
2353	3	08/29/2019	01/30/2020	154	142	Old	56.57	-168.64	109	56.60	-168.46	112	12.0	0.078	73
2427	3	08/30/2019	02/02/2020	156	127	Old	56.63	-168.44	109	56.47	-168.53	115	18.0	0.116	198
2368	3	08/29/2019	02/03/2020	158	138	New	56.60	-168.57	110	56.41	-168.52	ND	21.7	0.137	171
2355	3	08/29/2019	02/03/2020	158	137	Old	56.62	-168.55	110	56.59	-168.69	113	8.9	0.056	251
2410	3	08/30/2019	02/04/2020	158	131	Old	56.68	-168.34	105	56.66	-168.35	110	1.6	0.010	204
2333	3	08/29/2019	02/03/2020	158	137	Very-old	56.64	-168.51	108	56.66	-168.51	108	1.9	0.012	358

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Table 7.–Page 2 of 3.

	Deployment information						Release location			Recovery location			Distance	Rate	Direction
Tag	Area	Deployed	Recovered	Days	CW (mm)	Shell	Lat	Long	Depth (m)	Lat	Long	Depth (m)	(km)	(km/d)	(°)
2442	3	08/30/2019	02/05/2020	159	150	New	56.61	-168.48	110	56.51	-168.60	106	13.0	0.082	215
2319	3	08/29/2019	02/04/2020	159	131	Old	56.67	-168.44	104	56.60	-168.38	110	9.1	0.057	158
2334	3	08/29/2019	02/04/2020	159	129	Old	56.64	-168.51	108	56.51	-168.46	114	14.4	0.090	169
2364	3	08/29/2019	02/04/2020	159	138	Old	56.60	-168.57	110	56.57	-168.74	110	11.2	0.070	248
2365	3	08/29/2019	02/04/2020	159	148	Old	56.60	-168.57	110	56.59	-168.67	110	6.2	0.039	256
2371	3	08/29/2019	02/04/2020	159	130	Old	56.60	-168.57	110	56.55	-168.67	110	8.8	0.055	222
2383	3	08/29/2019	02/04/2020	159	128	Old	56.57	-168.64	109	56.53	-168.65	108	4.3	0.027	184
2451	3	08/30/2019	02/05/2020	159	127	Old	56.59	-168.52	110	56.53	-168.53	106	6.0	0.038	186
2339	3	08/29/2019	02/04/2020	159	149	Very-old	56.63	-168.53	109	56.58	-168.43	112	8.4	0.053	133
2363	3	08/29/2019	02/05/2020	160	142	New	56.60	-168.57	110	56.58	-168.53	110	4.2	0.026	141
2325	3	08/29/2019	02/05/2020	160	133	Old	56.65	-168.48	106	56.47	-168.63	110	21.7	0.136	205
2336	3	08/29/2019	02/05/2020	160	131	Old	56.64	-168.51	108	56.63	-168.50	110	0.8	0.005	171
2392	3	08/29/2019	02/05/2020	160	146	Old	56.56	-168.67	107	56.51	-168.60	106	6.8	0.043	145
2349	3	08/29/2019	02/06/2020	161	141	Old	56.63	-168.53	109	56.66	-168.44	106	6.7	0.041	54
2357	3	08/29/2019	02/06/2020	161	140	Old	56.62	-168.55	110	56.63	-168.44	110	6.9	0.043	74
2335	3	08/29/2019	02/12/2020	167	125	Old	56.64	-168.51	108	56.61	-168.44	110	5.2	0.031	131
2317	3	08/29/2019	02/13/2020	168	135	Old	56.71	-168.37	103	56.62	-168.37	110	9.9	0.059	179
2381	3	08/29/2019	02/13/2020	168	130	Old	56.59	-168.60	110	56.55	-168.49	112	8.1	0.048	127
2415	3	08/30/2019	02/14/2020	168	132	Old	56.66	-168.36	104	56.61	-168.26	108	8.4	0.050	136
2361	3	08/29/2019	02/14/2020	169	135	Old	56.62	-168.55	110	56.67	-168.47	108	7.5	0.044	42
2348	3	08/29/2019	02/15/2020	170	146	Old	56.63	-168.53	109	56.58	-168.51	112	5.6	0.033	169
2420	3	08/30/2019	02/17/2020	171	126	Old	56.66	-168.36	104	56.64	-168.64	110	17.6	0.103	260
2328	3	08/29/2019	02/16/2020	171	137	Very-old	56.64	-168.51	108	56.67	-168.62	106	7.7	0.045	298
2338	3	08/29/2019	02/16/2020	171	139	Very-old	56.63	-168.53	109	56.64	-168.47	108	4.0	0.024	72
2401	3	08/30/2019	02/22/2020	176	133	Old	56.72	-168.24	103	56.67	-168.34	106	8.9	0.051	227

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Table 7.–Page 3 of 3.

	Deployment information						Release location			Recovery location			Distance	Rate	Direction
Tag	Area	Deployed	Recovered	Days	CW (mm)	Shell	Lat	Long	Depth (m)	Lat	Long	Depth (m)	(km)	(km/d)	(°)
2408	3	08/30/2019	02/22/2020	176	129	Old	56.68	-168.34	105	56.67	-168.34	106	0.6	0.003	206
2480	3	08/30/2019	02/24/2020	178	127	Old	56.54	-168.62	109	56.55	-168.62	110	2.1	0.012	7
2475	3	08/30/2019	02/25/2020	179	140	Old	56.54	-168.62	109	56.60	-168.69	110	8.6	0.048	330
2388	3	08/29/2019	02/25/2020	180	143	New	56.56	-168.67	107	56.61	-168.68	110	5.7	0.031	352
2406	3	08/30/2019	02/26/2020	180	131	Old	56.69	-168.32	104	56.75	-168.18	102	11.1	0.062	48
2411	3	08/30/2019	03/06/2020	189	143	Very-old	56.66	-168.36	104	56.65	-168.50	108	8.6	0.045	260
2331	3	08/29/2019	03/06/2020	190	130	Old	56.64	-168.51	108	56.73	-168.52	106	10.3	0.054	356
2345	3	08/29/2019	03/11/2020	195	134	Old	56.63	-168.53	109	56.72	-168.31	99	16.7	0.086	52
2748	5	09/02/2019	03/11/2020	191	128	New	57.36	-171.16	92	57.14	-171.14	98	24.9	0.131	177
2827	6[a]	09/03/2019	02/19/2020	169	141	Old	57.33	-171.46	99	57.42	-171.76	101	20.4	0.121	300

Note: CW = carapace width.

Note: Depths were not recorded for some recovery locations. ND = no data.

[a] Only spaghetti-tagged crab were released in area 6.

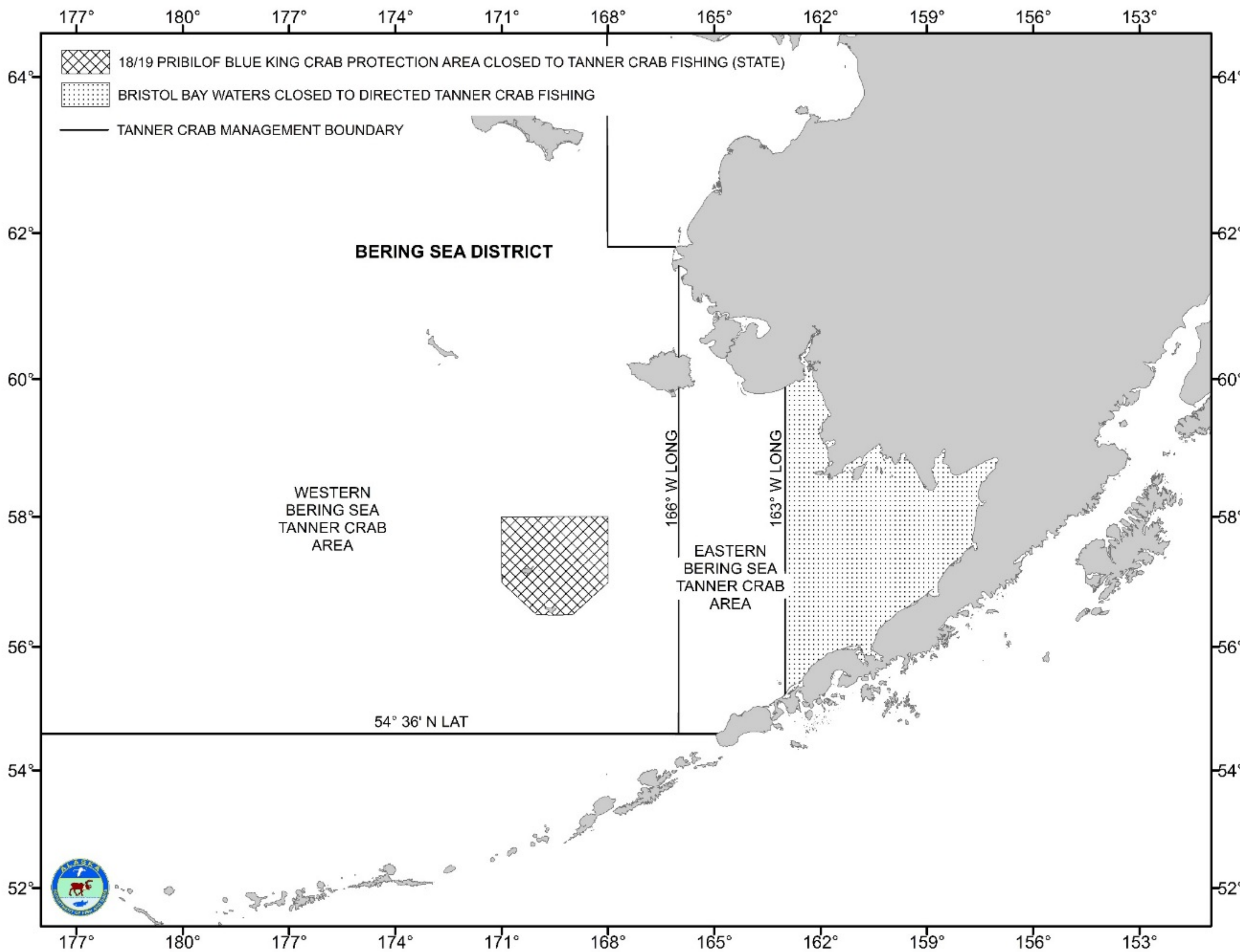


Figure 1.–Fishery areas and management boundaries for Bering Sea Tanner crab.

