Assessing the Impact of Climate Change on Harbor Seals: Haul-out Patterns in Iceland using CMIP6 projections

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SIT Study Abroad

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Abstract

Harbor seals (*Phoca vitulina*) are known to exhibit a preference for specific environmental and weather conditions when hauling out, particularly during the pupping and molting cycles during summer. Climate change is projected to have a significant impact on the haul-out patterns and site conditions of harbor seals in Iceland, which could further diminish their dwindling population. A comprehensive literature review was conducted to identify and discuss the environmental variables that can affect haul-out probability. Among them, surface wind speed and air temperature are reported to have the biggest influence on harbor seal haul-out numbers between May and August. Climate projections for the year 2100 were made using a statistically downscaled climate model for two scenarios (SSP2-4.5 and SSP5-8.5) to compare the monthly and regional shifts in these two variables. Results indicate a statistically significant increase in surface wind speed and air temperature under both scenarios with a large regional difference across Iceland. Stronger wind will likely deter haul-outs due to wind chill effects, while warmer temperature, which increases molting rate, will increase haul-out probability. While the findings represent just a fraction of the widespread impact of climate change on harbor seals' haul-out, they highlight the urgent need for further investigations into other biotic factors to fully grasp the intricate relationship between harbor seals and the ever-changing environment.

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Introduction

The impact of climate change has been experienced worldwide, yet perhaps nowhere more profoundly than in the Arctic (Kovacs & Lydersen, 2008). Around two-thirds of the Arctic is classified as marine region, and climate change impacts on these ecosystems are exacerbating in various aspects, from sea surface temperature (SST) increase to melting of sea ice and changes in ocean stratification (Grémillet & Descamps, 2023). These abiotic effects are felt especially by marine megafauna, such as whales and pinnipeds, which play a pivotal role in food webs and are highly specialized in specific ecological habitats and conditions. They are also known to be less resilient to climate change as they are less likely to adapt to quick changes than small, short-lived animals (von Hammerstein et al., 2022). Thus, they are often referred to as indicator species by scientists when studying the impact of climate change on marine ecosystems (Grémillet & Descamps, 2023). In this paper, the changes in haul-out patterns and site conditions of harbor seals in Iceland under climate projections will be analyzed and discussed.

The harbor seal (*Phoca vitulina*) is one of the two pinniped species that reside and breed in Iceland (Granquist, 2022). It is also the most widely distributed pinniped species in the world geologically, ranging from temperate to Arctic regions in the North Atlantic and Pacific seas (NAMMCO, 2021). Harbor seals are considered generalists as they prey on a broad array of fish species, cephalopods, and crustaceans (Kovacs & Lydersen, 2008). Unlike some ice-associated seals which rely on sea ice as breeding and haul-out sites, harbor seals are not dependent on ice platforms and mainly haul-out on land. Based on their foraging and haul-out preferences, some researchers suggest that harbor seals would likely be less vulnerable to climate change compared to other pinniped species. In fact, they even predict an increase in distribution in the Arctic region under a warmer climate (Kovacs & Lydersen, 2008). Current census estimates around 200,000 individuals in the North Atlantic (NAMMCO, 2021), and approximately 10,000 of them are found in Iceland (Granquist, 2021b).

Despite their widespread distribution and seemingly abundance in population, their population in Iceland has seen a concerning 69% decline since aerial survey counts started in 1980 (Figure 1). Due to the observed decline, the population is currently classified as endangered under the Iceland Institute of Natural History Red List for Mammals (IINH). Factors that affect the population of harbor seals in Iceland can be broadly classified into three categories: anthropogenic, environmental, and ecological. Seal hunting has been a long tradition in Iceland since the arrival of the first settlers, and a bounty of catching harbor seals off-coast from 1982 to 1989 contributes to a large proportion of this decline. In response to the dwindling population, a direct seal hunting ban was implemented by Marine and Freshwater Research Institute (MFRI) in 2019 to minimize anthropogenic impacts, which permitted only licensed individuals to hunt for their own consumption (Hafrannsóknastofnun, 2019). By-catch from fishing nets is currently one of the highest mortality causes of harbor seals caused by humans. According to a MFRI gillnet survey, between 2014 to 2018, approximately 1400 bycatches of harbor seals have been recorded in the lumpfish fishery every year. Prey availability and climate change are also expected to impact harbor seal populations; however, little research has been done regarding these factors (Granquist, 2021a).

Harbor seals need to haul-out regularly on land to rest, thermoregulate, avoid predators, molt, and pup (London et al., 2012). Haul-out probability is affected by an array of different temporal and environmental factors. Harbor seal haul-out is often the highest during the summer months, which coincides with the pupping between May/June and molting season around early-August in Iceland (Granquist & Hauksson, 2016). Harbor seals are frequently observed gathering in groups during molting season because being out of the water is optimal for maintaining an ideal skin surface temperature for hair growth (Paterson et al., 2012). Different factors such as human-caused stimuli, including the presence of tourism vessels and pedestrians, are reported to have a negative impact on haul-out, increasing vigilance and causing flushing (Blundell & Pendleton, 2015; Granquist and Sigurjónsdóttir, 2014; Jorgensen, 2023). Frequent flushing decreases the fitness of individuals as it increases energy expenditure and reduces the time spent on land to rest. It also causes unsustainable heat loss to cold water and lengthens the time required to molt (Paterson et al., 2012).

Harbor seals have a range of optimal weather conditions for hauling-out, such as warm temperatures, calm wind conditions, low tide, etc (Granquist and Hauksson, 2016). The effect of different environmental variables on haul-out behavior will be discussed and ranked in the "Literature Review" section based on past research. It is worth noting that despite there being a lot of documentation on harbor seals, little to no research has been done on how climate change will affect them, and their resilience and ability to adapt. This research aims to predict changes in surface wind speed and air temperature of haul-out areas under two different SSP scenarios using statistically downscaled CMIP6 projections. Considering these predicted changes, a discussion on how the different scenarios will affect the future haulout behavior of harbor seals.

