# A Predictive Thermal Habitat Model for Harbor Seals in the Northwest Atlantic

By
Sarah Belle Stockton-Tekeste
Dr. David W. Johnston, Advisor
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## Executive Summary

# A PREDICTIVE THERMAL HABITAT MODEL FOR HARBOR SEALS IN THE NORTHWEST ATLANTIC

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Predictive thermal habitat models are powerful geospatial tools used to project potential distributions of marine organisms. Some marine mammals, such as Atlantic harbor seals (*Phoca vitulina*) have a widespread geographic range, stretching from the shores of North Carolina to the eastern Canadian Arctic, and respond to environmental variability through changes in distribution, abundance, migration and foraging behavior. Conservation efforts increasingly depend on the prediction of potential species habitats.

One approach to addressing these needs uses well-known temperature thresholds that limit organisms to a particular area in time and space to establish range limits under alternate temperature regimes. Using historical sighting data of Atlantic harbor seals, retrieved from OBIS-SEAMAP, an online database for marine protected species, the relationship between Atlantic Harbor seals and ambient temperature are mapped.

The analysis focuses on the southern most portion of Florida up to the northern most portion of Maine. Although this encapsulates a relatively large geographic range, a coastline spatial resolution of 0.86 $km^2$ was used throughout the entire study. Although it is widely accepted that harbor seals occupy areas in the Northeast during warmer months, they rarely venture past the coastal waters of New York. However, there are sparse sightings as far south as Virginia within the historical dataset used for this habitat model. Based on the historical sightings, Atlantic harbor seals are most likely to occupy areas with ambient temperatures that do not exceed 21.33°C.

The first section of the report defines the motivation of the study and how ambient temperature changes impact the thermoregulation of pinnipeds. Although climate change includes a host of environmental variables, previous studies on the physiology of harbor seals have shown that ambient temperature, unlike sea surface temperature and a host of other variables, may be the fundamental environmental variable that defines the distribution of harbor seals.

The second portion of the report provides an overview of the history of Atlantic harbor seals in regards to federal legislation and their geographic range. Federal legislation, such as the Marine Mammal Protection Act of 1972 (MMPA) played an integral role in the revitalization of the Atlantic harbor seal stock that had fewer than 4,000 individuals in the early 1970s. Over the last 25 years, unprecedented changes in global climate have tested the adaptive capability of harbor seals as the prevalence of warm ambient temperatures has impacted their behavior.

The third section of the report describes the earth systems model (ESM), created by the Met Office Hadley Centre HadGEM2-ES, as well as the temperature thresholds that were used to create a baseline for current environmental preferences as well predictions for future behavior. The data focused on the current climate scenario that included data from 1950-2000 as well as future scenarios representative of the years 2050 and 2070. The model uses three metrics: current preferences, thermal limits of juveniles, and the thermal limits of adult harbor seals. Each of these metrics represents a different temperature threshold that was accounted for in the model and used as a comparison technique. Although the study is focused on the eastern United States, a coastline factor was created, which selected cells that neighbor the Atlantic Ocean so that an area of potential habitat could be calculated for each individual metric.

The fourth section of the report addresses potential areas of suitable habitat for Atlantic harbor seals based on the three metrics of interest, focusing closely on the findings in 2050 and 2070. Areas that are deemed suitable for both juveniles and adults are the primary focus, as areas for pupping would constitute only areas that are suitable for both.

Ultimately, the usefulness of potential habitat models will vary significantly, particularly when only a single environmental variable is used. However, research has indicated that ambient temperature is one of the most important environmental factors influencing harbor seal haul out sites. This research shows that both juvenile and adult harbor seals will be significantly impacted in the coming decades due to rising ambient temperatures, which will reshape their distribution and abundance within the United States.

This report makes several key points and recommendations:

- Understanding a species and their interactions with the environment in space and time has considerable effects on impact assessments and fisheries management strategies
- Successful fisheries management hinges on the frequent reassessment of habitats as minute climate variable will result in more acute fisheries management issues as a species approaches a thermal tolerance
- Climate models have increasing variable as predictions move further and further into the future

**Abstract**
We analyzed projections of current and future ambient temperatures along the eastern United States in relationship to the thermal tolerance of harbor seals in air. Using the earth systems model (HadGEM2-ES) and representative concentration pathways (RCPs) 4.5 and 8.5, which are indicative of two different atmospheric $CO_2$ concentrations, we were able to examine possible shifts in distribution based on three metrics: current preferences, the thermal limit of juveniles, and the thermal limits of adults. Our analysis focused on average ambient temperatures because harbor seals are least effective at regulating their body temperature in air, making them most susceptible to rising air temperatures in the coming years. Our study focused on the months of May, June, and August from 2041-2060 (2050) and 2061-2080 (2070) as these are the historic months in which harbor seals are known to annually come ashore to pup, breed, and molt. May, June, and August are also some of the warmest months of the year. We found that breeding colonies along the eastern United States will be limited by the thermal tolerance of juvenile harbor seals in air, while their foraging range will extend as far south as the thermal tolerance of adult harbor seals in air. Our analysis revealed that in 2070, harbor seal pups should be absent from the United States coastline nearing the end of the summer due to exceptionally high air temperatures.

## Introduction

Climate change is adversely affecting both terrestrial and marine environments, however, organisms that thrive at the land-sea interface are particularly vulnerable (Hoegh-Guldberg and Bruno 2010). In particular, many marine mammals, such as Atlantic harbor seals (*phoca vitulina*), forage at sea, but rest, pup, breed, and molt on land (Baird 2001). Pupping, breeding, and molting are energetically taxing, which requires harbor seals to spend more time ashore than during the winter months. Harbor seals pup (give birth) onshore during the months of May and June, spending at least half the day on land. Following weaning, mating takes place. Much like pupping and breeding, molting requires harbor seals to haul out for extended periods of time. Molting typically occurs between July and August (National Parks Service). The premise of this paper is how life history and thermal physiology of Atlantic harbor seals will structure their distribution in the North Atlantic in response to rising ambient temperatures (Hoegh-Guldberg and Bruno 2010).

Much of our understanding of thermoregulation in pinnipeds relates to the energetic demands of maintaining homeostasis in subfreezing temperatures (Hansen and Lavigne 1997). Nonetheless, climate change remains one of the greatest threats to ecological diversity in the 21$^{st}$ century due to rising ambient and sea surface temperatures. Pinniped ranges are likely to be affected by their upper thermal limits rather than their lower thermal limits, which often takes precedence in the literature (Burrows 2014; Hansen and Lavigne 1997).