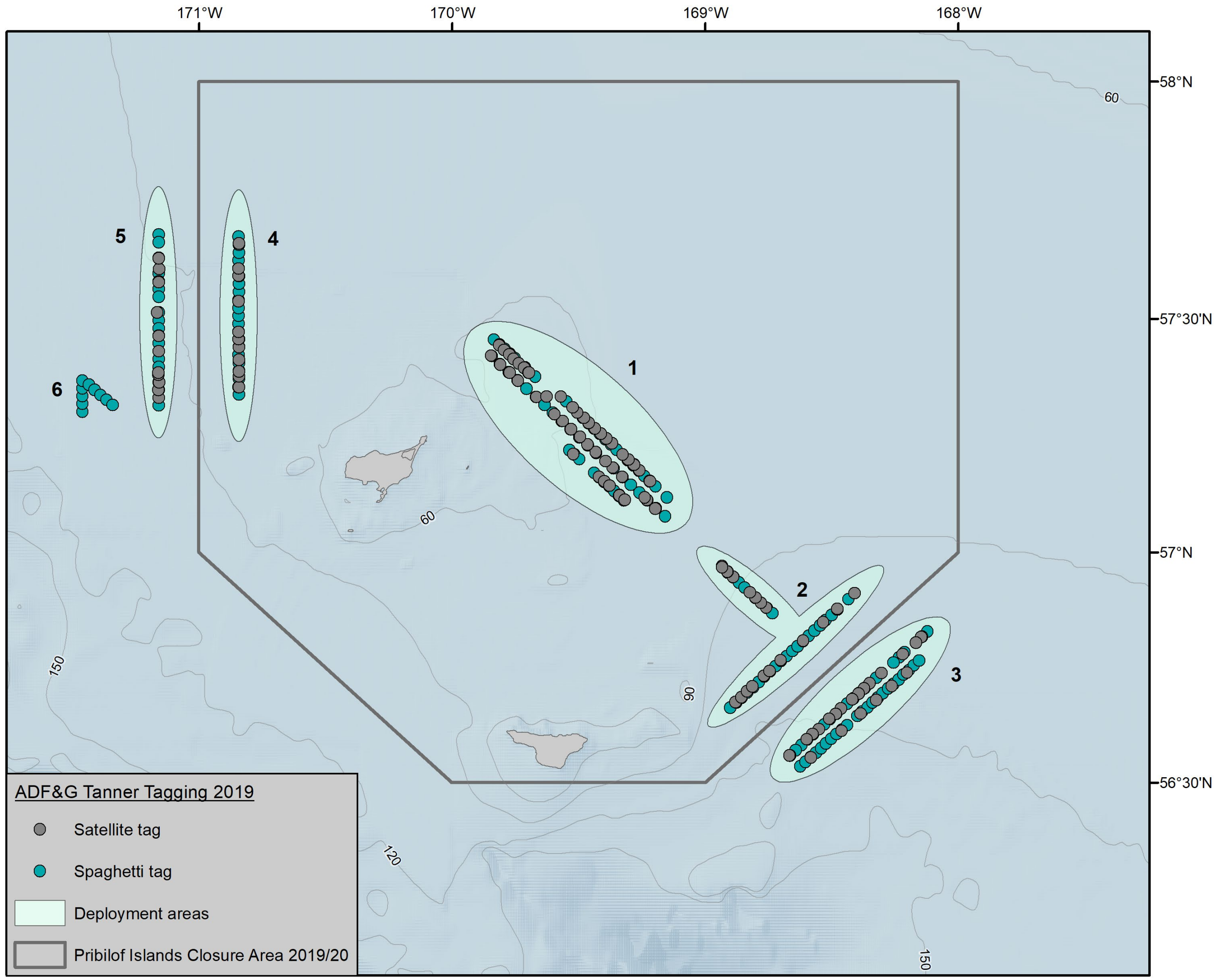
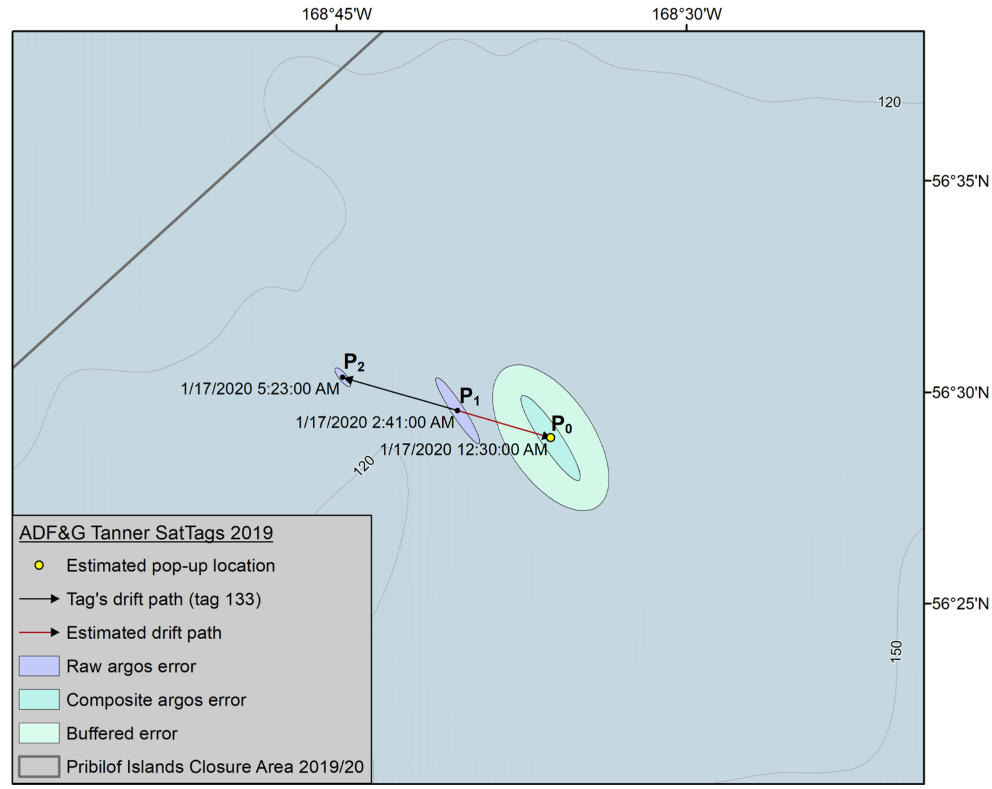


Figure 2.–Locations and areas where crab were captured, tagged, and released during the 2019 Bering Sea Tanner crab tagging study.



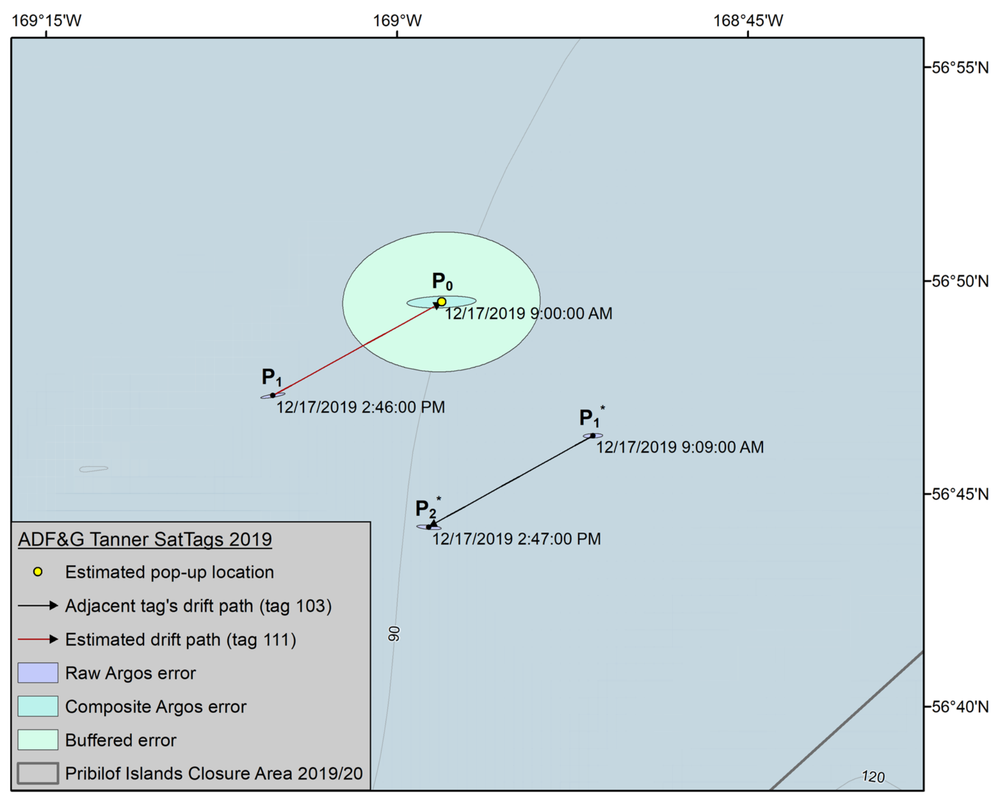


Figure 3.–Estimation of tag pop-up location based on the tag's subsequent drift (top) or using the drift of another spatiotemporally adjacent tag (bottom).

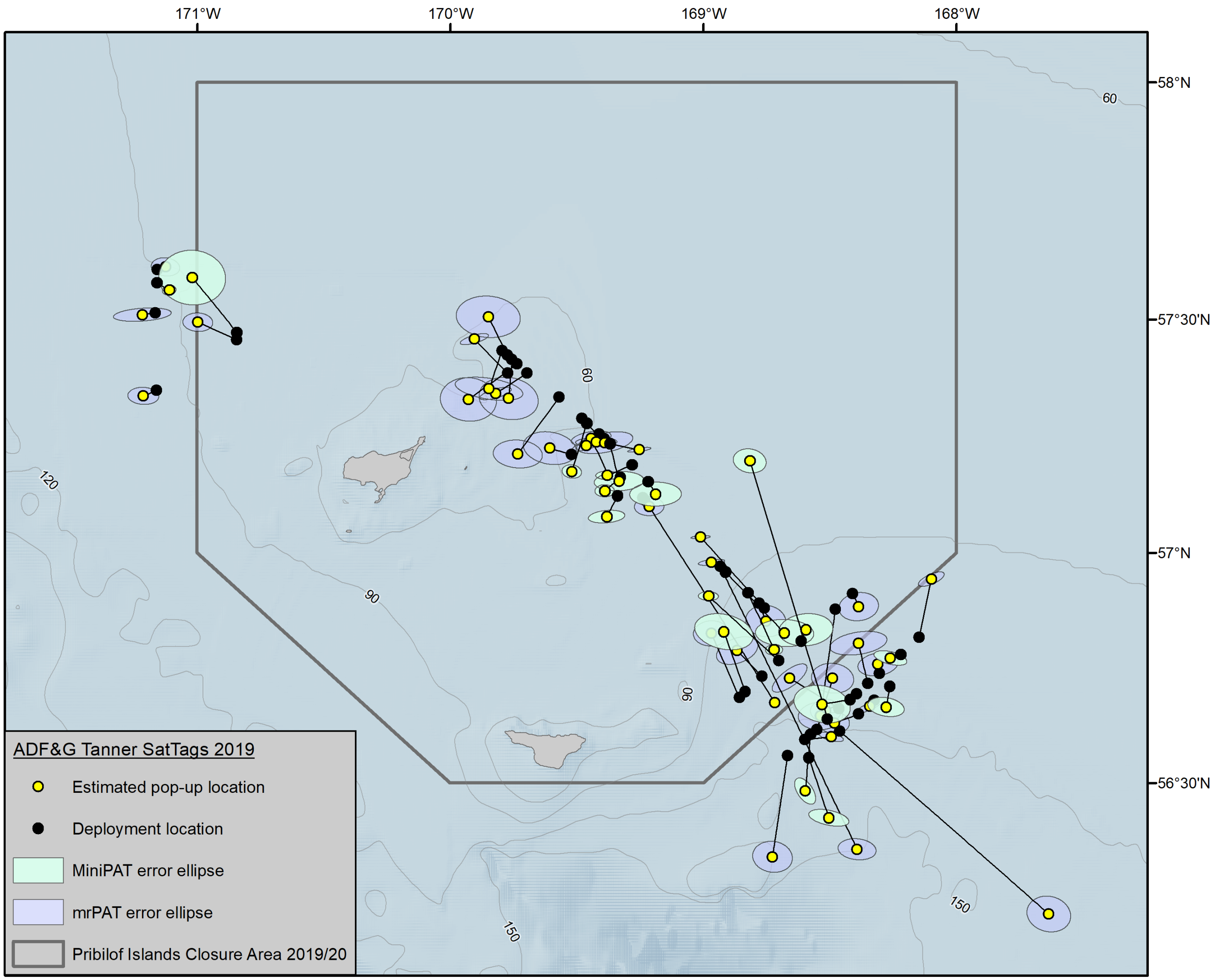


Figure 4.–Deployment and estimated pop-up locations of satellite tags deployed on Tanner crab for tags with category 1 locations.

