

<sup>1</sup> **Spring haul-out behavior of seals in the Bering  
2 and Chukchi Seas: implications for abundance  
3 estimation**

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<sup>15</sup> **ABSTRACT**

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

## 43 INTRODUCTION

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

60 had, or will have, on seal demography.

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

76       How ice-associated seals use sea ice as a haul-out platform varies among species. Ribbon seals  
77 (*Histriophoca fasciata*) haul out of the water almost exclusively on sea ice and are mostly pelagic  
78 outside the spring pupping, breeding, and molting season (Boveng & Lowry, 2018). Although  
79 spotted (*Phoca largha*) and bearded (*Erignathus barbatus*) seals occasionally rest on coastal land,  
80 they primarily use sea ice as a haul-out platform during the spring and early summer (Frost & Burns,  
81 2018). Ringed seals (*Phoca (pusa) hispida*) — not included in this study — haul out on sea ice but  
82 primarily use snow lairs on sea ice during winter and spring.

83       The remoteness of the Bering and Chukchi seas means direct scientific observation of seal behavior  
84 is impractical. Thus, bio-logging devices are especially useful tools for collecting key information  
85 on movement and haul-out behavior for these species. Bio-logging records of time spent out of the  
86 water provide valuable data for identifying covariates that explain variation in haul-out behavior. For  
87 instance, Von Duyke et al. (2020) used satellite-linked bio-loggers to corroborate seasonal changes  
88 between diurnal and nocturnal haul-out behavior of ringed seals previously described by Kelly and  
89 Quakenbush (1990) using VHF radio tags and direct observation. Bengtson et al. (2005) documented  
90 a higher propensity for ringed seal basking near solar noon, as did Ver Hoef et al. (2014) in an analysis  
91 of bearded, ribbon, and spotted seals using much larger sample sizes. Olnes et al. (2020) showed  
92 that the proportion of time bearded seals spent hauled out progressively increased through spring  
93 and summer, and Ver Hoef et al. (2014) found haul-out probabilities increased gradually starting in  
94 March and peaked in May and June for bearded, ribbon, and spotted seals. Such analyses have not  
95 been limited to the Arctic. In the Antarctic, Bengtson and Cameron (2004) relied on bio-logging data  
96 to demonstrate greater haul-out propensity in juvenile crabeater seals (*Lobodon carcinophaga*) than  
97 adults, with highest probabilities in February and at times close to solar noon.

98       Knowledge of haul-out patterns is not only important for understanding natural history and  
99 ecology, but also for developing “availability” correction factors for aerial surveys. Specifically,  
100 researchers need to know the fraction of seals hauled out (versus in the water) when aerial surveys are  
101 conducted. Studies estimating availability correction factors for seals typically use logistic regression-  
102 style analyses to estimate the time-specific probability of being hauled out based on ‘wet/dry’ data  
103 relayed by bio-loggers. In these models, haul-out probabilities were expressed as a function of

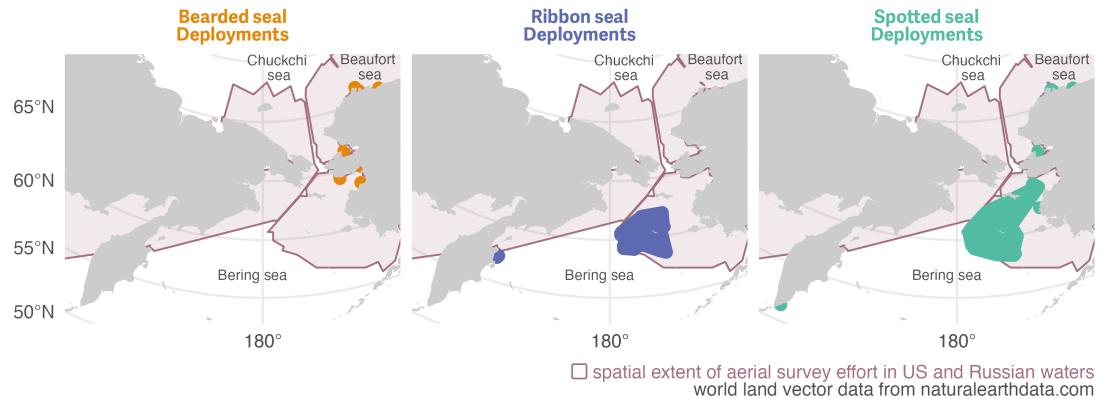
<sup>104</sup> predictive covariates, such as time-of-day, day-of-year, sex, age class, and environmental conditions  
<sup>105</sup> (e.g., Reder et al. (2003), Bengtson & Cameron (2004), Bengtson et al. (2005), Udevitz et al. (2009),  
<sup>106</sup> Lonergan et al. (2013), Ver Hoef et al. (2014), Southwell et al. (2008), and Niemi et al. (2023)).  
<sup>107</sup> However, sample sizes have often been insufficient to permit strong inference about demographic  
<sup>108</sup> and/or seasonal variation in haul-out probabilities. For instance, Bengtson and Cameron's (2004)  
<sup>109</sup> study included 5 adult and 2 juvenile crabeater seals, while Bengtson et al.'s (2005) study was based on  
<sup>110</sup> 6 ringed seals in the Chukchi and Beaufort seas. These studies were often further limited by logistical  
<sup>111</sup> constraints on fieldwork and the attachment duration or operational life of bio-loggers. In this study,  
<sup>112</sup> we addressed some of these limitations by deploying small bio-loggers designed for longer-term  
<sup>113</sup> attachment on rear flippers of a subset of the study individuals. These devices are designed to collect  
<sup>114</sup> data through the molt period (when those adhered to the hair – a more conventional method – would  
<sup>115</sup> fall off) and, in some situations, provide multiple years of data.

<sup>116</sup> In this study, we used data collected from multiple bio-logging deployments spanning a 16-year  
<sup>117</sup> period to investigate the haul-out behavior of bearded, ribbon, and spotted seals in the Bering and  
<sup>118</sup> Chukchi seas. Our goals were threefold. First, we wished to establish baseline estimates for the  
<sup>119</sup> chronology of haul-out behavior in the critical spring season for each species across different age and  
<sup>120</sup> sex classes. Second, we sought to refine estimates of haul-out availability corrections for aerial surveys  
<sup>121</sup> in order to improve estimates of seal abundance. Previously estimated availability correction factors  
<sup>122</sup> (e.g., Bengtson et al. (2005), Conn et al. (2014), and Ver Hoef et al. (2014)) accounted for variables  
<sup>123</sup> such as the time-of-day and day-of-year, but did not investigate the impact of weather variables. Such  
<sup>124</sup> variables have been shown to influence walrus haul-out behavior (Udevitz et al., 2009) and we expect  
<sup>125</sup> weather conditions to also influence seal haul-out behavior and including them within the model  
<sup>126</sup> framework will benefit our estimates of seal availability during aerial surveys. Third, we aimed to  
<sup>127</sup> assess the annual variability in haul-out timing and possible linkage to changes in the extent of  
<sup>128</sup> seasonal sea ice between 2005 and 2021. Our work extends the scope of previous haul-out analyses,  
<sup>129</sup> includes the influence of weather variability, and investigates the potential impact of changing sea-ice  
<sup>130</sup> extent on the behavior of these species.

## <sup>131</sup> METHODS

### <sup>132</sup> Data collection

<sup>133</sup> For this study we used haul-out behavior data and location estimates from bio-loggers deployed on  
<sup>134</sup> bearded, ribbon, and spotted seals in the Bering, Chukchi, and western Beaufort seas by multiple  
<sup>135</sup> organizations as part of collaborative investigations from 2005 through 2021. Seals were captured  
<sup>136</sup> using nets and bio-loggers were attached during studies based in coastal communities or on research  
<sup>137</sup> ships (Figure 1). Ship-based capture events occurred during spring near the southern ice edge in the  
<sup>138</sup> Bering Sea between 2005 and 2018. Land-based capture events occurred between 2005 and 2020 from  
<sup>139</sup> May to October, generally between the Alaska coastal communities of Scammon Bay in the Bering Sea,  
<sup>140</sup> Utqiagvik in the Chukchi Sea, and Nuiqsut in the Beaufort Sea. Data from additional deployments  
<sup>141</sup> along the Kamchatka peninsula in the western Bering Sea are also included. We refer readers to  
<sup>142</sup> the primary literature for detailed capture and bio-logger attachment methods (see publications  
<sup>143</sup> listed in Supplemental Material, S1). NOAA-led research was conducted under the authority of  
<sup>144</sup> Marine Mammal Protection Act Research Permits Nos. 782-1676, 782-1765, 15126, and 19309 issued  
<sup>145</sup> by the National Marine Fisheries Service, and Letters of Assurance of Compliance with Animal  
<sup>146</sup> Welfare Act regulations, Nos. A/NW 2010-3 and A/NW 2016-1 from the Alaska Fisheries Science



**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. World land vector data from <https://naturalearthdata.com>.

147 Center/Northwest Fisheries Science Center Institutional Animal Care and Use Committee (IACUC).  
 148 ADF&G and NSB field work was covered by Research Permits Nos. 358-1585, 358-1787, 15324, and  
 149 20466 and by ADF&G IACUC permits Nos. 06-16, 09-21, 2014-03, 2015-25, 2016-23, 0027-2017-27,  
 150 0027-2018-29, 0027-2019-041.

151 We created a subset of haul-out behavior data from 250 bio-loggers deployed on 35 bearded, 110  
 152 ribbon, and 105 spotted seals to include only records from 1 March to 15 July between 2005 and  
 153 2022. Bio-loggers were of the 'SPLASH' or 'SPOT' family of tags developed by Wildlife Computers  
 154 (Redmond, Washington, USA). Deployments consisted of either a single 'SPLASH' device, a single  
 155 'SPOT' device, or both types. Devices were either adhered to the hair on the seal or attached through  
 156 the rear flipper inter-digital webbing. The use of bio-loggers adhered to the back or head provides  
 157 some benefits over flipper mounted devices (e.g. increased satellite transmittal rates, locations at  
 158 sea) but these fall off during the following annual molt, which, depending on deployment date,  
 159 limits the duration of haul-out data they provide especially during the focus months of our study.  
 160 Additionally, bio-loggers attached to the head or dorsal region are often dry while the seal is floating at  
 161 the surface, inducing a slight positive bias in the hourly percent-dry values reported by the bio logger.  
 162 For this study, in cases where both bio logger types were deployed, we preferred hourly percent-dry  
 163 observations from the flipper tag. All data were transmitted by the deployed instruments via the  
 164 Argos satellite network and location data were either derived from Argos transmissions or transmitted  
 165 FastLoc GPS data.