One of the reasons why air temperatures rather than sea surface temperatures are of greatest concern for Atlantic harbor seals is because water conducts 25 times more effectively than air. Passive heat dissipation occurs at a much slower rate on shore than in water, which means overheating is of greatest concern in a terrestrial environment rather than in a marine environment. This causes a huge issue for any animal that is equipped with the heat-retaining adaptations, such as blubber. The same insulation that prevents hypothermia in an immersed endotherm increases the dangers of overheating in air. This is of most concern for animals that use blubber as their primary insulator. Phocids possess a thick layer of blubber, but also lack adaptive strategies for enhancing evaporative heat loss. The only effective thermoregulatory strategy that remains is behavioral, which means when these animals begin to overheat, their only real option is to return to sea (Watts 1991).

Due to adaptations for thermoregulation in cooler waters, a major concern for pinnipeds is regulating their body temperature at exceptionally high air temperatures while ashore (Hansen and Lavigne 1997). Throughout their range, harbor seals routinely haul out for hours at a time, often daily. Hauling out generally follows a diel cycle, with numbers on land peaking near mid-day and declining at night. However, hauling out is greatly impacted by a number of environmental factors including tidal height, wind, and precipitation. Tidal height constrains the amount of coastline available to seals; therefore, the number of individuals observed on land is greatly reduced during high tide. Hauling out is most common in the summer months due to routine behaviors, such as pupping and molting and are minimal during the winter (Watts 1991). Pinnipeds are forced to reconcile the conflicting demands of two completely different thermal environments on land and at sea. An adaptation that is beneficial in one environment could be counterproductive in the other (Watts 1991).

In order to better understand the fate of Atlantic harbor seals with the impending environmental changes to come, we examined future ambient temperature projections coupled with what we know about their current distribution and the thermal tolerance of juvenile and adult harbor seals in air. In both Hansen et al. (1995) and Hansen and Lavigne (1997), the upper critical temperature for juvenile harbor seals in air was experimentally demonstrated as 25.1°C, while adult harbor seals had an upper critical temperature of 28.6 °C. These findings suggest that in the face of climate change, rising air temperatures are likely to impact these two demographic groups in different ways. However, breeding colonies should occur in areas that are deemed suitable for both juveniles and adults. We examine future air temperatures along the United States coastline in order to determine suitable terrestrial habitat both under their current preferences and what we know about the thermal limit of juvenile and adult harbor seals. However, before going through this reports methodology, we examine a brief history of harbor seals and the data collection process.

*Federal Legislation and Population Status*

Atlantic harbor seals are protected under the Marine Mammal Protection Act (MMPA) of 1972, which allocated regulatory powers to the National Oceanic and Atmospheric Administration (NOAA), United States Department of Commerce. The guidelines were a direct result of bounty policies that suffocated many marine mammal populations to the verge of extinction. Suddenly concerned with natural resources management and conservation, Congress

passed the federal legislation, which prohibits the "take" of any marine mammal without a proper permit. In theory, the law was meant to bolster depleted stocks closer to carrying capacity. "Take" in this sense is defined as "to harass, hunt, capture, or kill, or attempt to harass, hunt, capture, or kill any marine mammal" (DMR Rockweed Working Group 2015). Although the law is very clearly defined, regulating and enforcing said laws across such a broad geographic range is problematic. These fissures in the MMPA are further exacerbated by a lack of community knowledge and self-regulation. Unfortunately, unlawful human interactions are frequent, disrupting the migratory, foraging, and reproductive patterns of marine mammals on a global scale (Baird 2001; Waring et al. 2006).

In order to better measure the recovery of marine mammal populations, NOAA began conducting aerial surveys in the early 1980s. Harbor seals were targeted during the spring and summer months, a period of time that coincides nicely with when they birth, breed, and molt ashore (DMR Rockweed Working Group 2015). The most in depth surveys in recent history transpired in 1981, 1986, 1993, 1997, and 2001. Today, irregular surveys are conducted and sightings are reported by boat, shore, or plane. Although the exact population is unknown, a 2012 survey found that harbor seal abundance consists of 75,834 individuals, much improved from the 1980s, when the population was thought to consist of less than 4,000 individuals (Halpin et al. 2009; Waren et al. 2015). However, Waren et al. (2015) found that from 2001 to 2012, harbor seal numbers went from 99,340 to 75,834 individuals, but did not consider the population to be declining because the two counts were not statistically different. With steady counts, Atlantic harbor seals have been listed as a "least concerned" species by the IUCN Red List due to their widespread abundance and seemingly stable population trends (Thomson and Harkonen 2008).

*Habitat and Geographic Range*

As it stands today, Atlantic harbor seals have the broadest geographic range of any other pinniped in the North Atlantic, stretching from the shores of North Carolina to the eastern Canadian Arctic and Greenland (State of Maine 2014). Harbor seals rely heavily on shoreline habitats, including beaches, intertidal rocks, mudflats, and sandbars, to give birth, breed, and molt (Spradlin et al. 2001). These annual behaviors vary geographically, but for the Western North Atlantic stock, harbor seals tend to give birth, which is also referred to as pupping, in May and June, breed in June and July, and molt in August (Baird 2001). A majority of Atlantic harbor

seals pup and breed along the shores of Maine and New Hampshire, with sparse sightings as far south as Cape Cod, Massachusetts (State of Maine 2014). Other life strategies, such as rest and thermoregulation, also occur on land and take place intermittently throughout the year (Gilbert and Guldager 1998).

**Methods**

Sightings of Atlantic harbor seals were downloaded from OBIS-SEAMAP, which is a geospatial online database, which aggregates species observation data from across the globe. We used point data from 1971 through the year 2000. Within the observed data points were absence points, which were excluded from our analysis. Finally, we performed three selections on the harbor seal sightings data in order to create point data based on each month of interest: May, June, and August.

To estimate future air temperature conditions along the US east coast, we used data generated by an Earth System Model originating from the Met Office Hadley Centre - HadGEM2-ES, which had a spatial resolution of 0.86 $km^2$. The data consisted of spatially explicit ambient temperatures from the years 2050, which was an average for 2041 to 2060, and 2070, which was an average for 2061 to 2080. For this model, we used future climatological outputs from representative concentration pathways (RCPs) 4.5 and 8.5. RCP 4.5 is a stabilization scenario in which total radiative forcing is steadied before the year 2100 by new technologies and tactics meant to decrease greenhouse emissions (Khan et al. 2013). RCP 4.5 is associated with radiative forcing being stabilized at 4.5 W $m^{-2}$ after 2100. RCP 8.5, a scenario that best reflects today's trends, coincides with increasing greenhouse gas emissions overtime, lending way to concentration levels that exceed radiative forcing of 8.5 W $m^{-2}$ by 2100 and steadily increasing (Khan et al. 2013). Both RCPs are examples of a range of possible conditions that mimic the range represented by a previous Special Report on Emissions Scenarios A1FI and B1 that was used in the IPCC's $4^{th}$ Assessment Report (Rogelj et al. 2012).

