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# <sup>1</sup> Spring haul-out behavior of seals in the Bering and Chukchi seas

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## <sup>14</sup> ABSTRACT

<sup>15</sup> Ice-associated seals rely on sea ice for a variety of activities, including pupping, breeding, molting, and resting. In  
<sup>16</sup> the Arctic, many of these activities occur in spring (April – June) as sea ice begins to melt and retreat northward.  
<sup>17</sup> Rapid acceleration of climate change in Arctic ecosystems is therefore of concern as the quantity and quality  
<sup>18</sup> of suitable habitat is forecast to decrease. Improved estimates of seal population abundance are needed to  
<sup>19</sup> properly monitor the impacts of these changes over time. In this paper, we use hourly percent-dry data from  
<sup>20</sup> satellite-linked bio-loggers deployed between 2005 and 2021 to quantify the proportion of seals hauled out on  
<sup>21</sup> ice. This information is needed to accurately estimate abundance from aerial survey counts of ice-associated  
<sup>22</sup> seals (i.e., to correct for the proportion of animals that are in the water while surveys are conducted). In addition  
<sup>23</sup> to providing essential data for survey ‘availability’ calculations, our analysis also provides insights into the  
<sup>24</sup> seasonal timing and environmental factors affecting haul-out behavior by ice-associated seals. We specifically  
<sup>25</sup> focused on bearded (*Erignathus barbatus*), ribbon (*Histriophoca fasciata*), and spotted seals (*Phoca largha*) in the  
<sup>26</sup> Bering and Chukchi seas. Because ringed seals (*Phoca (pusa) hispida*) can be out of the water but hidden from  
<sup>27</sup> view in snow lairs analysis of their ‘availability’ to surveys requires special consideration; therefore, they were  
<sup>28</sup> not included in this analysis. Using generalized linear mixed pseudo-models to properly account for temporal  
<sup>29</sup> autocorrelation, we fit models with covariates of interest (e.g., day-of-year, solar hour, age-sex class, wind  
<sup>30</sup> speed, barometric pressure, temperature, precipitation) to examine their ability to explain variation in haul-out  
<sup>31</sup> probability. We found evidence for strong diel and within-season patterns in haul-out behavior, as well as strong  
<sup>32</sup> weather effects (particularly wind and temperature). In general, seals were more likely to haul out on ice in the  
<sup>33</sup> middle of the day and when wind speed was low and temperatures were higher. Haul-out probability increased  
<sup>34</sup> through March and April, peaking in May and early June before declining again. The timing and frequency of  
<sup>35</sup> haul-out events also varied based on species and age-sex class. For ribbon and spotted seals, models with year  
<sup>36</sup> effects were highly supported, indicating that the timing and magnitude of haul-out behavior varied among  
<sup>37</sup> years. However, we did not find broad evidence that haul-out timing was linked to annual sea-ice extent. Our  
<sup>38</sup> analysis emphasizes the importance of accounting for seasonal and temporal variation in haul-out behavior, as  
<sup>39</sup> well as associated environmental covariates, when interpreting the number of seals counted in aerial surveys.

40 INTRODUCTION

41 Global climate disruption is causing considerable reduction in Arctic sea ice extent, volume, and  
42 seasonal presence (Meier et al., 2014; Wang et al., 2018; Kwok, 2018; Overland, 2021). These  
43 changes have tangible effects on Arctic organisms, ecosystems, and the people who live in the region  
44 (Huntington et al., 2020). Such disruptions are a particular cause of concern for the ice-associated  
45 seals that depend on spring and early summer sea ice (March-June) in the Bering and Chukchi  
46 seas as a platform for important life history functions, such as pupping, nursing, breeding behavior,  
47 and molting (Boveng et al., 2009, 2013; Cameron et al., 2010; Kelly et al., 2010). Limited data and  
48 large knowledge gaps complicate predictions about the ultimate effects of changes in sea ice on the  
49 behavior, health, abundance, and distribution of these seals. To date, indices of seal health sampled  
50 during periods of declining sea ice differ regionally (Crawford, Quakenbush & Citta, 2015; Harwood  
51 et al., 2020). Knowledge about evolutionary constraints on the timing of reproductive and molting  
52 behavior is generally lacking, so it is difficult to predict how or if ice-associated seal species will  
53 adjust to future changes (e.g., by adjusting pupping or molting schedules to earlier dates or different  
54 locales). This is further complicated by the spatio-temporal variation in the phenology of these life  
55 history events within regions and throughout their full ranges. Additionally, trends in abundance of  
56 these species are unknown, so it is difficult to assess the effect, if any, declines in sea-ice habitat have  
57 had, or will have, on seal demography.

58 Statutory requirements (e.g., United States Marine Mammal Protection Act (MMPA), United  
59 States Endangered Species Act (ESA)) for timely estimates of population abundance and trend mean  
60 improved aerial survey effort is needed for these species. Those survey efforts must also be paired  
61 with improved knowledge of haul-out behavior to ensure appropriate survey design, robust methods,  
62 and accurate estimates. Several studies have contributed estimates of the distribution and abundance  
63 of ice-associated seal species in the Arctic using aerial surveys (e.g., Bengtson et al. (2005), Conn et al.  
64 (2014), and Ver Hoef et al. (2014)) and more recent efforts have significantly expanded on previous  
65 survey effort. Such abundance studies are conducted over very large areas and estimation of absolute  
66 abundance requires making inference about numerous issues affecting the observation of seals on  
67 ice. These include availability (only seals on ice are available to be counted), detection probability  
68 (observers or automated detection systems may miss some seals on ice), species misclassification,  
69 and possible disturbance of seals by aircraft (Ver Hoef et al., 2014; Conn et al., 2014). Refining  
70 these inferences will improve the accuracy of abundance estimates and, hopefully, allow credible  
71 predictions about the effects of climate disruptions on the abundance and distribution of Arctic seal  
72 populations.

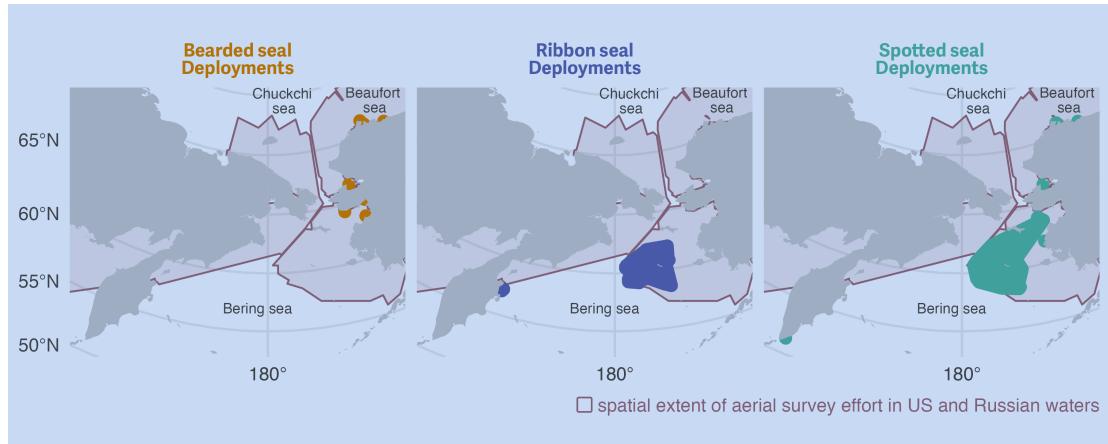
73 How ice-associated seals use sea ice as a haul-out platform varies among species. Ribbon seals  
74 (*Histriophoca fasciata*) haul out of the water almost exclusively on sea ice and are mostly pelagic  
75 outside the spring pupping, breeding, and molting season (Boveng & Lowry, 2018). Although  
76 spotted (*Phoca largha*) and bearded (*Erignathus barbatus*) seals occasionally rest on coastal land,  
77 they primarily use sea ice as a haul-out platform during the spring and early summer (Frost & Burns,  
78 2018). Ringed seals (*Phoca (pusa) hispida*) — not included in this study — haul out on sea-ice but  
79 primarily use snow lairs on sea-ice during winter and spring.

80 The remoteness of the Bering and Chukchi seas means direct scientific observation of seal behavior  
81 is impractical. Thus, bio-logging devices are especially useful tools for collecting key information  
82 on movement and haul-out behavior for these species. Bio-logging records of time spent out of the  
83 water provide valuable data for identifying covariates that explain variation in haul-out behavior. For

84 instance, Von Duyke et al. (2020) used satellite-linked bio-loggers to corroborate seasonal changes  
85 between diurnal and nocturnal haul-out behavior of ringed seals previously described by Kelly and  
86 Quakenbush (1990) using VHF radio tags and direct observation. Bengtson et al. (2005) documented  
87 a higher propensity for ringed seal basking near solar noon, as did Ver Hoef et al. (2014) in an analysis  
88 of bearded, ribbon, and spotted seals using much larger sample sizes. Olnes et al. (2020) showed  
89 that the proportion of time bearded seals spent hauled out progressively increased through spring  
90 and summer, and Ver Hoef et al. (2014) found haul-out probabilities increased gradually starting in  
91 March and peaked in May and June for bearded, ribbon, and spotted seals. Such analyses have not  
92 been limited to the Arctic. In the Antarctic, Bengtson and Cameron (2004) relied on bio-logging data  
93 to demonstrate greater haul-out propensity in juvenile crabeater seals (*Lobodon carcinophaga*) than  
94 adults, with highest probabilities in February and at times close to solar noon.

95 Knowledge of haul-out patterns is not only important for understanding natural history and  
96 ecology, but also for developing “availability” correction factors for aerial surveys. Specifically,  
97 researchers need to know the fraction of seals hauled out (versus in the water) when aerial surveys are  
98 conducted. Studies estimating availability correction factors for seals typically use logistic regression-  
99 style analyses to estimate the time-specific probability of being hauled out based on ‘wet/dry’ data  
100 relayed by bio-loggers. In these models, haul-out probabilities were expressed as a function of  
101 predictive covariates, such as time-of-day, day-of-year, sex, age class, and environmental conditions  
102 (e.g., Reder et al. (2003), Bengtson & Cameron (2004), Bengtson et al. (2005), Udevitz et al. (2009),  
103 Lonergan et al. (2013), Ver Hoef et al. (2014), Southwell et al. (2008), and Niemi et al. (2023)).  
104 However, sample sizes have often been insufficient to permit strong inference about demographic  
105 and/or seasonal variation in haul-out probabilities. For instance, Bengtson and Cameron’s (2004)  
106 study included 5 adult and 2 juvenile crabeater seals, while Bengtson et al.’s (2005) study was based on  
107 6 ringed seals in the Chukchi and Beaufort seas. These studies were often further limited by logistical  
108 constraints on fieldwork and the attachment duration or operational life of bio-loggers. In this study,  
109 we addressed some of these limitations by deploying small bio-loggers designed for longer-term  
110 attachment on rear flippers of a subset of the study individuals. These devices are designed to collect  
111 data through the molt period (when those adhered to the hair would fall off) and, in some situations,  
112 provide multiple years of data.

113 In this study, we used 16 years of bio-logging data to investigate the haul-out behavior of bearded,  
114 ribbon, and spotted seals in the Bering and Chukchi seas. Our goals were threefold. First, we wished  
115 to establish baseline estimates for the chronology of haul-out behavior in the critical spring season  
116 for each species across different age and sex classes. Second, we sought to refine estimates of haul-out  
117 availability corrections for aerial surveys in order to improve estimates of seal abundance. Previously  
118 estimated availability correction factors (e.g., Bengtson et al. (2005), Conn et al. (2014), and Ver  
119 Hoef et al. (2014)) accounted for variables such as the time-of-day and day-of-year, but did not  
120 investigate the impact of weather variables. Such variables have been shown to influence walrus  
121 haul-out behavior (Udevitz et al., 2009) and we expect weather conditions to also influence seal  
122 haul-out behavior and including them within the model framework will benefit our estimates of seal  
123 availability during aerial surveys. Third, we aimed to assess the annual variability in haul-out timing  
124 and possible linkage to changes in the extent of seasonal sea ice between 2005 and 2021. Our work  
125 extends the scope of previous haul-out analyses, includes the influence of weather variability, and  
126 investigates the potential impact of changing sea-ice extent on the behavior of these species.



**Figure 1. Initial bio getLogger deployment areas for bearded, ribbon, and spotted seals in the study between 2005 and 2020 across multiple regions within the Bering, Chukchi, and western Beaufort seas.**

Solid regions shown for each species are minimum concave polygons buffered by 60 km for enhanced visibility. The larger, shaded region indicates the spatial extent of aerial survey effort to date in the Bering, Chukchi, and Beaufort seas. Deployments were initiated across a range of months but only haul-out data from 1 March to 15 July were included in the analysis. See Figure 3 for the spatial distribution of observed data used in the study and Supplemental Materials S1 for additional deployment details.

## 127 METHODS

### 128 Data collection

129 For this study we used haul-out behavior data and location estimates from bio-loggers deployed on  
 130 bearded, ribbon, and spotted seals in the Bering, Chukchi, and western Beaufort seas by multiple  
 131 organizations as part of collaborative investigations from 2005 through 2021. Seals were captured  
 132 using nets and bio-loggers were attached during studies based in coastal communities or on research  
 133 ships. Ship-based capture events occurred during spring near the southern ice edge in the Bering  
 134 Sea between 2005 and 2018. Land-based capture events occurred between 2005 and 2020 from May  
 135 to October, generally between the Alaska coastal communities of Scammon Bay in the Bering Sea,  
 136 Utqiagvik in the Chukchi Sea, and Nuiqsut in the Beaufort Sea (Supplemental Material, S1). Data  
 137 from additional deployments along the Kamchatka peninsula in the western Bering Sea are also  
 138 included. We refer readers to Figure 1 and the primary literature for detailed capture and bio logger  
 139 attachment methods (see also Supplemental Material, S1).

140 We created a subset of haul-out behavior data from 250 bio-loggers deployed on 35 bearded, 110  
 141 ribbon, and 105 spotted seals to include only records from 1 March to 15 July between 2005 and  
 142 2021. Bio-loggers were of the 'SPLASH' or 'SPOT' family of tags developed by Wildlife Computers  
 143 (Redmond, Washington, USA). Deployments consisted of either a single 'SPLASH' device, a single  
 144 'SPOT' device, or both types. Devices were either adhered to the hair on the seal or attached through  
 145 the rear flipper inter-digital webbing. The use of bio-loggers adhered to the back or head provides  
 146 some benefits over flipper mounted devices (e.g. increased satellite transmittal rates, locations at  
 147 sea) but these fall off during the following annual molt, which, depending on deployment date,  
 148 limits the duration of haul-out data they provide especially during the focus months of our study.

149 Additionally, bio-loggers attached to the head or dorsal region are often dry while the seal is floating at  
 150 the surface, inducing a slight positive bias in the hourly percent-dry values reported by the bio-logger.  
 151 For this study, in cases where both bio-logger types were deployed, we preferred hourly percent-dry  
 152 observations from the flipper tag. All data were transmitted by the deployed instruments via the  
 153 Argos satellite network and location data were either derived from Argos transmissions or transmitted  
 154 FastLoc GPS data.