Note: Category 1 locations are tags with surface drift <24 h and semi-major axis of buffered composite error ellipse <8.35 km.

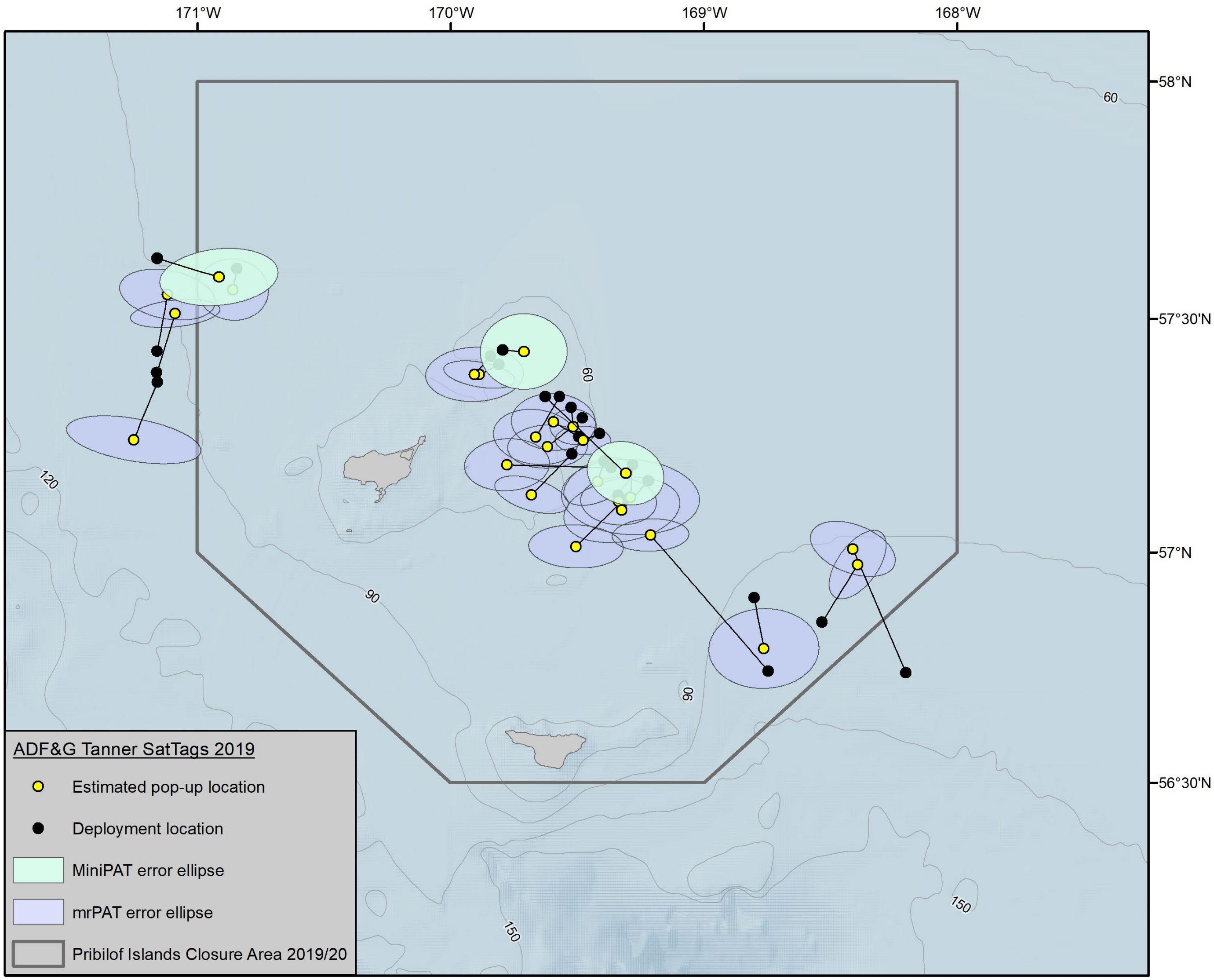


Figure 5.–Deployment and estimated pop-up locations of satellite tags deployed on Tanner crab for tags with category 2 locations.

Note: Category 2 locations are tags with surface drift <48 h and semi-major axis of buffered composite error ellipse in 8.35–16.7 km.

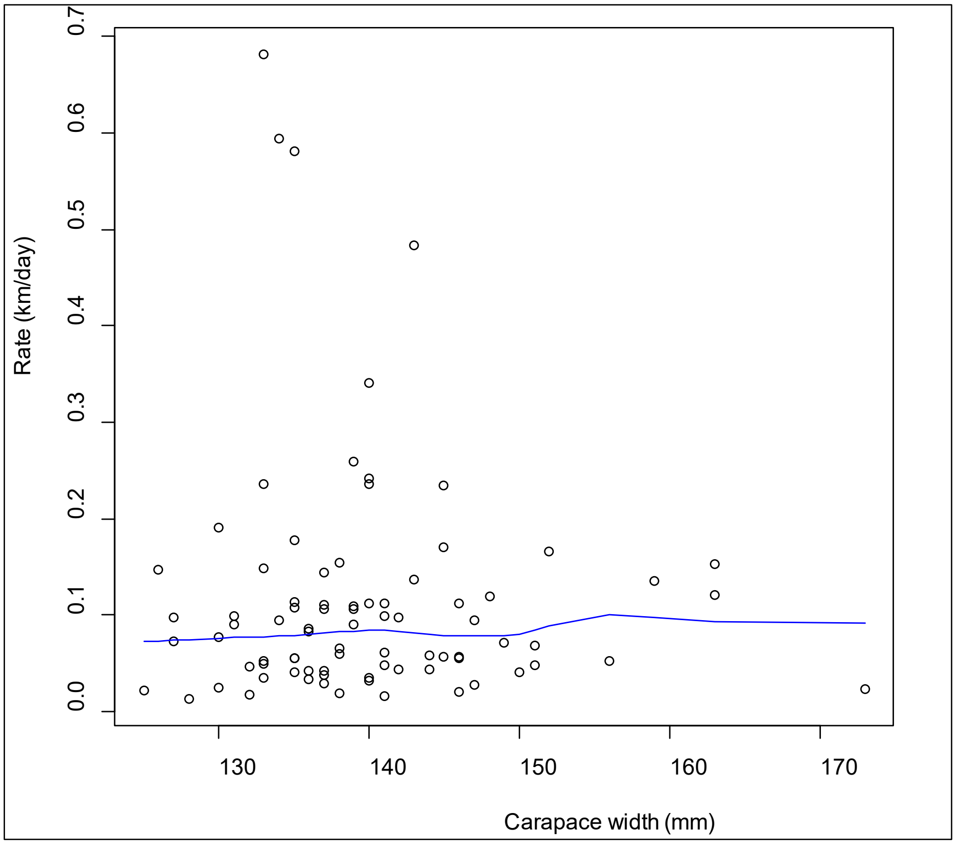
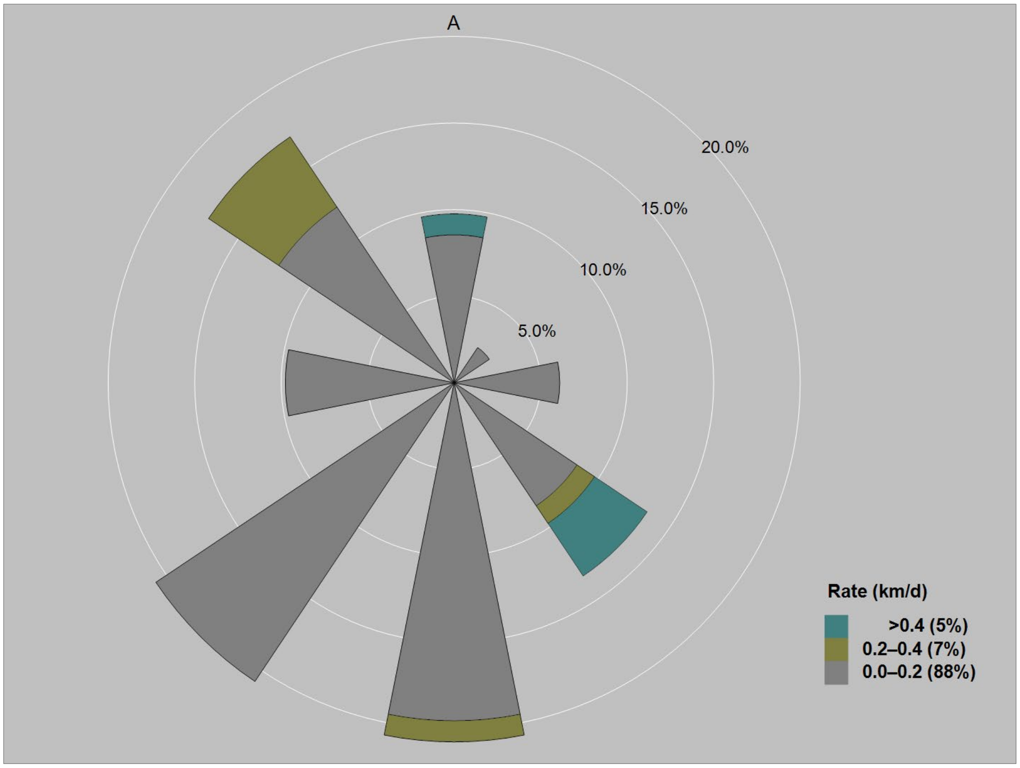


Figure 6.–Relationship between horizontal movement rate (km/d) of satellite-tagged crab (n = 82) and crab size, carapace width (mm).