We created a baseline of current ambient temperatures by importing monthly data. The data reflected averages from 1950 to the year 2000 and was downloaded from the WorldClim, an archive of consolidated climate data for ecological modeling. After importing the data into Geographic Information System as image files, the data was clipped to focus exclusively on the most eastern states: Maine, New Hampshire, Massachusetts, Rhode Island, Connecticut, New

York, Delaware, Maryland, Virginia, North Carolina, South Carolina, Georgia, and Florida. We analyzed monthly data for the average minimum, mean, and maximum ambient temperatures in the months of May, June, and August. Historically, May and June are the two months out of the year in which harbor seals come ashore to pup and breed, while August, which generally is the warmest month of the year, is the time in which harbor seals tend to come ashore to molt.

For each month, the current mean ambient temperatures were sampled using the corresponding harbor seal monthly observation data points. The sampling technique samples values to the corresponding baseline data points, which can be exported as a table and used to make inferences about species preferences. This data, alongside the count data, which corresponds to the number of individuals observed at that particular GPS location, were used to calculate the actual mean and standard deviation for all of the historic data. A matrix in R software was created to replicate the mean ambient temperature observed for a particular sighting based on the number of individuals to ensure that each mean ambient temperature was appropriately weighted. The result provided the current mean and standard deviation of the dataset that would serve as one of three metrics to analyze future ambient temperature rasters.

Our study consisted of three metrics: current preference, upper thermal limit for pups, and upper thermal limit for adult harbor seals. The current preferences used the mean temperature in which harbor seals were observed within one and two standard deviations of the mean. The mean ambient temperature observed using seal sightings from 1971 to 2000 was 16.07°C. The current preference within one and two standard deviation was 18.70° and 21.33°C, respectively. The upper thermal limit for pups and adult harbor seals was discussed extensively in Hansen et al. (1995) and Hansen and Lavigne (1997) in which the authors tested the hypothesis that exceptionally warm air temperatures influence the distribution of harbor seals. They found that adult harbor seals had a mean upper critical temperature of 28.6°C, which was considerably higher, by 3.5°C, than the mean upper critical temperature of the same individual during its initial year of life.

Using these three metrics in conjunction with the current and future raster datasets, a conditional statement if/else was used to evaluate each of the input cells in each input raster. All three metrics were applied to each month, May, June, and August, within each study year: current, 2050, and 2070. Each condition resulted in a binary raster dataset, where green signifies suitable habitat and red signifies unsuitable habitat.

Lastly, if a cell bordered the Atlantic Ocean, the cell was selected to create a coastline mask. The coastline mask spanned from the tip of Maine to the Dry Tortugas in Florida. Each cell was equivalent to 0.86 $km^2$. The coastline mask was used to calculate the average ambient temperature along the eastern United States. Using the mask, we were also able to calculate the area for each scenario that was deemed suitable for harbor seals based on the three metrics described above.

**Results**

*Current Conditions*

We found stark differences between suitable and unsuitable habitat among each month, statistic, and metric were not consistent. The current minimum, mean, and maximum temperature along the coast in May was 12.35°, 17.71°, and 23.12° C, respectively. We began our analysis by examining the current minimum ambient temperature in relation to three metrics: current preferences, the thermal limit of pups, and the thermal limit of adults. Our study of current harbor seal preferences and the current minimum ambient temperature dataset revealed that 91.44% of the coastline fell within one standard deviation and 96.78% of the coastline fell within two standard deviations of current harbor seal preferences. In addition, the following two metrics, which are based on Hansen et al. (1995) and Hansen and Lavigne (1997) findings regarding the thermal limits of harbor seal pups and adults. They found that the thermal limit for juveniles is 25.1°C in air and 28.6°C for adults under the same conditions. Based on these thermal limits, we found that 100% of the coastline should be accessible to both juveniles and adults.

Next, we examined current harbor seal preferences in relation to the current mean ambient temperatures observed in the month of May to determine their current range. Our findings revealed that only 59.66% of the coastline fell within one standard deviation, while 80.41% of the coastline fell within two standard deviation of the current mean ambient temperature. For the final two metrics, we ascertained that 65.57% of the coastline was available to juveniles, while adults should be able to access 100% of the coastline.

Lastly, we examined current harbor seal preferences in relation to the current maximum ambient temperatures observed in the month of May. We found that 21.25% of the coastline fell within one standard deviation and 34.90% of the coastline fell within two standard deviations of

the current mean ambient temperature. As far as juvenile habitat goes, we determined that 67.82% of the coastline was available to pups. Adults should fair better with 90.32% of the coastline deemed suitable habitat for adults.