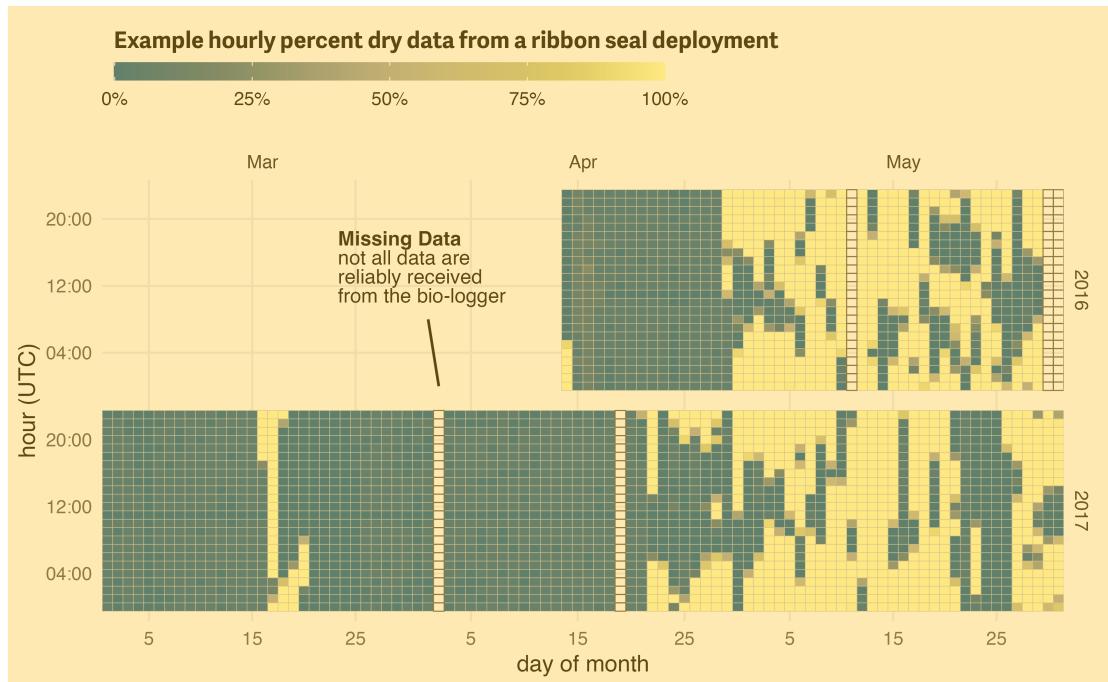
155 Sex and age class (non-dependent *young-of-the-year*, sexually immature *subadults*, and mature  
 156 *adults*) were estimated at the time of deployment by various combinations of length, claw growth  
 157 ridges (McLaren, 1958), and pelage characteristics. Seals determined to be less than one year were  
 158 classified as young-of-the-year. For those bio-loggers deployed on young-of-the-year and transmitting  
 159 into the next year, the age class was advanced to subadult on 1 March of the following year – the  
 160 assumed anniversary of their birth. Subadults are those seals likely greater than one year of age but  
 161 less than four years. Adults are individuals that are likely older than four years. Table 1 provides a  
 162 summary of these deployments and data received from them.

**Table 1. Summary of bio-logger data by seal species and age classification from 1 March to 15 July 2005-2021.**

Seal hours represents the sum of hourly observations across all seals used in the analysis. Because young-of-the-year are advanced to subadult on 1 March of the following year, some individual seals are represented in both columns in this table

Species	Sex	Age Class		
		Adult	Subadult	Young-of-the-Year
Bearded seal	F	1 ( 1,776 seal hours)	16 (21,648 seal hours)	
Bearded seal	M	2 ( 2,108 seal hours)	16 (17,232 seal hours)	
Ribbon seal	F	33 (35,128 seal hours)	18 (15,984 seal hours)	13 ( 3,734 seal hours)
Ribbon seal	M	24 (27,465 seal hours)	19 (13,046 seal hours)	9 ( 4,228 seal hours)
Spotted seal	F	23 (21,588 seal hours)	21 (19,559 seal hours)	11 (13,417 seal hours)
Spotted seal	M	20 (31,793 seal hours)	21 (17,210 seal hours)	12 (11,285 seal hours)

163 Haul-out behavior data were recorded in a manner standard across Wildlife Computers bio-  
 164 loggers and transmitted via the Argos satellite network as hourly percent-dry timelines. For each  
 165 hour of a day, the wet/dry sensor was polled by the tag firmware every few seconds and the percent  
 166 of the hour in the dry state was calculated (Figure 2). On board the bio-logger, hourly percent-dry  
 167 calculations were rounded to the nearest 10% inclusive of 0% and 100% along with additional values  
 168 at 3% and 98%. This compression resulted in additional data transmission as each message consisted  
 169 of two complete 24-hour records. Memory capacity allowed caching of percent-dry records for several  
 170 weeks or months and each message was transmitted several times to ensure reception at the satellite.  
 171 Bio-loggers were deployed and programmed in a manner to maximize data transmission during the  
 172 spring pupping and molting period, though hourly percent-dry data were not always successfully  
 173 transmitted. This is due to a variety of factors including satellite coverage, tag availability (e.g., tags



**Figure 2. Example percent-dry actogram from bio-logger data**

Haul-out behavior observations recorded by a bio-logger deployed on a ribbon seal over two years during the months of March, April, and May. This actogram plot represents the transmitted hourly percent-dry values. Not all data during a deployment are reliably transmitted from the bio-logger and because data are transmitted in 24-hour chunks occasional missing days are present in the record. Here, missing data that were not successfully received from the device are represented as empty rectangles.

174 mounted to the rear flipper often do not transmit while at sea), tag performance, duty cycling, and  
 175 atmospheric interference. Fortunately, missing records do not substantially bias inference about  
 176 haul-out probabilities (Conn et al., 2012).

177 Tags that fell off due to molt, attachment failure, or seal mortality and remained on ice or land  
 178 may have continued to send data to satellites; i.e., a detached bio-logger that is dry (either on ice  
 179 or land) will record and transmit data suggesting the seal is hauled out. Therefore, end times of  
 180 each deployment were identified by examining bio-logger locations, percent-dry records, and dive  
 181 behavior (if available) to determine when bio-loggers ceased providing data consistent with seal  
 182 behavior. For example, a data record that ended with several consecutive days (~10+ days) of 100%  
 183 dry observations and with locations indicating the tag was on land were truncated to the final stretch  
 184 of 100% dry observations. The vast majority of deployments ended with the device detaching in  
 185 the water and the deployment end date was obvious. There is no perfect algorithm for identifying  
 186 deployment end dates and each deployment in question was considered separately. While not perfect,  
 187 we are confident our reliance on expert opinion and examination of multiple data streams provided  
 188 the best option. Data outside of the deployment start and end times were discarded prior to analysis.

189 Of key interest in this study was the relationship between haul-out behavior and weather covariates  
 190 that vary with time and seal location. The use of modern bio-loggers that record and transmit  
 191 behavioral data while simultaneously providing location estimates was key to this objective. We

192 explored the use of a continuous-time correlated random walk (Johnson et al., 2008) movement  
193 model to predict locations at specific times. However, the sparse nature of data from some bio-loggers,  
194 especially those mounted to the rear flipper, resulted in poor modeling performance or convergence  
195 issues. For this study, we calculated a weighted average daily location where the inverse of the  
196 estimated Argos or FastLoc GPS location error was used for the weight. Each Argos location estimate  
197 was assigned an error radius based on either the categorical location quality ( $3 = 250$  m,  $2 = 500$  m,  
198  $1 = 1500$  m,  $0 = 2500$  m (Lopez et al., 2013); we chose 2500 m for location classes A and B) or, when  
199 available, the estimated error radius from the Argos Kalman filter algorithm. Location estimates  
200 from FastLoc GPS were all assigned an error radius of 50 m. On days when haul-out observations  
201 were present but location data were missing we used the seal's last calculated weighted average  
202 daily location; days when the location intersected with land were removed from the seal's record.  
203 We recognize that bearded and spotted seals haul out on land. However, assessing the relationship  
204 between haul-out behavior and weather covariates and seals' availability for aerial surveys on land  
205 was outside the scope of this study. Additionally, any daily locations on land were likely more  
206 reflective of coordinate averaging and measurement error, rather than actual use of coastal features.

### 207 Explanatory variables

208 In addition to sex and age class, we analyzed variables that might help explain variation in haul-out  
209 probabilities. These included day-of-year (for seasonal effects) and local solar hour (for diurnal  
210 effects). We calculated local solar hour using the {solarR} package (Perpiñán, 2012) within the R  
211 statistical environment (R Core Team, 2021) based on the weighted daily average locations. We also  
212 linked the weighted average daily locations to weather values from the North American Regional  
213 Reanalysis (NARR) model produced by the National Centers for Environmental Prediction (Mesinger  
214 et al., 2006). The NARR model assimilates observational data to produce a long-term picture of  
215 weather over North America and portions of the surrounding seas. Weather variables are made  
216 available across the region 8 times daily. For this study, NARR weather values were limited to the  
217 extent of our study area over the Bering, Chukchi, and Beaufort seas at 3-hr intervals based on the  
218 original grid resolution of 32 km ( $1024 \text{ km}^2$ ). The following weather variables are known to affect  
219 haul-out behavior in other Arctic pinnipeds (Reder et al., 2003; Udevitz et al., 2009; Perry, Stenson &  
220 Buren, 2017) and were interpolated and assigned to daily seal locations using a bilinear method: 1)  
221 air temperature at 2 m above the Earth's surface, 2) wind consisting of northerly and easterly vector  
222 components converted to wind speed using the Euclidean norm, 3) barometric pressure at sea level,  
223 and 4) precipitation (Table 2).

224 For all seal species, we considered the following variables when modeling the hourly haul-out  
225 behavior: day-of-year, solar hour, temperature, wind speed, barometric pressure, precipitation, and  
226 wind chill (represented by a *wind:temperature* interaction (Udevitz et al., 2009)). Ribbon and spotted  
227 seal models included age-sex class and interactions between day-of-year and age-sex class, but we  
228 omitted these from bearded seal models due to poor representation of age-sex classes (Table 1).  
229 Bearded seal models included a latitudinal effect (and an interaction with day-of-year), because  
230 bearded seals occupy a substantial range during the spring and we were interested in possible  
231 differences in the timing of haul-out behavior along a latitudinal gradient. We omitted the latitudinal  
232 effect from ribbon and spotted seal models because, during the spring, these species are most prevalent  
233 near the southern ice edge in the Bering Sea (Conn et al., 2014).



**Table 2. Explanatory covariates used in analyses of binary haul-out records for bearded, spotted, and ribbon seals.**

Note that we also considered select interactions (see article text) between these primary covariates. For instance, wind chill was represented by the interaction temperature:wind.

Covariate	Type	Description
Age-sex class	Categorical	young-of-the-year, subadult, adult male and adult female
Hour	Continuous; Fourier basis	local solar hour using 6 variables of Fourier-series basis
Day	Continuous	linear, quadratic, and cubic effects of day-of-year
Precip	Continuous	convective precipitation kg/m <sup>2</sup> (NARR)
Pressure	Continuous	atmospheric pressure at sea level (kPa) (NARR)
Temp	Continuous	air temperature (C) at 2m above the earth's surface (NARR)
Wind	Continuous	northly and easterly vector components for wind (NARR) converted into a single wind speed via the Euclidean norm
Northing	Continuous	latitude divided by the mean latitude across all locations (for bearded seals only)
Year	Continuous	For the set of models examining inter-annual variation in sea ice use, we fitted models with the addition of year by day-of-year interactions

234

### Haul-out modeling

235

Haul-out records for seals are often characterized by sequential hours spent hauled out on ice alternating with long periods in the water (Figure 2). Commonly used statistical models for binary data (e.g. logistic regression) assume independence among responses, an assumption that is clearly violated if hourly responses are modeled. Any analysis that ignores temporal autocorrelation in responses will thus have overstated precision (Betts et al., 2006).

240

To properly account for temporal dependence and to take advantage of computational efficiency, we used generalized linear mixed pseudo-models (GLMPMs; Ver Hoef, London & Boveng (2010)) to model variation in haul-out behavior as a function of (1) covariate predictors, (2) temporally autocorrelated random effects, and (3) individual random effects representing heterogeneity in individual behavior. We used the glmmLDT package (Ver Hoef, London & Boveng, 2010) to implement GLMPMs. We explored two different model formulations for our data and we fit separate models to bearded, ribbon, and spotted seal data sets as we expected differing behavior by species. Separate models for each species were also needed because a single, very large data set proved computationally intractable. In our first model formulation and for each species, we fitted a year-

249 independent model that predicted average haul-out behavior as a function of demographic, weather,  
 250 seasonal, and diurnal effects. Second, for ribbon and spotted seals (which had considerably more  
 251 data than bearded seals), we fitted models that included all the effects from the first model, but  
 252 also permitted annual variation in haul-out timing. This second set of models was used to examine  
 253 whether haul-out patterns varied by year and to determine the annual timing of apparent peaks in  
 254 haul-out behavior. For both models, we assumed an hourly Bernoulli response (a binary 0-1 response  
 255 dependent upon whether the tag was greater than 50% dry for a given hour) where the linear predictor  
 256 was modeled on the logit scale. This is consistent with previous approaches (London et al., 2012; Ver  
 257 Hoef et al., 2014) and only 6.995% of our observations fell between 10% and 90% hourly percent-dry.  
 258 We followed Ver Hoef et al. (2014) in using linear, quadratic, and cubic effects of day-of-year  
 259 to represent temporal changes in behavior during the season. However, unlike previous models  
 260 for harbor seals (London et al., 2012) and ice-associated seals (Ver Hoef et al., 2014), which treated  
 261 hour-of-day as a 24-level categorical variable to capture diurnal cycles, we adopted a continuous  
 262 formulation based on Fourier series that provides a flexible model while preserving the inherent  
 263 circularity needed for time-of-day effects (i.e., hour 0 should be equal to hour 24). It also represents  
 264 hour-of-day with 6 parameters, which is a considerable reduction when compared to a 24-parameter  
 265 variable. According to this approach, we used the following specification for hour-of-day effects:

$$H_t = \alpha_1 \cos\left(\frac{\pi t}{4}\right) + \alpha_2 \sin\left(\frac{\pi t}{4}\right) + \alpha_3 \cos\left(\frac{\pi t}{6}\right) + \alpha_4 \sin\left(\frac{\pi t}{6}\right) + \alpha_5 \cos\left(\frac{\pi t}{12}\right) + \alpha_6 \sin\left(\frac{\pi t}{12}\right)$$

266 where  $H_t$  gives the effect for solar hour  $t$  and  $\alpha_i$  are estimated parameters (regression coefficients).  
 267 For the second set of models examining inter-annual variation in sea ice use, we fitted models  
 268 with year by day-of-year interactions. However, in this case we only included  $year:day$  and  $year:day^2$ ,  
 269 omitting the main effects of year as well as  $year:day^3$  interactions because models with the latter  
 270 effects were numerically unstable. However, the modeled interactions were sufficient to allow shifts  
 271 in haul-out distribution, as one can show mathematically that a simple horizontal shift in timing  
 272 of haul-out distributions does not affect the main effects or cubic terms in a polynomial regression  
 273 model. Bearded seals were not included in this examination of inter-annual variation because of  
 274 limited data across many years in the study.

275 A typical model fitting exercise would also include a model selection process. However, AIC  
 276 (and similar criteria) is not suitable when using pseudo-likelihoods, because pseudo-data generated  
 277 in the model fitting process (Ver Hoef, London & Boveng, 2010) differ between models (Ten Eyck  
 278 & Cavanaugh, 2018). After fitting GLMPM models, we instead used “type III”  $F$ -tests to calculate  
 279  $p$ -values (Ver Hoef, London & Boveng, 2010) to evaluate model performance and important terms.  
 280 We also produced predictions of haul-out behavior as a function of three influential predictors  
 281 (e.g. solar hour, day-of-year, age-sex). Weather covariates for these predictions were based on daily  
 282 or hourly smoothed weather covariate values across the study region. Such predictions were then  
 283 used to develop haul-out probability surfaces, explore conditional effects of weather covariates, and  
 284 determine annual peaks in haul-out activity. The timing of peak haul-out behavior was further used  
 285 to regress against the annual maximum sea-ice extent in the study region. Predictions before 15  
 286 March and after 30 June were not included in visualizations or other evaluations to avoid spurious  
 287 model predictions at the edge of the data range.