Note: The blue line indicates LOWESS smoother.



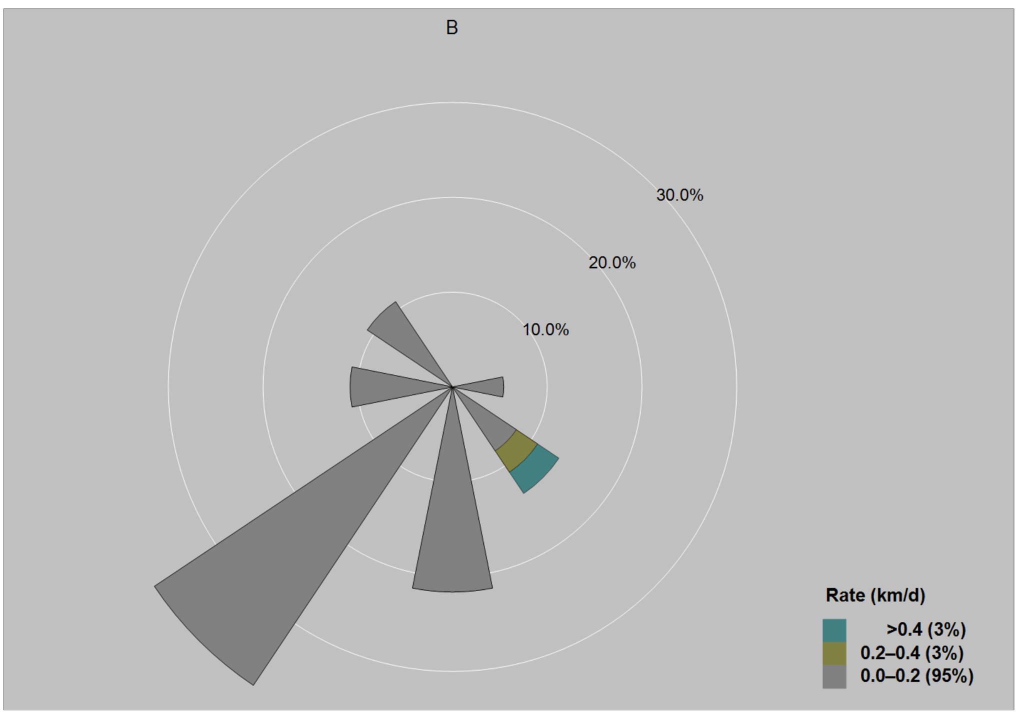


Figure 7.–Movement directions and rates (km/d) of satellite-tagged Tanner crab released at all deployment areas (A) and at the center of the PIBKCPA only (B).

Note: For crab tagged and released at all deployment areas (A) n = 82, mean time at liberty = 117 days. For crab tagged and released at the center of the PIBKCPA (area 1; B) n = 37, mean time at liberty = 119 days.

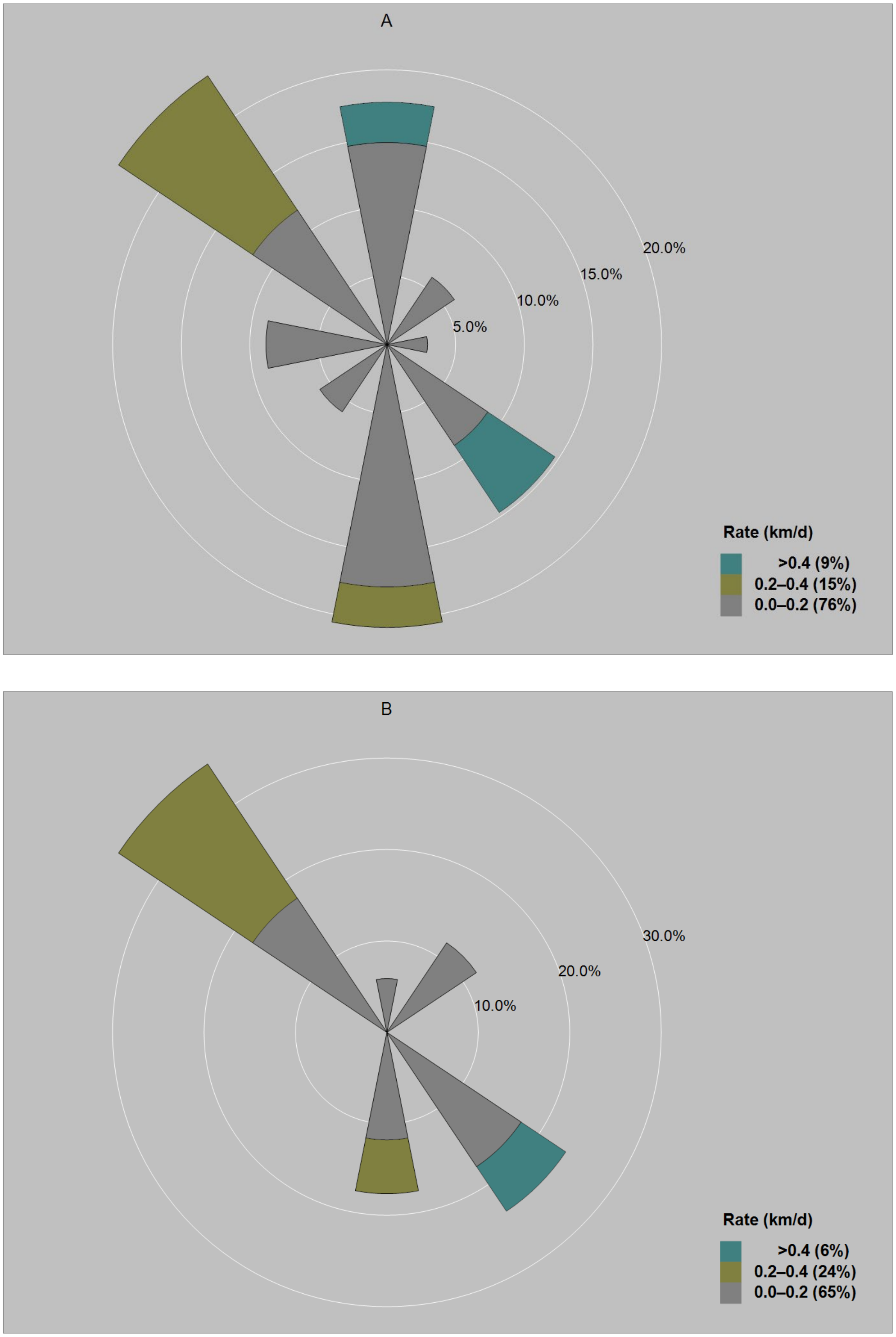


Figure 8.–Movement directions and rates (km/d) of satellite-tagged Tanner crab released inside and outside the southeast (SE) border of the PIBKCPA (A) and inside the SE border of the PIBKCPA only (B).

Note: For crab tagged and released inside and outside the SE border of the PIBKCPA (areas 2 and 3; A) n = 34, mean time at liberty = 117 days. For crab tagged and released inside the SE border of the PIBKCPA (area 2; B) n = 16, mean time at liberty = 117 days.

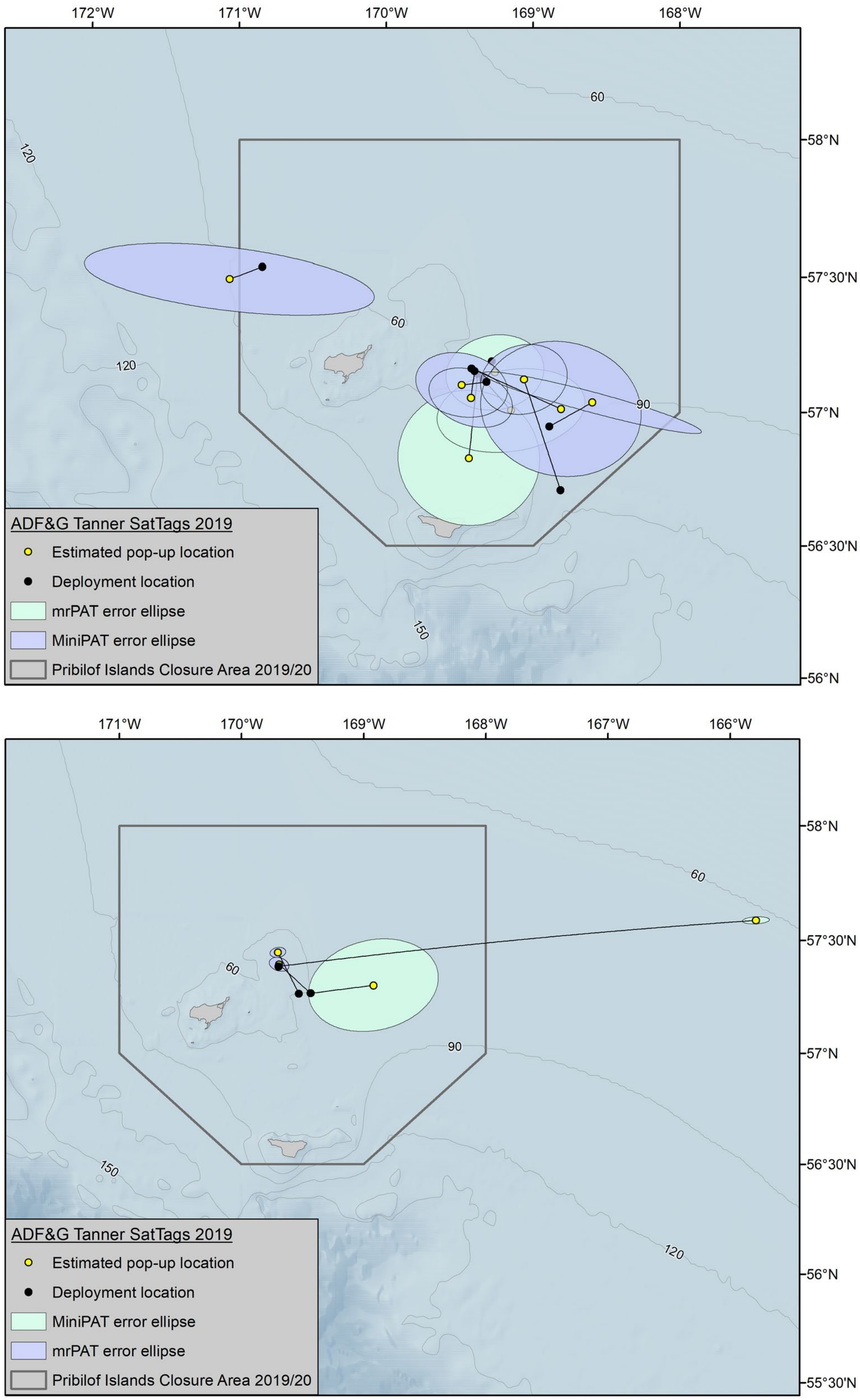


Figure 9.–Deployment and estimated pop-up locations of satellite tags deployed on Tanner crab for tags with category 3 pop-up locations (top) and for tags that were programmed to pop-up in early April 2020 (bottom).