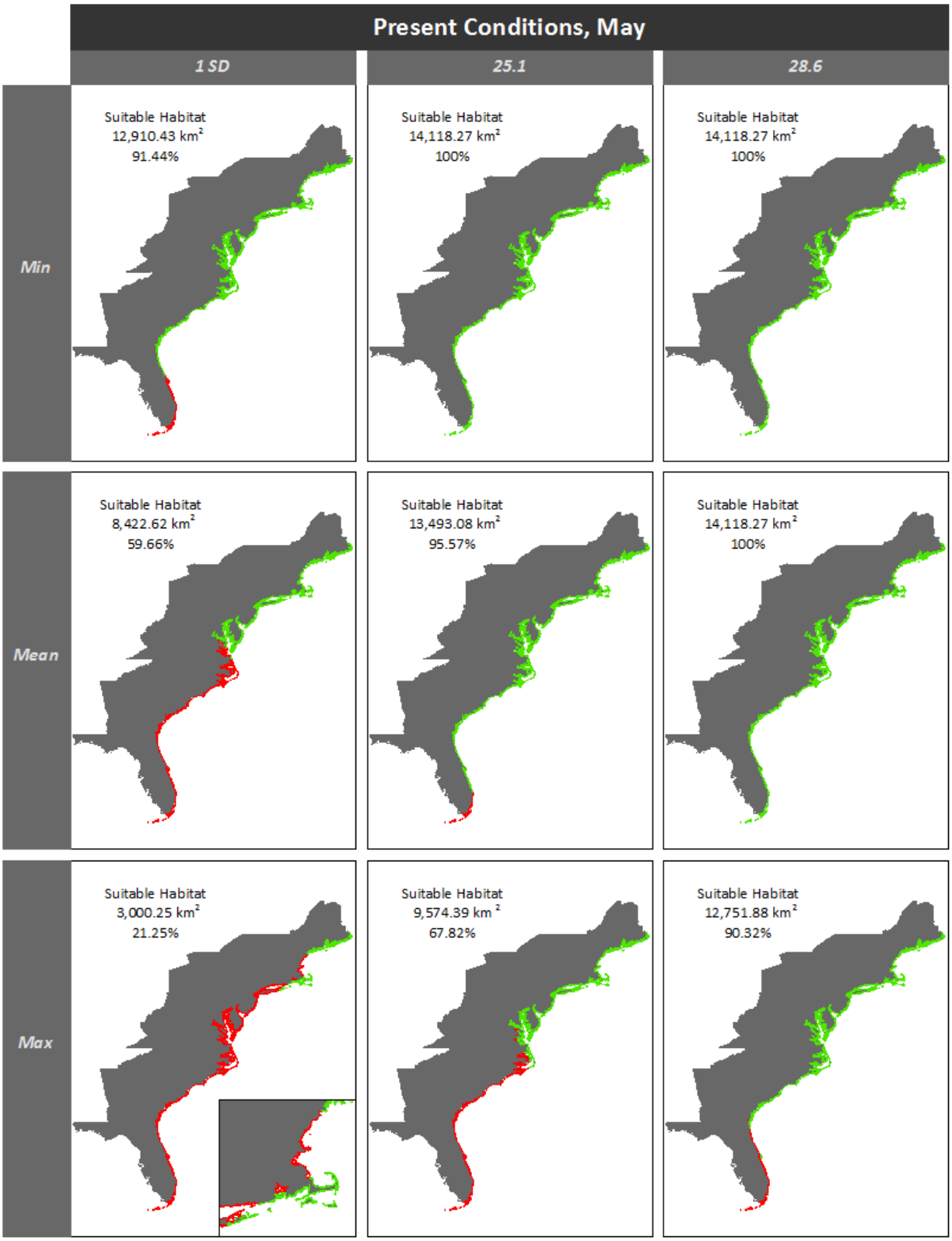


*Figure 1. The current minimum, mean, and maximum ambient temperatures in the month of May based on the three metrics of interest: current preferences, thermal limit of juveniles, and the thermal limit of adult harbor seals.*

During the month of June, the current minimum, mean, and maximum temperature along the coast was 16.88°, 22.01°, and 27.19°C, respectively. Our study of current harbor seal preferences coupled with the current mean ambient temperature dataset showed that 67.95% of the coast fell within one standard deviation and 88.66% fell within two standard deviations of the current mean ambient temperature. Using the thermal limits of juveniles, we determined that 99.98% of the shoreline would be conducive to pups based on their thermal limits in air. However, adults should be able to
make use of 100% of the coast.

Next, we examined current harbor seal preferences in relation to the current maximum ambient temperatures in the month of June. Our results showed that only 21.95% of the coastline fell within one standard deviation and 36.10% of the coast fell within two standard deviations of the current mean ambient temperature. Juveniles should be able to access 81.50% of the shore and 100% should be accessible to adult harbor seals based on their thermal tolerance in air.

Lastly, we studied current harbor seal preferences in relation to the current maximum ambient temperatures observed in
the month of June. We found that 0% of the coastline fell within one standard deviation and 3.63% of the coastline fell within two standard deviations of the current mean ambient temperature. Based on the thermal limits of juvenile and adult harbor seals, 29.08% of the coastline was suitable for pups and 62.23% of the coast was available to adults.

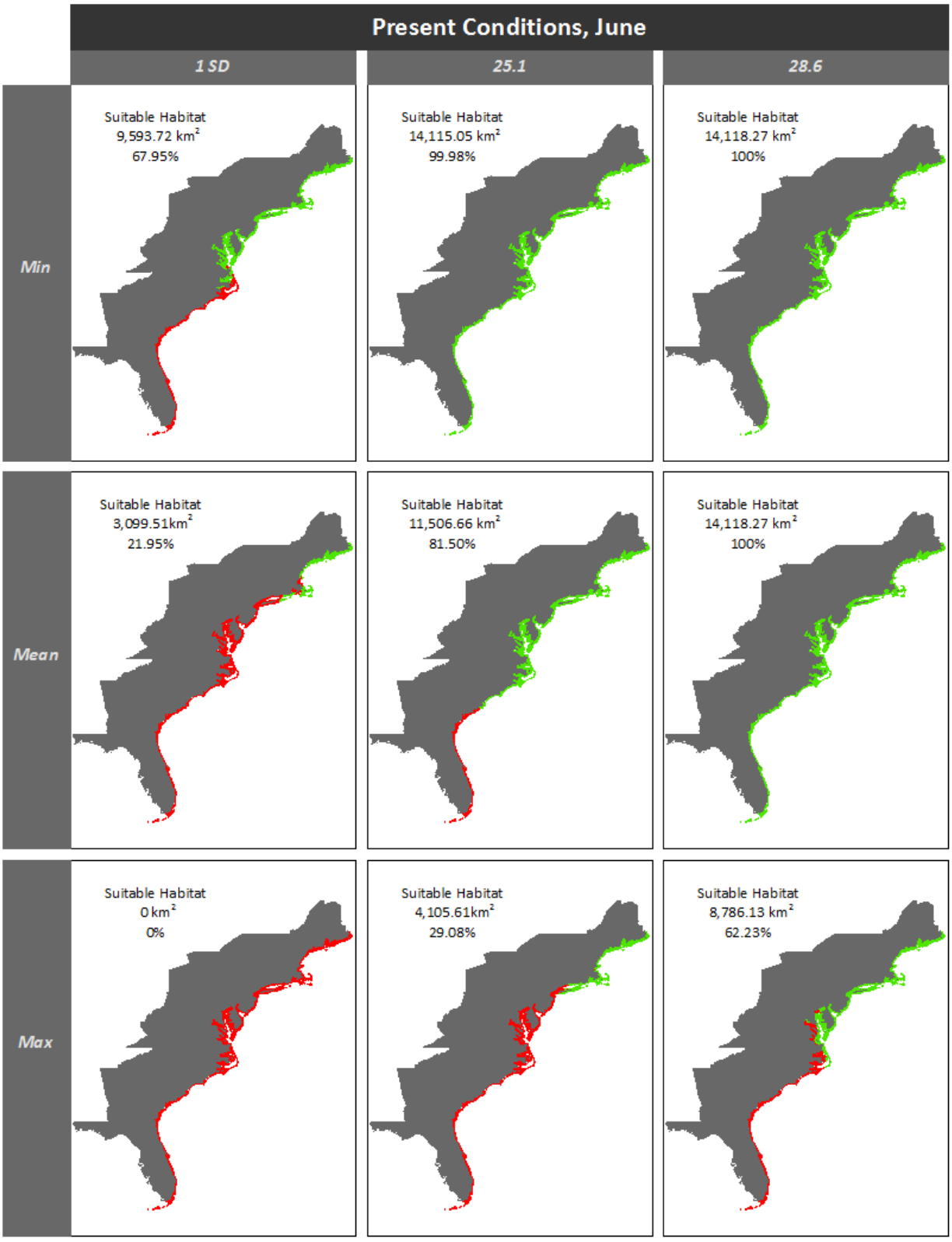


*Figure 2. The current minimum, mean, and maximum ambient temperatures in the month of June based on the three metrics of interest: current preferences, thermal limit of juveniles, and the thermal limit of adult harbor seals.*

The current minimum, mean, and maximum temperature along the coast in August was 19.02°, 23.91°, and 28.84°C, respectively. Our study of current harbor seal preferences and the current minimum ambient temperature dataset revealed that 41.58% of the coastline fell within one standard deviation and 75.48% fell within two standard deviations of the current mean ambient temperature. Juveniles were able to access 99.14% of the coast, while adults could reach 100% of the coastline.