166 Sex and age class (non-dependent *young-of-the-year*, sexually immature *subadults*, and mature  
 167 *adults*) were estimated at the time of deployment by various combinations of length, claw growth  
 168 ridges (McLaren, 1958), and pelage characteristics. Seals determined to be less than one year were

169 classified as young-of-the-year. For those bio-loggers deployed on young-of-the-year and transmitting  
170 into the next year (6 ribbon seals; 3 spotted seals), the age class was advanced to subadult on 1 March  
171 of the following year – the assumed anniversary of their birth. Subadults are those seals likely greater  
172 than one year of age but less than four years. Adults are individuals that are likely older than four  
173 years. Table 1 provides a summary of these deployments and data received from them.

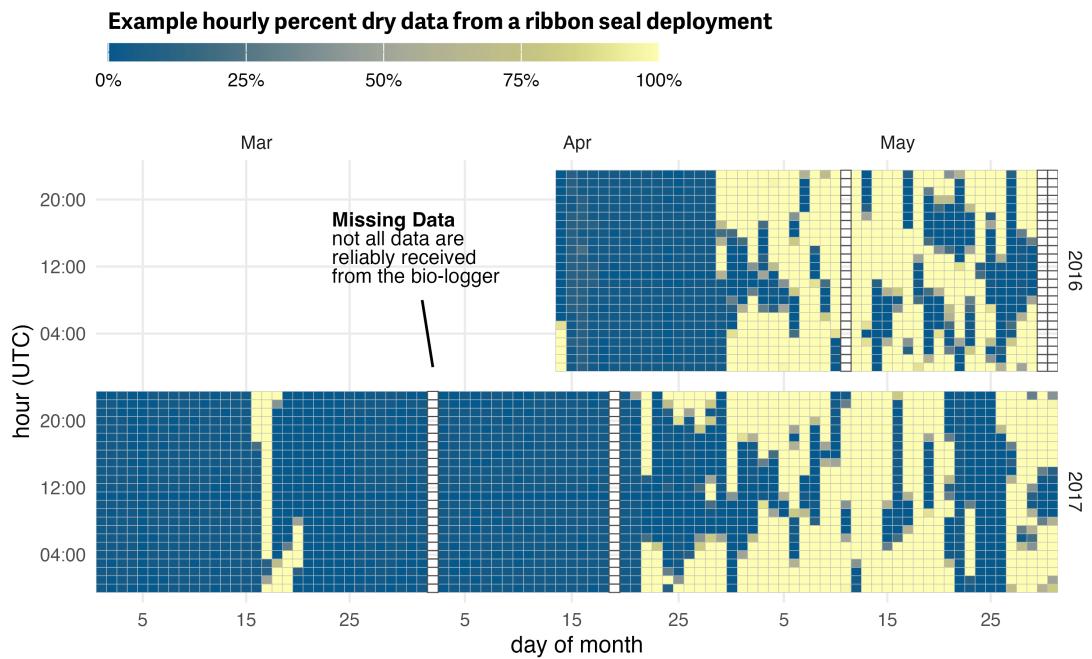
**Table 1. Summary of bio-logger data by seal species and age classification from 1 March to 15 July 2005-2021.**

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 (21,970 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)

174 Haul-out behavior data were recorded in a manner standard across Wildlife Computers bio-  
175 loggers and transmitted via the Argos satellite network as hourly percent-dry timelines. For each  
176 hour of a day, the wet/dry sensor was polled by the tag firmware every few seconds and the percent  
177 of the hour in the dry state was calculated (Figure 2). On board the bio-logger, hourly percent-dry  
178 calculations were rounded to the nearest 10% inclusive of 0% and 100% along with additional values  
179 at 3% and 98%. This compression resulted in additional data transmission as each message consisted  
180 of two complete 24-hour records. Memory capacity allowed caching of percent-dry records for several  
181 weeks or months and each message was transmitted several times to ensure reception at the satellite.  
182 Bio-loggers were deployed and programmed in a manner to maximize data transmission during the  
183 spring pupping and molting period, though hourly percent-dry data were not always successfully  
184 transmitted. This is due to a variety of factors including satellite coverage, tag availability (e.g., tags  
185 mounted to the rear flipper often do not transmit while at sea), tag performance, duty cycling, and  
186 atmospheric interference. Fortunately, missing records do not substantially bias inference about  
187 haul-out probabilities (Conn et al., 2012).

188 Tags that fell off due to molt, attachment failure, or seal mortality and remained on ice or land  
189 may have continued to send data to satellites; i.e., a detached bio-logger that is dry (either on ice  
190 or land) will record and transmit data suggesting the seal is hauled out. Therefore, end times of  
191 each deployment were identified by examining bio-logger locations, percent-dry records, and dive  
192 behavior (if available) to determine when bio-loggers ceased providing data consistent with seal  
193 behavior. For example, a data record that ended with several consecutive days (~10+ days) of 100%



**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.

dry observations and with locations indicating the tag was on land were truncated to the final stretch of 100% dry observations. The vast majority of deployments ended with the device detaching in the water and the deployment end date was obvious. There is no perfect algorithm for identifying deployment end dates and each deployment in question was considered separately. While not perfect, we are confident our reliance on expert opinion and examination of multiple data streams provided the best option. Data outside of the deployment start and end times were discarded prior to analysis.

Of key interest in this study was the relationship between haul-out behavior and weather covariates that vary with time and seal location. The use of modern bio-loggers that record and transmit behavioral data while simultaneously providing location estimates was key to this objective. We explored the use of a continuous-time correlated random walk (Johnson et al., 2008) movement model to predict locations at specific times. However, the sparse nature of data from some bio-loggers, especially those mounted to the rear flipper, resulted in poor modeling performance or convergence issues. For this study, we calculated a weighted average daily location where the inverse of the estimated Argos or FastLoc GPS location error was used for the weight. Each Argos location estimate was assigned an error radius based on either the categorical location quality ( $3 = 250 \text{ m}$ ,  $2 = 500 \text{ m}$ ,  $1 = 1500 \text{ m}$ ,  $0 = 2500 \text{ m}$  (Lopez et al., 2013); we chose 2500 m for location classes *A* and *B*) or, when available, the estimated error radius from the Argos Kalman filter algorithm. Location estimates from FastLoc GPS were all assigned an error radius of 50 m. On days when haul-out observations

were present but location data were missing we used the seal's last calculated weighted average daily location; days when the location intersected with land were removed from the seal's record. We recognize that bearded and spotted seals haul out on land. However, assessing the relationship between haul-out behavior and weather covariates and seals' availability for aerial surveys on land was outside the scope of this study. Additionally, any daily locations on land were likely more reflective of coordinate averaging and measurement error, rather than actual use of coastal features.

### Explanatory variables

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

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

**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
Hour	Continuous; Fourier basis	local solar hour using 6 variables of a 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	northerly 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.

#### 245 Haul-out modeling

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

251 To properly account for temporal dependence and to take advantage of computational efficiency,  
 252 we used generalized linear mixed pseudo-models (GLMPMs; Ver Hoef, London & Boveng (2010))  
 253 to model variation in haul-out behavior as a function of (1) covariate predictors, (2) temporally  
 254 autocorrelated random effects, and (3) individual random effects representing heterogeneity in  
 255 individual behavior. We used the glmmLDTs package (Ver Hoef, London & Boveng, 2010) to  
 256 implement GLMPMs. We explored two different model formulations for our data and we fit separate  
 257 models to bearded, ribbon, and spotted seal data sets as we expected differing behavior by species.  
 258 Separate models for each species were also needed because a single, very large data set proved  
 259 computationally intractable. In our first model formulation and for each species, we fitted a year-  
 260 independent model that predicted average haul-out behavior as a function of demographic, weather,  
 261 seasonal, and diurnal effects. Second, for ribbon and spotted seals (which had considerably more  
 262 data than bearded seals), we fitted models that included all the effects from the first model, but

263 also permitted annual variation in haul-out timing. This second set of models was used to examine  
264 whether haul-out patterns varied by year and to determine the annual timing of apparent peaks in  
265 haul-out behavior. For both models, we assumed an hourly Bernoulli response (a binary 0-1 response  
266 dependent upon whether the tag was greater than 50% dry for a given hour) where the linear predictor  
267 was modeled on the logit scale. This is consistent with previous approaches (London et al., 2012; Ver  
268 Hoef et al., 2014) and only 7.005% of our observations fell between 10% and 90% hourly percent-dry.

269 We followed Ver Hoef et al. (2014) in using linear, quadratic, and cubic effects of day-of-year  
270 to represent temporal changes in behavior during the season. However, unlike previous models  
271 for harbor seals (London et al., 2012) and ice-associated seals (Ver Hoef et al., 2014), which treated  
272 hour-of-day as a 24-level categorical variable to capture diurnal cycles, we adopted a continuous  
273 formulation based on Fourier series that provides a flexible model while preserving the inherent  
274 circularity needed for time-of-day effects (i.e., hour 0 should be equal to hour 24). It also represents  
275 hour-of-day with 6 parameters, which is a considerable reduction when compared to a 24-parameter  
276 variable. According to this approach, we used the following specification for hour-of-day effects:

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

277 where  $H_t$  gives the effect for solar hour  $t$  and  $\alpha_i$  are estimated parameters (regression coefficients).

278 For the second set of models examining inter-annual variation in sea-ice use, we fitted models  
279 with year by day-of-year interactions. However, in this case we only included *year:day* and *year:day<sup>2</sup>*,  
280 omitting the main effects of year as well as *year:day<sup>3</sup>* interactions because models with the latter  
281 effects were numerically unstable. However, the modeled interactions were sufficient to allow shifts  
282 in haul-out distribution, as one can show mathematically that a simple horizontal shift in timing  
283 of haul-out distributions does not affect the main effects or cubic terms in a polynomial regression  
284 model. Bearded seals were not included in this examination of inter-annual variation because of  
285 limited data across many years in the study.

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

299 Visualizing the marginal or conditional effect of an individual weather covariate (where all other  
300 weather covariates are being held at mean values) on haul-out probability was difficult in this analysis  
301 because of the collinearity between covariates as well as the spatial and temporal variation across  
302 such a large region. The relationship of each weather covariate with haul-out probability, averaged  
303 over the other weather conditions, was more variable than model coefficients would imply. That said,

304 important insights can be gained from plots of marginal effects. To create these plots, we predicted  
305 haul-out probability across the full range of each weather covariate while fixing hour of the day at  
306 local solar noon and day-of-year at 15 May. For the other weather covariate values, we chose not  
307 to use a fixed mean value because we expect weather to vary within day over the season (e.g. the  
308 temperature at solar noon will gradually increase from March through June). To account for this, we  
309 fit a simple generalized additive model for each weather covariate with smooth terms for day-of-year  
310 and solar hour. We used predicted values from the generalized additive model in lieu of holding  
311 other weather covariates at a fixed mean value which would not capture seasonal change. The  
312 visualizations also include vertical lines representing 95% confidence intervals around the predicted  
313 haul-out probability to better communicate the variation in model uncertainty.