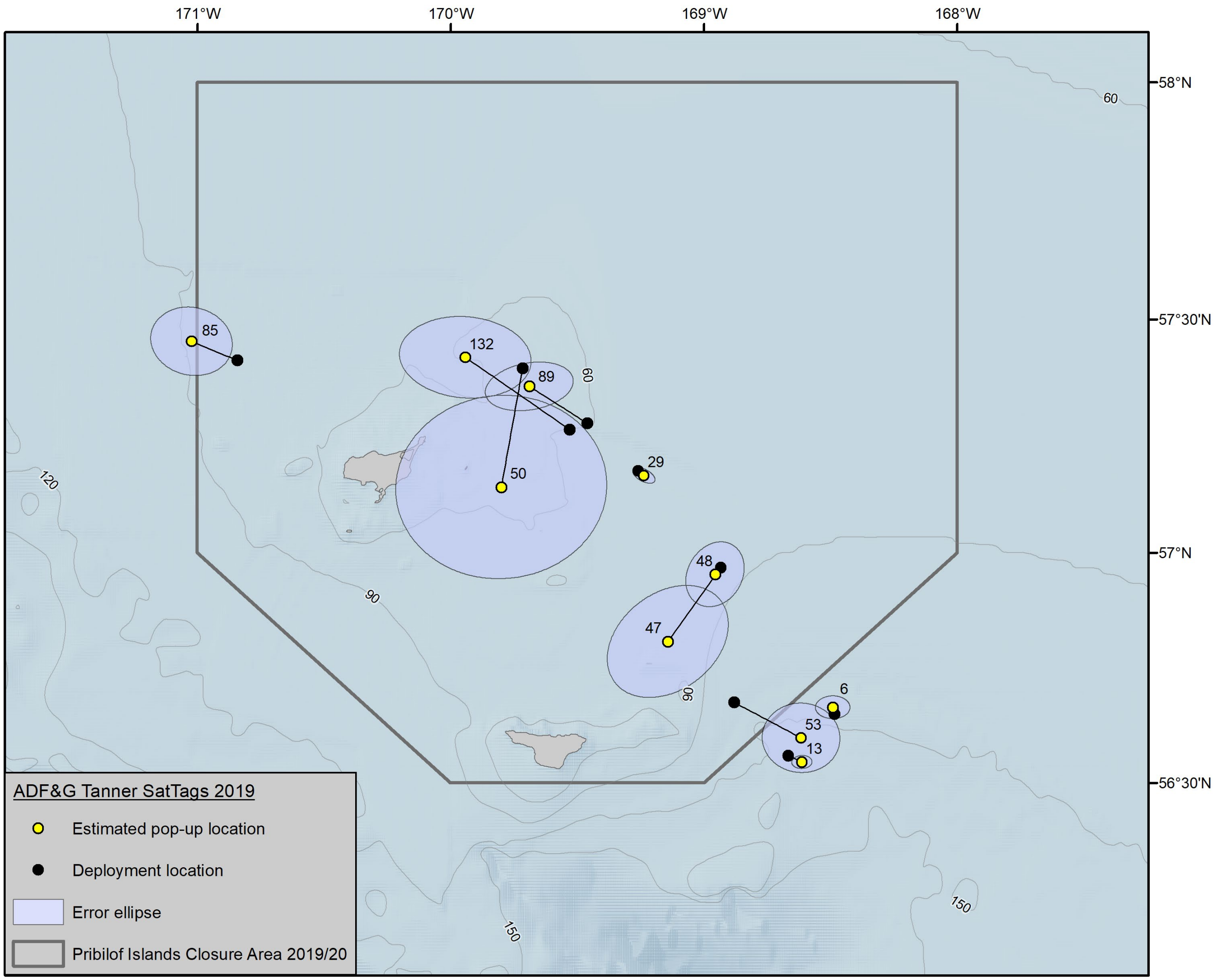


Figure 10.–Deployment and estimated pop-up locations of satellite tags deployed on Tanner crab for tags that surfaced prior to their programmed release dates.

Note: Bold numbers represent days at liberty before tag prematurely detached from crab.

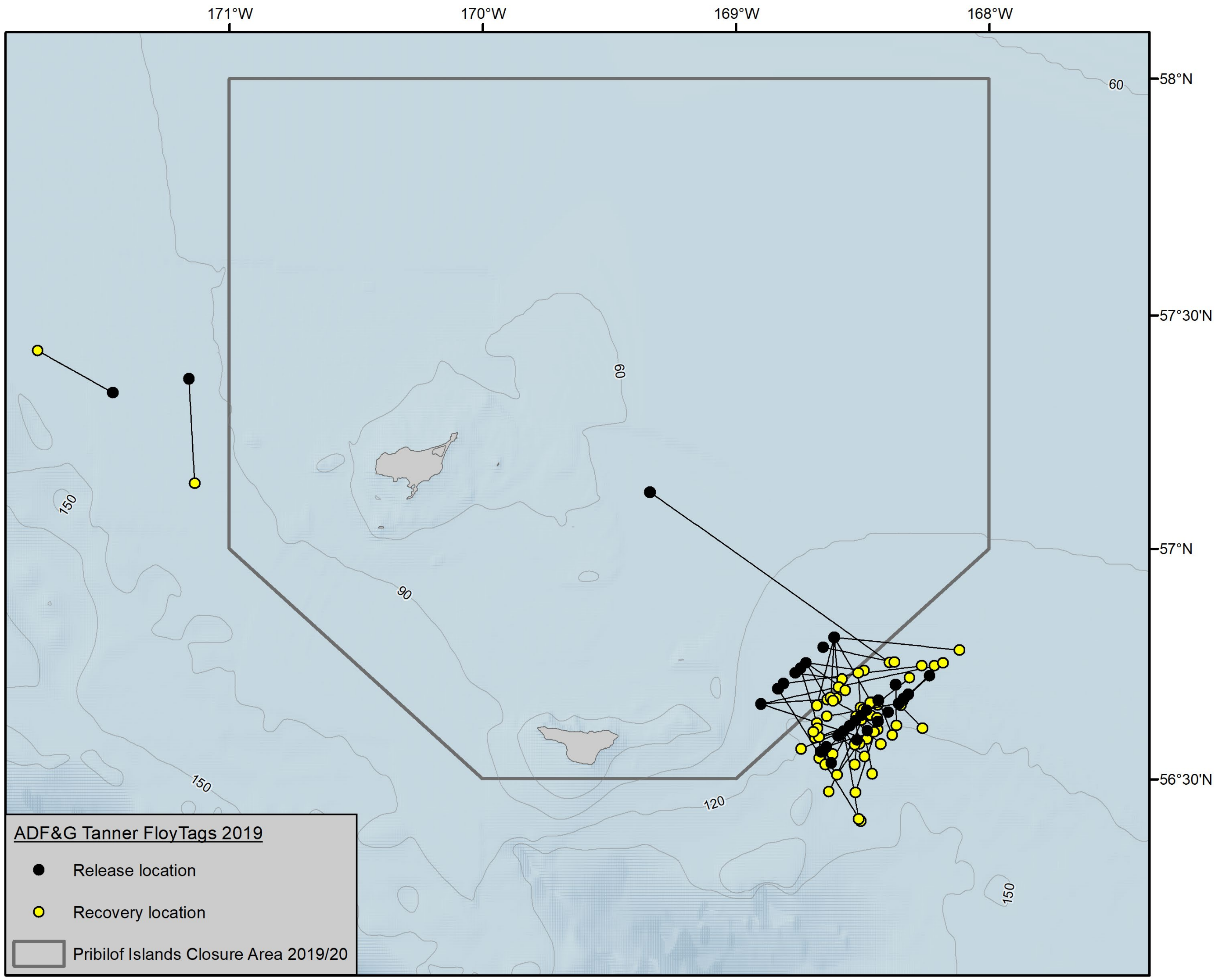


Figure 11.–Release and recovery locations of spaghetti-tagged Tanner crab re-captured as bycatch during the 2019/20 snow crab fishery (n = 60).

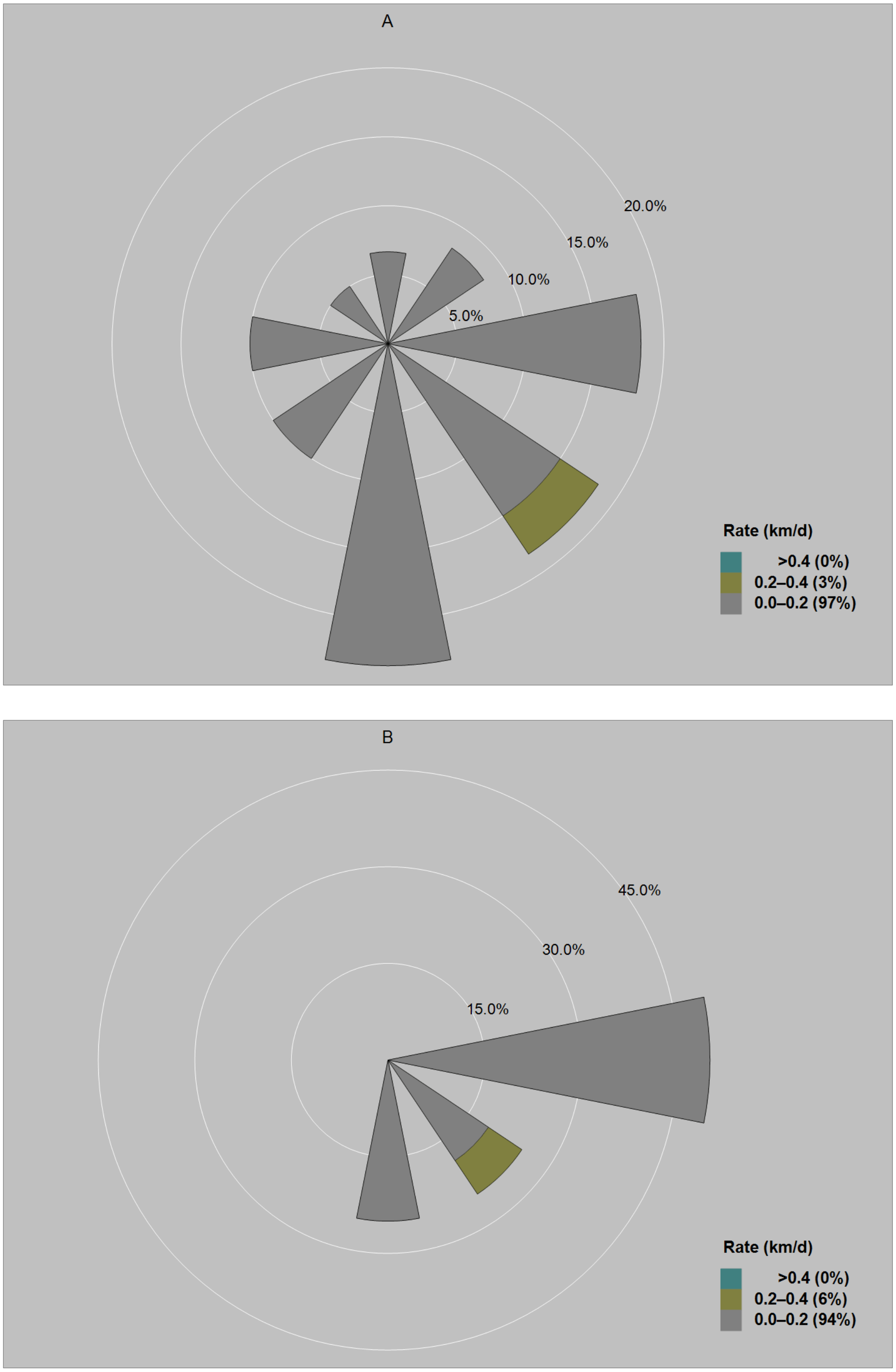


Figure 12.–Movement directions and rates (km/d) of spaghetti-tagged Tanner crab released at all tagging areas (A) and inside the southeast (SE) border of the PIBKCPA only (B).