Next, we examined current harbor seal preferences in relation to the current mean ambient temperatures observed in the month of August. We determined that only 3.53% of the coastline fell within one standard deviation and 21.12% of the coastline fell within two standard deviations of the current mean ambient temperature. Based on thermal limits of juveniles, pups could reach 63.74% of the coastline, while adults could reach 99.65% of the coastline.

Lastly, we studied the current harbor seal preferences in relation to the current maximum ambient temperatures observed in August. Our study revealed that 0% of the coastline fell within one standard deviation and two standard deviations of the mean ambient temperature. However, based on the thermal limits of juvenile harbor seals, 9.33% of the coast was deemed suitable for pups, while the thermal limits of adult harbor seals allowed 37.76% of the coastline to be accessible.

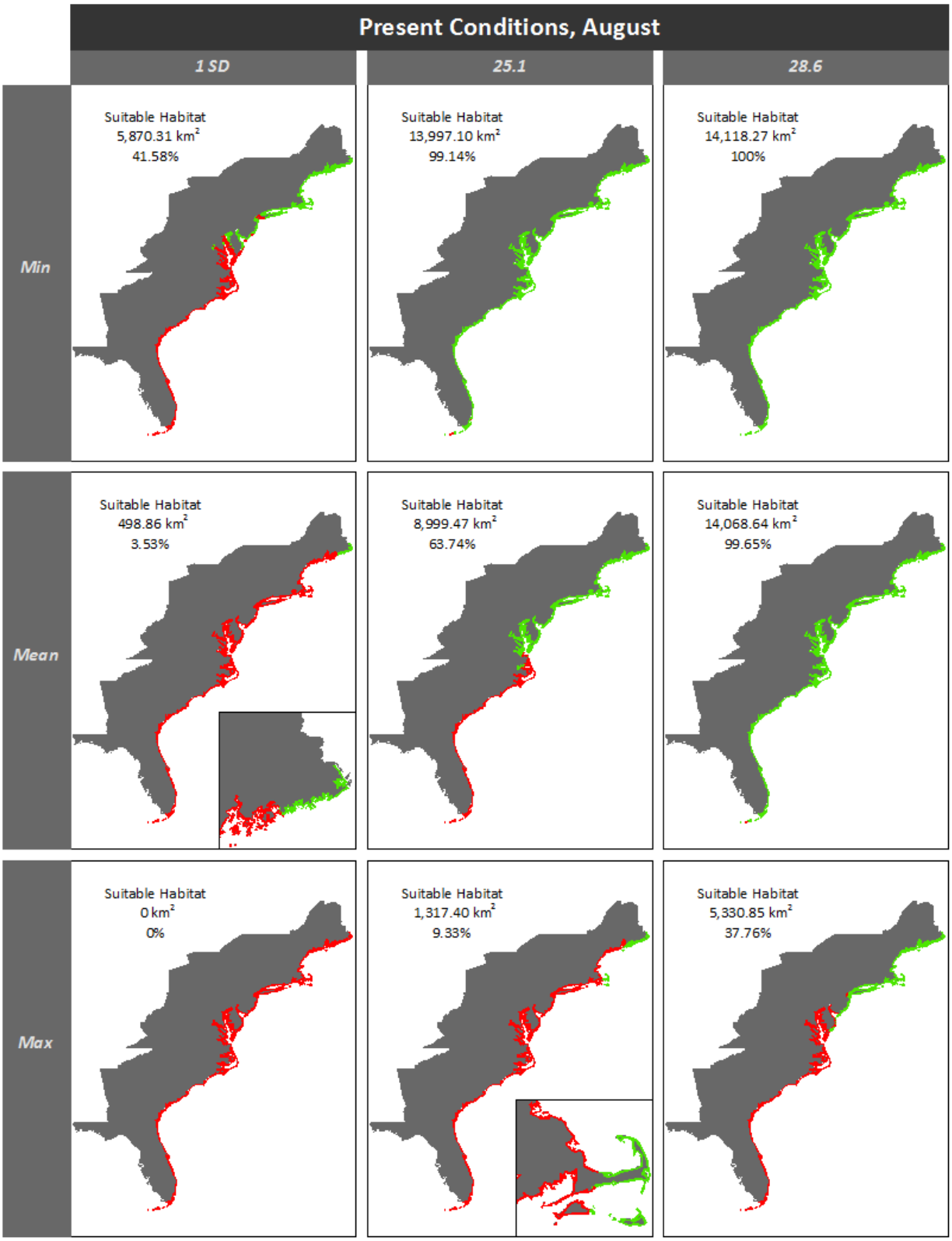


*Figure 3. The current minimum, mean, and maximum ambient temperatures in the month of August based on the three metrics of interest: current preferences, thermal limit of juveniles, and the thermal limit of adult harbor seals.*

*Future Conditions*

*2050 RCP 4.5, Minimum Temperature*

Future minimum ambient temperatures in May, June, and August in the year 2050 using the RCP 4.5 scenario are predicted to be 14.83°, 19.40°, and 21.99°C, which is an increase of 2.48°, 2.52°, and 2.97°C, respectively. Our analysis revealed that in May 2050, 81.73% of the coastline should fall within one standard deviation and 92.22% of should fall within two standard deviations of the current mean ambient temperature based on current preferences. Because the thermal limits of pups and adults exceed that of the current preferences, the study revealed that 99.28% of the coast would be accessible to harbor seal pups and 100% of the coastline would be suitable for adults.

As we have seen, May historically is the coolest month out of the three study years, followed by June, and then the warmest month of the year, August. We found that during the month of June 2050, 35.80% of the coastline should be within one standard deviation and 72.68% of the coast would be within two standard deviations of the mean ambient temperatures observed based on current conditions. Finally, our analysis revealed that juveniles could access 97.13%, while adults could make use of 100% of the coastline under this scenario.

Our results for August 2050 revealed that only 14.71% of the coastline should fall within one standard deviation and 34.97% of the coast should fall within two standard deviations of the mean ambient temperatures observed under current conditions. Based on the thermal limits of both juveniles and pups, we expect that 86.19% of the coastline to be suitable for harbor seal pups and 100% of the shore to be suitable for adults.

*2050 RCP 4.5, Maximum Temperature*

Future maximum ambient temperatures in May, June, and August in the year 2050 based on the RCP 4.5 scenario are predicted to be 25.38°, 29.72°, and 31.71°C, which is an increase of the monthly maximum by a value of 2.26°, 2.53°, and 2.87°C, respectively. Our study revealed that in May 2050, 3.61% of the coast should fall within one standard deviation and 21.40% of the coastline should be within two standard deviations of the mean ambient temperatures observed during current conditions. Pups should be able to access 40.90% of the coastline with 78.06% of the coast deemed suitable for adults.