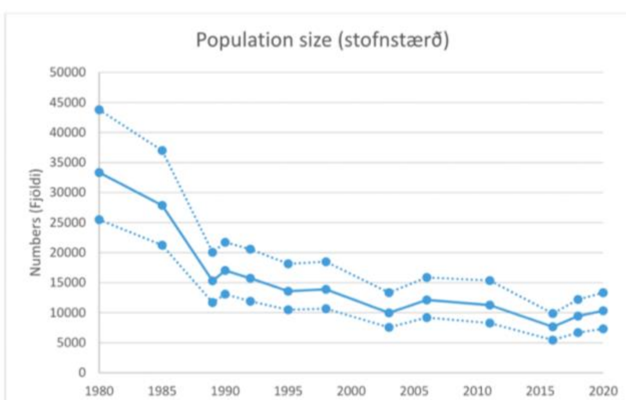

Figure 1: Changes in harbor seal population size in Iceland from 1980 to 2020 (solid blue line) and the 90% confidence intervals (dotted line). (Adapted from Granquist, 2021b)

Literature Review

Various environmental factors can influence the haul-out probability of pinnipeds. To understand the relationship between climate change and harbor seal haul-out patterns in Iceland, a comprehensive literature review was conducted based on previous research papers. This section aims to provide crucial background information and context for readers on the research topic and identify areas where further investigation is needed. In total, 28 peer-reviewed articles were reviewed in detail. The main climatic factors that affect harbor seal habitat and haul-out site conditions will be discussed and ranked.

Surface wind speed and direction

Wind speed is identified as one of the major factors that affect haul-out probability by numerous studies (Granquist & Hauksson, 2016; Galatius et al., 2021). Stronger wind causes significant convective heat losses through different body sites among pinnipeds, especially extremities like the fore and hind flippers (Guerrero et al., 2021). This may be beneficial for harbor seals that haul-out in warmer climates, as their thick layer of blubber and fur dissipates heat slowly and increases the risk of overheating when hauling out for a prolonged period (Stockton-Tekeste & Johnston, 2016). In higher latitudes, where colder climates are observed, this risk becomes less of a concern for individuals as overheating is less likely to occur.

It is reported that surface wind speed has a negative effect on haul-out probability among harbor seals in Iceland (Granquist & Hauksson, 2016). Additionally, higher wind speed contributes to stronger swells, which could compromise their views of the surroundings and increase body heat loss (Hamilton et al., 2014). According to a study in Alaska, the ideal wind speed is 10.3 mph (around 4.5 m/s), with an IQR of 9.6-10.7 (Simpkins et al., 2003).

Wind direction is a crucial component of surface wind, but it varies greatly between subareas, and is harder to quantify its relationship with haul-out probability. In general, harbor seals prefer sheltered areas away from the wind. At Illugastadir, a haul-out site located in the Vatnsnes peninsula in Northwest Iceland, harbor seals show a higher probability of haul-out when wind direction is northeasterly (50°) or southerly (180°), which in both cases are sheltered from strong gusts (Granquist & Hauksson, 2016).

Air temperature

Air temperature has a direct positive effect on haul-out probability and duration, especially in regions with higher latitudes. One reason for this is its influence on the rate of molting (Reder et al., 2003; Feltz and Fay, 1966). The annual molting of harbor seals takes place a few weeks after the end of lactation, which suggests the peak of haul-out season (Granquist, 2021b; Paterson et al., 2012). During that period, harbor seals haul out for an extended period of time and at a higher frequency to increase body surface temperature, which optimizes molting rate (Granquist & Hauksson, 2016). According to Feltz and Fay, 1966, the ideal temperature for skin cell cultures to grow is between 33°C and 37°C. The rate of molting is largely affected by air temperature, as warmer temperatures will increase the surface temperature faster and thus accelerate the process (Simpkins et al., 2003). A paper reported the mean ambient temperature of Atlantic harbor seal haul-out along the East Coast of the United States from 1971 to 2000 was 16.07°C (Stockton-Tekeste & Johnston, 2016). Based on one study in Vatnsnes, Northwest Iceland, there is a significant positive effect of air temperature on haul-out numbers over the span of four summers (Granquist & Hauksson, 2016). In Iceland, a warmer temperature also creates a more ideal condition for mother-pup pairs to haul-out and feed during the pupping period (Reder et al., 2003).

On the other hand, due to its outstanding heat-retaining ability to survive the winter, harbor seals also face the risk of overheating in warmer climates (Watts, 1992). Juvenile harbor seals have a lower thermal tolerance than adult seals, and thus are more vulnerable to extreme hot weather events caused by climate change (Stockton-Tekeste & Johnston, 2016). Therefore, further research on its resilience to increasing air temperature and climate modeling is crucial for conservation measures.

Sea level rise

Sea level rise (SLR), coupled with the increasing frequency and intensity of storms, is expected to have a great impact on coastal areas and haul-out sites of harbor seals (Backe, 2018). SLR is mainly caused by the melting of glaciers and ice sheets, alongside the thermal expansion of seawater as temperature increases (Mimura, 2013). The rate of SLR has reached an unprecedented level of 3.6 mm/year from 2006-2015, and the global mean sea level is expected to increase between 0.43m and 0.84m by 2100 (Oppenheimer et al., 2019). While harbor seals have a wide selection of haul-out sites, most of these habitats are flat sandbanks, rocky islets, and pebbled beaches located marginally above sea level (Whitlock, 2023; Papp, 2018). These areas are particularly vulnerable to climate change, especially during stormy weather where swells are stronger than normal. At this current rate of SLR, a large area of suitable haul-out sites would be inundated (Whitlock, 2023). Tidal fluctuations also increase the complexity of this situation, as water can reach a higher level during high tide and erode quality haul-out areas. Eventually, the decrease in haul-out areas may lead to an increase in competition over space with grey seals, whose niches generally overlap with each other (Granquist, 2022). While it is generally less of a concern in Iceland, this can also lead to an increase in encounters with humans over these areas, which can cause disturbances. Future studies will be required to assess the combined impact of SLR and extreme weather on harbor seals in Iceland, as various data, such as coastal area land types, accurate location, and attitude data of haul-out areas are missing.