Note: For crab tagged and released at all tagging areas (A) n = 60, mean time at liberty = 174 days. For crab tagged and released inside the SE border of the PIBKCPA (area 2; B) n = 16, mean time at liberty = 193 days.

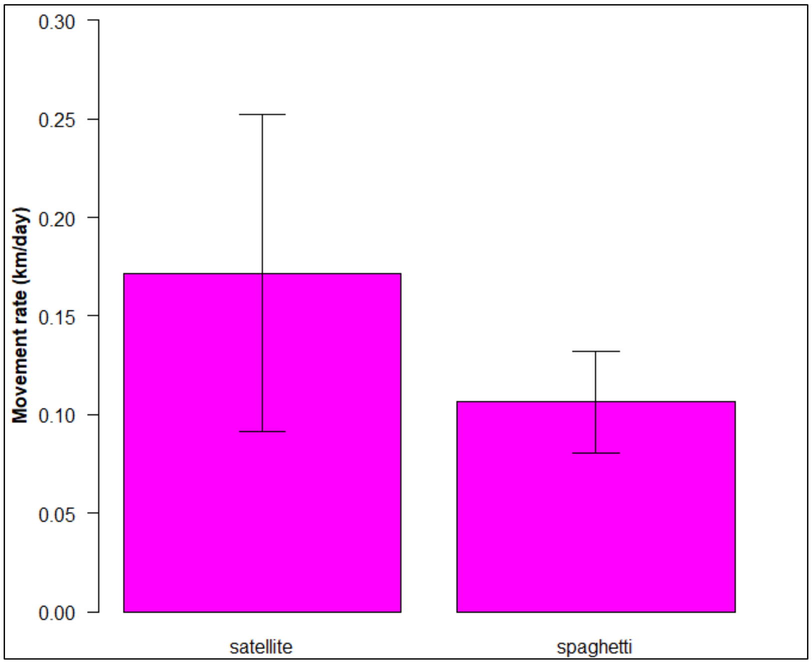


Figure 13.–Average (±95% CI) horizontal movement rate (km/d) of Tanner crab by tag type.

Note: Data included in the comparison shown here are from crab tagged and released inside the SE border of the PIBKCPA only (n = 16 each for both tag types; see Figures 8B and 12B).

APPENDIX A. DETATILS ON SATELLITE TAG DEPLOYMENTS

Appendix A1.–Details on satellite tags deployed during the 2019 Bering Sea Tanner crab tagging study with category 1–3 pop-up locations.

			Deployment information				First HQ location		Pre-location drift parameters[a]			Est. pop-up location			Buffered composite error ellipse[b]		
Tag	Type	Anti foul	Area	Days	Lat	Long	Lat	Long	Time (h)	Distance (km)	Direction (°)	Lat	Long	Loc. cat.	$\lVert S_M \rVert$ (km)	$\lVert S_m \rVert$ (km)	$\angle S_M$ (°)
93	mrPAT	Y	1	97	57.123	-169.339	57.227	-169.449	5.4	2.1	191	57.246	-169.443	1	4.8	1.6	81
82	mrPAT	Y	1	98	57.385	-169.697	57.325	-169.827	4.9	1.9	191	57.341	-169.821	1	3.9	1.0	74
76	mrPAT	N	1	98	57.433	-169.796	57.401	-169.814	5.3	5.8	19	57.351	-169.846	1	8.1	2.5	99
62	mrPAT	Y	1	98	57.255	-169.411	57.218	-169.467	3.5	1.4	191	57.230	-169.462	1	3.5	0.9	74
70	mrPAT	N	1	99	57.311	-169.523	57.329	-169.359	30.8	11.5	55	57.269	-169.515	2	5.6	4.2	96
43	mrPAT	Y	1	99	57.385	-169.773	57.443	-169.910	4.2	1.6	191	57.457	-169.904	1	3.5	0.9	74
26	mrPAT	Y	1	100	57.113	-169.231	56.675	-168.717	0.4	–	–	56.675	-168.717	1	0.8	0.3	136
96	mrPAT	Y	1	112	57.122	-169.338	57.020	-169.488	19.9	13.6	222	57.109	-169.336	2	9.1	5.6	93
77	mrPAT	Y	1	113	57.423	-169.774	57.464	-170.069	10.2	13.9	251	57.505	-169.849	1	7.6	4.9	95
84	mrPAT	N	1	113	57.211	-169.521	57.308	-169.657	9.0	9.8	342	57.224	-169.606	1	6.4	3.8	100
71	mrPAT	N	1	113	57.334	-169.570	57.283	-169.778	7.5	8.3	341	57.212	-169.733	1	5.9	3.3	94
44	mrPAT	Y	1	114	57.402	-169.808	57.387	-170.015	10.1	7.8	275	57.381	-169.886	2	8.6	2.9	100
27	mrPAT	Y	1	115	57.118	-169.238	57.125	-169.296	3.6	5.8	300	57.099	-169.213	1	3.5	2.2	89
97	mrPAT	Y	1	128	57.113	-169.317	56.792	-169.243	42.6	37.4	157	57.101	-169.486	3	19.2	13.0	103
88	mrPAT	N	1	129	57.153	-169.398	56.769	-169.306	32.0	32.5	167	57.054	-169.424	3	17.9	11.4	110
85	mrPAT	Y	1	129	57.211	-169.521	57.033	-169.656	6.3	10.2	172	57.124	-169.680	2	9.1	3.8	107
78	mrPAT	N	1	129	57.414	-169.756	57.220	-169.747	6.5	12.4	174	57.331	-169.769	1	7.1	5.0	100
72	mrPAT	N	1	129	57.334	-169.570	57.094	-169.628	9.6	17.2	173	57.247	-169.663	2	10.2	6.5	98
67	mrPAT	Y	1	129	57.288	-169.479	57.109	-169.594	6.8	13.1	174	57.227	-169.617	2	9.5	5.2	88
55	mrPAT	N	1	130	57.188	-169.281	56.898	-169.165	22.3	25.6	163	57.118	-169.290	2	16.5	9.0	93
60	mrPAT	Y	1	130	57.244	-169.390	57.225	-169.436	1.4	1.6	211	57.238	-169.422	1	5.0	1.1	89
45	mrPAT	Y	1	130	57.420	-169.843	57.239	-169.873	8.9	15.9	173	57.381	-169.905	2	11.6	6.4	88
35	mrPAT	N	1	131	57.248	-169.494	57.121	-169.558	9.9	17.7	173	57.280	-169.594	2	10.0	6.8	93
29	mrPAT	Y	1	131	57.181	-169.365	57.045	-169.749	8.3	16.0	174	57.188	-169.777	2	10.2	6.2	87
98	mrPAT	Y	1	143	57.113	-169.317	57.099	-169.672	11.7	14.0	314	57.012	-169.505	2	11.3	5.2	92

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									Pre-location drift parameters[a]						Buffered composite error ellipse[b]		
		Anti	Deployment information				First HQ location		Time	Distance	Direction	Est. pop-up location		Loc.	$\|\|S_M\|\|$	$\|\|S_m\|\|$	$\angle S_M$
Tag	Type	foul	Area	Days	Lat	Long	Lat	Long	(h)	(km)	(°)	Lat	Long	cat.	(km)	(km)	(°)
79	mrPAT	Y	1	144	57.405	-169.736	57.414	-170.101	9.1	14.0	312	57.329	-169.928	1	6.7	5.2	96
68	mrPAT	Y	1	144	57.288	-169.479	57.260	-169.475	5.7	5.8	297	57.236	-169.389	1	6.8	2.3	79
48	mrPAT	Y	1	145	57.153	-169.219	57.159	-169.657	20.5	21.5	291	57.091	-169.324	2	14.0	7.5	80
59	mrPAT	N	1	145	57.234	-169.369	57.221	-169.252	0.5	–	–	57.221	-169.252	1	2.8	0.4	82
30	mrPAT	Y	1	146	57.196	-169.394	57.205	-169.603	15.5	12.6	298	57.152	-169.419	2	8.7	4.7	64
61	mrPAT	Y	1	146	57.255	-169.411	57.199	-169.474	28.6	4.6	178	57.240	-169.476	2	6.7	3.4	92
86	mrPAT	N	1	155	57.162	-169.419	57.041	-169.481	52.0	40.8	274	57.012	-168.810	3	33.4	27.7	102
64	mrPAT	Y	1	221	57.266	-169.434	57.430	-169.671	9.4	4.2	17	57.394	-169.692	1	5.0	3.2	108
37	mrPAT	N	1	222	57.264	-169.529	57.457	-169.673	6.6	2.1	56	57.447	-169.702	1	3.9	2.4	81
118	mrPAT	Y	2	95	56.849	-168.533	56.999	-168.193	16.4	12.4	77	56.973	-168.392	2	9.5	4.8	36
106	mrPAT	N	2	96	56.958	-168.911	56.977	-168.952	6.6	0.9	100	56.979	-168.967	1	3.2	0.7	84
99	mrPAT	Y	2	97	56.880	-168.758	57.033	-169.011	0.1	–	–	57.033	-169.011	1	2.3	0.4	87
119	mrPAT	N	2	110	56.877	-168.478	56.663	-168.682	4.7	9.1	282	56.646	-168.537	1	5.4	3.4	87
111	mrPAT	Y	2	111	56.686	-168.857	56.789	-169.088	5.8	8.4	241	56.825	-168.968	1	4.3	3.0	88
107	mrPAT	N	2	111	56.970	-168.933	56.324	-168.489	4.7	6.9	241	56.355	-168.392	1	4.7	2.6	96
100	mrPAT	Y	2	112	56.890	-168.779	56.827	-168.920	7.4	10.6	255	56.852	-168.752	1	4.9	3.8	98
113	mrPAT	N	2	126	56.709	-168.814	56.792	-168.739	96.8	41.6	152	57.122	-169.062	3	18.1	14.2	75
115	mrPAT	Y	2	126	56.743	-168.745	56.945	-169.209	7.1	10.3	179	57.037	-169.210	2	9.2	3.9	88
102	mrPAT	Y	2	127	56.902	-168.801	56.555	-168.609	31.9	28.0	161	56.792	-168.762	2	13.3	9.6	88
120	mrPAT	Y	2	141	56.911	-168.409	56.929	-168.516	4.7	9.4	303	56.883	-168.385	1	4.8	3.4	82
114	mrPAT	N	2	142	56.732	-168.768	56.767	-168.976	2.6	7.1	251	56.788	-168.866	1	5.2	3.0	69
104	mrPAT	Y	2	143	56.947	-168.889	57.113	-168.684	12.8	10.0	328	57.037	-168.595	3	46.8	4.2	105
139	mrPAT	Y	3	94	56.680	-168.325	56.675	-168.354	2.8	1.1	319	56.667	-168.341	1	4.1	0.8	65
134	mrPAT	N	3	94	56.594	-168.599	56.605	-168.509	7.1	1.1	301	56.600	-168.494	1	3.0	0.9	104
121	mrPAT	Y	3	96	56.817	-168.147	56.932	-168.075	1.8	1.9	130	56.943	-168.098	1	3.4	1.2	66