288 Visualizing the marginal or conditional effect of an individual weather covariate (where all other  
 289 weather covariates are being held at mean values) on haul-out probability was difficult in this analysis

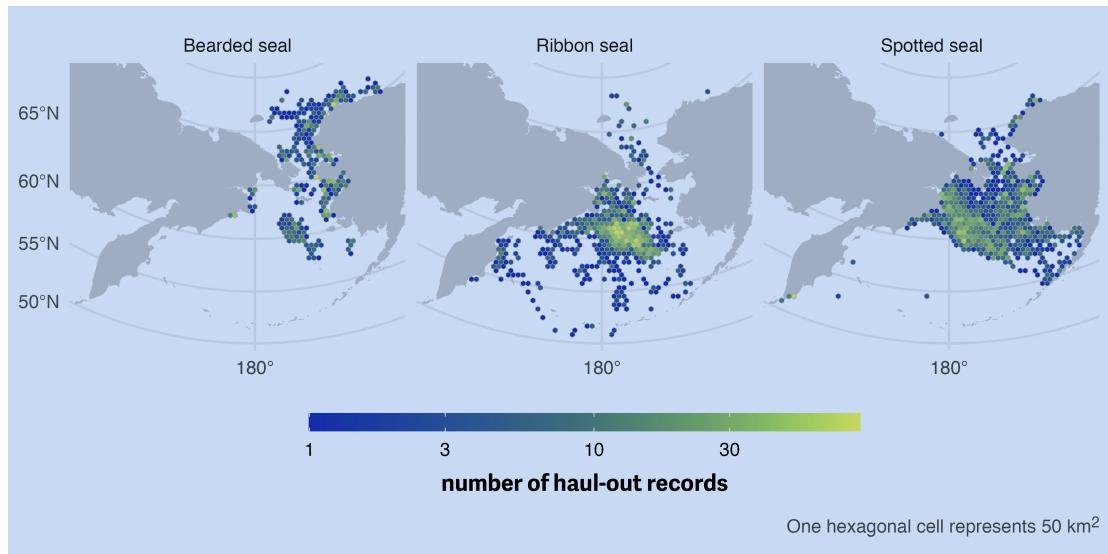
290 because of the collinearity between covariates as well as the spatial and temporal variation across  
291 such a large region. The relationship of each weather covariate with haul-out probability, averaged  
292 over the other weather conditions, was more variable than model coefficients would imply. That said,  
293 important insights can be gained from plots of marginal effects. To create these plots, we predicted  
294 haul-out probability across the full range of each weather covariate while fixing hour of the day at  
295 local solar noon and day-of-year at 15 May. For the other weather covariate values, we chose not  
296 to use a fixed mean value because we expect weather to vary within day over the season (e.g. the  
297 temperature at solar noon will gradually increase from March through June). To account for this, we  
298 fit a simple generalized additive model for each weather covariate with smooth terms for day-of-year  
299 and solar hour. We used predicted values from the generalized additive model in lieu of holding  
300 other weather covariates at a fixed mean value which would not capture seasonal change. The  
301 visualizations also include vertical lines representing 95% confidence intervals around the predicted  
302 haul-out probability to better communicate the variation in model uncertainty.

303 We also assessed whether the annual variation in maximum spring sea-ice extent in the Bering Sea  
304 influenced the seasonal peak of seal haul-out probability. In particular, we used sea ice concentration  
305 data from the Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Dataset, Version 1  
306 (Cavalieri et al., 1996) to calculate maximum sea-ice extent. All sea ice concentration grid cells (25  
307 km<sup>2</sup>) in the study area with greater than 15% concentration were counted daily to get the total sea ice  
308 extent for each day between 15 February and 15 July across all years. Maximum spring sea-ice extent  
309 was simply the largest daily count of grid cells with greater than 15% concentration for each year.  
310 A separate regression model, built on the results of the haul-out model, was used to evaluate the  
311 relationship between the annual computed peak haul-out day (as the response) with the maximum  
312 sea-ice extent (as the predictor).

## 313 RESULTS

314 Figure 3 shows the spatial distribution of weighted locations with available haul-out behavior data  
315 used for analysis of each species across the study area. Figure 4 shows the temporal distribution of  
316 all haul-out data across the study season for each species. Observations of ribbon and spotted seals  
317 were concentrated in the months of May and June due to the timing of deployment (April and May)  
318 and the timing of molt (May and June). During molt, seals (and their attached bio-loggers) spend  
319 more time out of the water and more data are transmitted. Molt timing also impacts when many  
320 deployments end as any bio-loggers adhered to the hair will fall off. Relative to the other species in  
321 the study, there were fewer deployments of bio-loggers on bearded seals. This resulted in fewer data  
322 observations overall and noticeably lower in numbers May and June. The majority of deployments  
323 on bearded seals occurred in August and September and, by May, bio-loggers had either fallen off or  
324 their batteries were depleted. Therefore, observations for bearded seals were concentrated in March  
325 (Figure 4).

326 Across all three seal species, generally, models omitting year effects suggested that day-of-year,  
327 solar hour, age-sex class, temperature, and wind substantially influenced haul-out behavior of all  
328 three species, with *F* tests producing *p*-values less than 0.05 for variables embodying these effects  
329 and/or their interactions. Haul-out probabilities typically increased throughout March and April,  
330 reaching a peak in May and early June before declining again. Diurnal patterns were present, with  
331 maximum haul-out behavior centered around local solar noon.



**Figure 3. Spatial distribution of haul-out records from 1 March through July 15 for bearded, ribbon, and spotted seal.**

Linking location estimates with haul-out records in space and time allows for inclusion of weather covariates in the final model. For this visualization, data were collated across all years between 2005 and 2020 and each hexagonal cell represents an area of 50 km<sup>2</sup>

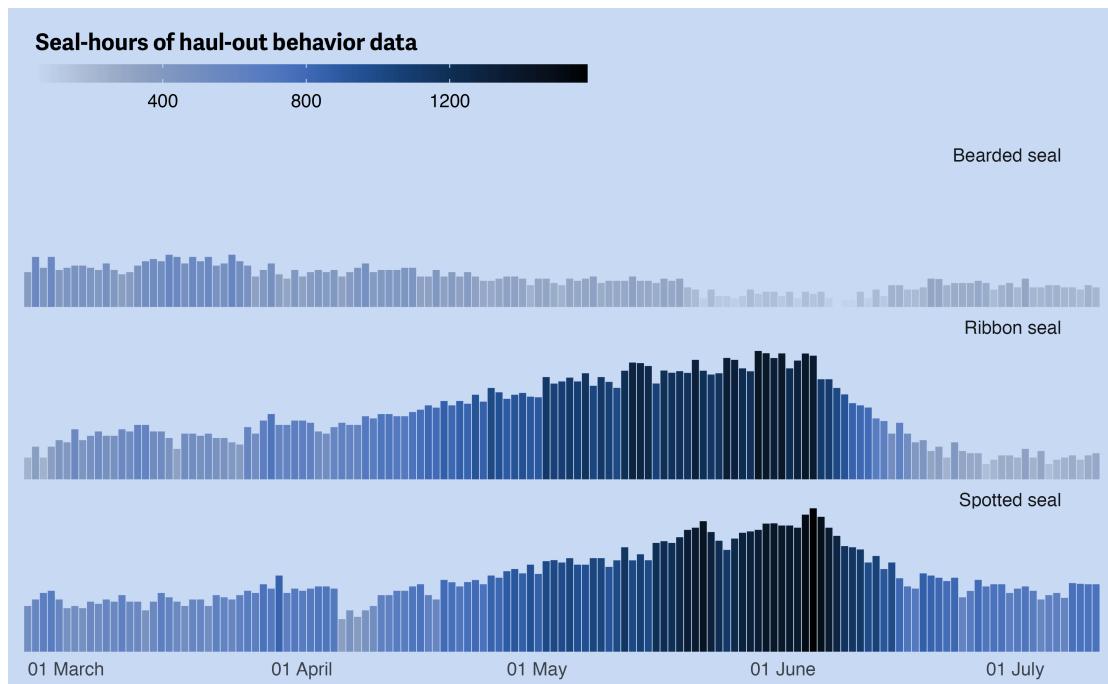
### 332 **Bearded Seals**

333 Age and sex class were not included in the model for bearded seals due to our lower sample size for  
 334 adult and young-of-year age classes. As such, results are shown for all ages (Figure 5; see also S1).  
 335 Additionally, after approximately 9 months, 7 devices deployed on the rear flipper of bearded seals  
 336 reported implausible hourly percent-dry data (100% dry for several weeks but indicative of movement  
 337 and increasing transmission rates (see Boveng & Cameron (2013))). All data after the first instance of  
 338 unrealistic values were censored from this analysis. In addition to a peak around local solar noon, the  
 339 bearded seal model predicted additional haul-out activity around local midnight. In concert with the  
 340 lower magnitude of haul-out probability, bearded seal haul-out behavior was also more protracted  
 341 throughout the spring season compared to ribbon (Figure 7) and spotted seals (Figure 9). Overall,  
 342 bearded seals were less likely to haul out and had a bi-modal distribution of haul-out probability  
 343 across the day.

344 When exploring the influence of weather, bearded seal haul-out probability was strongly affected  
 345 by wind ( $F_{1,42728} = 130.468$ ;  $p = <0.001$ ) and temperature ( $F_{1,42728} = 19.5$ ;  $p = <0.001$ ) with much  
 346 higher haul-out probability during periods of higher temperatures and low wind speeds (Figure 6).  
 347 Not surprisingly, wind chill ( $F_{1,42728} = 14.54$ ;  $p = <0.001$ ) was also important. Barometric pressure  
 348 ( $F_{1,42728} = 7.779$ ;  $p = 0.005$ ) was also significant factor although less apparent (Figure 6). Any effect  
 349 of precipitation was not a significant influence on haul-out probability ( $F_{1,42728} = 0.519$ ;  $p = 0.471$ ).

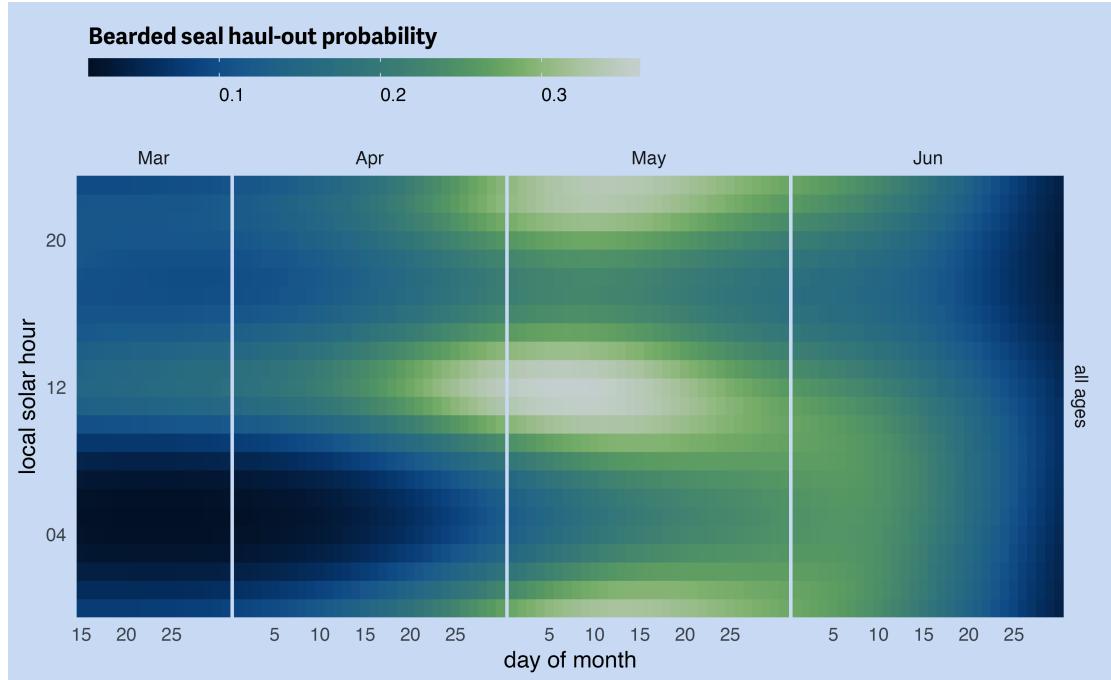
### 350 **Ribbon Seals**

351 Ribbon seals exhibited a pattern of gradually increasing haul-out probability in April that peaks in late  
 352 May for subadults and in early June for adults (Figure 7; see also S2). There is an apparent seasonal  
 353 progression with subadults hauling out earlier in the season followed by adult males and, then, adult  
 354 females. Haul-out behavior was clearly centered around local solar noon and expanded to other



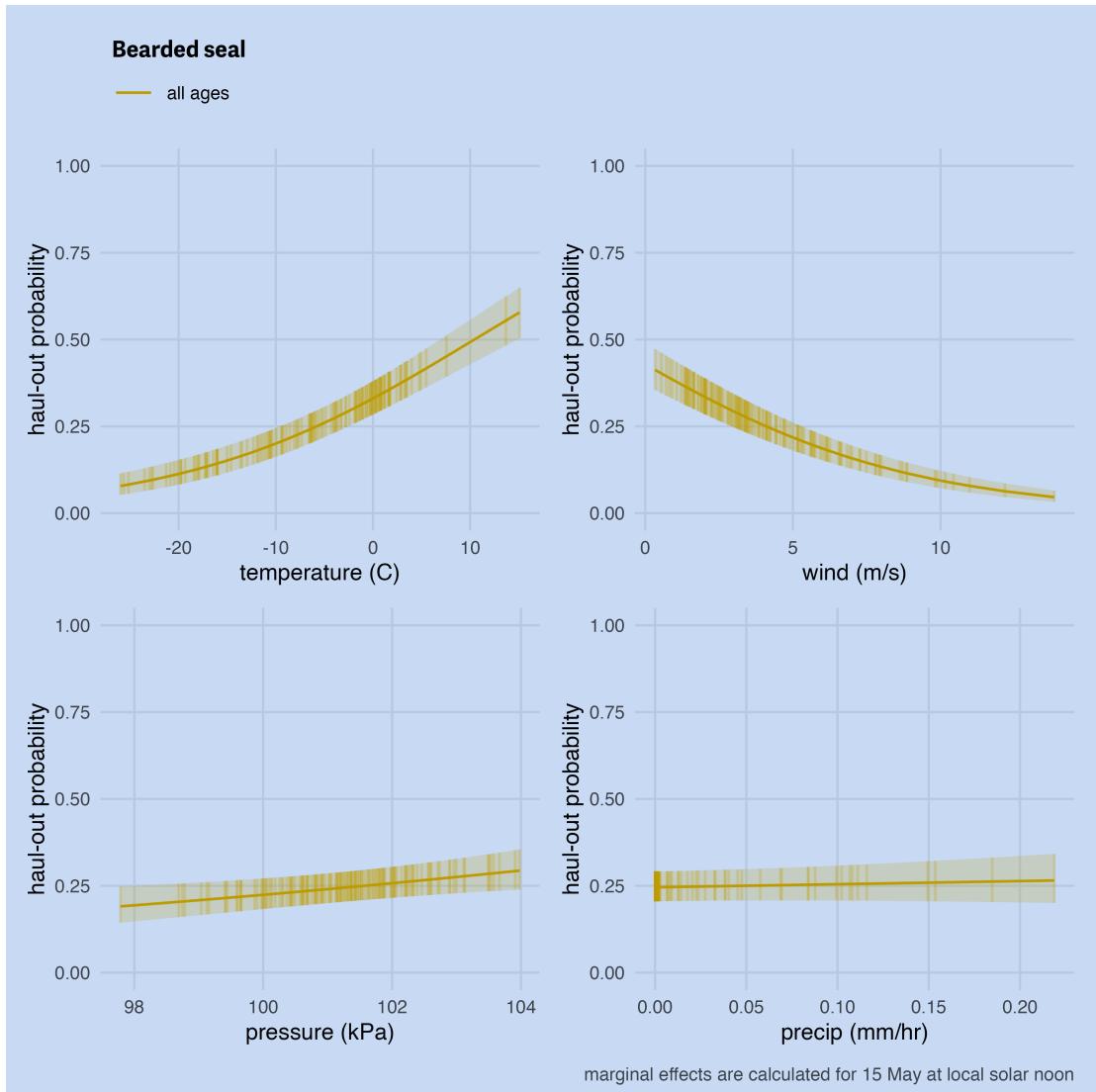
**Figure 4. Seasonal distribution of haul-out behavior observations by species**

Distribution of hourly percent-dry bio-logger data from 1 March to 15 July for each species. Data are grouped by day-of-year and presented in seal-hours collated across all years between 2005 and 2020. Seal-hours of data are represented as a color gradient and bar height. The higher amount of data from May and June in ribbon and spotted seals coincides with peak molting when seals (and their attached bio-loggers) are more likely hauled out. Additionally, many bio-logger deployments started in April and May. The overall reduced quantity of observations from bearded seals is reflective of the lower number of bio-logger deployments in the study and the fact that the majority of deployments on bearded seals occurred in August and September; therefore most bio-loggers deployed had exhausted their batteries.