Others

To study the entirety of climate change's impact on harbor seals, there are a lot of other environmental variables to consider. A crucial factor not to overlook is the rise of sea surface temperature (SST), which has a significant effect on marine ecosystems. No other region has SST risen more rapidly than the Arctic, and climate models project this biome will have the highest rate of increase in the future (Kovacs & Lydersen, 2008). While there is no documentation that proves a significant relationship between SST and haul-out probability, the rise of SST will displace fish population and affect prey availability of harbor seals, which will likely affect their preferences for haul-out sites (Kovacs & Lydersen, 2008). Like air temperature, sea water temperature, to a lesser extent, plays a role in thermoregulatory strategies (Stockton-Tekeste & Johnston, 2016). Water conducts heat 25 times more effectively than air, thus entering the water during haul-out will incur a high energetic cost (Stockton-Tekeste & Johnston, 2016; Paterson et al., 2012). A warmer SST will undoubtedly have a large impact on harbor seal populations and their prey availability (Risebrobakken et al., 2023).

Sea ice cover, largely affected by air temperature and SST, is expected to decrease exponentially throughout the 21st century under all CMIP5 scenarios (Senftleben, 2020). In the RCP8.5 scenario, sea ice is projected to be completely gone in the Arctic in summer by 2100 (Senftleben, 2020). While sea ice is not a main habitat requirement for harbor seals, it is reported that they use drifting ice as a resting spot during long-distance foraging trips (Womble et al., 2021). Conversely, ice-associated seals, such as harp seals and ringed seals, are more vulnerable to sea ice decrease (Kovacs & Lydersen, 2008; NOAA, 2023). These species rely heavily on seasonal sea ice for pupping, molting, and nursing their young (Johnston, 2012). With the decline of sea ice cover, these species may adapt to haul-out on land, which will increase competition over space and resources with harbor seals.

Cloud cover and precipitation are also common factors included in previous research to study haul-out behaviors. One study reported that on warmer days, more cloud cover increases haul-out probability, whereas clear days have a slightly negative effect on the count (Galatius et al., 2021). This is predicted that on warm and cloudy days, harbor seals have a lower risk of overheating. Non-significant impacts were found for cloud cover in Iceland, where the range of temperature is considerably lower than in the former study (Granquist & Hauksson, 2016). Precipitation has a slight negative effect on haul-out probability (Pauli & Terhune, 1987; Simpkins et al., 2003). Inclement weather conditions (stronger wind, higher precipitation) will likely decrease haul-out probability of harbor seals.

Summary

There is still a lot of uncertainty and unknowns in how environmental factors or climate change can impact harbor seal population trends. While it is impractical to include all the environmental variables that impact haul-out patterns of harbor seals, it is imperative to identify key factors and analyze their future trends. Among them, surface wind speed and air temperature are expected to change most due to climate change (Vavrus & Alkama, 2022; Ballinger et al., 2023), making them the focus of further analysis in this paper. Their potential impact on the haul-out behavior of harbor seal population will be hypothesized and modeled. Sea-level rise can cause a decrease in haul-out area suitability and availability, which will be a major concern for the future. However, there is currently inadequate open-sourced data to conduct spatial analysis for sea level rise in 2100.

Materials and methods

Data collection

In order to monitor the trend of harbor seal population change, aerial surveys are conducted regularly by the Marine and Freshwater Research Institute (MFRI) along the coastline of Iceland (Granquist, 2021b). Since 1980, 13 complete aerial censuses have been carried out in 98 counting areas across Iceland. These counting areas are divided into seven coastal sub-areas, which were used in this paper to analyze and compare the environmental changes of these regions (Figure 2). Haul-out numbers and location data were provided by MRFI.

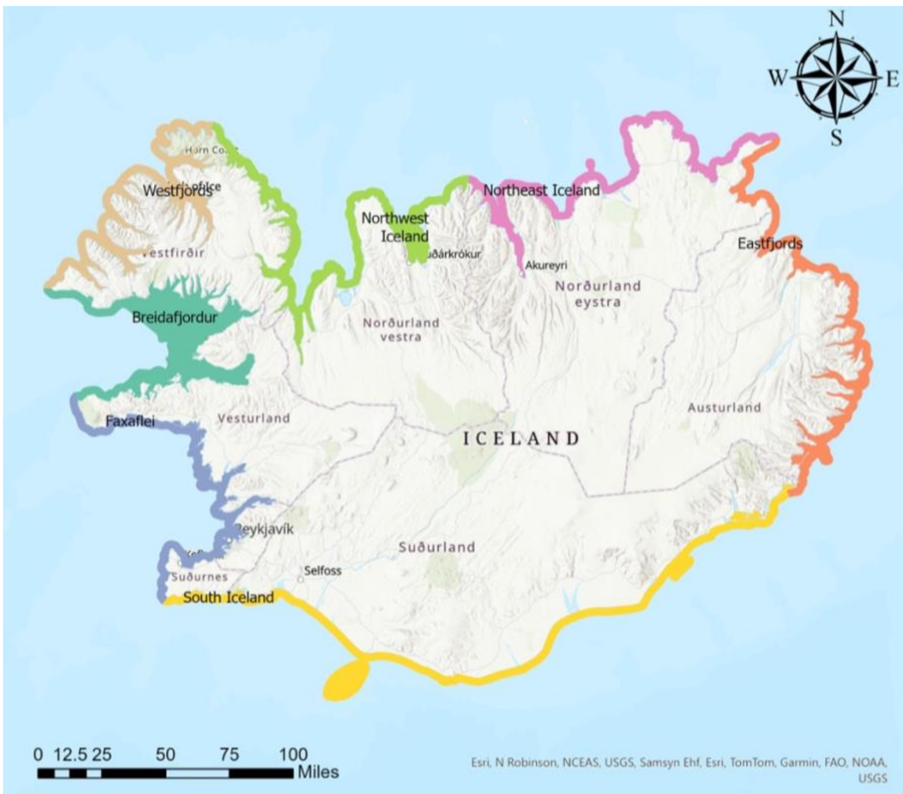

Figure 2: The seven coastal subareas used for seal surveys.