Unfortunately, harbors seals will fair far worse during the month of June in the year 2050. Based on current preferences, 0% of the coastline will be within one and two standard

deviations of the mean ambient temperature observed under current conditions. However, based on the thermal limits of juveniles, we expect that 6.10% of the coastline to be suitable for pups and 33.18% of the coast to be suitable for their predecessors.

The success of harbor seals during the month of August 2050 declines drastically from June as less of the coastline is deemed suitable habitat. 0% of the coast is within one or two standard deviations of the mean ambient temperatures seen under present day conditions. The success of juveniles is also compromised as only 0.14% of the coast is deemed suitable habitat, while 13.91% of the coast is suitable for adult harbor seals based on their thermal limits.

*2050 RCP 8.5, Minimum Temperature*

Future minimum ambient temperatures in May, June, and August in the year 2050 based on the RCP 8.5 scenario are predicted to be 15.39°, 19.90°, 22.73°C, which is an increase of 3.04°, 3.02°, and 3.71°C, respectively. We found that in May 2050, 81.53% of the coast would be within one standard deviation and 91.71% of the coast would fall within two standard deviations of the mean ambient temperature observed under current conditions. The thermal limits of juveniles would allow 99.46% of the coastline to be suitable habitat, while the thermal limits of adult harbor seals would allow them to use 100% of the eastern United States shoreline.

Rising temperatures in June 2050 will reduce the amount of shoreline that will fall within one standard deviation to 32.77%, while 67.66% will fall within two standard deviations of the mean ambient temperatures observed today. The thermal limits of juveniles should constrain the suitable habitat to 95.96% of the coast, while 100% of the coastline should be suitable to adult harbor seals.

During the month of August in the year 2050, we would expect that only 11.65% of the eastern shore to be within one standard deviation and 50.60% of the coast to be within two standard deviations of the mean ambient temperature based on present day observations. The thermal limits of juveniles should limit their habitat to 80.24% of the coastline, while adults should be able to make use of 100% of the coastline based exclusively on ambient temperatures.

*2050 RCP 8.5, Maximum Temperature*

Future maximum ambient temperatures in May, June, and August in the year 2050 based on the RCP 8.5 scenario are predicted to be 23.12°, 27.19°, and 28.84°C, which is an increase of 2.87°, 3.00°, and 3.73°C, respectively. Our analysis revealed that in May, 1.68% of the coastline would fall within one standard deviation and 13.45 percent of the coastline would fall within two

standard deviations of the current mean ambient temperature. Based on the thermal tolerance of pups, 38.59% of the coastline should be suitable. Meanwhile, we found that 75.33% of the coastline should be accessible to adults based on their own thermal tolerance.

June 2050 proved to be a much warmer month, which caused less of the eastern United States to be conducive to harbor seals. We found that 0% of the coastline fell within one and two standard deviations of the current mean ambient temperature. Due to the thermal limits of juveniles exceeding that of current day preferences, pups should be able to access 4.51% of the coast, while adults should be able to make use of 31.13% of the coastline.

The monthly maximum temperatures in August 2050 are likely to exceed the thermal limits for harbor seals. Our analysis revealed that 0% of the coastline fell within one standard deviation and two standard deviations of the mean ambient temperature indicative of current day temperatures. In a similar fashion, the thermal limits of juveniles were exceeded with 0% of the United States coastline falling within their upper thermal tolerance. However, adult harbor seals should be able to access a small amount of coastline, 5.35%, that is suitable for hauling out.

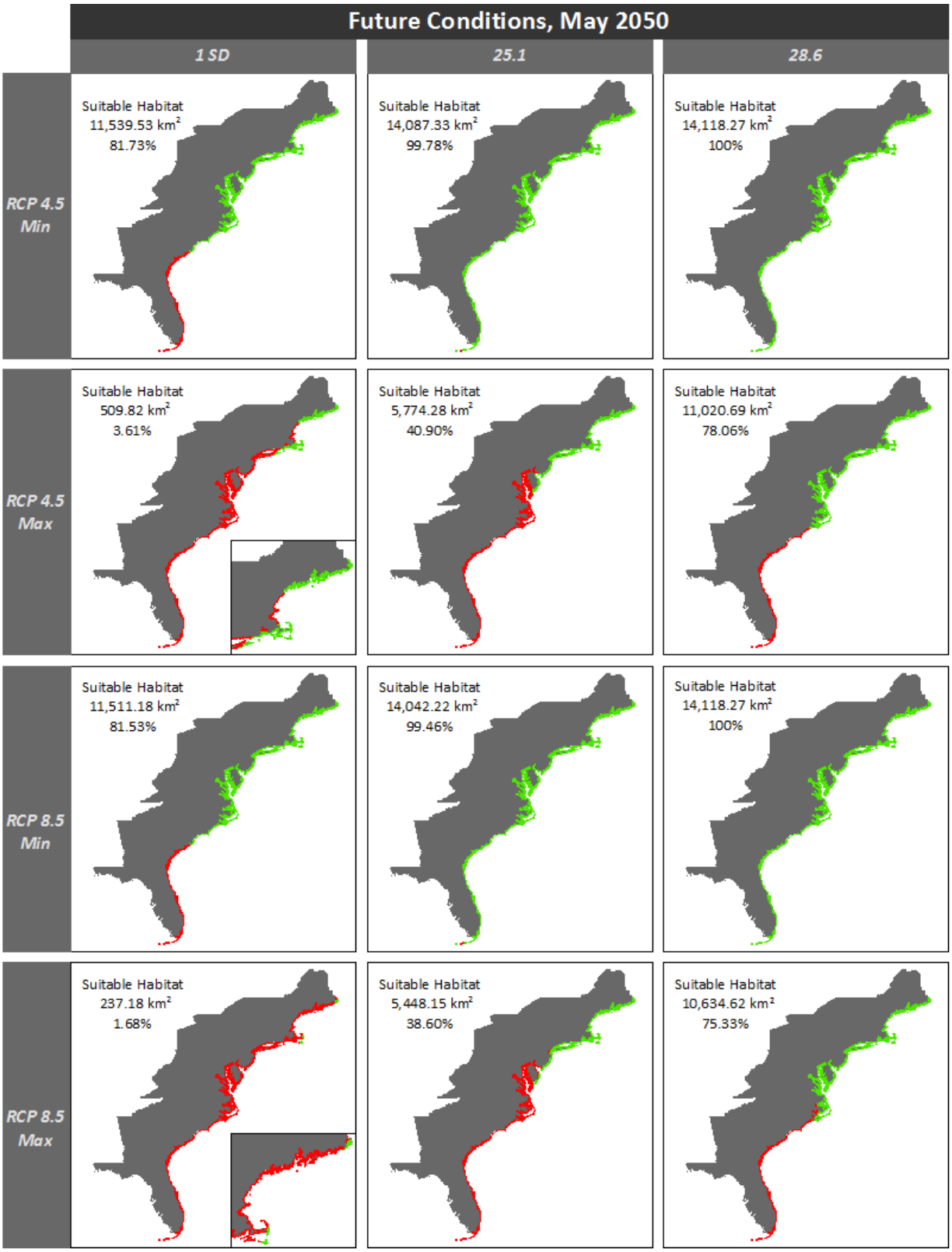


*Figure 4. Future conditions in May 2050 based on RCP 4.5 and 8.5 scenarios, using both minimum and maximum ambient temperatures coupled with the three metrics of interest: current preferences, thermal limit of juveniles, and thermal limit of adults.*

