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Article

# Seasonal Variation in Pacific Sleeper Shark (*Somniosus pacificus*) Habitat Use in Prince William Sound, AK

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## Abstract

The Pacific sleeper shark (*Somniosus pacificus*, PSS) is a long-lived, deep-water and sub-polar species that exhibits flexible foraging strategies, likely combining scavenging with active predation on a broad range of prey, yet their role in marine food chains and impact on commercial species remain undetermined. Tracking the location of PSS in Alaskan coastal waters is extremely challenging given the predominantly aphotic depths that these sharks occupy, often in spatially constrained and critically under-sampled regions: deep, steep-flanked, convoluted fjords of Prince William Sound (PWS). From the first ever, year-long depth and temperature records recovered from archiving pop-up satellite-linked transmitters (n=7), we characterized the residence distributions, depth, and thermal habitat for sharks within the PWS fjords and identified seasonal and temporal variation in habitat use. Depths recorded from the seven sharks ranged from 3-572m, and pop-up tag locations suggested a high degree intra-annual residency within western PWS. Ambient water temperatures ranged from 2.65 to 11.1 °C, with little deviation from the median of 5.9 °C. Seasonal patterns emerged within and across individuals relative to the variation in vertical movements, ambient temperatures, and horizontal movements that could reflect resource-oriented strategies. The high degree of residency combined with extensive use of the water column facilitates the use of physically recoverable, high-resolution behavioral and environmental samplers on PSS. This adaptive sampling using PSS as platforms of opportunity may in turn enable the use of PSS as climate and ecosystem sentinels.

**Keywords:** elasmobranch; *Somniosus*; HMM; behavioral ecology; polar; sharks

## 1. Introduction

World-wide, sharks are positioned at or near the apex of the trophic structures that support them, and as a result may function as keystone species, central to dynamics of marine food webs [1]. Their distributions globally, and at finer spatial scales, are driven by a combination of abiotic and biotic factors. Amongst these, temperature has been well-established for many sharks as a driver of distribution and behavioral patterns [2–4] by influencing movement, foraging efficiency [5,6] and reproduction [7]. Considerable emphasis has been placed investigating the drivers of fine spatial and temporal variability in habitat use and behavior for shallow-water, tropical species of sharks [8,9], yet similar information for high-latitude shark species is extremely limited [10].

The Pacific sleeper shark (*Somniosus pacificus*) is a large, subpolar and deep-water species distributed across the Pacific [11–14]. Reliable estimates from underwater photographs suggest Pacific sleeper sharks may reach up to 6.6 m total length, with regional variability [14]. In the Gulf of Alaska, estimates of population abundance and distributions have largely been derived from fisheries surveys and bycatch data [15,16]. Between 1989 and 2003, sablefish longline surveys suggested an

increase in Pacific sleeper shark bycatch rates [15] but recent reports suggest a decline in relative abundance since 2013 [16]. It is unclear what mechanism is associated with the observed decline in Pacific sleeper shark abundance estimates, but the pattern aligns temporally with an extreme marine heatwave in the Gulf of Alaska [17]. During this environmental perturbation, ecosystem-level responses were observed across all trophic levels, including species distribution shifts and significant die-offs [18–20]. Establishing baselines for Pacific sleeper shark behavior, habitat use, and movement is critical for determining the role of abiotic and biotic factors, including fisheries bycatch, in sleeper shark population dynamics and for assessing shark's vulnerability to future environmental shifts predicted to increase in frequency and intensity [2].

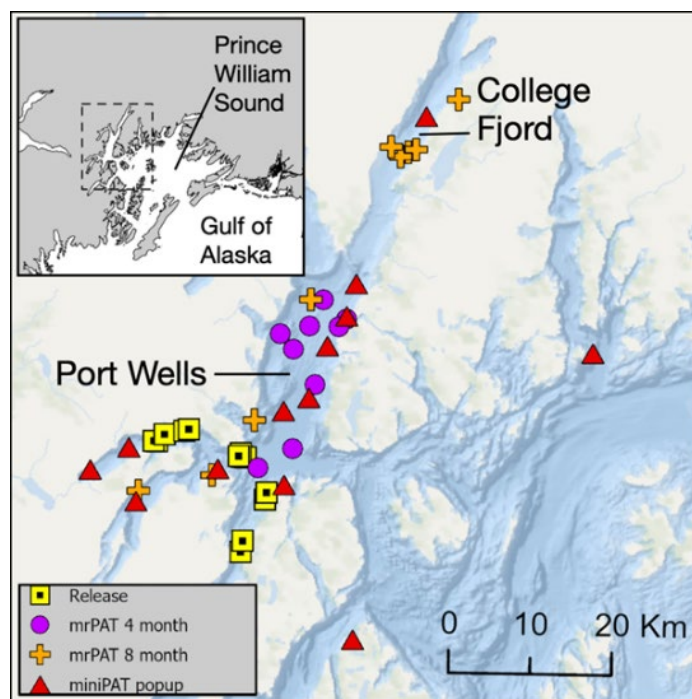
Extant, published knowledge of Pacific sleeper shark movement and behavior comes from a study of 24 immature sharks (TL: 1.5-2.5 m) in the Gulf of Alaska, using satellite-linked pop-up and archival tags [21]. Broadly, sharks moved continuously through the water column, commonly ascending above 100m but spending most time between 150-450 m depths, and appeared stenothermic, with over 90% of the ambient water temperatures within a narrow range of 5.5-8.2 °C [21]. The duration and resolution of the data varied across individuals due to tag attachment and data transmission failures, but there were no consistent seasonal patterns related to depth ranges, and only some individuals exhibited diel vertical migrations during a portion of their records [21].