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									Pre-location drift parameters[a]						Buffered composite error ellipse[b]		
		Anti	Deployment information				First HQ location		Time	Distance	Direction	Est. pop-up location		Loc.	$\|S_M\|$	$\|S_m\|$	$\angle S_M$
Tag	Type	foul	Area	Days	Lat	Long	Lat	Long	(h)	(km)	(°)	Lat	Long	cat.	(km)	(km)	(°)
140	mrPAT	N	3	109	56.650	-168.386	56.601	-168.577	4.7	6.8	241	56.630	-168.480	1	3.6	2.5	89
132	mrPAT	Y	3	109	56.616	-168.551	56.705	-168.643	6.9	9.8	255	56.728	-168.488	1	5.1	3.6	97
127	mrPAT	Y	3	110	56.694	-168.393	56.625	-168.620	5.1	7.3	241	56.657	-168.515	1	3.7	2.8	90
137	mrPAT	Y	3	125	56.739	-168.203	56.864	-168.366	11.8	16.1	170	57.007	-168.411	2	10.7	5.8	111
129	mrPAT	N	3	125	56.662	-168.463	56.728	-168.658	1.1	–	–	56.728	-168.658	1	5.1	1.9	53
124	mrPAT	Y	3	126	56.739	-168.304	56.705	-168.355	4.7	6.5	205	56.758	-168.309	1	4.9	2.7	81
141	mrPAT	N	3	140	56.613	-168.461	56.294	-167.764	5.5	12.1	318	56.212	-167.634	1	5.4	4.3	104
125	mrPAT	N	3	140	56.717	-168.350	56.832	-168.485	6.6	6.7	297	56.804	-168.387	1	7.0	2.7	81
136	mrPAT	Y	3	141	56.559	-168.666	56.388	-168.867	5.1	10.3	303	56.338	-168.726	1	4.9	3.8	99
152	mrPAT	N	4	91	57.606	-170.844	57.664	-170.568	35.2	20.8	57	57.561	-170.860	2	8.4	7.2	98
148	mrPAT	Y	4	107	57.456	-170.843	57.536	-171.049	7.6	5.6	327	57.493	-170.997	1	3.5	2.2	93
150	mrPAT	N	4	122	57.537	-170.844	57.168	-171.001	20.5	36.3	174	57.492	-171.067	3	59.6	12.9	97
161	mrPAT	N	5	91	57.513	-171.166	57.539	-171.178	6.0	4.0	35	57.509	-171.217	1	6.9	1.5	86
163	mrPAT	Y	5	105	57.606	-171.158	57.623	-171.219	10.6	5.7	284	57.611	-171.125	1	3.4	2.1	97
155	mrPAT	N	5	106	57.348	-171.160	57.329	-171.297	7.2	5.1	261	57.336	-171.213	1	3.7	2.0	93
159	mrPAT	Y	5	122	57.430	-171.158	57.431	-171.094	7.0	13.4	174	57.551	-171.118	2	11.5	5.7	101
156	mrPAT	N	5	137	57.365	-171.158	57.357	-171.373	13.3	14.8	330	57.241	-171.251	2	16.2	5.1	100
158	mrPAT	Y	5	137	57.385	-171.160	57.579	-171.149	8.7	8.4	334	57.511	-171.088	2	10.6	3.2	84
95	MiniPAT	Y	1	97	57.122	-169.338	57.095	-169.330	4.4	3.7	58	57.077	-169.382	1	4.4	1.5	85
75	MiniPAT	N	1	97	57.433	-169.796	57.563	-169.370	45.2	25.2	54	57.430	-169.711	2	10.3	9.0	89
58	MiniPAT	N	1	98	57.234	-169.369	57.193	-169.263	16.4	6.0	44	57.153	-169.333	1	5.9	2.3	87
49	MiniPAT	Y	1	98	57.153	-169.217	57.169	-169.113	17.9	6.6	44	57.126	-169.188	1	6.2	2.9	89
83	MiniPAT	Y	1	112	57.333	-169.626	57.082	-169.589	31.0	19.5	240	57.170	-169.309	2	9.3	7.4	107
66	MiniPAT	Y	1	113	57.278	-169.460	57.160	-169.558	1.9	2.8	235	57.174	-169.519	1	2.3	1.6	99
52	MiniPAT	N	1	113	57.189	-169.281	57.162	-169.403	1.4	1.5	251	57.166	-169.380	1	2.7	1.0	90

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		Anti	Deployment information				First HQ location		Pre-location drift parameters[a]			Est. pop-up location		Loc.	Buffered composite error ellipse[b]		
Tag	Type	foul	Area	Days	Lat	Long	Lat	Long	Time (h)	Distance (km)	Direction (°)	Lat	Long	cat.	$\lVert S_M \rVert$ (km)	$\lVert S_m \rVert$ (km)	$\angle S_M$ (°)
28	MiniPAT	Y	1	114	57.162	-169.328	57.130	-169.444	3.5	3.3	264	57.133	-169.389	1	2.3	1.5	90
90	MiniPAT	N	1	128	57.143	-169.377	56.467	-169.361	159.1	40.6	173	56.829	-169.437	3	29.5	28.0	102
53	MiniPAT	Y	1	129	57.189	-169.281	56.787	-169.081	33.4	41.5	165	57.147	-169.260	3	20.3	15.4	80
92	MiniPAT	Y	1	143	57.123	-169.339	57.240	-169.809	40.6	47.5	303	57.006	-169.150	3	30.9	16.8	81
81	MiniPAT	Y	1	219	57.385	-169.697	57.584	-165.864	4.2	4.6	264	57.588	-165.788	1	6.6	1.7	87
63	MiniPAT	N	1	220	57.266	-169.434	57.834	-168.534	101.8	63.5	21	57.301	-168.920	3	32.5	22.2	77
116	MiniPAT	Y	2	95	56.766	-168.701	56.922	-168.949	4.3	2.6	46	56.906	-168.979	1	2.4	1.1	92
103	MiniPAT	Y	2	111	56.913	-168.823	56.776	-168.754	2.4	2.6	235	56.790	-168.720	1	2.1	1.3	88
117	MiniPAT	N	2	126	56.809	-168.613	56.753	-168.579	5.8	9.0	174	56.833	-168.594	1	6.6	3.9	85
112	MiniPAT	N	2	126	56.699	-168.835	56.751	-168.920	4.2	8.7	181	56.829	-168.918	1	7.2	4.2	103
105	MiniPAT	Y	2	142	56.958	-168.911	56.835	-168.784	2.5	6.5	278	56.826	-168.678	1	7.0	3.3	92
142	MiniPAT	Y	3	93	56.556	-168.583	56.431	-168.436	8.4	4.2	79	56.423	-168.503	1	5.0	1.8	102
123	MiniPAT	N	3	94	56.780	-168.220	56.777	-168.208	6.4	3.2	79	56.772	-168.260	1	4.1	1.5	104
131	MiniPAT	N	3	109	56.639	-168.509	57.167	-168.915	5.2	6.8	241	57.197	-168.816	1	4.0	2.8	101
138	MiniPAT	Y	3	124	56.710	-168.263	56.626	-168.278	2.1	4.4	181	56.665	-168.277	1	4.5	2.2	100
128	MiniPAT	Y	3	125	56.682	-168.419	56.578	-168.532	5.0	10.4	181	56.672	-168.530	1	6.9	4.4	103
133	MiniPAT	N	3	140	56.606	-168.576	56.493	-168.664	2.2	4.3	286	56.482	-168.597	1	3.7	1.9	146
149	MiniPAT	Y	4	122	57.472	-170.843	57.432	-170.989	9.1	17.4	174	57.588	-171.019	1	7.9	6.4	95
162	MiniPAT	Y	5	90	57.578	-171.159	57.577	-171.111	4.5	1.7	359	57.562	-171.110	1	1.6	1.1	78
164	MiniPAT	N	5	136	57.628	-171.160	57.672	-171.164	7.9	17.5	302	57.588	-170.915	2	14.0	6.6	84

Note: Location categories are defined as:

1) tag with surface drift prior to first high-quality (HQ) location (t_1) < 24 h and semi-major axis of buffered composite error ellipse ($\lVert S_M \rVert$) < 8.35 km

2) t_1 < 48 h and 8.35 km < $\lVert S_M \rVert$ < 16.7 km

3) t_1 > 48 h or $\lVert S_M \rVert$ > 16.7 km

[a] Drift time (t_1) and estimated drift distance (d) and direction between the estimated pop-up location (P_0) and the first high-quality (HQ) location (P_1).

[b] Error ellipse size and orientation defined by the semi-major axis length ($\lVert S_M \rVert$), semi-minor axis length ($\lVert S_m \rVert$), and direction of the semi-major axis ($\angle S_M$).

Appendix A2.–Details on satellite tags deployed during the 2019 Bering Sea Tanner crab tagging study that surfaced prior to their programmed release dates.