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

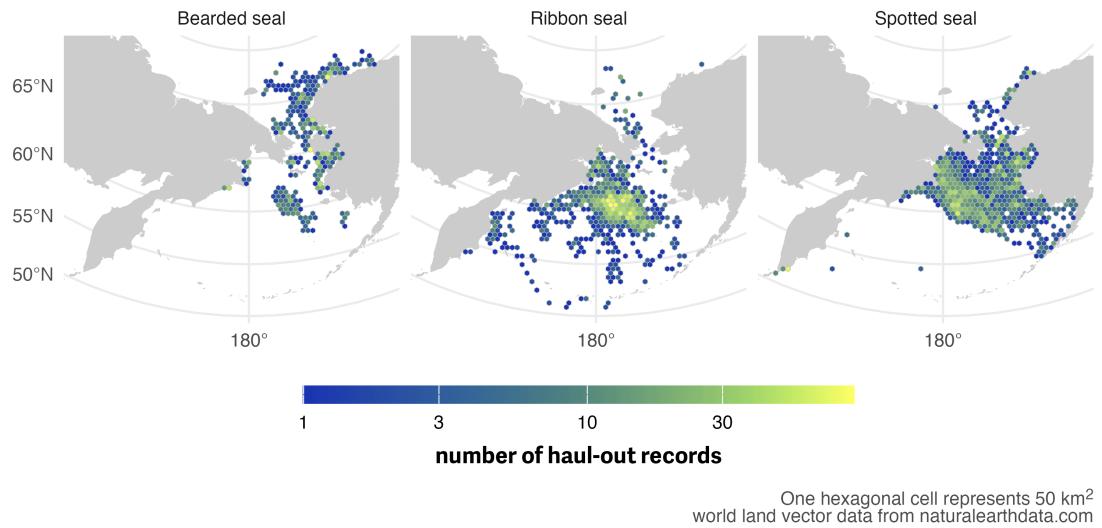
## 324 RESULTS

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

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

### 343 Bearded Seals

344 Age and sex class were not included in the model for bearded seals due to our lower sample size for  
345 adult and young-of-year age classes. As such, results are shown for all ages (Figure 5; see also S1).



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

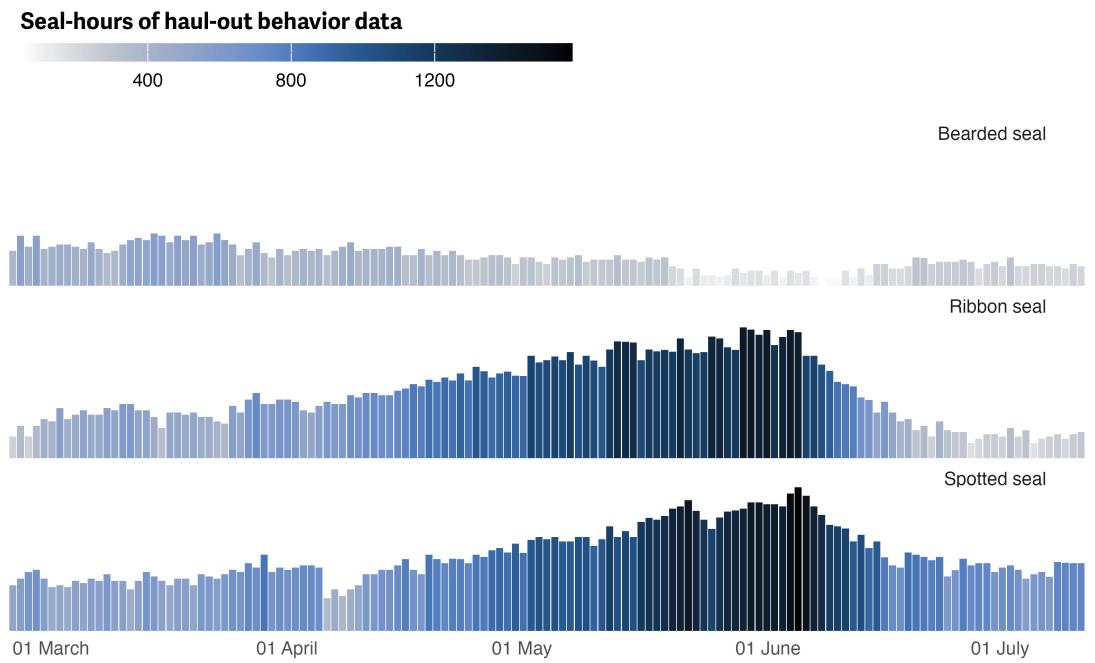
Linking location estimates with haul-out records in space and time allows for inclusion of weather covariates in the final model. For this visualization, data were collated across all years between 2005 and 2020 and each hexagonal cell represents an area of 50 km<sup>2</sup>. World land vector data from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

346 Additionally, after approximately 9 months, 7 devices deployed on the rear flipper of bearded seals  
 347 reported implausible hourly percent-dry data (100% dry for several weeks but indicative of movement  
 348 and increasing transmission rates (see Boveng & Cameron (2013))). All data after the first instance of  
 349 unrealistic values were censored from this analysis. In addition to a peak around local solar noon, the  
 350 bearded seal model predicted additional haul-out activity around local midnight. In concert with the  
 351 lower magnitude of haul-out probability, bearded seal haul-out behavior was also more protracted  
 352 throughout the spring season compared to ribbon and spotted seals (see below). Overall, bearded  
 353 seals were less likely to haul out and had a bi-modal distribution of haul-out probability across the  
 354 day.  
 355

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

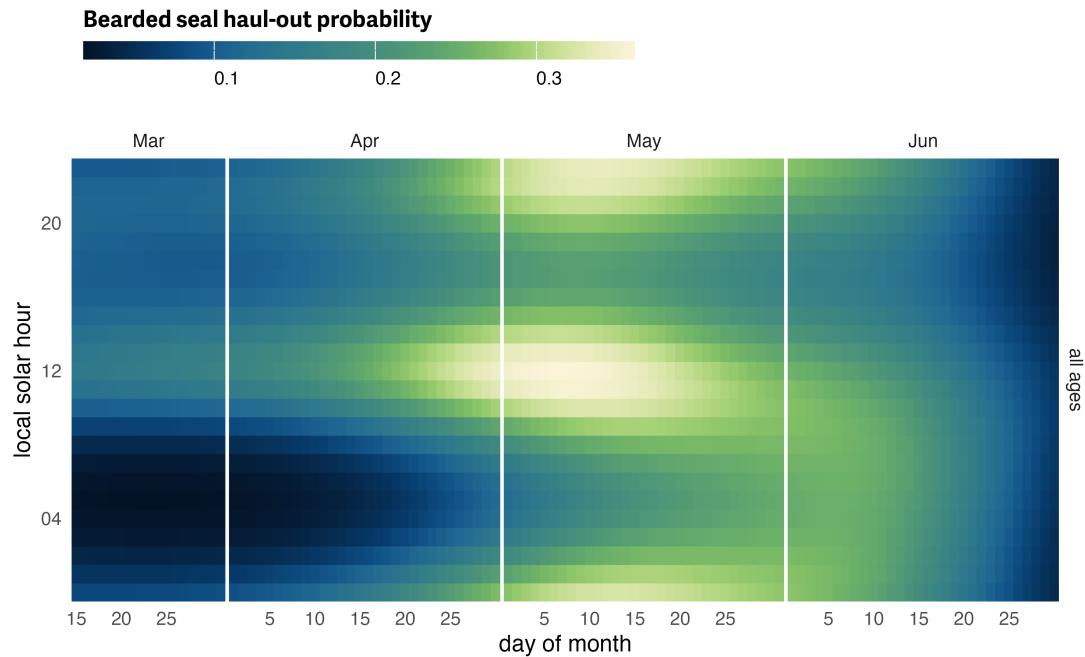
### 361 **Ribbon Seals**

362 Ribbon seals exhibited a pattern of gradually increasing haul-out probability in April that peaks in late  
 363 May for subadults and in early June for adults (Figure 7; see also S2). There is an apparent seasonal  
 364 progression with subadults hauling out earlier in the season followed by adult males and, then, adult  
 365 females. Haul-out behavior was clearly centered around local solar noon and expanded to other  
 366 hours later in the spring as seals entered their molting period. Subadults showed an earlier start and  
 367 more intense haul-out activity in April and May. The young-of-the-year records began after weaning



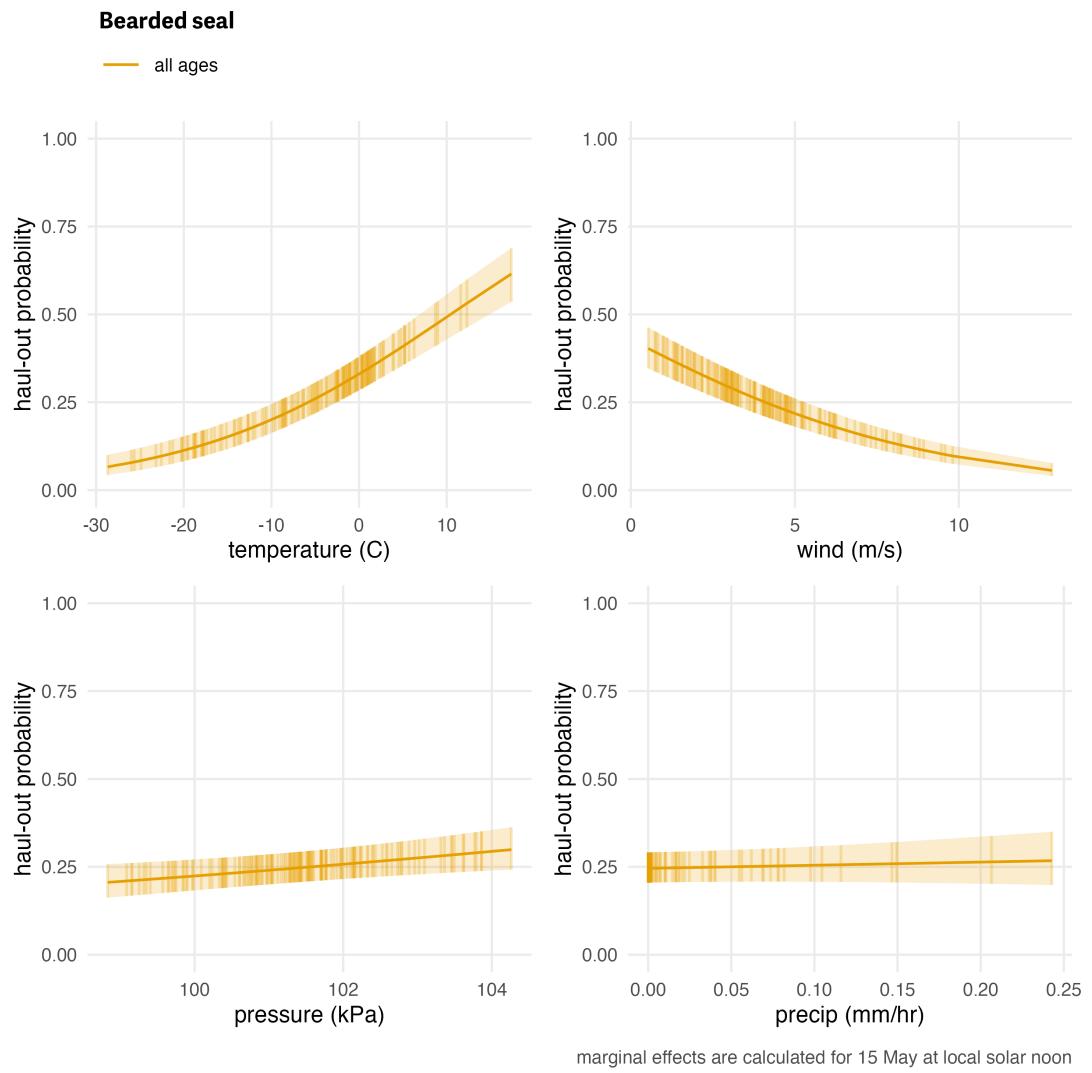
**Figure 4. Seasonal distribution of haul-out behavior observations by species**