Most sharks in the Hulbert et al. [21] study were tagged near Steller sea lion (*Eumetopias jubatus*) rookeries, but six individuals tagged with satellite depth recording tags, and one individual with a pop-up archival transmitting tag had end-point locations within Prince William Sound. Though often considered part of the Gulf of Alaska, Prince William Sound is a semi-enclosed deep-water marine basin, with depths ranging up to 750m [22], that is surrounded by many glaciated fjords and inlets. Fjords are seasonally important habitat for the closely related Greenland shark (*Somniosus microcephalus*) in the north Atlantic, particularly for the juvenile age-class [10,23]. Fjords have also been hypothesized as potentially important nursery habitat for Pacific sleeper sharks [14], yet there is limited information on Pacific sleeper shark behaviors within fjord habitats, or at fine temporal scales. This study expands upon the broadscale work of Hulbert et al. [21] by examining behavior and movement of Pacific sleeper sharks specifically within the glaciated fjords and inlets of PWS. Our objectives were to (1) characterize the residence distributions, depth, and thermal habitat for sharks within the PWS fjords, and (2) identify seasonal and temporal variation in habitat use.

## 2. Materials and Methods

### *Study Location and Sampling Operations*

Pacific sleeper sharks were caught in the northwest fjords of PWS (Figure 1), between June and August 2022 using a modified version of the approach described in Smith et al. [24]. Briefly, we used 4 sets of capture gear, where an individual set consists of two, three or four 16-20 gauge circle hooks individually connected via 1-1.5m gangions and longline clips to a vertical line leading to a surface buoy, and positioned approximately 5-10m from the bottom anchor. The hooks were baited with salmon and sets were placed at depths between 150 and 350 m for 2-6 hour duration daytime soaks. In the present study, sharks were handled at the surface alongside a 14ft aluminum chambered research skiff, while secured in a rectangular floating stretcher. Morphometric measurements were taken, and all sharks then received one or more electronic tags, or numbered markers. Following all sampling and tag attachments, sharks were released in situ. Handling times from reaching the surface to release were, on average,  $29 \pm 7.3$  min S.D. All animal captures, restraint, sampling, tagging, release and tracking was conducted under ADF&G Aquatic Resources Permit CF-22-069, and under Animal Use Protocols issued by the IACUC of UAF (1700224-3/4).



**Figure 1.** Pacific sleeper shark satellite tag release and pop-up locations in Prince William Sound (PWS). Pop-up locations for mrPAT tags (4-month and 8-month programmed durations) and miniPAT tags (365 day programmed durations).

#### *Satellite Transmitter Deployments*

Across 30 catch effort days, we caught 16 sharks (Table 1), of which 15 were released with a combination of one or more transmitters. External transmitters were secured to the sharks via short tethers connected to subdermal titanium anchors. MiniPAT-348 archiving pop-up satellite transmitters (Wildlife Computers, Redmond, WA, USA) were deployed on 14 sharks. The MiniPAT tags (length 124 mm, width 38 mm, weight in air 60 g) recorded information on depth (0 – 1700 m, resolution 0.5 m), temperature ( $-40\text{ }^{\circ}\text{C}$  –  $60\text{ }^{\circ}\text{C}$ , resolution  $0.05\text{ }^{\circ}\text{C}$ ), tri-axial acceleration ( $-2$  –  $2\text{ g}$ , resolution  $0.05\text{ g}$ ), and light levels ( $5 \times 10^{-12}\text{ W}\cdot\text{cm}^{-2}$  –  $5 \times 10^{-2}\text{ W}\cdot\text{cm}^{-2}$ ) at 5 sec intervals. MiniPAT tags were programmed to detach from the shark (or “pop up”) after 365 days ( $n=13$ ) or 730 days ( $n = 1$ ) and transmit recorded data in summarized form as depth and temperature ranges and histograms. All tags except one (SP22-07) reported via the Argos satellite system upon release, and 10 MiniPAT tags were physically recovered at sea. The entire archival data set can be downloaded as originally recorded from physically recovered tags, including all depth, temperature, light level and accelerometer values. The Argos system provides location estimates calculated from multiple sequential post-emergence transmissions received during a single pass by one of a constellation of polar orbiting low-earth orbit satellites and is assigned a location classification based on estimate uncertainty [25,26].

Of the 15 tagged animals, 12 sharks received an additional two separate Wildlife Computers mrPAT-376 mark-report pop-up transmitters, with programmed detachment set for 120 and 240 days, respectively. Coded 69k Hz acoustic transmitters (models V16-4x or V16-6x, Vemco/Innovasea, Nova Scotia, Canada) were also attached to 11 of the sharks, either externally or internally (Table 1). This approach of using sequential releases of multiple PATs per shark has been used for studying the movement and migration of Greenland sharks [27].