Historical monthly climatological data from 1961-1990 were extracted from the Icelandic Met Office website (https://en.vedur.is/climatology/data/) as the baseline period of the climate model. 1961-1990 is defined as "normal" 30-year period by the World Meteorological Organization for long-term climate assessments, and therefore chosen as the baseline period in this research (IPCC). For each of the subareas, weather stations that are within 500m of the coast and less than 30m above sea level were identified and listed below in Table 1. It is worth noting that monthly data from some of these weather stations were absent or partially missing as they were opened after 1961. These weather stations will not be taken into consideration in the analysis and are highlighted in red. Two variables will be used for detailed analysis, including the average daily maximum temperature and the mean wind speed. Only data during the peak haul-out seasons (May to August) will be kept and the rest of the months will be filtered out.

Subcoastal area	Station name	No.	Location	Height ASL (m)	Data available?	Remarks
Faxafloi (1)	Bláfeldur	167	64°50.358', 23°18.107'	17.7	N	Opened in 1998
	Hvanneyri	105	64°33.697', 21°46.479'	11.0	Y	
	Seltjarnarnes - Suðurnes	1471	64°09.270', 22°01.951'	4.5	N	Opened in 2019
	Kjalarnes	31579	64°12.639', 21°46.002'	10.0	N	Opened in 1998
Breiðafjörður (2)	Stykkishólmur	178	65°04.442', 22°44.033'	13.2	Y	
	Gufuskálar	170	64°54.247', 23°55.896'	7.0	Y	Missing data from 1961-70
Westfjords (3)	Lambavatn	220	65°29.543', 24°05.551'	4.0	Y	
	Bíldudalur	2428	65°40.765', 23°36.730'	16.0	N	Opened in 1998
	Flateyri	2631	66°02.987', 23°30.603'	3.0	N	Opened in 1997
	Æðey	260	66°06.039', 22°39.562'	21.0	Y	
	Hornbjargsviti	285	66°24.639', 22°22.734'	22.0	Y	
Northwest Iceland (4)	Litla-Ávík	293	66°01.280', 21°25.500'	15.0	N	Opened in 1995
	Hólmavík	2481	65°41.239', 21°40.878'	10.0	N	Opened in 2007
	Reykir í Hrútafirði	2197	65°15.257', 21°05.867'	9.8	N	Opened in 2003
	Blönduós	341	65°39.480', 20°17.551'	8.0	Y	Missing data 1965-81
	Skagatá	3720	66°07.153', 20°05.932'	9.0	N	Opened in 1996
	Sauðárkrókur flugvöllur	360	65°43.556', 19°34.421'	0.5	Y	Missing data 1978-90
Northeast Iceland (5)	Ólafsfjörður	407	66°04.431', 18°39.935'	5.0	N	Opened in 1997
	Mánárbakki	479	66°11.964', 17°06.165'	17.0	Y	
	Raufarhöfn	505	66°27.360', 15°57.162'	4.0	Y	
	Húsavík	477	66°02.509', 17°19.685'	28.2	Y	
Eastfjords (6)	Bjarnarey	4472	65°47.140', 14°18.490'	20.0	N	Opened in 1996
	Seyðisfjörður	615	65°15.292', 14°00.387'	7.0	Y	
	Teigarhorn	675	64°40.540', 14°20.663'	20.7	Y	
	Hvalnes	35666	64°24.445', 14°32.360'	20.0	N	Opened in 2000
South Iceland (7)	Höfn í Hornafirði	705	64°16.145', 15°12.811'	5.0	Y	Missing data 1961-65, 85-90
	Skarðsfjöruviti	6176	63°31.072', 17°58.711'	6.0	N	Opened in 1994
	Vatnsskarðshólar	802	63°25.416', 19°10.982'	20.0	Y	
	Þykkvibær	6208	63°44.865', 20°37.089'	10.0	N	Opened in 1996
	Eyrarbakki	923	63°52.152', 21°09.611'	3.0	Y	
	Grindavík	1361	63°50.627', 22°25.023'	9.3	N	Opened in 2008

Table 1: List of selected weather stations with station name, number, location, and height above sea level.

Climate model and SSPs

Climate projections are extracted from NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6) (https://www.nccs.nasa.gov/services/data-collections/land-based-products/nex-gddp-cmip6). The NEX-GDDP dataset comprised global downscaled climate scenarios derived from the thirty-five General Circulation Model runs conducted under the CMIP6 projections. Since it is statistically downscaled, it has a much higher spatial resolution (0.25° x 0.25°) than global climate models and can be used to conduct climate change assessments at local to regional scales. The two variables in use are Maximum Near-Surface Air Temperature and Mean Near-Surface Wind Speed. Among the five greenhouse gas emissions scenarios known as the Shared Socioeconomic Pathways (SSPs), SSP2-4.5 and SSP5-8.5 are chosen for comparison of two possible levels of severity of climate change. SSP2-4.5 represents a "middle of the road" emission trajectory that faces medium challenges to mitigation and challenges, with income inequality persisting and historical patterns of development continuing (O'Neill et al., 2017). Radiative forcing levels are at an expected level of 4.5 W/m^2 in 2100 in this scenario. SSP5-8.5 represents a "fossil-fueled development" scenario with rapid growth in economic output and limited mitigation policies, causing an exploitation of fossil fuel resources and irreversible effects of climate change. 8.5 W/m^2 of radiative forcing is expected in 2100 for SSP5-8.5.