**Figure 5. Bearded seal predicted haul-out probability**

Predicted hourly haul-out probability of bearded seals (all ages and sex classes) from 15 March to 30 June for all age and sex classes combined. Predictions in July and before 15 March were not included to avoid spurious model predictions at the edge of the data range. Weather covariate values in the prediction were based on a simple generalized additive model for each weather covariate with smooth terms for day-of-year and solar hour to account for anticipated variability within a day over the season. Note, our model predicts lower haul-out probability for bearded seals overall compared to ribbon and spotted seals and the color scales are not directly comparable.



**Figure 6. Influence of weather covariates on bearded seal haul-out probability**

Marginal effects of temperature, wind, barometric pressure, and precipitation on the predicted haul-out probability of bearded seals combined across all age and sex classifications. Hour of the day was fixed at local solar noon and day-of-year fixed at 15 May. The other weather covariate values were predicted from a simple generalized additive model for each weather covariate with smooth terms for day-of-year and solar hour to account for anticipated variability within a day over the season. While the marginal effect of the covariate is continuous, points and vertical lines representing the 95% confidence interval around the predicted haul-out probability are shown only at observed weather values to give an indication of how the observations are distributed across the range of weather values.

355 hours later in the spring as seals entered their molting period. Subadults showed an earlier start and  
356 more intense haul-out activity in April and May. The young-of-the-year records began after weaning  
357 and the model predictions seemed to indicate development of in-water activities (e.g. swimming,  
358 foraging) in May. Adult females had a more protracted haul-out season compared to males, and more  
359 time was spent hauled out in June compared to adult males and subadults.

360 The haul-out probability for ribbon seals was mostly influenced by temperature ( $F_{1,99540} = 6.87$ ,  
361  $p = 0.009$ ) and wind ( $F_{1,99540} = 49.314$ ;  $p = <0.001$ ) with barometric pressure ( $F_{1,99540} = 3.446$ ;  $p$   
362 = 0.063) having a milder impact. Ribbon seals were more likely to haul out when temperatures  
363 were relatively warm and less likely to haul out at higher winds and lower pressure values (Figure  
364 8). Neither wind chill ( $F_{1,99540} = 1.83$ ;  $p = 0.176$ ) nor precipitation ( $F_{1,99540} = 0.000$ ;  $p = 0.989$ ) were a  
365 significant influence on haul-out probability. Compared with bearded seals, the effect of weather  
366 covariates on the predicted haul-out probability for ribbon seals was less striking. Because our ribbon  
367 seal model included age and sex class, we can visualize the different influences of weather covariates  
368 on those classes and see that subadults differ from adult males and females (Figure 8).

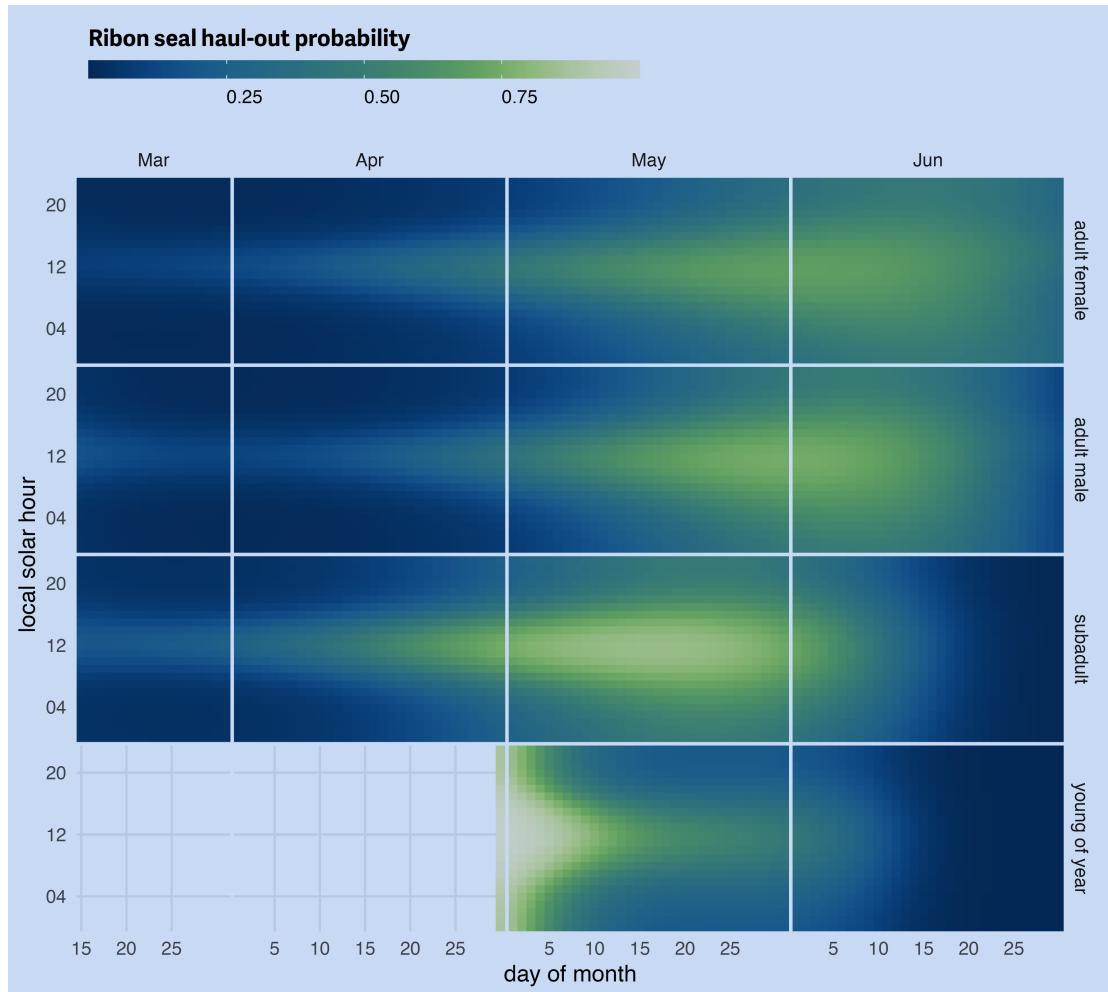
### 369 **Spotted Seals**

370 Compared to ribbon seals, spotted seals showed a longer spring haul-out season that was less intensely  
371 centered on solar noon (Figure 9; see also S3). Adults of both sexes spent considerable time in April,  
372 May and June hauled out. Adult spotted seal males had a more protracted haul-out season compared  
373 to females, and more time out of the water in June (Figure 9). This likely reflects the triad behavior  
374 in spotted seals when suitor males haul out with nursing females. As with ribbon seals, the young-of-  
375 the-year records began after weaning and the model predictions reflected development of in-water  
376 activities (e.g. swimming, foraging) in May.

377 Spotted seal haul-out behavior was less affected by the weather covariates compared to ribbon  
378 and bearded seals but their influence on the model was still significant in some cases. Temperature  
379 ( $F_{1,114807} = 5.462$ ;  $p = 0.019$ ), wind ( $F_{1,114807} = 46.954$ ;  $p = <0.001$ ), and barometric pressure ( $F_{1,114807}$   
380 = 10.214;  $p = 0.001$ ) were all significant. Spotted seals were more likely to be on the ice when  
381 temperatures were relatively warm and less likely to haul out at higher wind speeds. Wind chill  
382 ( $F_{1,114807} = 0.559$ ;  $p = 0.455$ ) and precipitation ( $F_{1,114807} = 0.763$ ;  $p = 0.382$ ) were not as influential  
383 as the other covariates. Differences in the magnitude of response between the age-sex classes were  
384 present and consistent across each of the weather covariates (Figure 10). There was a consistent  
385 ranking of adult males being the most likely to haul out, followed by adult females, and, then,  
386 subadults. This differs from ribbon seals which showed more overlap between adult males and  
387 adult females and that subadults were most likely to haul out across the presented range of weather  
388 covariates.

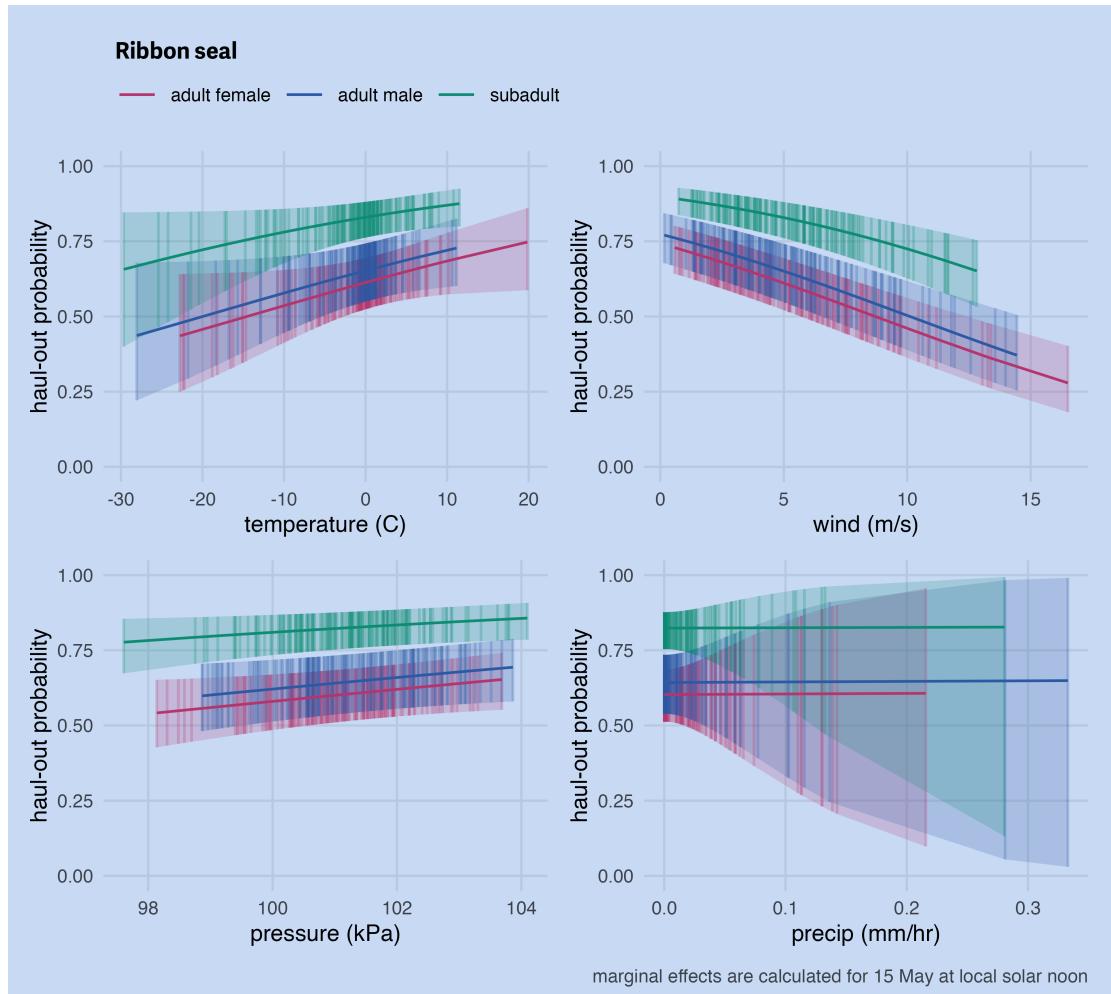
### 389 **Annual variation in haul-out timing**

390 The second set of models, which included annual variation in haul-out patterns, uncovered significant  
391 contributions for linear and quadratic interactions between day and year for only spotted seals  
392 (day:year,  $F_{15,114762} = 4.345$ ;  $p = <0.001$ ; day<sup>2</sup>:year,  $F_{15,114762} = 5.827$ ;  $p = <0.001$ ). Ribbon seals  
393 showed no significant contribution for interactions between day and year (day:year,  $F_{10,99510} = 0.516$ ;  
394  $p = 0.880$ ; day<sup>2</sup>:year,  $F_{10,99510} = 0.549$ ;  $p = 0.856$ ). Predicted distributions of haul-out activity were  
395 largely unimodal, but varied some among and within years with respect to the timing and magnitude  
396 of haul-out peaks (Figure 11). It is important to note that predicted variation in annual haul-out  
397 patterns likely reflected both process error and sampling variability. While we did remove any years



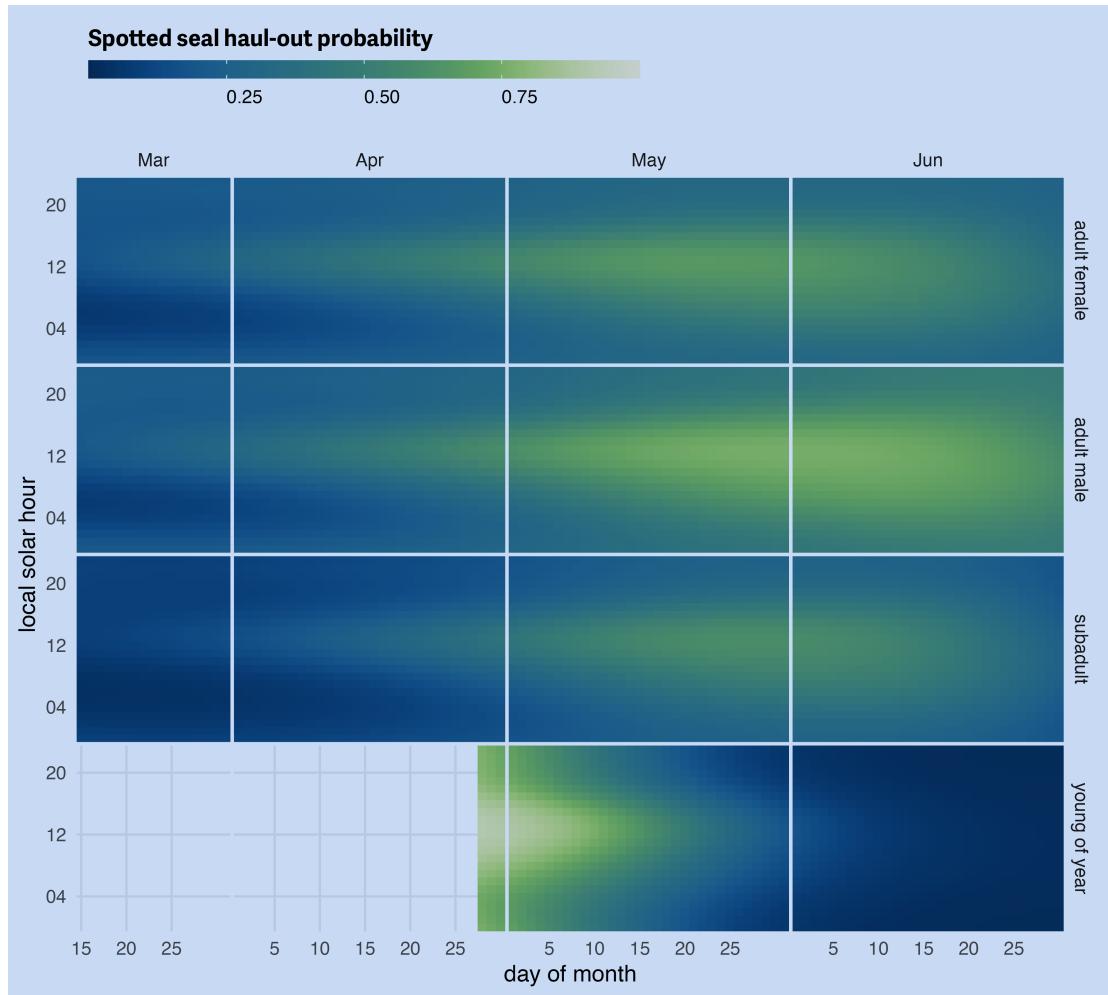
**Figure 7. Ribbon seal predicted haul-out probability**

Predicted hourly haul-out probability of ribbon seals from 15 March to 30 June for each age and sex class used in the model. Weather covariate values in the prediction were based on a simple generalized additive model for each weather covariate with smooth terms for day-of-year and solar hour to account for anticipated variability within a day over the season. Predictions for young of the year show their transition from newly weaned pups resting on the ice to more in-water activities. Predictions in July and before 15 March were not included to avoid spurious model predictions at the edge of the data range.