**Table 1.** Pacific sleeper sharks (*Sommiosus pacificus*) caught in 2022 in western Prince William Sound (n=16, bold indicates data used in this study). Time at liberty indicates when tags either prematurely detached and transmitted or as scheduled after 365 days. Recovery indicates whether the MiniPAT tag transmitted data only via satellite and how many valid messages were received via the Argos system (n = 3) and/or if all collected data was downloaded from a physically recovered tag (REC n=10). In addition to MiniPAT tags, some sharks received one or more mrPAT tags, which were set to release and transmit after 120 or 240 days, respectively. Actual release time is indicated in days for each mrPAT tag. Some sharks were also tagged with an acoustic tracking transmitter (Innovasea, Nova Scotia, Canada) externally (E) or internally (I).

Shark ID	Release Date	Sex	TL (cm)	Time at liberty (Days)	MiniPAT Recovery	mrPAT 120d	mrPAT 240d	Acoustic tag
SP22-01	6/24/22	M	229	17	REC	120	241	E
SP22-02	6/24/22	F	284	31	REC	32	26	E
SP22-03	7/12/22	M	241	357	Argos-172	120	148	E
SP22-04	7/13/22	F	305	86	REC	89	83	E
<b>SP22-05</b>	7/22/22	F	248	365	REC	121	241	-
SP22-06	7/22/22	F	>300*	-	-	-	-	-
SP22-07	7/24/22	F	244	-	-	-	-	-
<b>SP22-08</b>	7/24/22	F	230	365	REC	121	191	-
SP22-09	8/11/22	F	175 <sup>‡</sup>	-	-	-	-	E
SP22-10	8/12/22	M	343	365	Argos-440	120	241	E
SP22-11	8/14/22	F	262	46	Argos-892	-	-	-
<b>SP22-12</b>	8/25/22	F	321	365	REC	121	241	E
<b>SP22-13</b>	8/25/22	M	280	365	REC	121	241	E
<b>SP22-14</b>	8/25/22	M	273	365	REC	121	241	I
<b>SP22-15</b>	8/27/22	F	253	365	REC	121	241	E
<b>SP22-16</b>	8/27/22	F	271	365	REC	121	241	I

\*captured but broke free before measuring or sampling (SP22-06). <sup>‡</sup> was released due to size with only an acoustic pinger (SP22-09).

### Data Analysis

To address questions of fine-scale temporal variation in fjord habitat use, the depth and temperature data from seven full-year, complete data sets downloaded from physically recovered MiniPAT tags were used in this study (Table 1). After visual inspection of the sleeper shark depth profiles, irregular and shallow dive behaviors or a prolonged descent to depth were observed during the first 6-24hrs post-release (Supp Figure 1), followed by regular vertical movements. As many fish and sharks exhibit post-handling recovery periods [3,28], prior to analysis we removed the first 24hrs of data for each shark.

### Horizontal Displacement

The first Argos pop-up location estimate with a precision of 500 m or better (location class 2 or 3) was used as the end-point locations for transmitting satellite tags. Seasonal net horizontal displacements (distance between mrPAT/miniPAT release and the previous known location), as well as full year displacement (distance between miniPAT release and pop-up) were calculated using great circle distance. Spearman Rank correlation tests were used to examine whether horizontal displacement varied by size (TL, cm).

Pathways (daily location estimates) between release and pop-up locations were reconstructed using a hidden Markov model (HMM) developed for demersal fish based on maximum daily depth and known locations. The HMM used in this study was originally developed to reconstruct movement paths of Atlantic cod in the North Sea [29,30] and has been adapted to demersal fishes in the North Pacific Ocean [31]. The model is discrete in space and time and consists of coupled movement and data likelihood models that ultimately generate location probability surfaces for each day of the trajectory. The movement model is isotropic diffusion. The data likelihood model, which

links tag data to likely locations in the study area, is a key feature of the HMM and should be customized for different species, study areas, and tag types [32]. Light-based geolocation is extremely challenging for Pacific Sleeper Sharks given the depths that the sharks occupy as well as study area conditions. Geolocation for most pelagic fishes can utilize light-based latitude and longitude estimates obtained from light intensity records; however, for demersal fish, longitude estimates are more robust and are available for fish that occupy depths less than about 150 m and do not change depth in response to sunrise and sunset [29,33]. In the data sets we obtained for this study, very few light-based longitude observations were present even when sharks occupied depths that were shallow enough to collect them. In the fjord systems, glacial sediment may have affected the quality of light data and thus adversely affected light-based geolocation. Therefore, the data likelihood model we have implemented for sleeper sharks in PWS is based on maximum daily depth [31] and known locations including release, locations at 4 and 8 months from mrPAT satellite tags, and pop-up locations for MiniPAT satellite tags after 1 year (See: Supplemental Information for more details).

MrPAT locations were first used to assess model performance with different data likelihood models, values of diffusion, and spatial extents, and then were included in the data likelihood model for the final model run. Residence distributions that summarize location probability [34] for all sharks combined were produced for all sharks that most likely resided in the study area continuously throughout the duration of the study. Residence distributions were produced for two-month periods in summer 2022, fall/winter 2022, spring 2023, and summer 2023 that coincided with the availability of known locations from mrPATs.