Data analysis

Geospatial analyses are conducted using ArcGIS Pro with the ISN Lambert 1993 coordinate system. The shapefile of the seven coastal subareas is first imported into the map to define the study area. Then, the NEX-GDDP raster dataset of the two SSPs in 2100 containing maximum temperature and surface wind speed are added to the map respectively. Using the "Make Multidimensional Raster Layer" tool, they are defined by time range to include data between May 1 and August 31 only. To visualize the trend and changes of the variables over time, a temporal profile is created for each subarea in both scenarios. The raw data is exported as a CSV file and analyzed in Microsoft Excel.

Ethics

This research does not require any direct interaction with live seals, including experimentations and sampling. Fieldwork conducted throughout the research project period is led and supervised by staff members of the Icelandic Seal Center, and strict protocols are followed to minimize the impact and disturbance on the natural behavior of individual animals. No human participants are involved in any form of data collection. All data used in the geospatial analysis is properly sourced and cited in the Reference section. Research findings and results from data analysis will be shared in a separate Excel sheet under the Supplementary Materials section to ensure openness and transparency.

Results

Surface wind

Overall, average surface wind speed in Iceland is projected to increase under both SSP245 and SSP585 (Figure 3). One-way ANOVA test was performed ($p = 0.043$), suggesting a statistically significant difference between the mean wind speed of the three groups (baseline period, SSP245, SSP585). Three t-tests assuming unequal variances are further performed to compare the baseline conditions with the two SSPs, as well as between SSP245 and SSP585. There are significant differences between the baseline conditions with both SSP245 (*p-value* < 0.001) and SSP585 (*p-value* < 0.001). However, there was not enough evidence to conclude a statistically significant difference between the two SSPs.

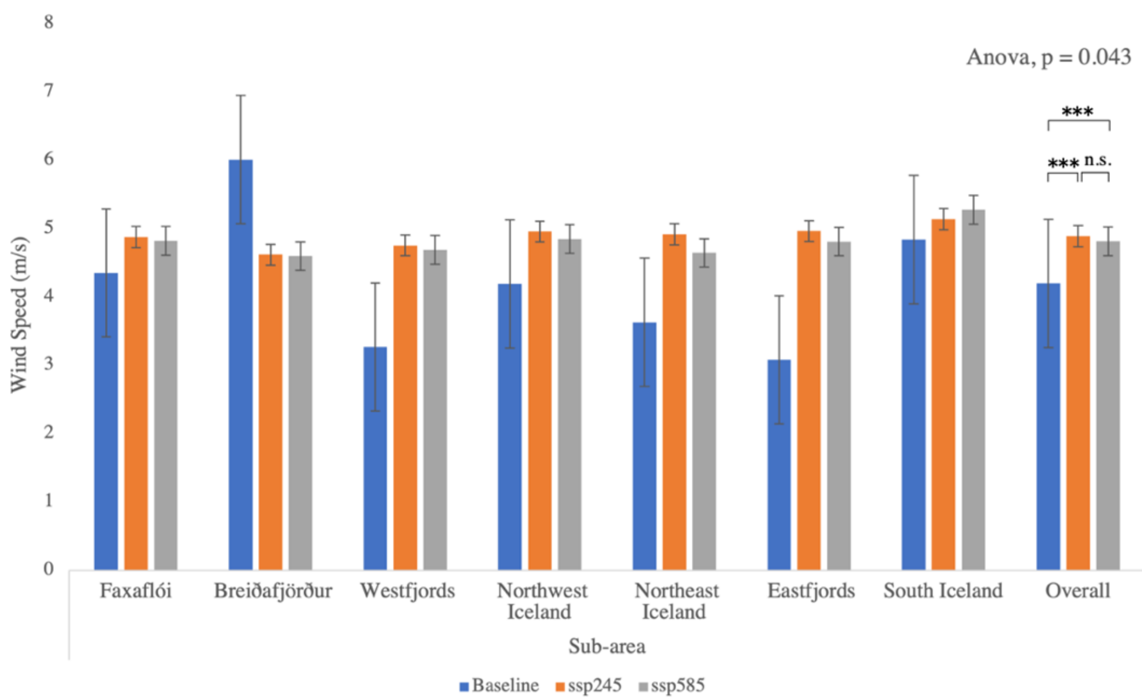

Figure 3: Comparison of average surface wind speed in 7 coastal subareas and the whole of Iceland between May and August under baseline period (1961-1990), SSP245, and SSP585

The effect of changes in surface wind is unevenly distributed among the seven subareas. All subareas are expected to face stronger wind in 2100 than the baseline period apart from Breiðafjörður, which sees a significant drop in wind speed from 6 m/s to approximately 4.5 m/s. The Eastfjords and the Westfjords face the largest increase by over 1.5 m/s in both climate scenarios. In general, it is observed that the northern and northeastern coastal parts of Iceland suffer a more significant increase than the south and south-western subareas.

The median wind speed projected in SSP245 across all subareas is 4.6 m/s, slightly higher than that in SSP585 at 4.5 m/s. There is a fairly large distinction between the monthly average of the two scenarios (Figure 4). SSP245 speculates the highest surface wind speed in June at 5.33 ± 0.38 m/s (95% CI), while SSP585 predicts the lowest in the same month at 4.1 ± 0.17 m/s. SSP585 records a higher average than SSP245 in the other months, with the predictions at the highest in August. Both scenarios project an increase in average wind speed in all summer months, compared to the baseline period.