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.

368 and the model predictions seemed to indicate development of in-water activities (e.g. swimming,  
369 foraging) in May and, like adults, haul-out behavior was centered around solar noon. Adult females  
370 had a more protracted haul-out season compared to males, and more time was spent hauled out in  
371 June compared to adult males and subadults.

372 The haul-out probability for ribbon seals was mostly influenced by temperature ( $F_{1,99540} = 6.87$ ;  
373  $p = 0.009$ ) and wind ( $F_{1,99540} = 49.314$ ;  $p = <0.001$ ) with barometric pressure ( $F_{1,99540} = 3.446$ ;  $p$   
374 = 0.063) having a milder impact. Ribbon seals were more likely to haul out when temperatures  
375 were relatively warm and less likely to haul out at higher winds and lower pressure values (Figure  
376 8). Neither wind chill ( $F_{1,99540} = 1.83$ ;  $p = 0.176$ ) nor precipitation ( $F_{1,99540} = 0$ ;  $p = 0.989$ ) were a  
377 significant influence on haul-out probability. Compared with bearded seals, the effect of weather  
378 covariates on the predicted haul-out probability for ribbon seals was less striking. Because our ribbon  
379 seal model included age and sex class, we can visualize the different influences of weather covariates  
380 on those classes and see that subadults differ from adult males and females (Figure 8).

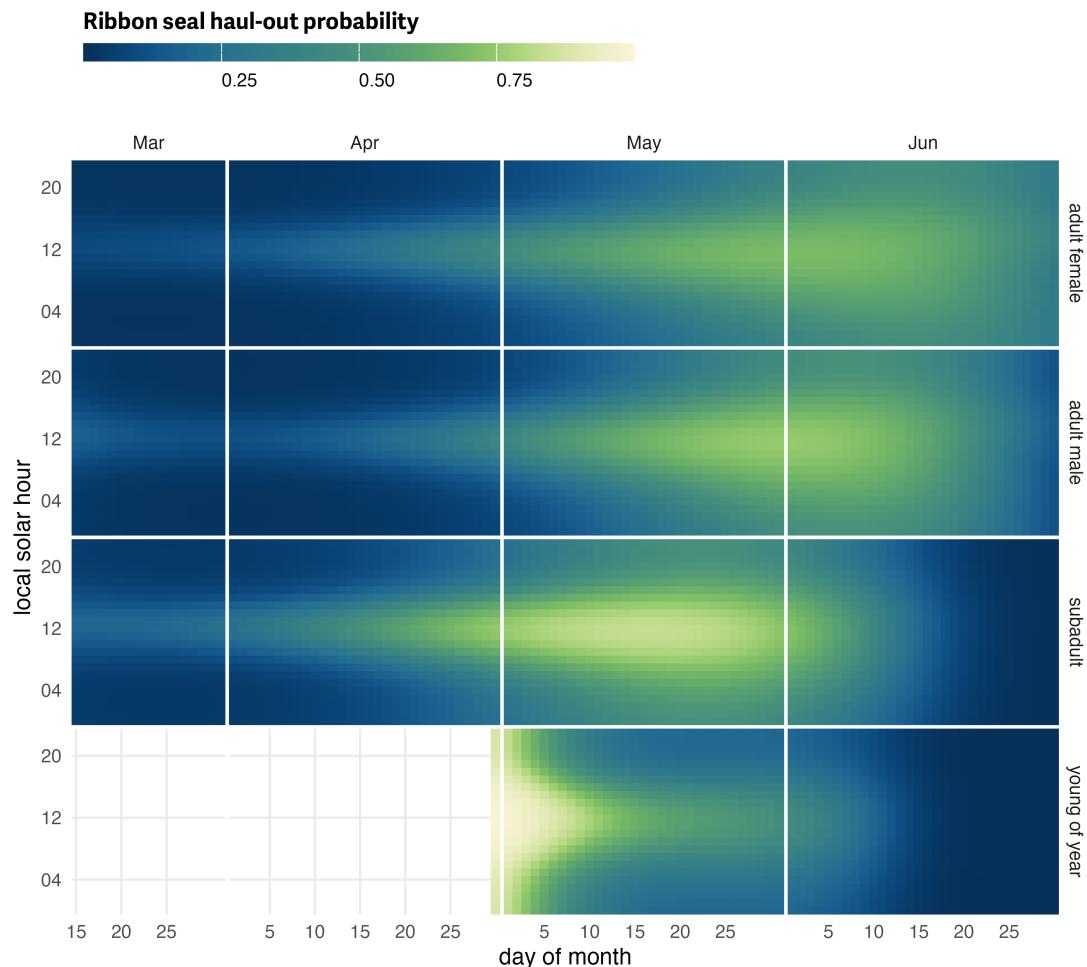
### 381 **Spotted Seals**

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

389 Spotted seal haul-out behavior was less affected by the weather covariates compared to ribbon  
390 and bearded seals but their influence on the model was still significant in some cases. Temperature  
391 ( $F_{1,115189} = 5.384$ ;  $p = 0.020$ ), wind ( $F_{1,115189} = 45.718$ ;  $p = <0.001$ ), and barometric pressure ( $F_{1,115189}$   
392 = 9.445;  $p = 0.002$ ) were all significant. Spotted seals were more likely to be on the ice when  
393 temperatures were relatively warm and less likely to haul out at higher wind speeds. Wind chill  
394 ( $F_{1,115189} = 0.72$ ;  $p = 0.396$ ) and precipitation ( $F_{1,115189} = 0.773$ ;  $p = 0.379$ ) were not as influential  
395 as the other covariates. Differences in the magnitude of response between the age-sex classes were  
396 present and consistent across each of the weather covariates (Figure 10). There was a consistent  
397 ranking of adult males being the most likely to haul out, followed by adult females, and, then,  
398 subadults. This differs from ribbon seals which showed more overlap between adult males and  
399 adult females and that subadults were most likely to haul out across the presented range of weather  
400 covariates.

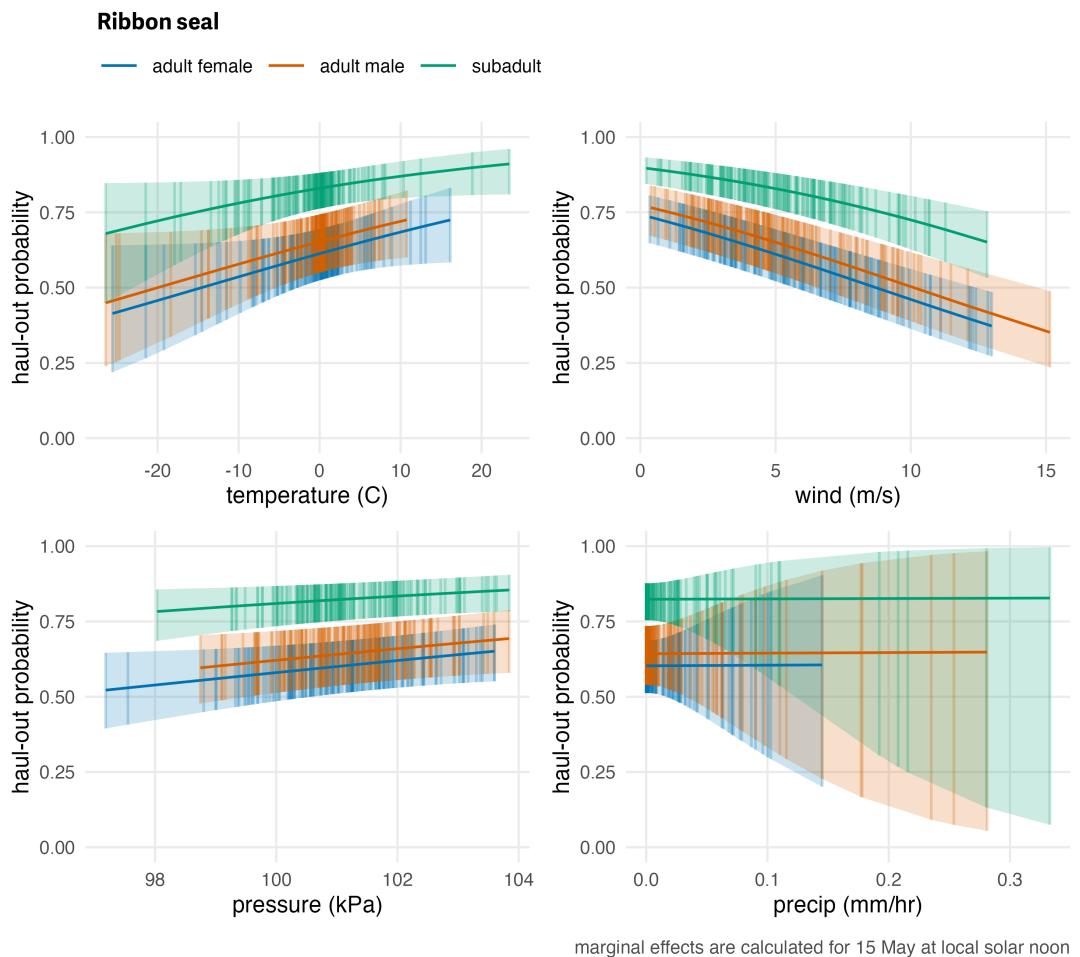
### 401 **Annual variation in haul-out timing**