#### *Diel Variation in Depth and Temperature*

Archived temperature and depth data subsampled at 1 minute intervals were assigned to two diel periods based on the given location (PWS: 60.8° N, 148° W) and time using the `suncalc` package in R v.4.5.2. “Day” was defined as the period from sunrise to sunset (evening civil twilight starts), and “Night” was defined as the period from when evening civil twilight ends until dawn (morning civil twilight starts). Summary statistics for each diel period, including mean, median, and interquartile range were calculated for all sharks combined, and by individual. Spearman Rank correlation tests were used to examine whether diel depth or temperature patterns varied by size (TL, cm). To examine diel variation in the proportion of time spent at depth, and time at temperature, we aggregated data into 50m and 1 °C bins respectively [35], and across all individuals combined, calculated the proportion of the total observations in each bin.

#### *Seasonal Variation in Depth and Temperature*

A clustering analysis was used to group days of the year based on the observed habitat variables: depth range, maximum temperature, and mean depth. This approach was selected as it allowed for flexibility in identifying patterns of intra-annual variation in habitat use patterns, as opposed to using pre-defined temporal windows (e.g., calendar month, or summer vs. winter). All variables were calculated by Night and Day and then normalized and scaled for equal variance. We selected to use a K-means cluster analysis as it is a relatively simple unsupervised classification approach that has been used for grouping animal behaviors and individual location observations [36,37]. The optimal number of clusters was defined using the silhouette method, wherein larger silhouette index values indicate better clustering quality and that the within-cluster dissimilarity is less than the between-cluster dissimilarity [38]. Cluster assignment and visualization was done for all sharks combined [R package `factoextra`; [39]].

### **3. Results**

#### *3.1. Horizontal Movement*

Satellite tag pop-up locations obtained over the course of the year from all sharks (n=37) suggest that horizontal movement was limited, with most pop-up locations occurring in Port Wells where

the tagged sharks were released (Figure 1). The mean net horizontal displacement from the release location after one year (i.e., distance between the release and miniPAT pop-up locations) was 18.65 km (s.d. 14.2 km, range 7.4-47.5 km,  $n = 7$ ) and had no significant association with total length of the animals ( $p < 0.05$ ). The quarterly net displacement did vary seasonally, ranging from a mean of 18.4 km to 24.5 km (Table 2).

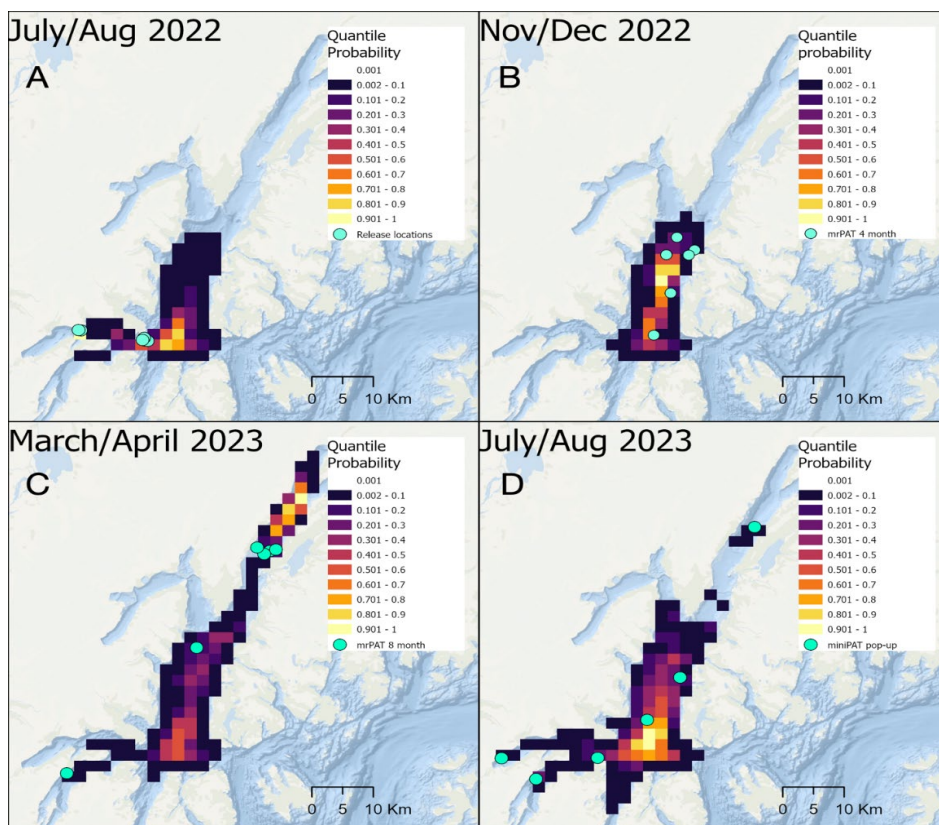
**Table 2.** Quarterly net horizontal displacement (great circle distance, km) between pairs of known locations from satellite tags, as well as over 1yr between release and pop-up of miniPAT tag. \*8mo mrPAT for SP22-08 popped-up early so displacement was not calculated.