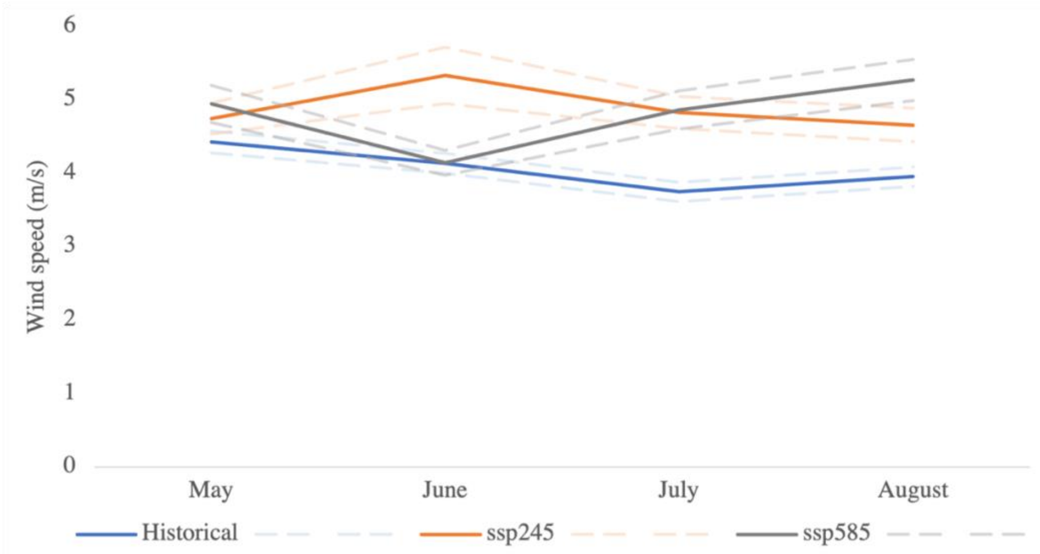

Figure 4: Monthly average surface wind speed under baseline period, SSP245, and SSP585 (solid line) with 95 % confidence bands (broken lines).

Maximum air temperature

The maximum air temperature is projected to increase significantly overall in 2100, ranging from around a 1.6 °C increase in SSP245 to a 3.4 °C increase in SSP585. ANOVA test yielded a *p-value* of 5.4913E-06, suggesting a significant difference between the temperature outcome of the baseline period, SSP245, and SSP585. T-tests further showed significant differences between the three groups. Among the seven coastal subareas, Northeast and South Iceland are anticipated to have a 2.5 °C or more increase in maximum air temperature in 2100 under the SSP245 scenario, compared to baseline conditions. Projections from the SSP585 scenario show a more extreme change, with Northeast Iceland and the Westfjords expecting over 5°C increase in air temperature in 2100. Aside from Northwest Iceland, all subareas are projected to have a bigger rise in temperature under SSP585, compared to SSP245. The most significant difference between the two scenarios is in the Westfjords, which has a projected maximum air temperature of 15.1 °C in SSP585, and a mere 10.8 °C in SSP245.

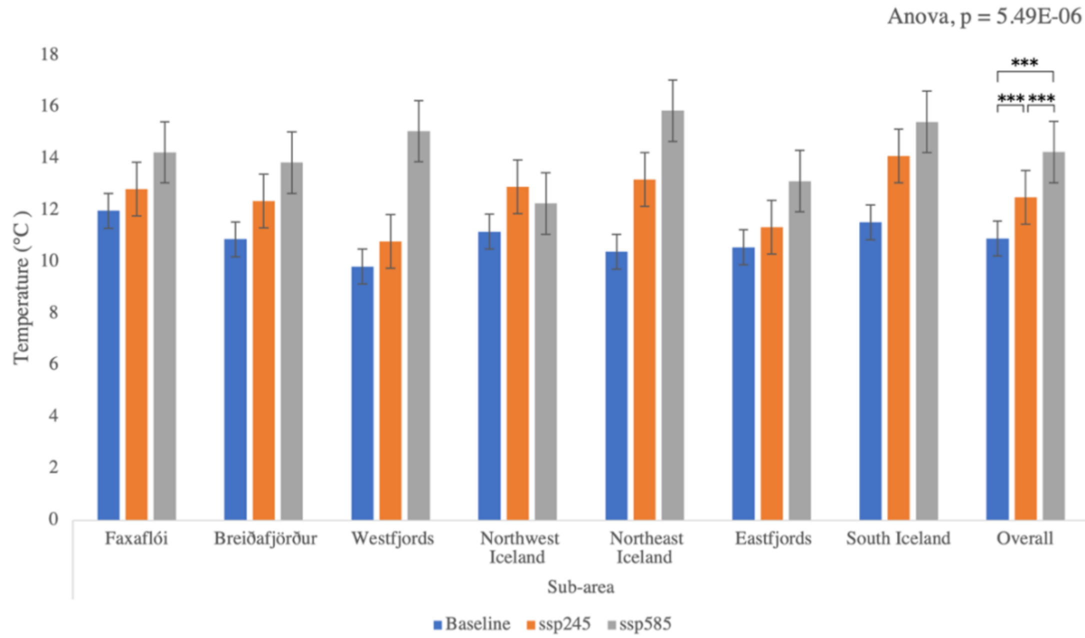

Figure 5: Comparison of average maximum air temperature in 7 coastal subareas and the whole of Iceland between May and August under baseline period (1961-1990), SSP245, and SSP585

The monthly maximum air temperature shows a more pronounced difference between baseline conditions, SSP245, and SSP585 (Figure 6). The baseline conditions recorded the highest monthly temperature in July at 12.6 ± 0.14 °C (95% CI). Projections from both scenarios are higher than baseline conditions in all summer months, with the highest in August at 14.6 ± 0.20 °C for SSP245 and 16.8 ± 0.20 °C for SSP585. The median maximum air temperature across all subareas in SSP245 is 12.8 °C, compared to 15.0 °C in SSP585.