402 The second set of models, which included annual variation in haul-out patterns, uncovered significant  
403 contributions for linear and quadratic interactions between day and year for only spotted seals  
404 (day:year,  $F_{15,115144} = 4.445$ ;  $p = <0.001$ ; day<sup>2</sup>:year,  $F_{15,115144} = 5.854$ ;  $p = <0.001$ ). Ribbon seals  
405 showed no significant contribution for interactions between day and year (day:year,  $F_{10,99510} = 0.516$ ;  
406  $p = 0.880$ ; day<sup>2</sup>:year,  $F_{10,99510} = 0.549$ ;  $p = 0.856$ ). Predicted distributions of haul-out activity were  
407 largely unimodal, but varied some among and within years with respect to the timing and magnitude  
408 of haul-out peaks (Figure 11). It is important to note that predicted variation in annual haul-out  
409 patterns likely reflected both process error and sampling variability. While we did remove any years  
410 where only one deployment in a species + age:sex group was present, there were still some years



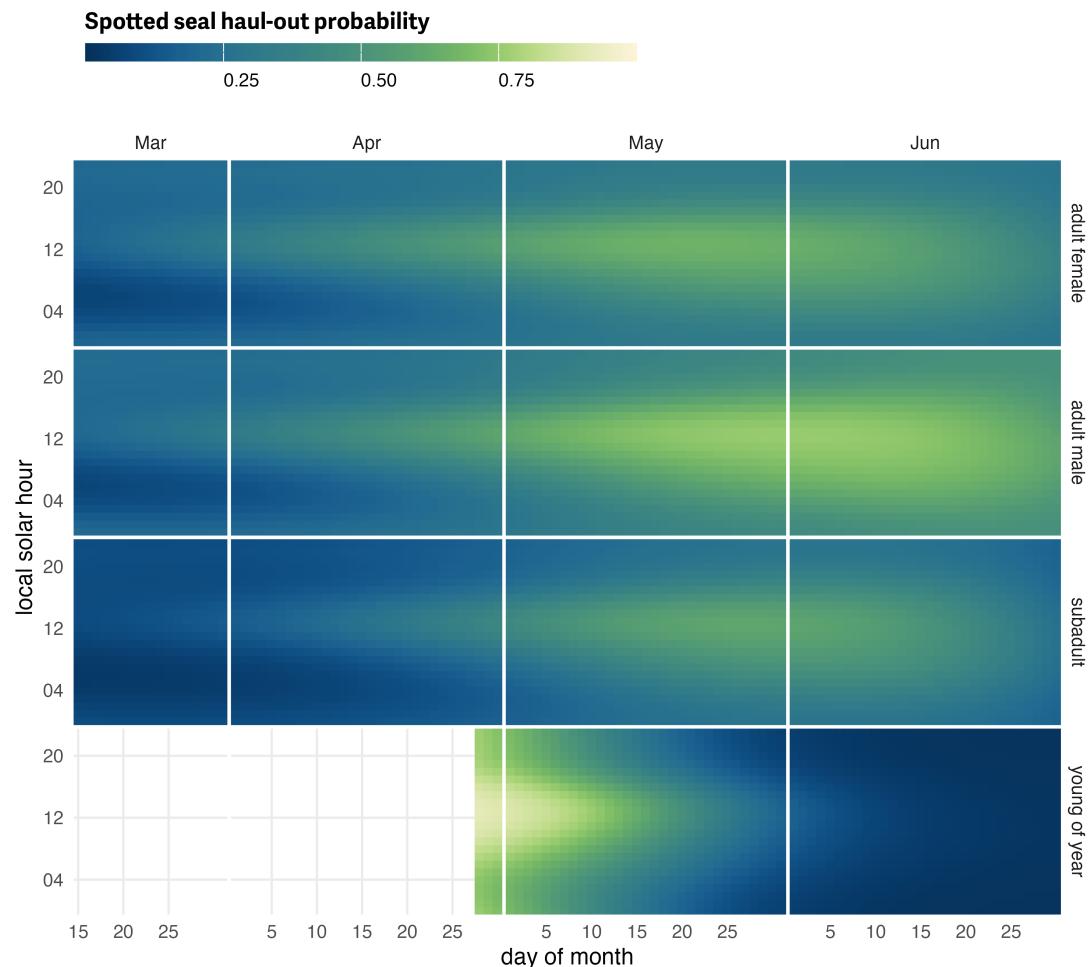
**Figure 7. Ribbon seal predicted haul-out probability**

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.



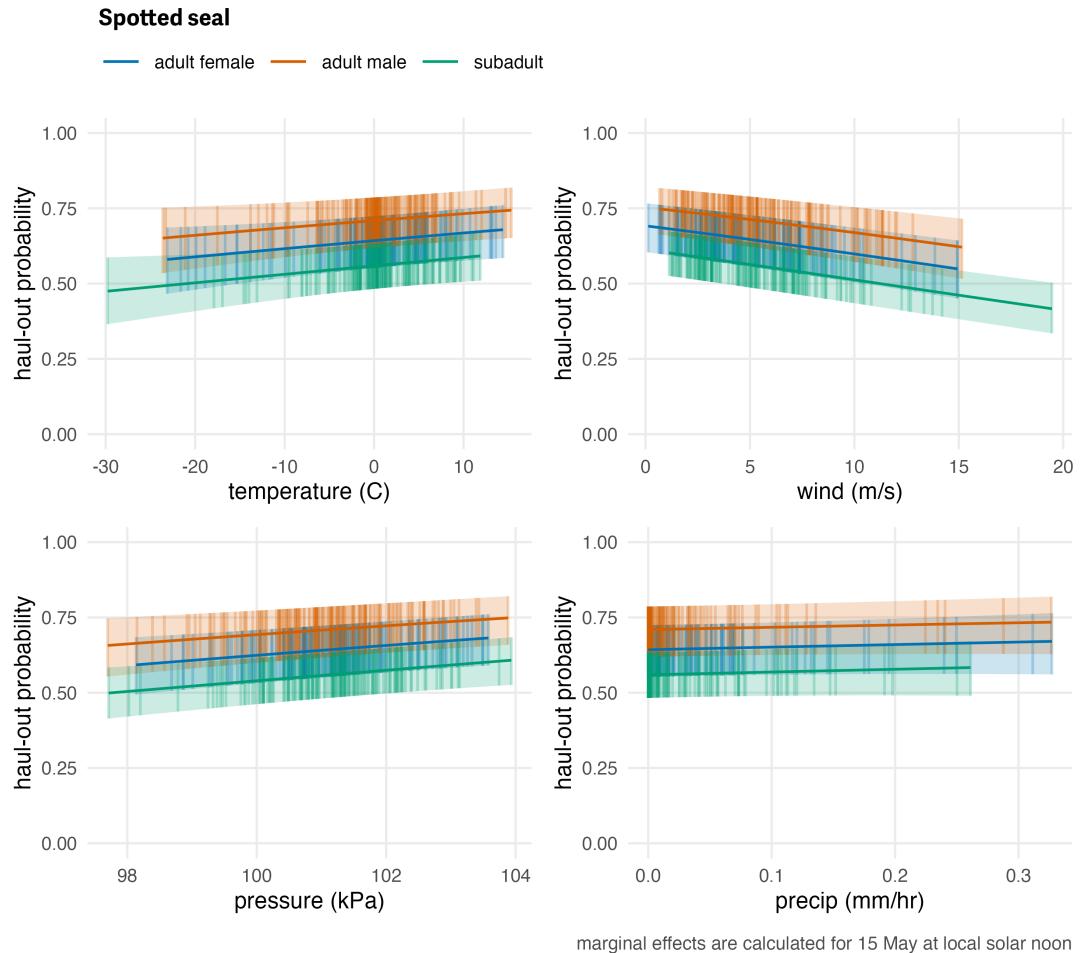
**Figure 8. Influence of weather covariates on ribbon seal haul-out probability**

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.



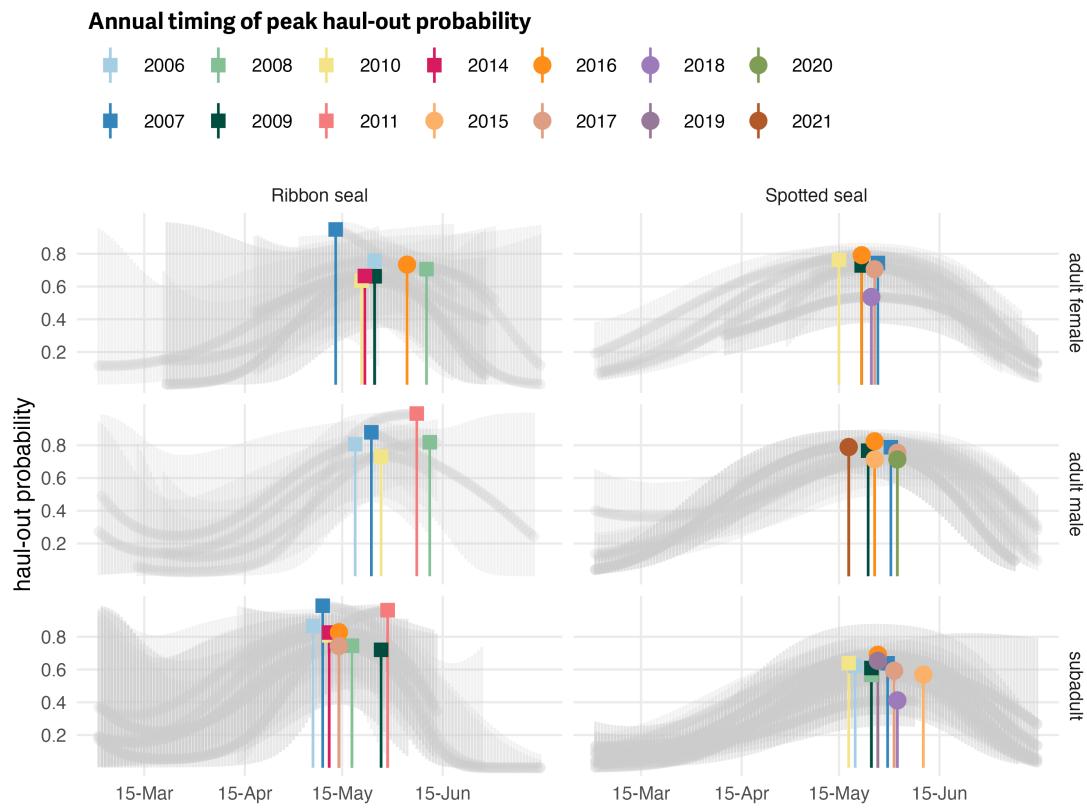
**Figure 9. Spotted seal predicted haul-out probability**

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.