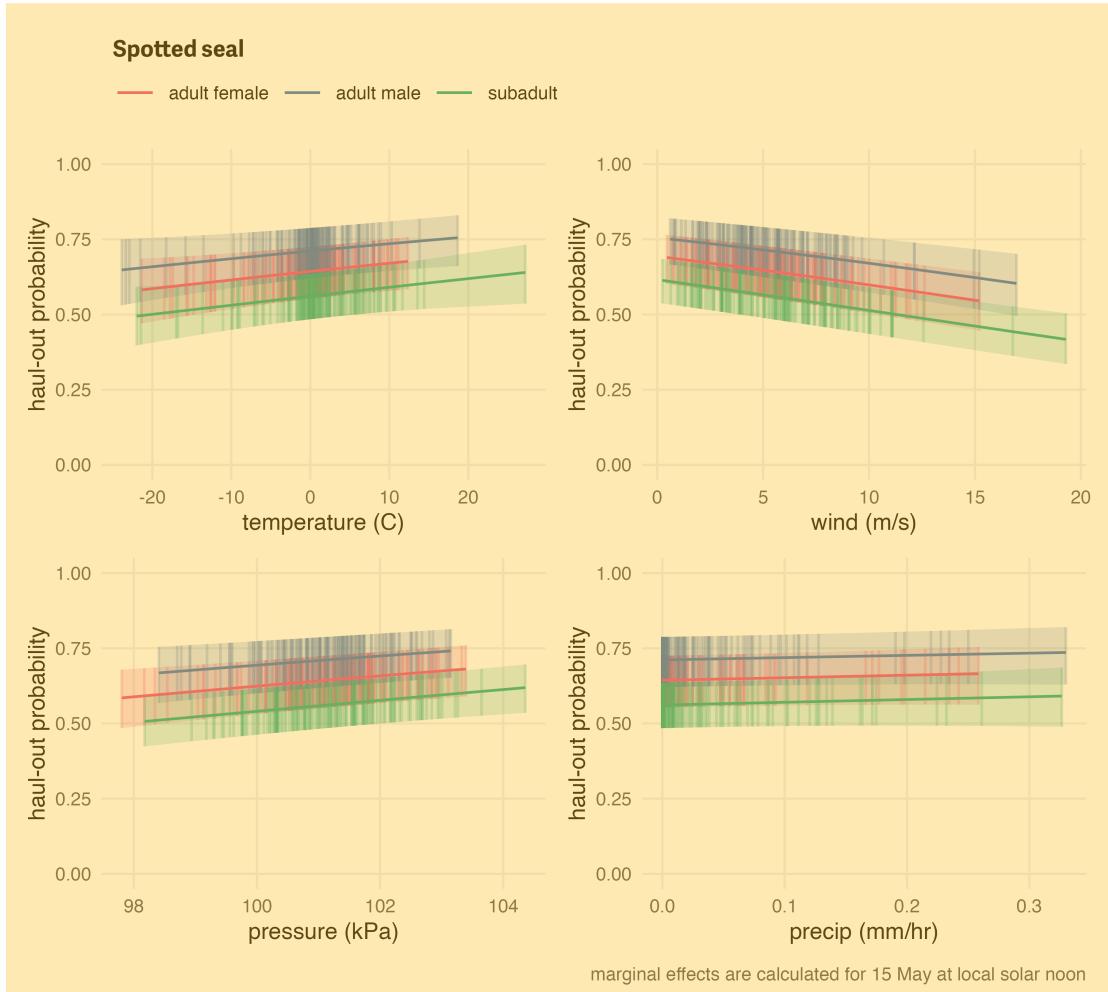
**Figure 8. Influence of weather covariates on ribbon seal haul-out probability**

Marginal effects of temperature, wind, barometric pressure, and precipitation on the predicted haul-out probability of ribbon seals within each age and sex classifications. Hour of the day was fixed at local solar noon and day-of-year fixed at 15 May. The other weather covariate values were predicted from a simple generalized additive model for each weather covariate with smooth terms for day-of-year and solar hour to account for anticipated variability within a day over the season. While the marginal effect of the covariate is continuous, points and vertical lines representing the 95% confidence interval around the predicted haul-out probability are shown only at observed weather values to give an indication of how the observations are distributed across the range of weather values.



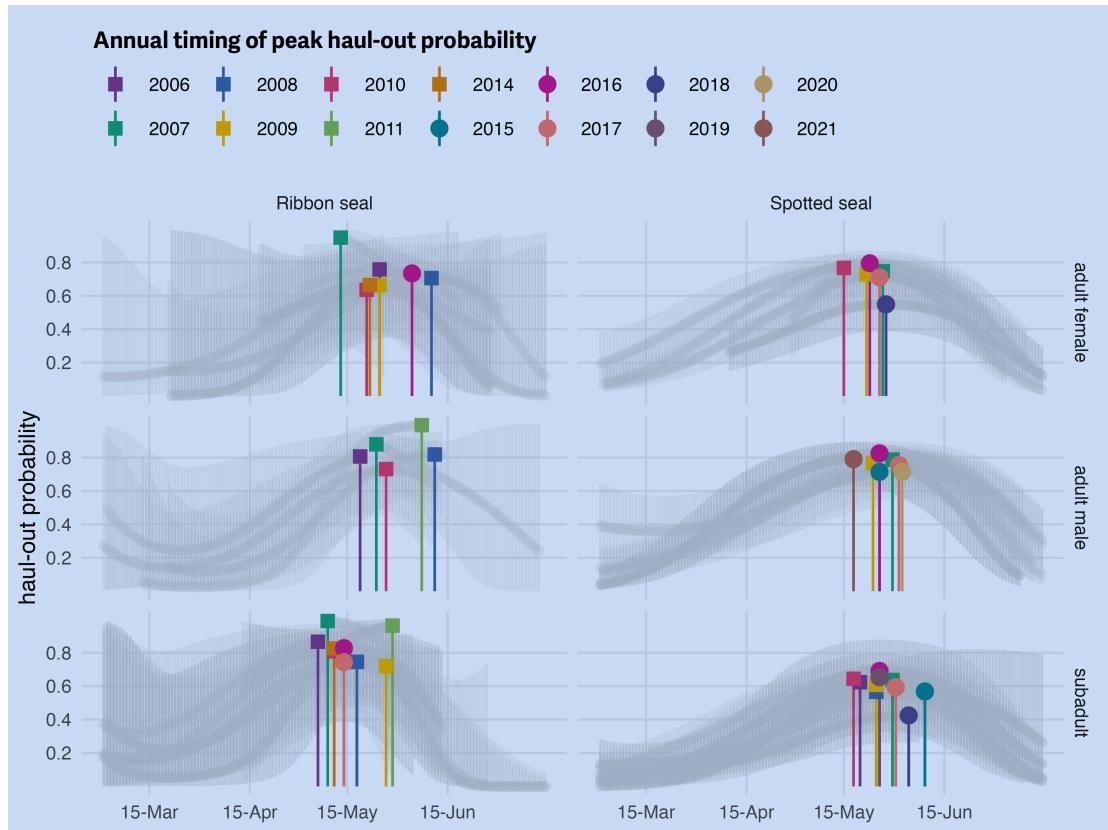
**Figure 9. Spotted seal predicted haul-out probability**

Predicted hourly haul-out probability of spotted seals from 1 March to 30 June for each age and sex class used in the model. Weather covariate values in the prediction were based on a simple generalized additive model for each weather covariate with smooth terms for day-of-year and solar hour to account for anticipated variability within a day over the season. As with ribbon seals, predictions for young of the year show their transition from newly weaned pups resting on the ice to more in-water activities. Predictions in July and before 15 March were not included to avoid spurious model predictions at the edge of the data range.



**Figure 10. Influence of weather covariates on spotted seal haul-out probability**

Marginal effects of temperature, wind, barometric pressure, and precipitation on the predicted haul-out probability of spotted seals within each age and sex classification. Hour of the day was fixed at local solar noon and day-of-year fixed at 15 May. The other weather covariate values were predicted from a simple generalized additive model for each weather covariate with smooth terms for day-of-year and solar hour to account for anticipated variability within a day over the season. While the marginal effect of the covariate is continuous, points and vertical lines representing the 95% confidence interval around the predicted haul-out probability are shown only at observed weather values to give an indication of how the observations are distributed across the range of weather values.



**Figure 11. Annual variability in the timing of peak haul-out probability for ribbon and spotted seals.**

Spring haul-out probability (colored markers) for ribbon and spotted seals across 14 years are shown. The full seasonal range of annual predictions along with uncertainty are presented as grey lines. Covariates were fixed at local solar noon and weather covariate values were predicted from a simple generalized additive model for each weather covariate with smooth terms for day-of-year and solar hour to account for anticipated variability within a day over the season. Only those groups (age:sex + year) that included observations from more than one seal are shown. Additionally, any groups where data were only available after 1 June or before 1 May are not included.

398 where only one deployment in a species + age:sex group was present, there were still some years  
 399 where the pattern shown was informed by a small number of individuals that may not represent  
 400 population-level patterns.

401 The annual timing of peak haul-out probability for ribbon seals and adult male spotted seals  
 402 appeared to have ~~no~~ relationship with the amount of yearly maximum sea-ice extent in the study area.  
 403 For ribbon seals and adult male spotted seals,  $p$ -values were substantially larger than 0.05 (ribbon  
 404 seal adult females:  $R^2 = 0.004$ ,  $p = 0.896$ ; ribbon seal adult males:  $R^2 = 0.059$ ,  $p = 0.693$ ; ribbon seal  
 405 subadults:  $R^2 = 0.007$ ,  $p = 0.828$ ; spotted seals adult males:  $R^2 = 0.003$ ,  $p = 0.903$ ). Adult female and  
 406 subadult spotted seals both showed a negative trend (peak haul-out occurs later in years with less  
 407 sea ice) with a significant relationship for adult female spotted seals (spotted seal adult female:  $R^2 =$   
 408 0.663,  $p = 0.049$ ; spotted seal subadults:  $R^2 = 0.384$ ,  $p = 0.056$ ).

409 **DISCUSSION**

410 We modeled data from bio-loggers deployed on bearded, ribbon, and spotted seals to examine factors  
411 affecting their haul-out behavior on sea ice in the Bering and Chukchi seas. Our analysis shows all  
412 three species of seal haul out progressively more through the spring and peak near mid-May to early  
413 June before declining again. This pattern aligns well with what has been previously documented  
414 qualitatively (Boveng et al., 2009; Cameron et al., 2010; Boveng & Cameron, 2013) and confirms our  
415 haul-out data are likely quantifying population-level behavioral patterns. Beginning in spring, seals  
416 preferentially haul out on ice shortly after solar noon, which allows seals to maximize absorption of  
417 solar radiation thought to facilitate the molting process (Feltz & Fay, 1966). Interestingly, bearded  
418 seals appear to have two peaks in haul-out activity within a day, one shortly after solar noon, and  
419 one centered near solar midnight. This, of course, could be an artifact of our limited sample size  
420 for bearded seal deployments across all age classes. However, a similar bi-modal pattern has been  
421 seen in ringed seals (Von Duyke et al., 2020) and suggests that bearded and ringed seals may be  
422 operating under different constraints than ribbon and spotted seals. Bearded and ringed seals are  
423 distributed across higher latitudes higher latitudes that experience extended daylight hours during  
424 spring which may allow more flexibility in alternating resting and foraging events. Other factors  
425 such as predation by polar bears (which is rare for ribbon and spotted seals in the Bering Sea) may  
426 also explain differing haul-out patterns. The change in haul-out behavior during the season was  
427 less pronounced in bearded seals compared to ribbon and spotted seals. This aligns with findings  
428 from Thometz et al. (Thometz et al., 2021) who observed a mean molting period of  $119 \pm 2$  days and a  
429 relatively stable resting metabolic rate for bearded seals during that time. While ribbon seals were  
430 not considered in that study, spotted and ringed seals underwent molt periods of just  $33 \pm 4$  and  $28 \pm 6$   
431 days and had increased resting metabolic rates.

432 Unlike previous analyses of seal haul-out behavior in spotted and ribbon seals (e.g. (Ver Hoef,  
433 London & Boveng, 2010), (Conn et al., 2014)), we also investigated the influence of sex-age class on  
434 haul-out probabilities of both species (but not for bearded seals because of low sample size). Field  
435 identification of age class can be inexact, particularly when differentiating subadults from adults. In  
436 the case of ribbon seals, subadults often have less distinct ribbons than adults. Spotted seal pelage  
437 cannot be used to reliably discern adults from subadults. Despite these challenges, we feel the age  
438 classifications used in this analysis are useful in testing for age-related effects on haul-out behavior.

439 Although ribbon and spotted seals exhibited a unimodal diel haul-out pattern generally centered  
440 around local solar noon, there were key differences across species, age, and sex that match our  
441 understanding from natural history descriptions of their ecological behavior. Spotted seals are known  
442 to form triads during the breeding season where a female and dependent pup are accompanied on  
443 the ice by a suitor male (Frost & Burns, 2018). The male waits for the female to wean the pup and  
444 enter estrus, and fends off any other potential suitor males. Triad formation results in both males  
445 and females spending a large portion of the day hauled out on ice and a protracted spring haul-out  
446 season for both sexes. While females are still nursing the pup and not yet in estrus they may be less  
447 inclined to interrupt their haul out and enter the water where the suitor male would attempt mating.  
448 We see this reflected in the predicted haul-out patterns, with both males and females exhibiting a  
449 broad distribution of time out of the water throughout the solar day and the season. Ribbon seals  
450 are not known to form triads and our model predicts a progression of increased haul-out behavior  
451 with females starting earlier in the season than males. Notably, female ribbon seals spend a large  
452 portion of the day in the water during the pupping period, aligning with the hypothesis that ribbon

453 seal females continue foraging while nursing. Subadult ribbon and spotted seals begin elevated  
454 haul-out behavior earlier in the spring and follow a pattern seen in other phocids where yearlings  
455 and subadults molt first followed by adult females and males (Thompson & Rothery, 1987; Kirkman  
456 et al., 2003; Reder et al., 2003).

457 We also investigated the influence of weather on haul-out probabilities, including wind speed,  
458 temperature, barometric pressure, precipitation, and wind chill. These have been investigated for  
459 walruses (e.g. Udevitz et al. (2009)) and a few select studies of ice-associated seals (Perry, Stenson &  
460 Buren, 2017; Hamilton & Evans, 2018). In our study, ribbon seal haul-out behavior seemed to be the  
461 most influenced by weather, with wind, temperature, and barometric pressure all being important  
462 components of the model. Spotted seals were most affected by wind and barometric pressure. For  
463 bearded seals, the model indicated wind and temperature had the greatest impact. In general, and as  
464 might be expected, seals were more likely to haul-out when daily temperatures were warmer, winds  
465 speeds were lower, barometric pressure was higher, and precipitation was lower. Those weather  
466 conditions are general indicators of increased solar radiation and lower convective heat loss, both of  
467 which provides energetic benefits (see additional discussion in Supplemental Material [Exploring](#)  
468 [Insolation \(Solar Radiation\) as a Model Covariate](#) regarding the potential use of solar radiation  
469 directly). Low winds and precipitation could also enhance predator detection. Our results highlight  
470 the importance of incorporating weather covariates when analyzing haul-out behavior and calculating  
471 availability corrections for aerial surveys.