Shark ID	Release -4mo mrPAT (120d)	4mo mrPAT-8mo mrPAT (120d)	8mo mrPAT-miniPAT PopUp (120d)	Release -miniPAT PopUp (367 d)
SP22_05	20.6	25.3	1.1	7.6
SP22_08	23.7	*	*	8.5
SP22_12	16.1	18.3	25.6	23.9
SP22_13	6.3	38.8	54.9	18.7
SP22_14	20.9	22.3	26.2	17.0
SP22_15	19.8	22.1	30.0	7.5
SP22_16	21.7	20.4	5.8	47.5
<i>Mean</i>	18.4	24.5	23.9	18.7
<i>S.d.</i>	5.8	7.4	17.6	14.2

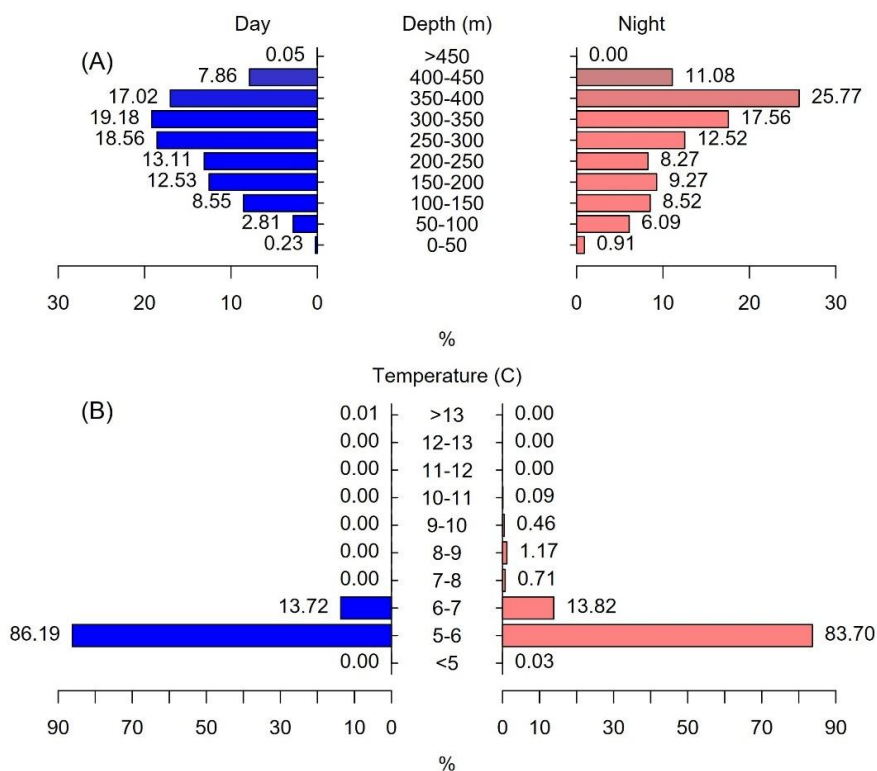
Geolocation results obtained from satellite tag pop-up locations suggest that 6 of the 7 tagged sharks with detailed data sets likely remained entirely within Port Wells over the course of the year (Figure 2). One of the 7 sharks (SP22-12) likely left Port Wells from mid-June to mid-July 2023, as it recorded greater depths than were available in Port Wells during this time. However, both the 4- and 8-month mrPAT and the 12-month miniPAT pop-up locations for SP22-12 were within Port Wells, and patterns in temperature and depth were similar to the other 6 geolocated sharks. Seasonal trends were observed for geolocated sharks that remained in Port Wells based on reconstructed movement paths using the HMM. In July/August 2022, the distribution was close to release locations (Figure 2A). By November/December 2022, the distribution had expanded northward into Port Wells (Figure 2B). During the spring (March/April 2023), most of the tagged sharks occupied shallower areas adjacent to active glaciers such as College Fjord (Figure 2C). By the following summer, the distribution had shifted south again into deeper waters (Figure 2D).

### 3.2. Diel Variation in Depth and Temperature

Across the seven year-long deployments, recorded depths ranged from 3-572 m. At Night, sharks used a median depth of 313.5 m ( $\pm 173$  IQR) with 84.5% of their time spent between 150-450 m and 7% of their time in shallow waters (0-100m). During the Day, sharks exhibited a median depth of 285.5 m ( $\pm 146$  IQR) with 88.2% of their time spent between 150-450 m, and 3% of their time in shallow waters (Figure 3a). Ambient water temperatures ranged from 2.65-11.1 °C. While ambient temperature varied very little from the median of 5.9 °C ( $\pm 0.1$  IQR), sharks in PWS exhibited diel variation, with waters warmer than 7 °C only used at Night (Figure 3b). Daytime Depth Range (m) exhibited a significant positive correlation with TL (Pearson  $cor = 0.926$ ,  $t=5.5$ ,  $p = 0.003$ ), but TL was not associated with any other individual diel depth and temperature metrics.



**Figure 2.** Seasonal composite location probabilities for 6 sharks with detailed data sets and known locations from release, 4-month mrPAT, 8-month mrPAT, and 12-month miniPAT tags within Port Wells, Prince William Sound (PWS).