411 where the pattern shown was informed by a small number of individuals that may not represent  
412 population-level patterns.

413 The annual timing of peak haul-out probability for ribbon seals and adult male spotted seals  
414 appeared to have no relationship with the amount of yearly maximum sea-ice extent in the study area.  
415 For ribbon seals and adult male spotted seals,  $p$ -values were substantially larger than 0.05 (ribbon  
416 seal adult females:  $R^2 = 0.004$ ,  $p = 0.896$ ; ribbon seal adult males:  $R^2 = 0.059$ ,  $p = 0.693$ ; ribbon seal  
417 subadults:  $R^2 = 0.007$ ,  $p = 0.828$ ; spotted seals adult males:  $R^2 = 0.004$ ,  $p = 0.889$ ). Adult female and  
418 subadult spotted seals both showed a negative trend (peak haul-out occurs later in years with less  
419 sea ice) with a significant relationship for adult female spotted seals (spotted seal adult female:  $R^2 =$   
420 0.456,  $p = 0.141$ ; spotted seal subadults:  $R^2 = 0.369$ ,  $p = 0.062$ ).

421 **DISCUSSION**

422 We modeled data from bio-loggers deployed on bearded, ribbon, and spotted seals to examine factors  
423 affecting their haul-out behavior on sea ice in the Bering and Chukchi seas. Our analysis shows all  
424 three species of seal haul out progressively more through the spring and peak near mid-May to early  
425 June before declining again. This pattern aligns well with what has been previously documented  
426 qualitatively (Boveng et al., 2009; Cameron et al., 2010; Boveng & Cameron, 2013) and confirms our  
427 haul-out data are likely quantifying population-level behavioral patterns. Beginning in spring, seals  
428 preferentially haul out on ice shortly after solar noon, which allows seals to maximize absorption of  
429 solar radiation thought to facilitate the molting process (Feltz & Fay, 1966). Interestingly, bearded  
430 seals appear to have two peaks in haul-out activity within a day, one shortly after solar noon, and  
431 one centered near solar midnight. This, of course, could be an artifact of our limited sample size for  
432 bearded seal deployments across all age classes. However, a similar bi-modal pattern has been seen  
433 in ringed seals (Von Duyke et al., 2020) and suggests that bearded and ringed seals may be operating  
434 under different constraints than ribbon and spotted seals. Bearded and ringed seals are distributed  
435 across higher latitudes that experience extended daylight hours during spring which may allow more  
436 flexibility in alternating resting and foraging events. Other factors such as predation by polar bears  
437 (which is rare for ribbon and spotted seals in the Bering Sea) may also explain differing haul-out  
438 patterns. The change in haul-out behavior during the season was less pronounced in bearded seals  
439 compared to ribbon and spotted seals. This aligns with findings from Thometz et al. (Thometz et al.,  
440 2021) who observed a mean molting period of  $119 \pm 2$  days and a relatively stable resting metabolic  
441 rate for bearded seals during that time. While ribbon seals were not considered in that study, spotted  
442 and ringed seals underwent molt periods of just  $33 \pm 4$  and  $28 \pm 6$  days and had increased resting  
443 metabolic rates.

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

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

465 continue foraging while nursing. Subadult ribbon and spotted seals begin elevated haul-out behavior  
466 earlier in the spring and follow a pattern seen in other phocids where yearlings and subadults molt  
467 first followed by adult females and males (Thompson & Rothery, 1987; Kirkman et al., 2003; Reder et  
468 al., 2003). Also of note is the early development in newly weaned pups of haul-out behavior centered  
469 around solar noon observed in this study.

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

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

502 Our models detected small deviations in the timing and magnitude of annual peaks in haul-out  
503 behavior for ribbon and spotted seals. The timing of peak haul-out activity appears to fall within  
504 a relatively narrow time window of 3-4 weeks in late May and early June. This consistency across  
505 15 years is likely a reflection of the relationship between a critical photoperiod and the timing of  
506 important life history stages (Temte, 1994; Bronson, 2009). However, along with a critical photoperiod,  
507 ribbon and spotted seals are dependent upon the presence of sea ice for pupping and molt. We did not  
508 find large support in our models for a relationship between the timing of peaks in haul-out behavior

509 and the amount of yearly maximum sea ice. This could indicate that, while the extent of spring sea ice  
510 in the Bering Sea varied widely during our study period, seals were still able to locate sea ice and haul  
511 out. Only a small portion of our data was from 2018 – 2019, years of extreme low spring ice extent in  
512 the Bering Sea that appeared to impact body condition of ribbon and spotted seals (Boveng et al.,  
513 2020), so we may currently lack sufficient contrast in ice extent to characterize an effect on the timing  
514 of peak haul-out probability. We should expect, however, that some minimal threshold in the spatial  
515 extent or density of sea ice will have a meaningful impact on the timing of peak haul-out behavior —  
516 if there is no sea-ice, seals will not haul out or they will be forced to use terrestrial haul-out sites which  
517 were not part of the evolution of their normal behaviors. Additionally, while from an ecological  
518 perspective the haul-out behavior appears consistent, the interannual differences in timing and  
519 magnitude are large enough to have important ramifications on calculations of abundance and trend.  
520 Those ramifications will only be exacerbated if climate variability amplifies interannual differences.

521 Previous attempts to estimate the abundance of phocid seals from aerial survey data in the Bering  
522 and Chukchi seas (e.g. Bengtson et al. (2005), Conn et al. (2014), Ver Hoef et al. (2014)) have used  
523 estimated haul-out probabilities to correct for the proportion of animals that are in the water and  
524 thus unavailable to be counted. Although several of these studies allowed haul-out probabilities to  
525 vary by day-of-year and time-of-day, they have not accounted for variability among years, weather  
526 conditions, or in the age-sex class of the sample. In this paper, we have shown that there can  
527 be considerable differences in the haul-out probability of seals on ice based on these factors and  
528 subsequent analyses have shown the potential for considerable bias in abundance estimates if such  
529 covariates are unaccounted for (see Conn & Trukhanova (2023) for discussion about the importance  
530 of including stable age- and stage-proportions). We recommend that future abundance analyses  
531 employ availability models that account for them. For instance, it is relatively straightforward to  
532 obtain weather reanalysis products (e.g. NARR, ERA5) for times and locations that are surveyed and  
533 to construct a relevant correction factor based on predictions of GLMPMs. The most challenging  
534 element in developing availability correction factors is with annual variability. It can be difficult to  
535 get a sufficient sample size to estimate year-specific correction factors, particularly because research  
536 teams would likely need to deploy bio-loggers on seals and conduct aerial surveys concurrently,  
537 requiring considerably more personnel and money. One possible suggestion is to include year as a  
538 random effect within models for aerial survey counts such that, without specific knowledge of any  
539 particular year, the among-year variance is included in the modeled standard errors. Regardless of  
540 the specific approach, future estimates of Arctic seal abundance will require specific consideration  
541 of annual variability and changes in the timing of peak haul-out behavior when estimating trends,  
542 as one will not know if moderate differences in abundance estimates are attributable to changes in  
543 abundance or changes in haul-out behavior.

544 Predictions of absolute haul-out probability in this paper were somewhat different than those  
545 previously reported for these species, especially for bearded seals. For instance, Ver Hoef et al. (2014)  
546 and Conn et al. (2014) used haul-out correction factors with maximums of 0.66 for bearded seals,  
547 0.62 for ribbon seals, and 0.54 for spotted seals, where these maximums corresponded to times near  
548 local solar noon in mid-late May. Results here suggest a haul-out probability on May 20 at local solar  
549 noon of 0.304 (95% CI: 0.258 – 0.354) for bearded seals across all age and sex classes, 0.715 (95% CI:  
550 0.62 – 0.794) for adult male ribbon seals, 0.661 (95% CI: 0.576 – 0.738) for adult female ribbon seals,  
551 0.74 (95% CI: 0.654 – 0.811) for adult male spotted seals, and 0.66 (95% CI: 0.571 – 0.739) for adult  
552 female spotted seals. Our estimates of haul-out probability reflect increased sample sizes in terms

553 of number of individuals, inclusion of weather covariates, and improvements to the way data were  
554 prepared prior to analysis and should be the basis for any future estimates of seal abundance from  
555 aerial surveys in the Bering and Chukchi seas.

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

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

## 573 AUTHOR CONTRIBUTIONS

- 574 • **Josh M. London:** investigation, conceptualization, methodology, formal analysis, validation,  
575 software, writing: original draft, writing: review and editing, visualization, and data curation
- 576 • **Paul B. Conn:** conceptualization, methodology, formal analysis, software, validation, writing:  
577 original draft, writing: review and editing
- 578 • **Stacie K. Hardy:** investigation, data curation, methodology, validation, writing: review and  
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- 580 • **Erin L. Richmond:** data curation, investigation, methodology, validation, writing: review and  
581 editing
- 582 • **Jay M. Ver Hoef:** conceptualization, methodology, software, writing: review and editing
- 583 • **Michael F. Cameron:** investigation, project administration, writing: review and editing
- 584 • **Justin A. Crawford:** investigation, methodology, validation, data curation, writing: review  
585 and editing
- 586 • **Lori T. Quakenbush:** investigation, methodology, supervision, project administration, writing:  
587 review and editing
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589 and editing
- 590 • **Peter L. Boveng:** investigation, conceptualization, supervision, project administration, writing:  
591 review and editing

## 592 DATA AVAILABILITY

593 This manuscript was developed as a reproducible research compendium and was originally  
594 published as a pre-print at bioRxiv (London et al. (2022); <https://doi.org/10.1101/>

595 2022.04.07.487572). All data used in the study and code are available on GitHub  
596 (<https://github.com/noaa-afsc/berchukseals-haulout>) and major versions  
597 archived at Zenodo (<https://doi.org/10.5281/zenodo.4638221>). Original data sources  
598 for telemetry are archived as part of datasets at the United States Animal Telemetry Network  
599 (<https://portal.atn.ioos.us/>; <https://doi.org/10.24431/rw1k8er>), archived  
600 at Movebank (see Movebank ID 732321226), or associated with other published manuscripts  
601 (see supplemental material S1). Collated and cleaned data products needed to replicate the  
602 analysis along with the results of all model fits are also available and versioned as an R package on  
603 GitHub (<https://github.com/noaa-afsc/berchuksealsHauloutFits>) and archived  
604 at Zenodo (<https://doi.org/10.5281/zenodo.10056308>).