472 Notably missing from our list of haul-out model explanatory variables is any spatial-temporal  
473 representation of sea ice concentration, area, or extent. This may seem counterintuitive when  
474 modeling the haul-out behavior of seal species with such a close association to sea ice; seals haul out  
475 in the presence of sea ice, and we could assess the local concentration of sea ice during these events  
476 (see (Olnes et al., 2020)). This, however, expands the scope of our analysis into the realm of habitat  
477 selection and many of our deployments consisted of a single device attached to the rear flipper of  
478 the seal which meant we only received locations when seals were hauled out on sea-ice, limiting  
479 our ability to fully evaluate fine-scale habitat preferences related to sea-ice. Insight into how seals  
480 use and interact with sea-ice during an extended period when the availability and characteristics of  
481 sea-ice is rapidly changing is important (Breed et al., 2018; Cameron et al., 2018) but ancillary to the  
482 focus of this analysis – and, in the end, not possible given key limitations of our data. Additionally,  
483 our study was limited to the spring season when seal haul-out behaviors are strongly influenced by  
484 pupping, nursing, breeding behavior, and molt. These drivers are likely more influential on haul-out  
485 behavior than sea-ice concentration. Crawford et al. (2019) compared haul-out probability models  
486 for ringed seals and found those that only included season (and not sea-ice concentration) were the  
487 most parsimonious. For all of these reasons, we have elected not to use sea ice concentration *as a*  
488 *predictor for haul-out probability* in the present study.

489 Our models detected small deviations in the timing and magnitude of annual peaks in haul-out  
490 behavior for ribbon and spotted seals. The timing of peak haul-out activity appears to fall within  
491 a relatively narrow time window of 3-4 weeks in late May and early June. This consistency across  
492 15 years is likely a reflection of the relationship between a critical photoperiod and the timing of  
493 important life history stages (Temte, 1994; Bronson, 2009). However, along with a critical photoperiod,  
494 ribbon and spotted seals are dependent upon the presence of sea ice for pupping and molt. We did not  
495 find large support in our models for a relationship between the timing of peaks in haul-out behavior  
496 and the amount of yearly maximum sea ice. This could indicate that, while the extent of spring sea ice

497 in the Bering Sea varied widely during our study period, seals were still able to locate sea ice and haul  
498 out. Only a small portion of our data was from 2018 – 2019, years of extreme low spring ice extent in  
499 the Bering Sea that appeared to impact body condition of ribbon and spotted seals (Boveng et al.,  
500 2020), so we may currently lack sufficient contrast in ice extent to characterize an effect on the timing  
501 of peak haul-out probability. We should expect, however, that some minimal threshold in the spatial  
502 extent or density of sea ice will have a meaningful impact on the timing of peak haul-out behavior —  
503 if there is no sea-ice, seals will not haul out or they will be forced to use terrestrial haul-out sites which  
504 were not part of the evolution of their normal behaviors. Additionally, while from an ecological  
505 perspective the haul-out behavior appears consistent, the interannual differences in timing and  
506 magnitude are large enough to have important ramifications on calculations of abundance and trend.  
507 Those ramifications will only be exacerbated if climate variability amplifies interannual differences.

508 Previous attempts to estimate the abundance of phocid seals from aerial survey data in the  
509 Bering and Chukchi seas (e.g. Bengtson et al. (2005), Conn et al. (2014), Ver Hoef et al. (2014))  
510 have used estimated haul-out probabilities to correct for the proportion of animals that are in the  
511 water and thus unavailable to be counted. Although several of these studies allowed haul-out  
512 probabilities to vary by day-of-year and time-of-day, they have not accounted for variability among  
513 years, weather conditions, or in the age-sex class of the sample. In this paper, we have shown that  
514 there can be considerable differences in the haul-out probability of seals on ice based on these factors  
515 and subsequent analyses have shown the potential for considerable bias in abundance estimates  
516 if such covariates are unaccounted for (Conn & Trukhanova, 2023). We recommend that future  
517 abundance analyses employ availability models that account for them. For instance, it is relatively  
518 straightforward to obtain weather reanalysis products for times and locations that are surveyed and  
519 to construct a relevant correction factor based on predictions of GLMPMs. The most challenging  
520 element in developing availability correction factors is with annual variability. It can be difficult to  
521 get a sufficient sample size to estimate year-specific correction factors, particularly because research  
522 teams would likely need to deploy bio-loggers on seals and conduct aerial surveys concurrently,  
523 requiring considerably more personnel and money. One possible suggestion is to include year as a  
524 random effect within models for aerial survey counts such that, without specific knowledge of any  
525 particular year, the among-year variance is included in the modeled standard errors. Regardless of  
526 the specific approach, future estimates of Arctic seal abundance will require specific consideration  
527 of annual variability and changes in the timing of peak haul-out behavior when estimating trends,  
528 as one will not know if moderate differences in abundance estimates are attributable to changes in  
529 abundance or changes in haul-out behavior.

530 Predictions of absolute haul-out probability in this paper were somewhat different than those  
531 previously reported for these species, especially for bearded seals. For instance, Ver Hoef et al. (2014)  
532 and Conn et al. (2014) used haul-out correction factors with maximums of 0.66 for bearded seals,  
533 0.62 for ribbon seals, and 0.54 for spotted seals, where these maximums corresponded to times near  
534 local solar noon in mid-late May. Results here suggest a haul-out probability on May 20 at local solar  
535 noon of 0.304 (95% CI: 0.258 – 0.354) for bearded seals across all age and sex classes, 0.715 (95% CI:  
536 0.62 – 0.794) for adult male ribbon seals, 0.661 (95% CI: 0.576 – 0.738) for adult female ribbon seals,  
537 0.742 (95% CI: 0.655 – 0.813) for adult male spotted seals, and 0.663 (95% CI: 0.574 – 0.742) for adult  
538 female spotted seals. Our estimates of haul-out probability reflect increased sample sizes in terms  
539 of number of individuals, inclusion of weather covariates, and improvements to the way data were  
540 prepared prior to analysis and should be the basis for any future estimates of seal abundance from

541 aerial surveys in the Bering and Chukchi seas.

542 We focused this paper on haul-out behavior of bearded, ribbon, and spotted seals. Ringed seals  
543 are also present in the Bering and Chukchi seas but exhibit a unique complicating factor. Adult  
544 ringed seals build subnivean lairs under the snow on top of the sea ice, where they haul out and  
545 where females rear pups until conditions are good for basking (Frost et al., 2004). Thus, the wet-dry  
546 sensor on a bio-logger could indicate that an animal is hauled out, but if it is within a lair, it is not  
547 available to be detected during an aerial survey. We hope to address availability of ringed seals using  
548 data from satellite tags, replicate survey tracks, and auxiliary information about snow depth and  
549 timing of melt in a future study (see, e.g., Lindsay et al. (2021)).

550 Our analysis emphasizes the importance of accounting for seasonal and temporal variation in  
551 haul-out behavior, as well as associated weather covariates, when interpreting the number of seals  
552 counted in aerial surveys. The rapid acceleration of climate change in Arctic ecosystems is already  
553 occurring and is forecast to decrease the quantity and quality of suitable habitat for ice-associated seals  
554 that rely on sea-ice for a variety of activities. Improved estimates of seal population abundance from  
555 aerial surveys are needed to properly monitor the impacts of these changes on seal populations over  
556 time. Those monitoring surveys will need to be paired with continued investigation and assessment  
557 of seal haul-out behavior to allow credible predictions about the effects of climate disruptions on the  
558 abundance and distribution of Arctic seal populations.

## 559 AUTHOR CONTRIBUTIONS

- 560 • **Josh M. London:** investigation, conceptualization, methodology, formal analysis, validation,  
561 software, writing: original draft, writing: review and editing, visualization, and data curation
- 562 • **Paul B. Conn:** conceptualization, methodology, formal analysis, software, validation, writing:  
563 original draft, writing: review and editing
- 564 • **Stacie K. Hardy:** investigation, data curation, methodology, validation, writing: review and  
565 editing
- 566 • **Erin L. Richmond:** data curation, investigation, methodology, validation, writing: review and  
567 editing
- 568 • **Jay M. Ver Hoef:** conceptualization, methodology, software, writing: review and editing
- 569 • **Michael F. Cameron:** investigation, project administration, writing: review and editing
- 570 • **Justin A. Crawford:** investigation, methodology, validation, data curation, writing: review  
571 and editing
- 572 • **Lori T. Quakenbush:** investigation, methodology, supervision, project administration, writing:  
573 review and editing
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575 and editing
- 576 • **Peter L. Boveng:** investigation, conceptualization, supervision, project administration, writing:  
577 review and editing

## 578 DATA AVAILABILITY

579 This manuscript was developed as a reproducible research compendium. All data and code are avail-  
580 able on GitHub (<https://github.com/noaa-afsc/berchukseals-haulout>) and major  
581 versions archived at Zenodo (<https://doi.org/10.5281/zenodo.4638221>). Original data  
582 sources for telemetry are archived at the United States Animal Telemetry Network, archived at

583 Movebank, or associated with other published manuscripts (see supplemental material S1). Collated  
584 and cleaned data products needed to replicate the analysis along with the results of all model fits are  
585 also available and versioned as an R package on GitHub (<https://github.com/noaa-afsc/berchuksealsHauloutFits>) and archived at Zenodo.  
586

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779 **SUPPLEMENTAL MATERIAL**

780 **0.1 Additional Bio-logger Deployment Details**

**Table S1.** The timing, location, and institutions responsible for the bio-logger deployments used in this study along with research permits and any associated publications.

Institution	Year Deployed	Location	Publication(s)	Permits	No. Seals	Sex	Age Class
<b>Bearded seal</b>							
ADFG	2005	Kotzebue Sound	Cameron et al 2018	358-1585	6	M, F	subadult
ADFG	2006	Kotzebue Sound	Cameron et al 2018	358-1585	2	F, M	subadult
ADFG	2009	Kotzebue Sound	Breed et al 2018	358-1787	4	F, M	subadult
ADFG	2014	Norton Sound, Koyuk River	Olnes et al 2020	15324	2	M	subadult
ADFG	2014	Norton Sound, Nome	Olnes et al 2020	15324	1	M	subadult
ADFG	2015	Norton Sound, St. Michael	Olnes et al 2020	15324	1	M	subadult
ADFG	2016	Elson Lagoon, Utqiagvik	Olnes et al 2020	15324	1	F	subadult
ADFG	2016	Norton Sound, Koyuk River	Olnes et al 2020	15324	2	F, M	subadult
ADFG	2016	Norton Sound, Nome	Olnes et al 2020	15324	1	M	subadult
ADFG	2016	Norton Sound, St. Michael	Olnes et al 2020	15324	2	M, F	subadult

ADFG=Alaska Department of Fish and Game; NSB=North Slope Borough; NMFS=NOAA National Marine Fisheries Service; NPWC=North Pacific Wildlife Consortium

Institution	Year Deployed	Location	Publication(s)	Permits	No. Seals	Sex	Age Class
ADFG	2017	Colville River, Nuiqsut	Olnes et al 2020	15324	1	F	subadult
ADFG	2017	Norton Sound, Koyuk River	Olnes et al 2020	15324	1	F	subadult
ADFG	2017	Norton Sound, Nome	Olnes et al 2020	15324	1	F	subadult
ADFG	2019	Dease Inlet, Utqiagvik	Olnes et al 2021	20466	1	M	adult
NMFS	2005	Kotzebue Sound		358-1585	1	F	subadult
NMFS	2009	Kotzebue Sound	McClintock et al 2017	782-1765	2	M	subadult, adult
NMFS	2011	Kotzebue Sound	McClintock et al 2017	15126	3	F, M	subadult
NMFS	2012	Kotzebue Sound	McClintock et al 2017	15126	1	F	adult
NSB	2012	Elson Lagoon, Utqiagvik		15324	1	M	subadult
NSB	2019	Pittalugruaq Lake		20466	1	F	subadult
<b>Ribbon seal</b>							
NMFS	2005	Ozemoy Gulf, Russia		782-1765	9	F, M	young of year, adult, subadult
NMFS	2006	Bering Sea		782-1765	7	M, F	adult, young of year
NMFS	2007	Bering Sea		782-1765	28	M, F	subadult, adult, young of year

ADFG=Alaska Department of Fish and Game; NSB=North Slope Borough; NMFS=NOAA National Marine Fisheries Service; NPWC=North Pacific Wildlife Consortium

Institution	Year Deployed	Location	Publication(s)	Permits	No. Seals	Sex	Age Class
NMFS	2008	Bering Sea		782-1765	1	M	subadult
NMFS	2009	Bering Sea		782-1765	28	F, M	adult, subadult, young of year
NMFS	2010	Bering Sea		358-1787, 15126	17	M, F	young of year, adult, subadult
NMFS	2014	Bering Sea		15126	13	M, F	subadult, adult, young of year
NMFS	2016	Bering Sea		19309	7	M, F	subadult, adult
<b>Spotted seal</b>							
ADFG	2005	Kotzebue Sound	Von Duyke et al in prep	358-1585	3	F, M	subadult, adult
ADFG	2016	Dease Inlet, Utqiagvik	Von Duyke et al in prep	15324	4	M, F	adult
ADFG	2017	Colville River, Nuiqsut	Von Duyke et al in prep	15324	1	F	subadult
ADFG	2017	Scammon Bay	Von Duyke et al in prep	15324	3	F, M	subadult, adult
ADFG	2018	Dease Inlet, Utqiagvik	Von Duyke et al in prep	20466	1	F	subadult
ADFG	2018	Scammon Bay	Von Duyke et al in prep	20466	1	M	subadult
ADFG	2019	Dease Inlet, Utqiagvik	Von Duyke et al in prep	20466	6	M	adult, subadult
NMFS	2006	Bering Sea		782-1676	5	M, F	young of year, subadult

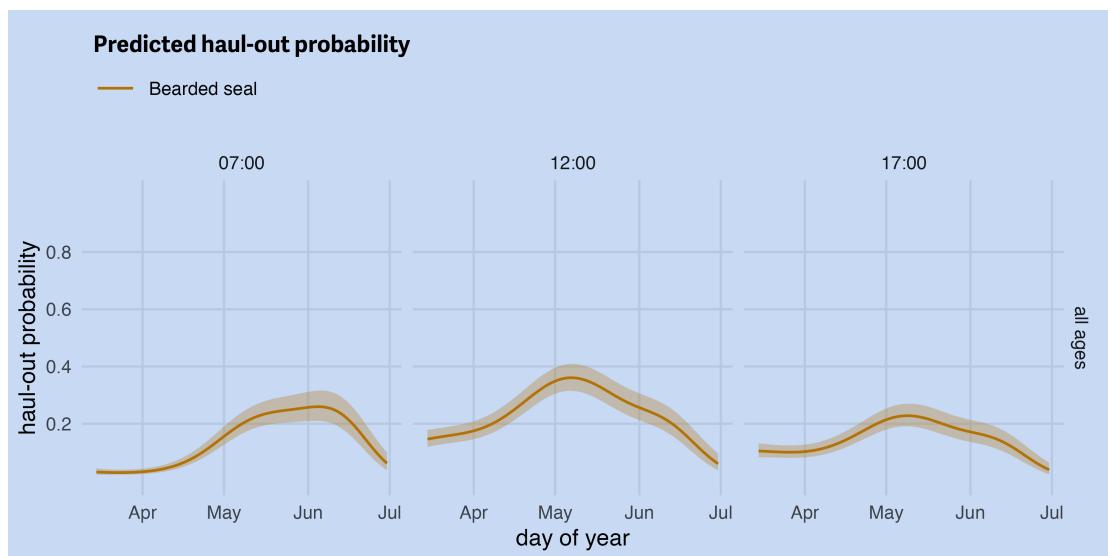
ADFG=Alaska Department of Fish and Game; NSB=North Slope Borough; NMFS=NOAA National Marine Fisheries Service; NPWC=North Pacific Wildlife Consortium