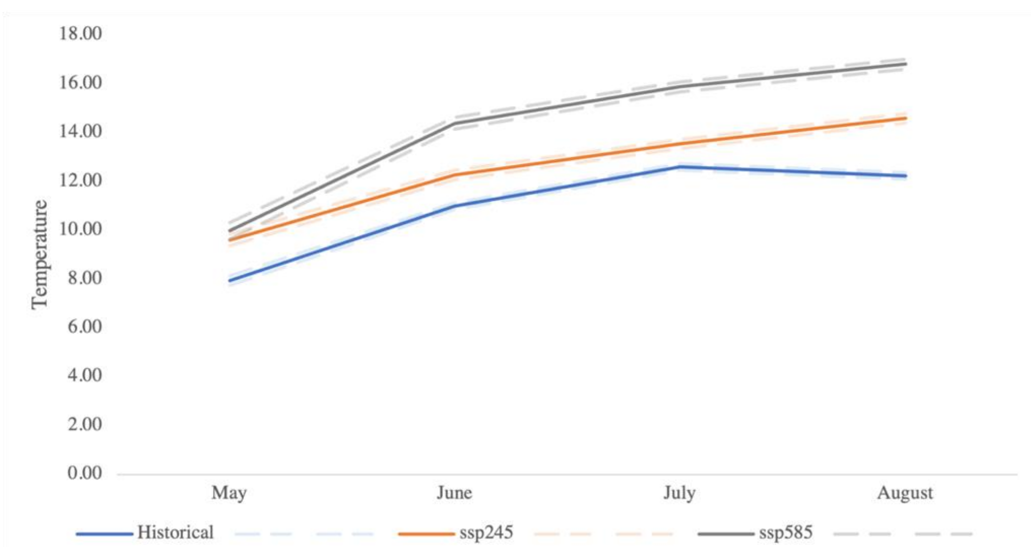

Figure 6: Monthly average maximum air temperature under baseline period, SSP245, and SSP585 (solid line) with 95 % confidence bands (broken lines).

Discussion

Implications of results

Both of the investigated scenarios (SSP245 and SSP585) suggest that surface wind speed will increase in 2100 as compared to the baseline conditions. Since previous studies have indicated that haul-out probability of harbor seals is adversely affected by strong wind and gusts above 4.5 m/s (Simpkins et al., 2003), the results imply that the number of days with ideal wind speed for haul-out will likely decrease, and the average wind speed is expected to be above 4.5 m/s at least 50% of all days between May and August. Among these, subpopulations that reside in the north to northeast of Iceland are expected to experience the biggest increase. This result is supported by a study conducted on wind speeds and storm frequencies using another climate model, which predicts an increase in wind speed and storm days in north to northeast of Iceland in 2100, while a 15-35% decrease in storm days in other parts of Iceland is expected (Sühring et al., 2023). The only discrepancy between the two studies is that Sühring et al. anticipate a drop in wind speeds in the Westfjords, which is opposite to our predictions. The reason for this discrepancy is unknown, but it could be attributed to variations in the climate models, baseline period, and the SSP scenario used. These regional differences may cause disproportionate impacts on harbor seal subpopulations and their haul-out patterns.

In addition to predicting regional changes, considering monthly variations is crucial, as the pupping and molting cycles of harbor seals are significantly influenced by the month. In Iceland, the main pupping period generally happens between late May and early June, while the main molting period starts in late July and lasts till late August (Granquist & Hauksson, 2016). Harbor seals haul-out to give birth and nurse their pups around June, and thus a significantly stronger wind speed in June (as predicted in SSP245) will cause a less ideal condition for mother-pup pairs. It is reported that pups with moms, compared to lone adults, spent less time resting and more time vigilant (Ferguson et al., 2021). A higher wind speed may cause rougher waves that compromise their views of the surroundings (Hamilton et al., 2014), which could potentially raise their difficulty in detecting danger, including marine predators. The decrease in duration and frequency of hauling-out could also limit resting and feeding for pups leading to a decrease in fitness of mother-pup pairs. It is reported that extreme inclement weather is the main cause of the separation of harbor seal mothers from their pups, which could impact pup mortality rate (Boness et al., 1992). Wind speed changes in July and August will likely affect the molting rate of harbor seals. Stronger wind may deter individuals from hauling-out for long periods of time due to increased body heat loss, which slows down the molting process (Hamilton et al., 2014).

The maximum air temperature exhibits an even more significant trend of increase both spatially and monthly. Nearly all subareas exhibit a temperature increase of 1.5°C or greater in SSP245, and a rise of 2.5°C or more in SSP585. A higher air temperature is directly correlated to both haul-out probability and molting rate (Paterson et al., 2012), and thus it is likely to benefit harbor seals. It is predicted that the time required to molt will be shorter due to the pronounced increase in air temperature in July and August (Granquist & Hauksson, 2016). However, this might also affect the timing of the molting period, which alters the synchronization of prey availability and environmental conditions of harbor seals. The pupping period will also be affected by temperature increase. Studies showed that seals rely on environmental cues including water and air temperature to synchronize their births to ensure pups are born at the optimal time of the year (Reijnders et al., 2010). Thus, a significant shift in air temperature may lead to disruption of the reproduction cycle and potentially affect their mortality rate (Huggins et al., 2013).

Warmer air temperatures can also lead to thermal stress among harbor seals and increase the risks of overheating (Stockton-Tekeste & Johnston, 2016). It is reported that juveniles and pups generally have a lower thermal limit in air (25.1 °C) than adult harbor seals (28.6 °C). The maximum air temperature predicted by the climate models on any given day in 2100 is 21.1 °C, which is still considerably lower than the thermal limit of pups. Therefore, it is unlikely that overheating will become a significant problem among harbor seals in 2100. However, there are also a lot of factors affected by the warmer temperatures that are not taken into account in this research, such as prey availability, habitat changes, ecosystem dynamics, etc.

Overall, the combined effect of wind speed and air temperature increase may alter haul-out patterns of harbor seals in various ways. Further research and observational data will be required to further examine the impact of climate change on their behavior and ecosystem alterations.