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790 **SUPPLEMENTAL MATERIAL**

791 **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	2017	Colville River, Nuiqsut	Olnes et al 2020	15324	1	F	subadult

Institution	Year Deployed	Location	Publication(s)	Permits	No. Seals	Sex	Age Class
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
NMFS	2008	Bering Sea		782-1765	1	M	subadult
NMFS	2009	Bering Sea		782-1765	28	F, M	adult, subadult, young of year

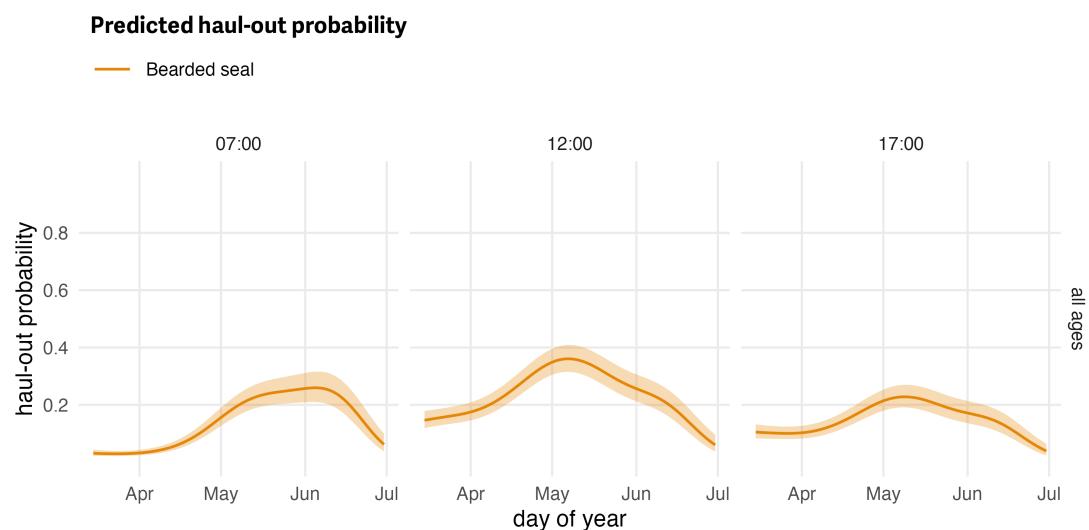
Institution	Year Deployed	Location	Publication(s)	Permits	No. Seals	Sex	Age Class
NMFS	2010	Bering Sea		358-1787, 15126	17	M, F	young of year, adult, subadult
NMFS	2014	Bering Sea		15126	13	M, F	subadult, adult, young of year
NMFS	2016	Bering Sea		19309	7	M, F	subadult, adult
<b>Spotted seal</b>							
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
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

Institution	Year Deployed	Location	Publication(s)	Permits	No. Seals	Sex	Age Class
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

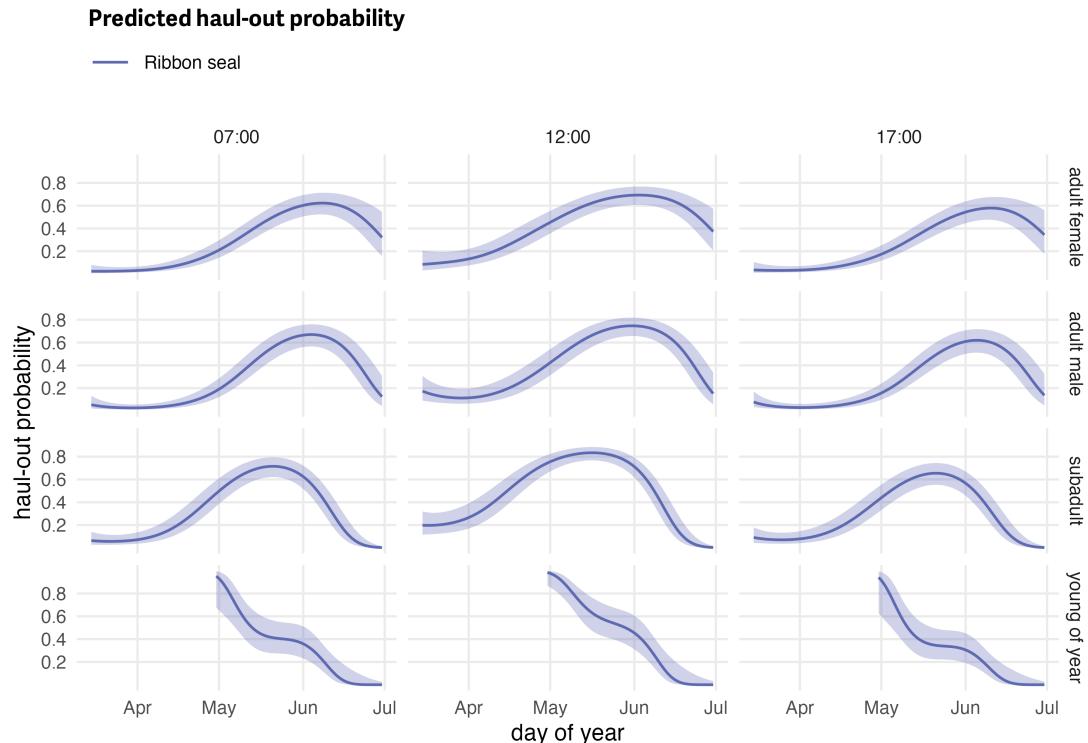
<sup>792</sup> **0.2 Supplemental Figures Showing Confidence Intervals Associated with Predictions**

<sup>793</sup> The following series of figures (**S1**, **S2**, and **S3**) show the seasonal variability in predicted haul-out  
<sup>794</sup> probability and the associated 95% confidence intervals for bearded, ribbon, and spotted seals. The  
<sup>795</sup> predictions shown are based on the same data used in **5**, **7**, and **9** but selected for three local solar  
<sup>796</sup> hours (07:00, 12:00, and 17:00) so the confidence intervals can also be shown and comparisons can  
<sup>797</sup> be made.



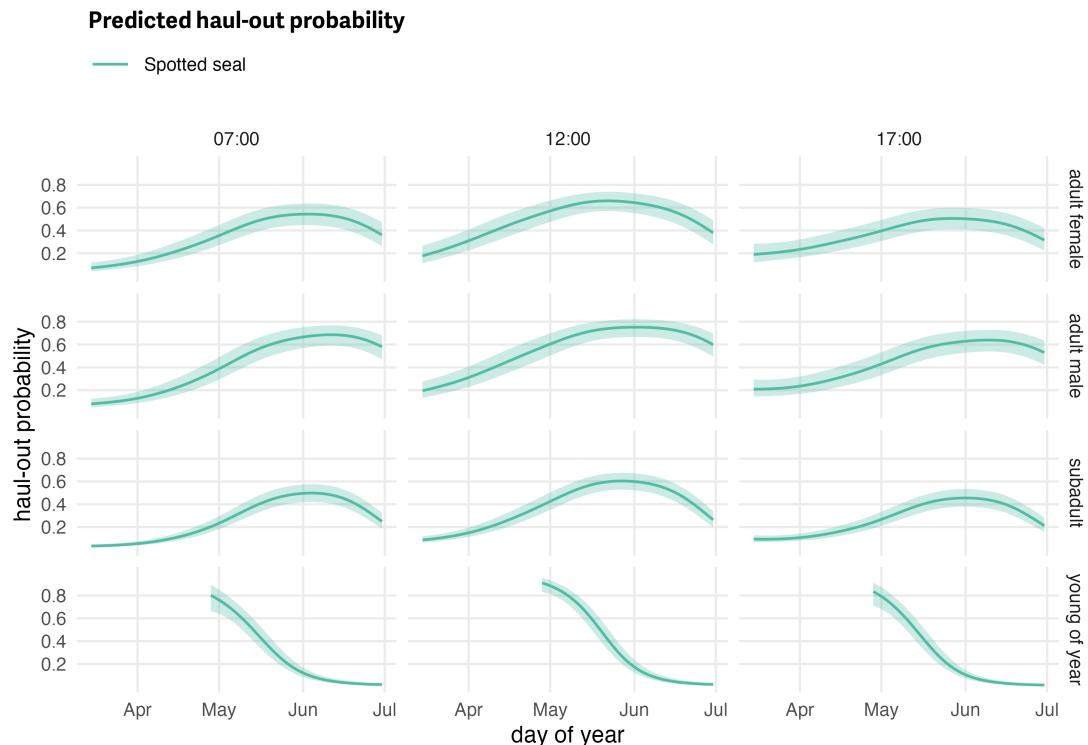
**Figure S1. Seasonal variability in haul-out probability and the associated 95% confidence intervals (shaded area) for bearded seals.**

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.

798 **0.3 Exploring Insolation (Solar Radiation) as a Model Covariate**

799 **0.3.1 Introduction**

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

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

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

828 **0.3.2 Methods**

829 In this manuscript, we rely on the NARR reanalysis model as the source for our weather covariates.  
830 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  
831 provides an increased temporal resolution to hourly (compared to the 3-hour resolution of NARR).  
832 The global coverage of ERA5 provides additional flexibility in that the area of interest is not limited  
833 to North America. The ERA5 model provides a number of solar radiation parameters and it was  
834 important to evaluate and understand each of these estimates in order to select the one that was  
835 likely most relevant to seals. Here, we used the ‘surface short-wave (solar) radiation downwards’  
836 parameter. This parameter is described as “*the amount of solar radiation (also known as shortwave  
837 radiation) that reaches a horizontal plane at the surface of the Earth and comprises both direct and  
838 diffuse solar radiation. To a reasonably good approximation, this parameter is the model equivalent of  
839 what would be measured by a pyranometer (an instrument used for measuring solar radiation) at the  
840 surface*” (<https://codes.ecmwf.int/grib/param-db/?id=169>). Thus, this is the value

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

844 ERA5 data is available via the Copernicus climate data store API which can be queried with the  
845 CDS-API Python package (<https://cds.climate.copernicus.eu/api-how-to>). The R  
846 code provided here documents the download of the *surface\_solar\_radiation\_downwards* parameter  
847 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,  
848 extra steps are required to download data on either side of the 180 anti-meridian.  
849

```
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 = ":"), # hours
      format = "netcdf"
    )
  )
  #query to get the ncdf
  server$retrieve("reanalysis-era5-single-levels",
                  query,
                  paste0("era5_ssrd_", y, "_right.nc"))
}
```

```

    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])
}