Institution	Year Deployed	Location	Publication(s)	Permits	No. Seals	Sex	Age Class
NMFS	2007	Bering Sea		782-1676	12	F, M	adult, young of year, subadult
NMFS	2009	Bering Sea		📍358-1787	23	F, M	adult, subadult, young of year
NMFS	2010	Bering Sea		358-1787, 15126	8	F, M	young of year, adult, subadult
NMFS	2014	Bering Sea		15126	5	M, F	young of year, adult
NMFS	2016	Bering Sea		📍19309	6	M, F	adult
NMFS	2018	Bering Sea		📍19309	5	F	adult
NPWC	2009	Kamchatka Peninsula		📍 NA	3	F	adult
NSB	2012	Tiny Island	Von Duyke et al in prep	15324	1	F	adult
NSB	2014	Oarlock Island	Von Duyke et al in prep	15324	6	M, F	subadult, adult
NSB	2014	Seal Island	Von Duyke et al in prep	15324	1	M	subadult
NSB	2015	Oarlock Island	Von Duyke et al in prep	15324	6	M, F	subadult, adult
NSB	2016	Pittalugruaq Lake	Von Duyke et al in prep	15324	3	F	subadult
NSB	2017	Pittalugruaq Lake	Von Duyke et al in prep	15324	1	M	subadult

ADFG=Alaska Department of Fish and Game; NSB=North Slope Borough; NMFS=NOAA National Marine Fisheries Service; NPWC=North Pacific Wildlife Consortium

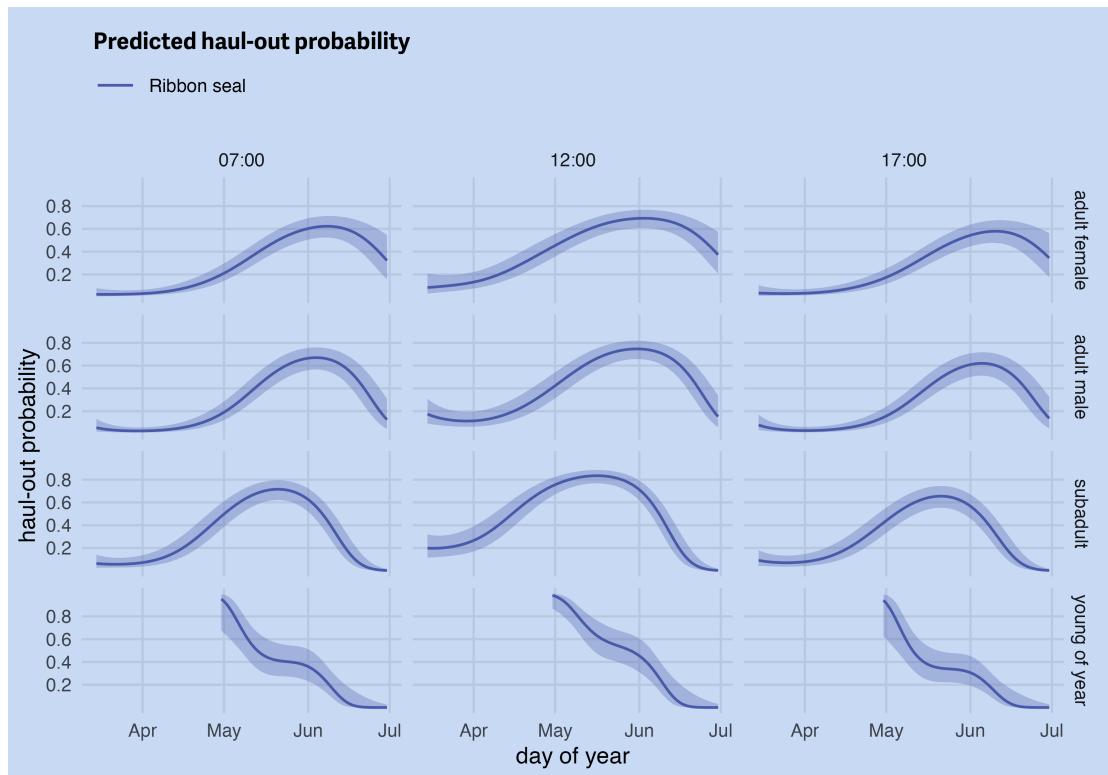
781    **0.2 Supplemental Figures Showing Confidence Intervals Associated with Predictions**

782    The following series of figures (S1, S2, and S3) show the seasonal variability in predicted haul-out  
783    probability and the associated 95% confidence intervals for bearded, ribbon, and spotted seals. The  
784    predictions shown are based on the same data used in 5, 7, and 9 but selected for three local solar  
785    hours (07:00, 12:00, and 17:00) so the confidence intervals can also be shown and comparisons can  
786    be made.



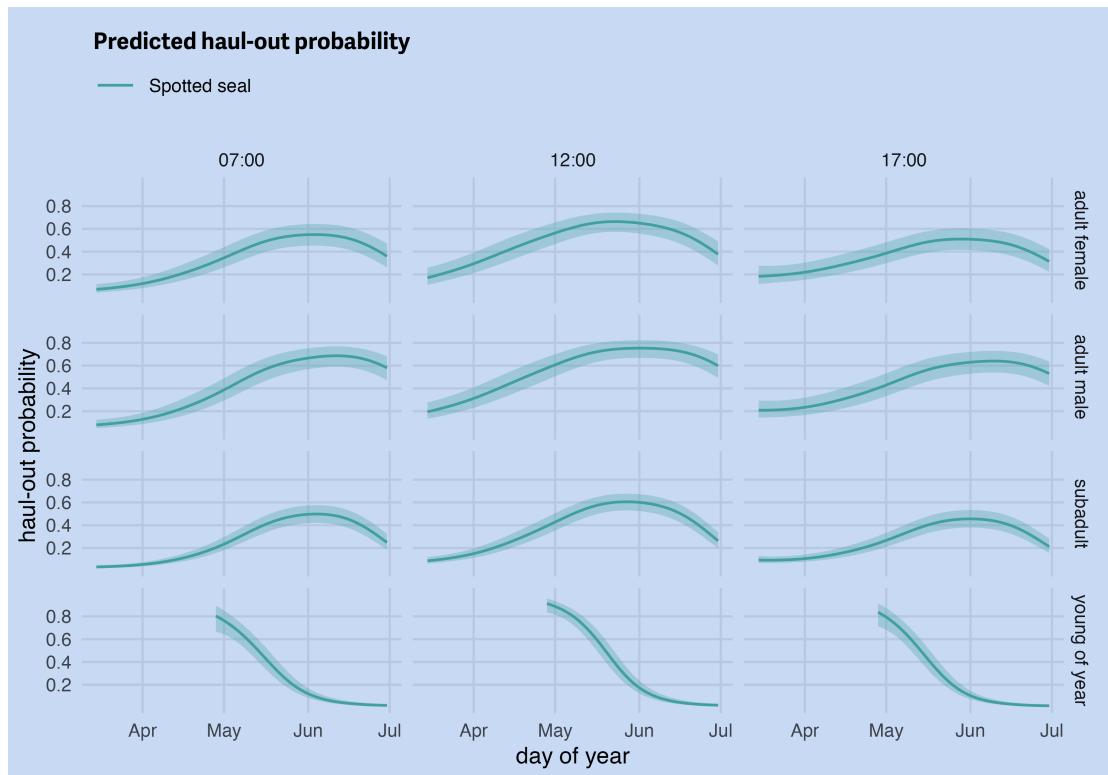
**Figure S1. Seasonal variability in haul-out probability and the associated 95% confidence intervals (shaded area) for bearded seals.**

Model predictions are shown for three local solar hours (07:00, 12:00, and 17:00). Weather covariate values in the prediction were based on a simple generalized additive model for each weather covariate with smooth terms for day-of-year and solar hour to account for anticipated variability within a day over the season. Age and sex classes are combined into a single 'all ages' category.



**Figure S2. Seasonal variability in haul-out probability and the associated 95% confidence intervals (shaded area) for ribbon seals.**

Model predictions are shown for three local solar hours (07:00, 12:00, and 17:00). Weather covariate values in the prediction were based on a simple generalized additive model for each weather covariate with smooth terms for day-of-year and solar hour to account for anticipated variability within a day over the season. Age and sex classes are separated to allow comparisons.



**Figure S3. Seasonal variability in haul-out probability and the associated 95% confidence intervals (shaded area) for spotted seals.**

Model predictions are shown for three local solar hours (07:00, 12:00, and 17:00). Weather covariate values in the prediction were based on a simple generalized additive model for each weather covariate with smooth terms for day-of-year and solar hour to account for anticipated variability within a day over the season. Age and sex classes are separated to allow comparisons.

787 **0.3 Exploring Insolation (Solar Radiation) as a Model Covariate**

788 **0.3.1 Introduction**

789 During the peer review process for this manuscript, Anthony Fischbach suggested the possibility of  
790 using predicted insolation (or solar radiation) values from the reanalysis model as a more direct and,  
791 potentially, more informative predictor of the daily haul-out cycle in seals compared to time of day.  
792 The notion being that seals are, likely, directly responding to changes in solar radiation throughout  
793 the day and not what time of day it is (i.e. seals don't have human watches). Additionally, given the  
794 energetic benefits of increased solar radiation it could be more informative as we would expect seals  
795 might have a higher haul-out probability on sunnier days and for there to be geographic variability  
796 in haul-out behavior associated with geographical differences in insolation. This approach has an  
797 additional benefit of being more parsimonious compared to our use of the Fourier series or other  
798 approaches to represent hour-of-day in the model (e.g. 24 factors for each hour).

799 Because of these reasons, we considered and explored this possibility for our model and the  
800 analysis presented in this manuscript. A key drawback to reliance on solar radiation, in our minds, is is  
801 that we would lose insight regarding potential diel patterns – solar radiation does not differentiate  
802 between dusk or dawn. Bi-modal patterns have been previously observed in ringed seals and our  
803 results in this analysis show some indication of increased haul-out probability during dawn compared  
804 to dusk periods for bearded seals and some age and sex classes for ribbon and spotted seals. For other  
805 phocid species, increased haul-out probability before solar noon or after solar noon has been observed.  
806 Importantly, understanding these relationships between haul-out probability and hour-of-day can  
807 have important ramifications on aerial survey study design – a key focus of this paper.  
808 Another hesitation we had was that solar radiation estimates from reanalysis models have not been  
809 previously used as a model covariate within a published study of pinniped haul-out behavior. Thus,  
810 for this analysis, we chose to keep our original approach and rely on the Fourier series to capture any  
811 hour-of-day effects.

812 That said, we think the idea of solar radiation as a model covariate in pinniped haul-out models  
813 is intriguing and worth further exploration. The current availability and increased accessibility to  
814 detailed climate reanalysis products that include solar radiation is exciting and we encourage future,  
815 more detailed exploration of this as a component in pinniped haul-out analysis. To provide some  
816 inspiration, we present some initial efforts and examples for comparison.

817 **0.3.2 Methods**

818 In this manuscript, we rely on the NARR reanalysis model as the source for our weather covariates.  
819 However, since our initiation of this analysis, the ERA5 reanalysis model (<https://doi.org/10.24381/cds.adbb2d47>) has become one of the go-to standards for global climate reanalysis and  
820 provides an increased temporal resolution to hourly (compared to the 3-hour resolution of NARR).  
821 The global coverage of ERA5 provides additional flexibility in that the area of interest is not limited  
822 to North America. The ERA5 model provides a number of solar radiation parameters and it was  
823 important to evaluate and understand each of these estimates in order to select the one that was  
824 likely most relevant to seals. Here, we used the ‘surface short-wave (solar) radiation downwards’  
825 parameter. This parameter is described as “*the amount of solar radiation (also known as shortwave  
radiation) that reaches a horizontal plane at the surface of the Earth and comprises both direct and  
diffuse solar radiation. To a reasonably good approximation, this parameter is the model equivalent of  
what would be measured by a pyranometer (an instrument used for measuring solar radiation) at the  
surface*” (<https://codes.ecmwf.int/grib/param-db/?id=169>). Thus, this is the value

831 which most closely represents the amount of solar radiation likely felt by a seal hauled out of the  
 832 water.

833 ERA5 data is available via the Copernicus climate data store API which can be queried with the  
 834 CDS-API Python package (<https://cds.climate.copernicus.eu/api-how-to>). The R  
 835 code provided here documents the download of the *surface\_solar\_radiation\_downwards* parameter  
 836 for our study area of interest and years of interest. The *reticulate* R package (<https://CRAN.R-project.org/package=reticulate>) allowed interaction with Python. Additionally, note,  
 837 extra steps are required to download data on either side of the 180 anti-meridian.  
 838

```
library(tidyverse)
library(reticulate)
library(sf)
library(terra)

#import python CDS-API
cdsapi <- import('cdsapi')
#for this step there must exist the file .cdsapirc
server = cdsapi$Client() #start the connection

get_era5 <- function(y) {
  #we create the query
  query <- r_to_py(
    list(
      variable = "surface_solar_radiation_downwards",
      product_type = "reanalysis",
      area = "75/152/47/180", # North, West, South, East
      year = y,
      month = str_pad(2:7, 2, "left", "0"),
      day = str_pad(1:31, 2, "left", "0"),
      time = str_c(0:23, "00", sep = ":") %>% str_pad(5, "left", "0"),
      format = "netcdf"
    )
  )
  #query to get the ncdf
  server$retrieve("reanalysis-era5-single-levels",
                  query,
                  paste0("era5_ssrd_", y, "_left.nc"))

  query <- r_to_py(
    list(
      variable = "surface_solar_radiation_downwards",
      product_type = "reanalysis",
      area = "75/-180/47/-142", # North, West, South, East
      year = y,
      month = str_pad(2:7, 2, "left", "0"),
      day = str_pad(1:31, 2, "left", "0"),
      time = str_c(0:23, "00", sep = ":") %>% str_pad(5, "left", "0"),
      format = "netcdf"
    )
  )
}
```

```

    day = str_pad(1:31, 2, "left", "0"),
    time = str_c(0:23, "00", sep = ":") %>% str_pad(5, "left", "0"),
    format = "netcdf"
  )
}

#query to get the ncdf
server$retrieve("reanalysis-era5-single-levels",
                 query,
                 paste0("era5_ssrd_", y, "_right.nc"))

}

years <- as.character(2005:2021)
for(i in 1:length(years)) {
  get_era5(years[i])
}

```

839 To explore performance of our solar radiation parameter within a haul-out model we replaced  
 840 the various Fourier series parameters in our model from the manuscript with the ERA5 *surface*  
 841 *solar radiation downwards* (era\_ssrd\_watts) parameter. As with other reanalysis values (from  
 842 NARR) in the manuscript, the era-ssrd-watts values are matched in time and space to the seal  
 843 haul-out observation data; we use the full hourly temporal resolution from ERA5. The glmmLDTs  
 844 framework used in the paper does not allow for model comparisons with AIC because of the reliance  
 845 on pseudo-likelihood. The bam() function within the mgcv package provides a quick model fitting  
 846 option that also allowed us to do some model comparison with AIC. This approach was sufficient  
 847 for the general demonstration and exploration purposes here but future research should consider a  
 848 range of model fitting frameworks and approaches that might be more appropriate.