Advantages and limitations of statistical downscaling

The NEX-GDDP-CMIP6 dataset is chosen for this study due to its high resolution from statistical downscaling, which is more suitable for regional climate change analysis than traditional general circulation models (GCMs). Statistical downscaling involves the comparison of GCM outputs with local weather data and the derivation of the "delta" value to adjust future climate projections, combined with bias correction to maximize its accuracy in predicting local climate (Copernicus). The Bias-Correction Spatial Disaggregation (BCSD) method is used for this dataset (NCCS), which downscaled its spatial resolution to 0.25 degrees x 0.25 degrees. This is an apparent difference compared to GCMs, which resolution is typically between 1 and 5 degrees. To demonstrate the difference, a non-downscaled GCM downloaded from the IPCC WGI Interactive Atlas (https://interactive-atlas.ipcc.ch/) and imported into ArcGIS Pro, shown side-by-side with the dataset from NEX-GDDP-CMIP6 (Figure 7).

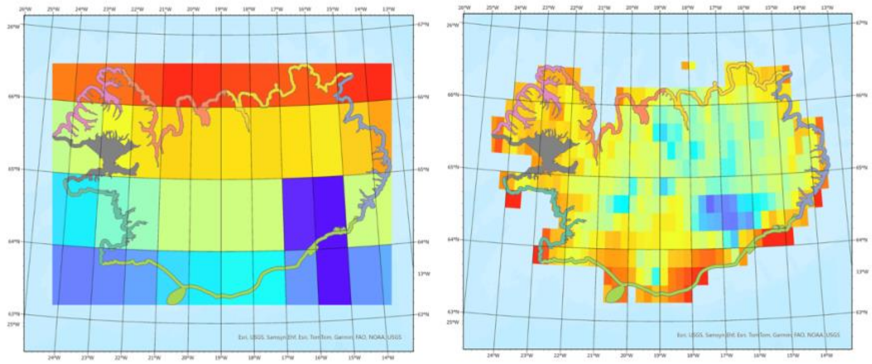

Figure 7: Comparison of maximum air temperature projections in 2100 using non-downscaled GCM (left) and statistically downscaled NEX-GDDP-CMIP6 dataset (right)

On the other hand, there are limitations in statistical downscaling which are present in the dataset used in this project. The BCSD approach assumes the relative spatial patterns from historical periods will remain constant under future climate change, which is unlikely to be the case. It also does not provide additional climate information beyond what is contained in the original CMIP6 scenarios (NCCS). Moreover, minor inaccuracies and information losses are possible when transforming projections from its original coordinate system (WGS-84) to the ISN Lambert 1993 map projection in ArcGIS.

Limitations of study

Several limitations are identified throughout the study. First, although this study can give an indication of future climate change related effects on haul-out behavior, is not a comprehensive study that projects the future harbor seal haul-out trends on climate change, as it only factors in two environmental variables, surface wind speed and maximum air temperature during summer months. In order to have an accurate projection, multivariate climate models that factor in other biotic variables, such as changes in prey availability, that affect haul-out patterns must be developed, and other seasons should also be included in the analysis. This project also relies solely on previous research papers to predict the impact of wind speed and air temperature on haul-out probability, which often are from another region or have a different scope of study. Therefore, there might be disparities in the actual haul-out patterns caused by other abiotic and anthropogenic factors.

A limitation present in the geospatial data comparison is the absence of continuous data for historical climatological data from 1961-1990. The only available data is point data obtained from weather stations operated by the Icelandic Met Office. Among these weather stations, some of the data were absent or partially missing. They also do not represent the haul-out areas as a lot of these measurements are taken higher above sea level. This weakens the comparison between conditions of the baseline period with climate projections, which are continuous raster datasets. Furthermore, only 1 year of data (2100) is used to project the climate scenarios. The results of the projections may be affected by outliers in that year and cause a larger standard error, which may lead to imprecise estimates of the effect. For example, in SSP245, the average surface wind speed in June is largely affected by a couple of extreme values from 6/22 to 6/24, which raises the average by over 0.5 m/s. An improvement in the future is to include data from a larger time range to minimize the effect of outliers on the overall result. Finally, the current projections for NEX-GDDP-CMIP6 only go up until 2100, which used to be a suitable benchmark for climate models back when it initially started in the 1980s (Lyon et al., 2022). With the current outlook of CMIP6 models, climate change is expected to continue for centuries into the future. Therefore, it is imperative that research on climate change impacts and climate models must look beyond 2100.

Conclusion

The study of climate change on haul-out patterns of harbor seals is extremely complex and intricate, and research in this area can provide valuable insights into the climate resilience of harbor seals and offer trend estimates on their future haul-out habitats and population shifts. Currently, there is still a lot of unknown on the impact of climate change on harbor seals due to a lack of research across the world, despite the rapid advancement in climate modeling. While this study is unable to cover all the biotic and abiotic factors that impact haul-out probability, it advocates for further research and serves as a precedent in this field. It demonstrates the use of a statistically downscaled climate model to predict climatic changes on a local to regional scale and discusses the advantages and limitations of using such climate models. With the harbor seal population in Iceland dwindling, the results of this study can be used to create a sense of urgency for policymakers to push for conservation measures in vulnerable areas. It can also raise awareness among the public to advocate for climate action and mitigation measures to prevent these scenarios from turning into a reality.

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Supplementary Materials

Details of selected weather station and monthly average climatological data extracted from Icelandic Metereological Office https://1drv.ms/x/s!AptxLGqA9a51jX6sCizDl9NvHmCs

Surface wind speed climate projections extracted from NEX-GDDP-CMIP6 https://1drv.ms/x/s!AptxLGqA9a51jgAYntt3NwbUoZRg

Maximum air temperature climate projections extracted from NEX-GDDP-CMIP6 https://1drv.ms/x/s!AptxLGqA9a51jgI_Y68YXhtYuWJ8