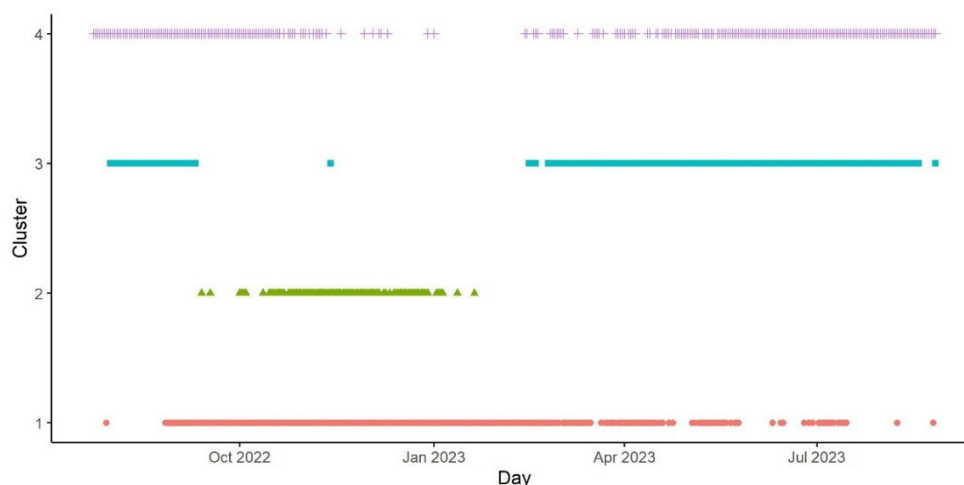
**Figure 3.** Diurnal patterns of the percentage of time at depth (A) and temperature (B) for all sharks and seasons combined (n=7).

### 3.3. Seasonal Variation in Depth and Temperature

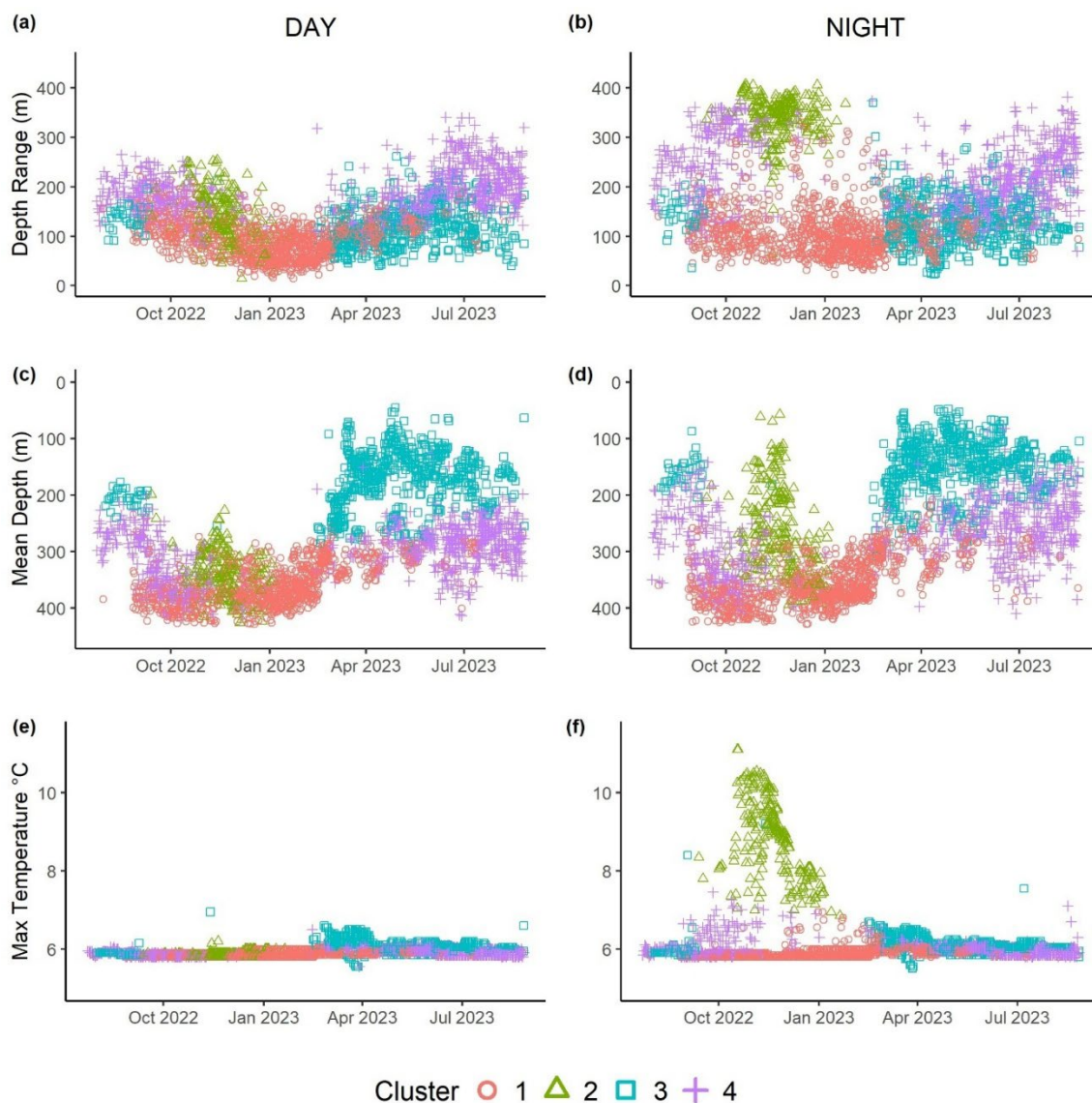
K-means clustering for all sharks combined identified four clusters (Table 3, Figs 4-5) based on dive and thermal metrics (BSS/TSS ratio = 62.6%). Cluster 1 included days when sharks exhibited reduced diurnal variation and depth ranges and used very deep waters (300-400 m) with cold ambient temperatures (Figure 5a-f). This pattern was exhibited mostly in the fall-winter (Sept-April; Figure 4). Cluster 2 was temporally constrained to days between October and January (Figure 4) and consisted of strong diurnal variation. Specifically, these sharks exhibited greater depth ranges at Night, moving into shallow waters where they encountered elevated ambient temperatures, routinely exceeding 7 °C (Figure 5). Clusters 3 and 4 overlapped temporally in the spring and summer (March-Aug, Figure 4). Cluster 3 included days where individuals used shallow depths (50-250 m) with reduced depth ranges and slightly elevated daytime ambient temperatures, whereas Cluster 4 days consisted of sharks using intermediate depths in the water column (100-300 m) and exhibiting greater depth ranges than Cluster 1 (Figure 5).