849 The model specification below was used to specify an mgcv::bam() model that matched the  
 850 formula used in the manuscript for ribbon seals. The s(speno, bs = "re") term is the smooth  
 851 term for the random effect. All other predictors were the same.

```

m1_ribbon <- mgcv::bam(
  dry ~ age_sex + s(speno, bs = "re") +
  sin1 + cos1 + sin2 + cos2 + sin3 + cos3 +
  poly(day, 3, raw=TRUE) +
  sin1:poly(day, 3, raw=TRUE) +
  cos1:poly(day, 3, raw=TRUE) +
  sin2:poly(day, 3, raw=TRUE) +
  cos2:poly(day, 3, raw=TRUE) +
  sin3:poly(day, 3, raw=TRUE) +
  cos3:poly(day, 3, raw=TRUE) +
  wind*temp2m + pressure + precip +
  age_sex:poly(day, 4, raw=TRUE),
  data = ribbon_model_data,
  family = binomial,

```

```
discrete = TRUE)
```

852 Note, the specification for *m1\_ribbon* here does not include any AR1 structure for temporal  
853 autocorrelation. To include this, we needed to provide a value for  $\rho$  (or *rho*). We examined the  
854 autocorrelation within the model and used the lag-1 value for  $\rho$ . The value for lag-1 autocorrelation  
855 was 0.8082 which is rather high but not surprising. We then updated our model specification with a  
856 value for  $\rho$  as well as the *A1.start* argument which specifies (as either **TRUE** or **FALSE**) the start  
857 point of each block.

```
m2_ribbon <- mgcv::bam(  
  dry ~ age_sex + s(speno, bs = "re") +  
    sin1 + cos1 + sin2 + cos2 + sin3 + cos3 +  
    poly(day, 3, raw=TRUE) +  
    sin1:poly(day, 3, raw=TRUE) +  
    cos1:poly(day, 3, raw=TRUE) +  
    sin2:poly(day, 3, raw=TRUE) +  
    cos2:poly(day, 3, raw=TRUE) +  
    sin3:poly(day, 3, raw=TRUE) +  
    cos3:poly(day, 3, raw=TRUE) +  
    wind*temp2m + pressure + precip +  
    age_sex:poly(day, 3, raw=TRUE),  
  data = ribbon_model_data,  
  family = binomial,  
  AR.start = ar1_start,  
  rho = lag1_ribbon,  
  discrete = TRUE)
```

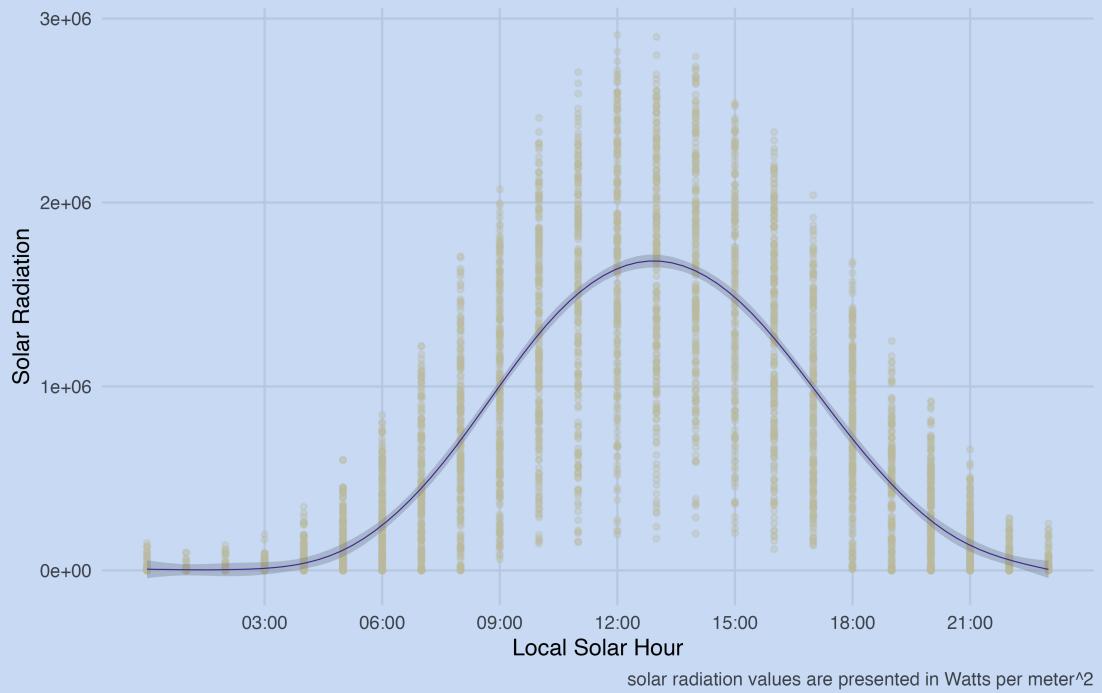
858 The model specification for exploring the use of solar radiation was specified similarly but without  
859 all of the Fourier series parameters and interactions.

```
m2_ssrd_ribbon <- mgcv::bam(  
  dry ~ age_sex + s(speno, bs = "re") +  
    era5_ssrd_watts +  
    poly(day, 3, raw=TRUE) +  
    era5_ssrd_watts:poly(day, 3, raw=TRUE) +  
    wind*temp2m + pressure + precip +  
    age_sex:poly(day, 3, raw=TRUE),  
  data = ribbon_model_data,  
  family = binomial,  
  AR.start = ar1_start,  
  rho = lag1_ribbon,  
  discrete = TRUE)
```

860 The two models were compared with AIC to evaluate whether the reduction in degrees of freedom  
861 with fewer terms in the solar radiation model was matched with improved explanatory power in

### ERA5 Reanalysis

● downward surface solar radiation



**Figure S4. Diel Pattern of Solar Radiation Values from ERA5 Reanalysis.**

Downward surface solar radiation estimates from the ERA5 climate reanalysis for 5000 random points within the study area between 2005 and 2021. Solar radiation values are presented in Watts per square-meter and the smoothed line highlights the strong diel pattern.

the model fit. While the model and code specified above is for ribbon seals, the same approach was repeated for bearded and spotted seals.

A similar approach to that presented in this manuscript for prediction was employed with solar radiation values in lieu of hour of day. For prediction values, quantiles (5% increments) of the observed range of ERA5 solar radiation values were used with 100% representing the maximum observed solar radiation value. This allowed similar data visualizations and easier comparisons to those predictions in the manuscript that include hour of day.

#### 0.3.3 Results

To evaluate whether the solar radiation parameter matched our expectations and compared well with hour of the day, we visualized the variability of the `era5_ssrd` values within our study area as they relate to hour of the day (S4). The unimodal distribution is centered around the middle of the solar day with peak solar radiation coinciding with 13:00 local solar. This suggests solar radiation could be an informative covariate for capturing unimodal diel patterns in haul-out behavior.

The bearded seal model matching the specification from the manuscript resulted in 126.13 degrees of freedom and an AIC value of -7428.929. The model with solar radiation resulted in 39.829 degrees of freedom and an AIC value of -6874.298. The ribbon seal model matching the specification from the manuscript resulted in 131.478 degrees of freedom and an AIC value of -16372.29. The model with

879 solar radiation resulted in 114.72 degrees of freedom and an AIC value of -15223.346. The spotted  
880 seal model matching the specification from the manuscript resulted in 125.54 degrees of freedom and  
881 an AIC value of -23482.051. The model with solar radiation resulted in 108.985 degrees of freedom  
882 and an AIC value of -22917.167. Despite the additional terms, the models with the Fourier series  
883 representation of hour of day resulted in a lower AIC value and were still preferred models for each  
884 of the species.

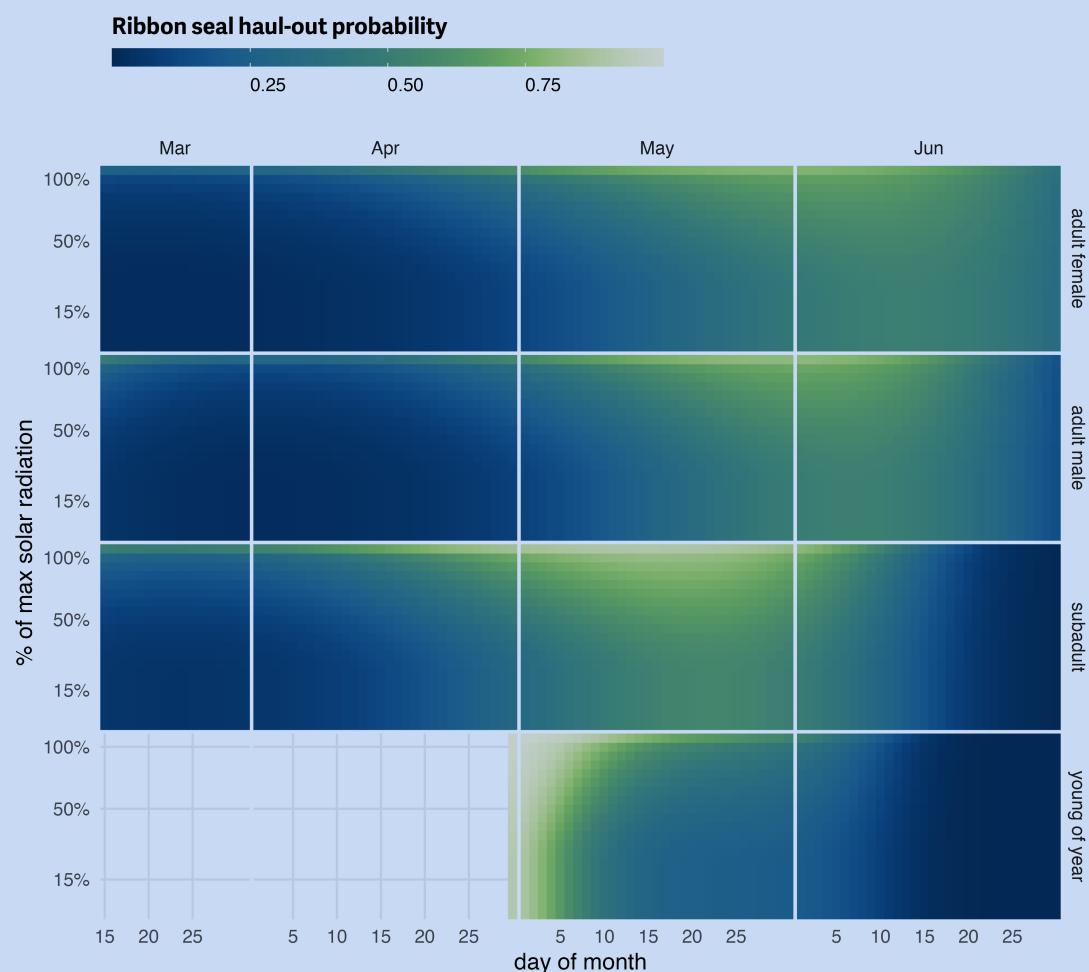
885 Predictions from the model fits and visualization of those predictions were produced for each  
886 species but, here, we only present visualizations from ribbon seals as an example (Figure S5 and  
887 Figure S6). Similar seasonal patterns previously observed were still apparent with subadults hauling  
888 out earlier in the season followed by adult males and, then, adult females. The observed relationship  
889 with hour of day and the centering of peak haul-out probability around solar noon was reflected  
890 in these predictions as a one-sided distribution with maximum solar radiation having the highest  
891 haul-out probability and minimal solar radiation the least. The seasonal distribution of haul-out  
892 probability along with 95% confidence intervals also provided comparable insights (see figures S2  
893 and S6). That said, subtle differences in the shape and extent of confidence limits were present.

894 **0.3.4 Discussion**

895 Solar radiation has potential as an informative covariate in pinniped haul-out models that can be  
896 directly linked to seal physiology and expected behavioral changes. The ERA5's *surface solar radiation*  
897 *downwards* values aligned with hour of day and maximum values occurred at or just after local solar  
898 noon. This highlighted the informative potential for this approach. However, despite an overall  
899 reduction in the total number of parameters and degrees of freedom, AIC comparison still favored  
900 the models for each species that included hour of day as a Fourier series.

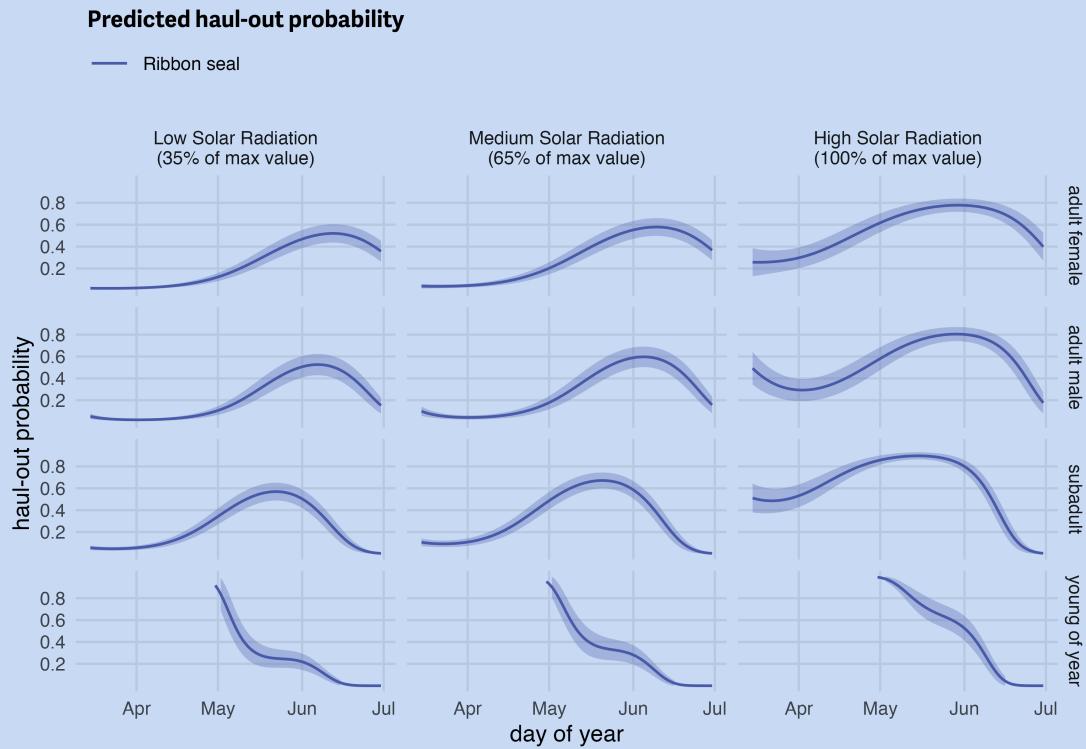
901 This analysis was not intended to be a full comparison – we simply want to demonstrate the  
902 potential and inspire further investigation – but, there are three possibilities that might explain the  
903 preference for hour of day. First, there are a broad range of solar radiation values represented for  
904 each hour of the day. Cloud cover, fog, and precipitation all reduce downward solar radiation at  
905 the surface and we might expect this to impact haul-out probability. However, the photoperiod  
906 and the timing of sunrise and sunset are not impacted by weather and seals may be responding to  
907 these signals more than the amount of solar radiation. Additionally, this study spans a range of  
908 physiological cycles and energetic needs and higher solar radiation may not be a consistent driving  
909 influence on seals. Increased energy from the sun may be important during molt but less so during  
910 pupping and breeding periods. Second, the timing and duration of haul-out behavior may also be  
911 influenced by diel patterns in weather (e.g. lower winds in the morning) or ecosystem dynamics  
912 (e.g. prey availability) that lead to a skewness in the distribution of haul-out behavior that wouldn't  
913 be reliably captured by solar radiation values. Third, this effort is only an initial effort to explore  
914 the use of solar radiation in pinniped haul-out models. A more in depth and rigorous exploration  
915 of this topic might discover an approach that results in a more parsimonious and preferred model  
916 formulation.

917 Again, we want to acknowledge Anthony Fischbach for the suggestion during the peer review  
918 process. We think this is an excellent example of the peer review process working to improve the  
919 quality of our manuscript and advance the scientific process. We hope others will take our example  
920 and expand on it within future analyses.



**Figure S5. Solar radiation as a predictor of ribbon seal haul-out probability.**

Predicted haul-out probability of ribbon seals from 15 March to 30 June for each age and sex class used in the model. In this model, solar radiation was used in lieu of hour of day. The apparent seasonal progression with subadults hauling out earlier in the season followed by adult males and, then, adult females is still notable although maybe not as clear. Predictions for young of the year still show their transition from newly weaned pups resting on the ice to more in-water activities. The overall pattern is in agreement with a one-sided view of Figure 7 where maximum solar radiation is equivalent to local solar noon.



**Figure S6. Solar radiation as a predictor of ribbon seal haul-out probability (with uncertainty).**

Seasonal variability in haul-out probability and the associated 95% confidence intervals (shaded area) for ribbon seals. In this model predictions are shown for low, medium, and high values of solar radiation (as percentages of the maximum value observed) in lieu of local solar hour. There's general agreement in the overall seasonal patterns between the two approaches but subtle differences in shape and extent of the confidence limits were present (see Figure S2 for comparisons).