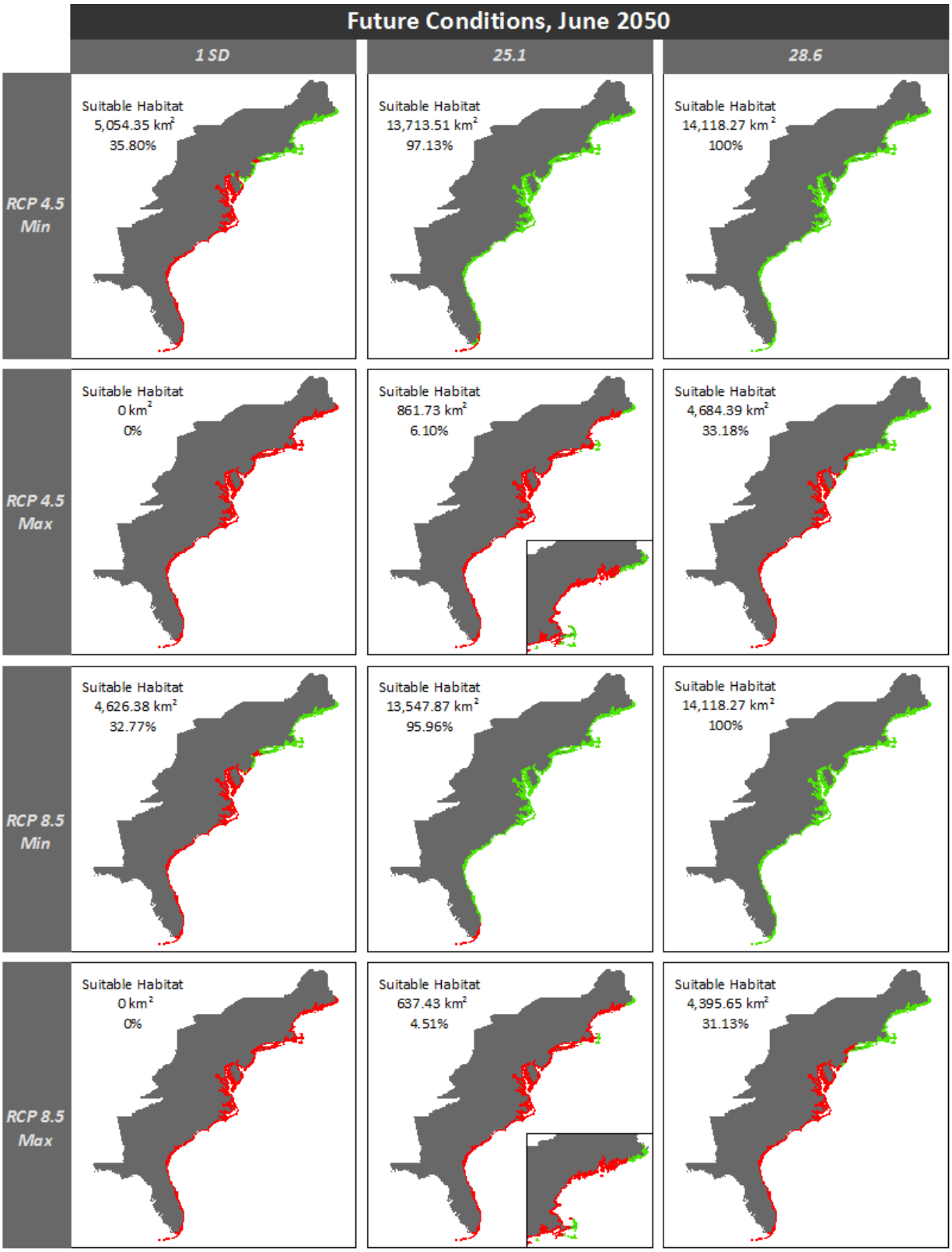


*Figure 5. Future conditions in June 2050 based on RCP 4.5 and 8.5 scenarios, using both the minimum and maximum ambient temperatures coupled with the three metrics of interest: current preferences, thermal limit of juveniles, and thermal limit of adults.*