**Table 3.** K-means cluster outputs for all sharks combined; means are presented based on the scaled-normalized predictor variables (e.g., negative mean depths indicate the sharks were in relatively shallow waters; negative max temperatures indicate the sharks were in colder ambient waters).

Cluster	n	Day			Night		
		Depth Range (m)	Mean Depth (m)	Max Temp (°C)	Depth Range (m)	Mean Depth (m)	Max Temp (°C)
1	980	-0.643	0.743	-0.461	-0.634	0.866	-0.400
2	240	0.075	0.587	-0.452	1.873	-0.052	2.838
3	363	-0.216	-1.404	0.977	-0.428	-1.257	-0.167
4	686	1.093	0.034	-0.089	0.646	-0.054	-0.267



**Figure 4.** Temporal distribution of cluster assignments based on shark diel depth and temperature data. Each point represents a day of the year for an individual shark (e.g., 7 points per day) with color and shape representing what cluster it was assigned to. Clusters 1 and 2 were common in the winter and early spring, while Clusters 3 and 4 were most common in spring and summer.



**Figure 5.** Daily values of depth range (m), mean depth (m), and maximum temperature (°C), during the daylight (left) and night (right). Each point represents a day of the year for an individual shark (i.e., 7 points per day), with color and shape representing what cluster it was assigned to.

#### 4. Discussion

Sleeper sharks remain an understudied species with little knowledge about their role in Alaskan coastal marine ecosystems, especially in a spatially constrained region which remains critically under sampled – such as glacial fjord ecosystems. Tracking the location of these sharks is extremely challenging given the predominantly aphotic depths that the sharks occupy as well as study area conditions, in deep, steep-flanked, convoluted fjords with often particularly turbid water. Little tracking infrastructure in the form of moored or mobile acoustic tracking receivers exists. Pop-up archiving satellite transmitters can provide summarized depth and ambient temperature distributions, as well as end-of-deployment location estimates, but commonly applied geolocation by light levels proved impracticable for sleeper sharks. Instead, we used sequential releases of multiple PATs per-shark to provide additional mid-deployment locations, as pioneered by Hussey et al. [27] on Greenland sharks. Furthermore, the semi-enclosed nature of the Prince William Sound study area combined with the high residency of tagged sharks facilitated the physical recovery of many MiniPATs. In this study, the first ever year-long continuous, higher-resolution archived data sets obtained from physically recovered tags enabled high-resolution quantification of previously

undetected seasonal variability in individual residency distributions and habitat profiles for immature individual Pacific sleeper sharks in the Gulf of Alaska region. This expands on prior research [14,21] and identifies several new areas of future inquiry.

Although our study is limited by a small sample size, a high degree of intra-annual residency was observed for geolocated Pacific sleeper sharks in Prince William Sound. Tagged sleeper sharks tended to occupy the deep basin in Port Wells for much of the year, with average 1-year net displacements of 18 km from release location. We did not observe any clear patterns between displacement and size. Previous research on the movement of Pacific sleeper sharks in Glacier Bay National Park, Alaska, had revealed limited range of movements in glacial fjords, but observations were restricted to during summer [40]. In contrast, only 36% of the final locations for Pacific sleeper sharks tagged in the open Gulf of Alaska by Hulbert et al. [21] were within 0-25 km of their starting location, and several sharks in that study exhibited long-distance, directional movements of > 100km. Coastal habitats have been shown to be ontogenetically favored for juveniles across a range of shark species, providing thermally optimal environments, reduced competition to prey, and reduced risk from predators [41–43]. PWS nearshore and offshore waters consist of diverse fish assemblages [44], including pink salmon and pacific cod which have been identified in Pacific sleeper shark stomach contents [45]. Additionally, observations and tagging locations from Eastern North Pacific offshore killer whales (*Orcinus orca*), the main predator of Pacific sleeper sharks, are also rare in the fjords of Prince William Sound [46,47]. At present, it is unclear if the risk of predation, resource availability, or abiotic factors (or a combination thereof) are driving the variation in sleeper shark residency observed across tagging locations. However, this high residency pattern may facilitate novel studies addressing these hypotheses that would not be feasible in areas with reduced shark residencies or lower tag recovery likelihoods. For example, the high archival recording device recovery probability could enable deployment of acoustic monitoring stations for predators to identify potential interaction rates.