			Deployment information				First HQ location		Pre-location drift parameters[a]			Est. pop-up location			Buffered composite error ellipse[b]		
Tag	Type	Anti foul	Area	Days	Lat	Long	Lat	Long	Time (h)	Distance (km)	Direction (°)	Lat	Long	Loc. cat.	$\|\|S_M\|\|$ (km)	$\|\|S_m\|\|$ (km)	$\angle S_M$ (°)
51	mrPAT	Y	1	29	57.175	-169.259	57.164	-169.219	5.1	1.0	99	57.166	-169.236	1	2.9	1.4	118
80	mrPAT	N	1	50	57.395	-169.716	57.046	-168.797	42.0	61.5	100	57.141	-169.800	3	25.3	21.9	85
65	mrPAT	Y	1	89	57.278	-169.460	57.228	-169.590	15.4	15.5	157	57.356	-169.689	2	10.6	5.6	80
36	mrPAT	N	1	132	57.264	-169.529	57.366	-169.481	51.2	28.2	102	57.419	-169.942	3	15.7	9.6	95
109	mrPAT	N	2	47	56.968	-168.932	56.979	-168.958	12.5	22.1	30	56.808	-169.142	2	16.1	11.6	52
108	mrPAT	N	2	48	56.968	-168.932	56.949	-168.711	9.2	14.9	92	56.953	-168.956	1	8.2	6.5	31
110	mrPAT	N	2	53	56.675	-168.881	56.620	-168.869	10.4	15.7	279	56.598	-168.616	2	9.4	8.4	94
130	mrPAT	Y	3	6	56.649	-168.485	56.675	-168.567	4.2	4.8	284	56.665	-168.491	1	4.2	2.8	90
135	mrPAT	N	3	13	56.559	-168.666	56.562	-168.583	4.7	2.6	44	56.545	-168.612	1	2.5	1.6	87
146	mrPAT	N	4	85	57.412	-170.843	57.515	-170.800	6.0	15.0	63	57.453	-171.023	2	9.8	8.0	104

Note: Location categories are defined as:

1) tag with surface drift prior to first high-quality (HQ) location (t_1) < 24 h and semi-major axis length of buffered composite error ellipse ($||S_M||$) < 8.35 km

2) t_1 < 48 h and 8.35 km < $||S_M||$ < 16.7 km

3) t_1 > 48 h or $||S_M||$ > 16.7 km

[a] Drift time (t_1) and estimated drift distance (d) and direction between the estimated pop-up location (P_0) and the first high-quality (HQ) location (P_1).

[b] Error ellipse size and orientation defined by the semi-major axis length ($||S_M||$), semi-minor axis length ($||S_m||$), and direction of the semi-major axis ($\angle S_M$).

APPENDIX B. ENVIRONMENTAL DATA RECORDED BY SATELLITE TAGS

Appendix B1.–Average, minimum, and maximum temperatures and average start and end temperatures recorded by mrPAT satellite tags that reported temperature data for at least 30 days.

		Temperature days				Temperature (°C)					
Tag	Area	Start	End	Total	Reported	Avg[a]	Min	Max	Avg start[b]	Avg end[b]	ΔTemp
26	1	09/04/2019	11/12/2019	69	30	4.8	4.5	5.0	4.8	4.8	0.0
77	1	09/19/2019	11/27/2019	69	50	6.4	4.5	8.5	5.8	4.8	-1.0
62	1	09/04/2019	12/02/2019	89	50	5.5	4.5	6.5	4.8	4.8	0.0
82	1	09/04/2019	12/02/2019	89	60	5.8	4.5	8.0	6.0	5.0	-1.0
43	1	08/25/2019	12/02/2019	99	90	6.2	4.5	8.5	6.5	5.3	-1.3
35	1	09/25/2019	12/03/2019	69	40	5.6	4.5	7.0	5.8	4.5	-1.3
60	1	10/16/2019	01/03/2020	79	60	5.7	3.0	8.5	8.3	3.0	-5.3
37	1	12/25/2019	04/02/2020	99	90	0.7	-1.0	4.0	3.8	-0.8	-4.5
118	2	08/29/2019	10/23/2019	55	36	4.9	4.5	5.0	4.5	5.0	0.5
99	2	08/27/2019	11/12/2019	77	38	5.1	4.0	7.0	4.3	5.3	1.0
111	2	09/09/2019	11/27/2019	79	50	4.6	4.0	5.0	4.3	4.8	0.5
115	2	10/05/2019	12/03/2019	59	50	5.4	4.5	7.5	4.8	5.3	0.5
107	2	09/19/2019	12/17/2019	89	50	4.5	4.0	5.5	4.5	5.0	0.5
114	2	10/21/2019	01/08/2020	79	40	4.8	3.5	5.5	4.8	4.0	-0.8
139	3	08/30/2019	10/13/2019	44	35	4.7	4.0	5.0	4.3	5.0	0.8
134	3	08/29/2019	12/02/2019	95	36	4.5	4.0	5.0	4.3	5.0	0.8
121	3	08/29/2019	12/04/2019	97	88	4.7	4.0	5.5	4.3	5.0	0.8
140	3	09/09/2019	12/07/2019	89	40	4.8	4.0	5.0	4.5	5.0	0.5
129	3	09/25/2019	12/23/2019	89	80	4.6	4.0	5.0	4.5	5.0	0.5
137	3	09/25/2019	01/02/2020	99	50	4.9	4.0	5.5	5.0	4.3	-0.8
125	3	10/20/2019	01/07/2020	79	60	4.5	3.5	5.5	4.3	3.8	-0.5
161	5	09/02/2019	12/02/2019	91	42	4.8	4.5	5.5	4.5	5.5	1.0
155	5	09/09/2019	12/17/2019	99	90	4.9	4.5	5.5	4.8	5.3	0.5

Note: Start and end dates may not reflect entire deployment period of tag.

[a] Average temperatures are the daily minimum and maximum temperatures averaged over days reported.

[b] Average start and end temperatures are the average of daily minimum and maximum temperatures for the first (start) and last (end) day reported, respectively.

Appendix B2.–Average, minimum, and maximum depths and temperatures recorded by MiniPAT satellite tags that reported data for at least 18 days.

		Depth days				Depth (m)			Temperature days				Temperature (°C)		
Tag	Area	Start	End	Total	Reported	Avg[a]	Min	Max	Start	End	Total	Reported	Avg[b]	Min	Max
49	1	08/26/2019	12/01/2019	97	18	78	76	81	08/30/2019	12/01/2019	93	18	6.0	5.0	8.0
95	1	08/29/2019	12/01/2019	94	22	78	75	82	09/06/2019	11/30/2019	85	20	7.0	5.6	8.9
58	1	08/30/2019	12/01/2019	93	57	75	74	77	08/26/2019	12/01/2019	97	58	5.9	4.8	8.1
52	1	08/26/2019	12/11/2019	107	21	75	72	78	08/26/2019	11/29/2019	95	22	6.0	4.9	7.9
66	1	08/27/2019	12/15/2019	110	68	72	65	74	08/27/2019	12/14/2019	109	68	5.9	4.7	8.4
53	1	08/30/2019	12/28/2019	120	21	77	75	80	09/07/2019	01/01/2020	116	25	5.4	3.8	8.0
103	2	08/27/2019	12/14/2019	109	77	99	87	107	08/27/2019	12/16/2019	111	82	5.0	4.6	5.5
117	2	08/31/2019	01/01/2020	123	51	103	97	107	08/31/2019	01/01/2020	123	43	5.0	4.7	5.4
112	2	09/02/2019	01/01/2020	121	44	103	91	108	08/29/2019	12/31/2019	124	64	5.1	4.4	5.6
105	2	09/14/2019	01/07/2020	115	27	92	84	101	09/18/2019	01/15/2020	119	27	5.1	3.7	5.6
123	3	09/08/2019	11/27/2019	80	20	104	103	106	09/07/2019	11/15/2019	69	23	5.0	4.7	5.4
142	3	09/09/2019	11/30/2019	82	25	116	112	122	09/01/2019	11/30/2019	90	14	5.0	4.7	5.5
131	3	08/30/2019	12/16/2019	108	80	92	77	115	08/29/2019	12/15/2019	108	84	5.1	4.8	5.9
138	3	09/02/2019	12/25/2019	114	28	112	111	114	08/30/2019	01/01/2020	124	21	5.3	4.7	5.9
128	3	09/04/2019	01/01/2020	119	29	110	109	112	08/30/2019	12/30/2019	122	33	5.1	4.7	5.8
133	3	09/17/2019	01/03/2020	108	24	126	115	139	09/09/2019	01/10/2020	123	25	5.2	4.9	5.7
162	5	09/04/2019	11/30/2019	87	35	97	96	100	09/03/2019	12/01/2019	89	38	5.0	4.6	5.6

Note: Start and end dates may not reflect entire deployment period of tag.

[a] Average depth is the sum of depths collected by an individual tag divided by the total number of depths collected by that tag.

[b] Average temperature is the sum of temperatures collected by an individual tag divided by the total number of temperatures collected by that tag.

Appendix B3.–Average start and end depths and temperatures recorded by MiniPAT satellite tags with reporting periods that best represented tag deployment periods.

		Depth days			Depth (m)			Temperature days			Temperature (°C)		
Tag	Area	Start	End	Total	Start[a]	End[a]	ΔDepth	Start	End	Total	Start[b]	End[b]	ΔTemp
49	1	08/26/2019	12/01/2019	97	78	80	2	08/30/2019	12/01/2019	93	5.0	5.2	0.2
95	1	08/29/2019	12/01/2019	94	80	77	-3	09/06/2019	11/30/2019	85	6.3	6.1	-0.2
58	1	08/30/2019	12/01/2019	93	75	76	1	08/26/2019	12/01/2019	97	5.0	5.1	0.1
28	1	09/23/2019	12/11/2019	79	76	73	-3	08/30/2019	11/24/2019	86	5.1	5.7	0.6
52	1	08/26/2019	12/11/2019	107	75	73	-3	08/26/2019	11/29/2019	95	4.9	5.1	0.2
66	1	08/27/2019	12/15/2019	110	73	67	-6	08/27/2019	12/14/2019	109	4.9	4.8	-0.1
53	1	08/30/2019	12/28/2019	120	77	78	1	09/07/2019	01/01/2020	116	5.4	3.8	-1.6
103	2	08/27/2019	12/14/2019	109	87	103	16	08/27/2019	12/16/2019	111	4.7	5.4	0.7
117	2	08/31/2019	01/01/2020	123	104	100	-4	08/31/2019	01/01/2020	123	4.7	4.7	0.0
112	2	09/02/2019	01/01/2020	121	107	93	-14	08/29/2019	12/31/2019	124	4.7	4.7	0.0
105	2	09/14/2019	01/07/2020	115	85	100	16	09/18/2019	01/15/2020	119	4.8	3.8	-1.0
123	3	09/08/2019	11/27/2019	80	106	103	-3	09/07/2019	11/15/2019	69	4.9	5.1	0.2
142	3	09/09/2019	11/30/2019	82	113	121	8	09/01/2019	11/30/2019	90	4.9	5.5	0.6
131	3	08/30/2019	12/16/2019	108	114	78	-36	08/29/2019	12/15/2019	108	4.8	5.1	0.3
138	3	09/02/2019	12/25/2019	114	112	113	1	08/30/2019	01/01/2020	124	4.8	5.8	1.0
128	3	09/04/2019	01/01/2020	119	110	111	1	08/30/2019	12/30/2019	122	4.8	5.6	0.8
133	3	09/17/2019	01/03/2020	108	115	130	15	09/09/2019	01/10/2020	123	4.9	5.1	0.2
162	5	09/04/2019	11/30/2019	87	97	98	1	09/03/2019	12/01/2019	89	4.7	5.6	0.9
164	5	10/13/2019	01/13/2020	92	96	94	-3	09/11/2019	01/12/2020	123	4.9	3.1	-1.8

Note: Start and end dates may not reflect entire deployment period of tag.

[a] Start and end depths are the average of measured depths for the first (start) and last (end) day reported, respectively.

[b] Start and end temperatures are the average of measured temperatures for the first (start) and last (end) day reported, respectively.