```

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

860 The model specification below was used to specify an mgcv::bam() model that matched the  
 861 formula used in the manuscript for ribbon seals. The s(speno, bs = "re") term is the smooth  
 862 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)
```

863 Note, the specification for *m1\_ribbon* here does not include any AR1 structure for temporal  
864 autocorrelation. To include this, we needed to provide a value for  $\rho$  (or *rho*). We examined the  
865 autocorrelation within the model and used the lag-1 value for  $\rho$ . The value for lag-1 autocorrelation  
866 was 0.8082 which is rather high but not surprising. We then updated our model specification with a  
867 value for  $\rho$  as well as the *A1.start* argument which specifies (as either **TRUE** or **FALSE**) the start  
868 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)
```

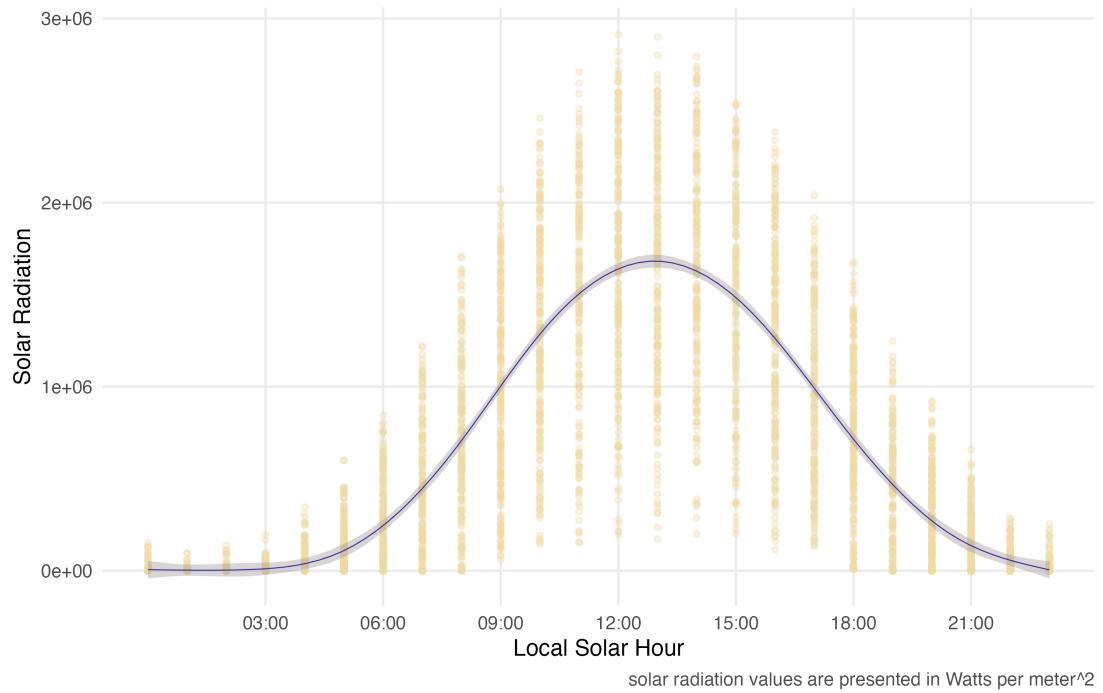
869 The model specification for exploring the use of solar radiation was specified similarly but without  
870 all of the Fourier series parameters and interactions.

```
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)
```

871 The two models were compared with AIC to evaluate whether the reduction in degrees of freedom  
872 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.

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

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

#### 880 0.3.3 Results

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

886 The bearded seal model matching the specification from the manuscript resulted in 126.13 degrees  
887 of freedom and an AIC value of -7428.929. The model with solar radiation resulted in 39.619 degrees  
888 of freedom and an AIC value of -6797.378. The ribbon seal model matching the specification from  
889 the manuscript resulted in 131.478 degrees of freedom and an AIC value of -16372.29. The model

890 with solar radiation resulted in 115.126 degrees of freedom and an AIC value of -16038.175. The  
891 spotted seal model matching the specification from the manuscript resulted in 125.506 degrees of  
892 freedom and an AIC value of -23584.373. The model with solar radiation resulted in 109.163 degrees  
893 of freedom and an AIC value of -23302.772. Despite the additional terms, the models with the Fourier  
894 series representation of hour of day resulted in a lower AIC value and were still preferred models for  
895 each of the species.

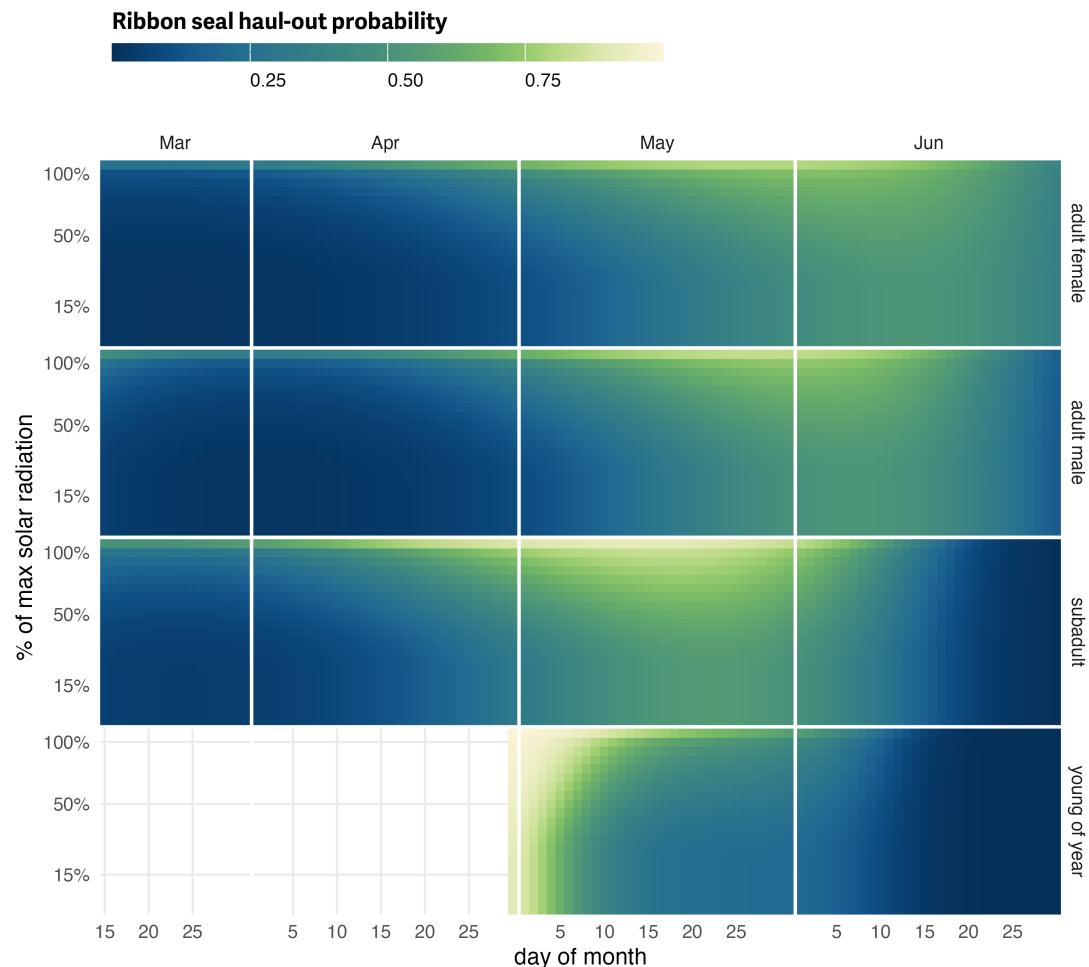
896 Predictions from the model fits and visualization of those predictions were produced for each  
897 species but, here, we only present visualizations from ribbon seals as an example (Figure S5 and  
898 Figure S6). Similar seasonal patterns previously observed were still apparent with subadults hauling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

905 **0.3.4 Discussion**

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

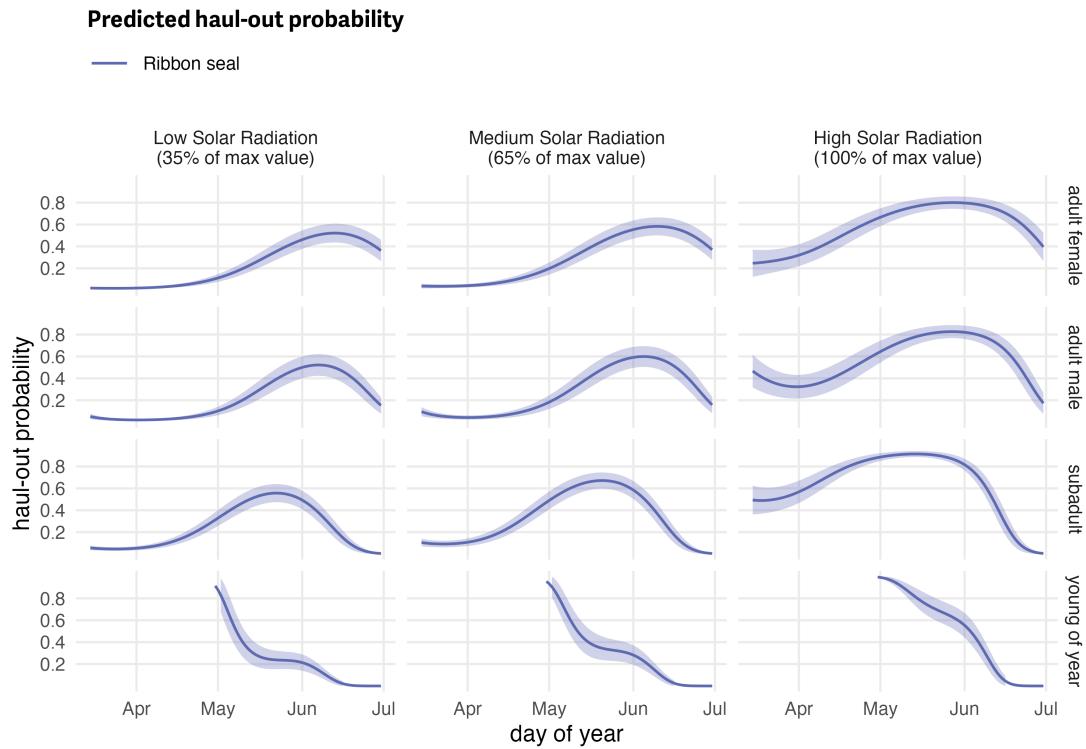
912 This analysis was not intended to be a full comparison – we simply want to demonstrate the  
913 potential and inspire further investigation – but, there are three possibilities that might explain the  
914 preference for hour of day. First, there are a broad range of solar radiation values represented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

928 Again, we want to acknowledge Anthony Fischbach for the suggestion during the peer review  
929 process. We think this is an excellent example of the peer review process working to improve the  
930 quality of our manuscript and advance the scientific process. We hope others will take our example  
931 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).