The ranges of depths and temperatures observed in our study, and the broad diel patterns of vertical movements are consistent with prior studies of Pacific sleeper sharks and Greenland sharks [21,48,49]. At a finer-temporal scale, in the northwest fjords of Prince William Sound, seasonal patterns emerged within and across-individuals relative to the variation in vertical movements, ambient temperatures, and horizontal movements that were not previously detected in Alaskan studies [21]. Cluster analysis provided a way to integrate across several metrics and identify periods of time that shared consistent patterns.

In the fall following their release, sharks were aggregated in the main channel of Port Wells and displayed pronounced diel vertical displacements moving into warm and shallow waters at night. The ambient water temperature for sharks over the whole year varied very little from the mean of 5.9 °C, but during the period from October to January, nighttime ambient temperatures routinely exceeded 8 °C. This matches the temporal establishment of thermoclines in Prince William Sound, which form in the spring with solar heating and reach their peak in late autumn [50]. The active excursions of sharks into warmer waters, and the consistent return to deeper, colder waters during the day suggest sharks may be foraging in the upper water column on a specific resource aggregated by/around a thermocline. This has been observed in other benthic sharks like the spiny dogfish (*Scyliorhinus canicula*), which moves into warmer waters only to obtain food and then retreats to cooler waters to potentially enhance digestive assimilation between foraging bouts [5,51].

During the period following the fall active period, from Jan – Feb, all sharks' days were assigned to Cluster 1: dates with the deepest, cold waters and limited vertical movement during the day and night. Cluster 1 designations also occurred at other times of the year, but the prolonged and inter-individual consistent identification during the winter could suggest a strategy of partitioning foraging and resting activity temporally, or seasonal shifts in prey selection from pelagic to benthic scavenging. Data from energetics studies show Pacific sleeper shark metabolic rates are comparable to other non-endothermic sharks, when scaled to temperature [24,52], suggesting a potential caloric intake requirement of one adult sockeye salmon every 2.5-3 days for the average sized shark this

study but as facultative scavengers, Pacific sleeper sharks also likely consume discarded bycatch in addition to natural carrion. Most of the diet information for Pacific sleeper sharks is temporally constrained to summer months [45], therefore the fall and winter behaviors observed here suggest the importance of conducting diet studies for Pacific sleeper sharks outside of the summer period.

In the spring (Feb-Jul), most animals appeared to move from the deep open channel of the fjord into the shallow bathymetry glacial areas and the cluster analysis conducted across all individuals combined revealed two distinct behavioral groups during this time (Cluster 3 and 4). When looking at which individuals whose mrPAT tags were observed near the glacier in spring (SP22-13, 14, 15, 16), the same individuals' dates were primarily assigned to Cluster 3, confirming the spatial and behavioral patterns were associated. Similar seasonal variation in habitat use has been observed across a range of sharks and rays, often driven by temperate or prey dynamics [2,8–10]. In Baffin Bay, Greenland shark presence in coastal fjords and offshore waters followed patterns of sea-ice formation and retreat, with fjords only being used during ice-free periods in the summer [10]. Prince William Sound and the Gulf of Alaska do not form sea-ice, but many pagophilic fish, birds, and mammals rely on ice input from tidewater glaciers into the marine environment for critical reproductive and energetically costly periods of their life histories [53–55], or as refuge habitats during adverse conditions [56]. Rapid acceleration and thinning of tidewater glaciers has been observed across Arctic coastal fjord regions, including Greenland [57] and Alaska [58].

High-resolution sampling of in situ abiotic and biotic environmental characteristics by animal-borne tags is considered adaptive sampling, since animals often seek areas of physical and biological interest [59]. Adaptive sampling is essential not only for understanding behaviors and food web interactions of keystone and critical species, but it may also functionally enable the use of marine top predators such as sharks as climate and ecosystem sentinels [60–62]. Focusing on this period of shallow tidewater glacier habitat use in the future may assist in assessments of how adaptive Pacific sleeper sharks are to shifts in their prey availability or changes in thermal profiles such as those observed during the Pacific marine heat wave [18–20]. The high degree of residency among individuals observed in this study also suggests that physically recoverable, high-resolution behavioral and environmental samplers could be deployed on PSS as platforms of opportunity in this region, in turn enabling the use of PSS as climate and ecosystem sentinels.

**Supplementary Materials:** The following supporting information can be downloaded at the website of this paper posted on Preprints.org.

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## Abbreviations

The following abbreviations are used in this manuscript:

PSS	Pacific sleeper shark
PWS	Prince William Sound
HMM	Hidden Markov model

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