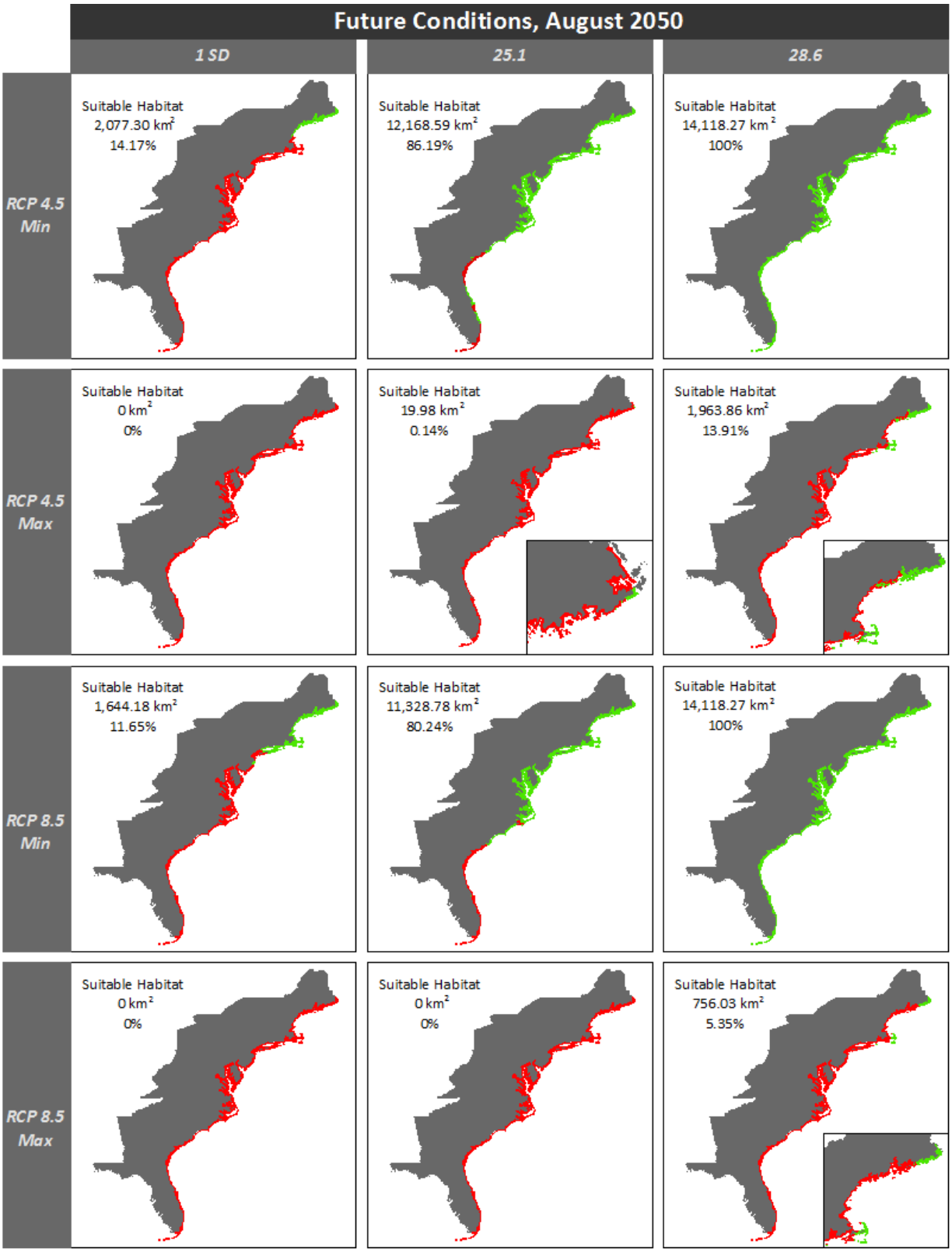


*Figure 6. Future conditions in August 2050 based on RCP 4.5 and 8.5 scenarios, using the minimum and maximum ambient temperatures coupled with the three metrics of interest: current preferences, thermal limit of juveniles, and thermal limit of adults.*

*2070 RCP 4.5, Minimum Temperature*

Future minimum ambient temperatures in May, June, and August in the year 2070 based on the RCP 4.5 scenario are predicted to be 15.15°, 19.82°, and 22.71°C, which is an increase of 2.80°, 2.94°, and 3.69°C, respectively. Our results showed that 81.58% of the coast fell within one standard deviation and 91.88% of the coast fell within two standard deviations of the current mean ambient temperature. Pups should be able to make use of 99.63% of the coast, while adults should be able to utilize the entire coastline based exclusively on the confines of ambient temperature thresholds.

Expected conditions in June 2050 should lead to 33. 54% of the coast falling within one standard deviation and 68.64% of the coastline falling within two standard deviations of the mean ambient temperature observed under current conditions. We would expect that 96.30% of the coast would be suitable to pups and 100% of the coastline would be accessible to adult harbor seals based on their thermal limits in air.

August being the warmest month of the year would cause a significant loss of habitat to Atlantic harbor seals based on current preferences. Our result indicated that only 11.38% of the coast should fall within one standard deviation and 28.83% of the coast should fall within two standard deviations of the mean ambient temperature observed today. Pups, however, should still be able to access 81.94% of the coast, while adults should be able to utilize 100% of the coast.

*2070 RCP 4.5, Maximum Temperature*

Future maximum ambient temperatures in May, June, and August in the year 2070 based on the RCP 8.5 scenario are predicted to be 25.72°, 30.05°, and 32.41°C, which represents an increase of the monthly maximum by a values of 2.60°, 2.86°, and 3.57°C, respectively. Our study revealed that in May 2070, only 2.47% of the coastline should fall within one standard deviation and 17.57% of the coastline should fall within two standard deviations of the mean ambient temperatures observed during current conditions. Based on the thermal limits of harbor seal pups, 39.86% of the coast should be suitable, while adult harbor seal thermal limits should restrict them to 77.00% of the coast.

With rising temperatures in the month of June, our analysis revealed that 0% of the coastline fell within one and two standard deviations of the current mean ambient temperature. Pups should be able to access 4.58% of the United States eastern seaboard, while 31.83% of the coastline should be suitable for adults.

August 2070 seems to be of even greater concern because we found that 0% of the coast fell within one and two standard deviations of the mean ambient temperature observed under current conditions. Unfortunately, 0% of the coastline will be suitable for harbor seal pups with a monthly average maximum temperature of 32.41°C. Fortunately, 5.44% of the coastline should still be suitable to adult harbor seals due to their higher heat threshold.

*2070 RCP 8.5, Minimum Temperature*

Future minimum ambient temperatures in May, June, and August in the year 2070 based on the RCP 8.5 scenario are predicted to be 16.81°, 21.46°, and 24.48° C, which is an increase of 4.46°, 4.58°, and 5.46° C, respectively. Our analysis of May ambient temperatures revealed that 73.69% of the coast should fall within one standard deviation and 84.41% of the coast should fall within two standard deviations of the mean ambient temperature observed under current conditions. Pups should be able to access 98.23% of the coast, while adults should be able to access 100% of the shore.

The warmer temperatures in June 2070 should reduce the area available to harbor seals. Only 23.12% of the coast should fall within one standard deviation and 41.07% should fall within two standard deviations of the mean ambient temperature indicative of current conditions. The thermal limits of pups should make 83.30% of the coast suitable for hauling out, while adults should be able to make use of 100% of the coastline.

During the month of August, only 0.71% of the coast should fall within one standard deviation and 12.19% of the coast should fall within two standard deviations of the mean ambient temperature indicative of current preferences. However, our analysis revealed that pups should be able to access 52.65% of the coast, while adults should be able to make use of 99.91% of the coastline.

*2070 RCP 8.5, Maximum Temperature*

The future maximum ambient temperatures in May, June, and August in the year 2070 based on the RCP 8.5 scenario are predicted to be 27.35°, 31.81°, and 34.36°C, which is an increase of 4.23°, 4.62, and 5.52°C, respectively. Our research revealed that in May, 0% of the coastline would fall within one standard deviation and 4.14% of the coastline would fall within two standard deviation of the mean ambient temperature observed under current conditions. The thermal tolerance of pups should facilitate 31.54% of the coastline being suitable to juvenile

harbor seals, while the thermal tolerance of adults should make 61.36% of the coastline suitable habitat.

We found that in June 2070, 0% of the coastline should fall within one and two standard deviations of the current mean ambient temperature due to unusually high warm temperatures. Our findings also revealed that based on the thermal tolerance of pups, 1.07% of the coastline should be suitable for them to haul out, while 19.46% of the coastline should be suitable for adult harbor seals.

Under this scenario, August 2070 is a record month with extremely high air temperatures. In August 2070, we would expect that 0% of the coastline to be within one and two standard deviations of the current day mean ambient temperature. Pups would be at a disadvantage along the United States coastline, giving way to 0% percent of the coastline being within their thermal limits in air. Adult harbor seals will also suffer habitat loss with 0.12% of the coastline expected to be within their thermal limits.

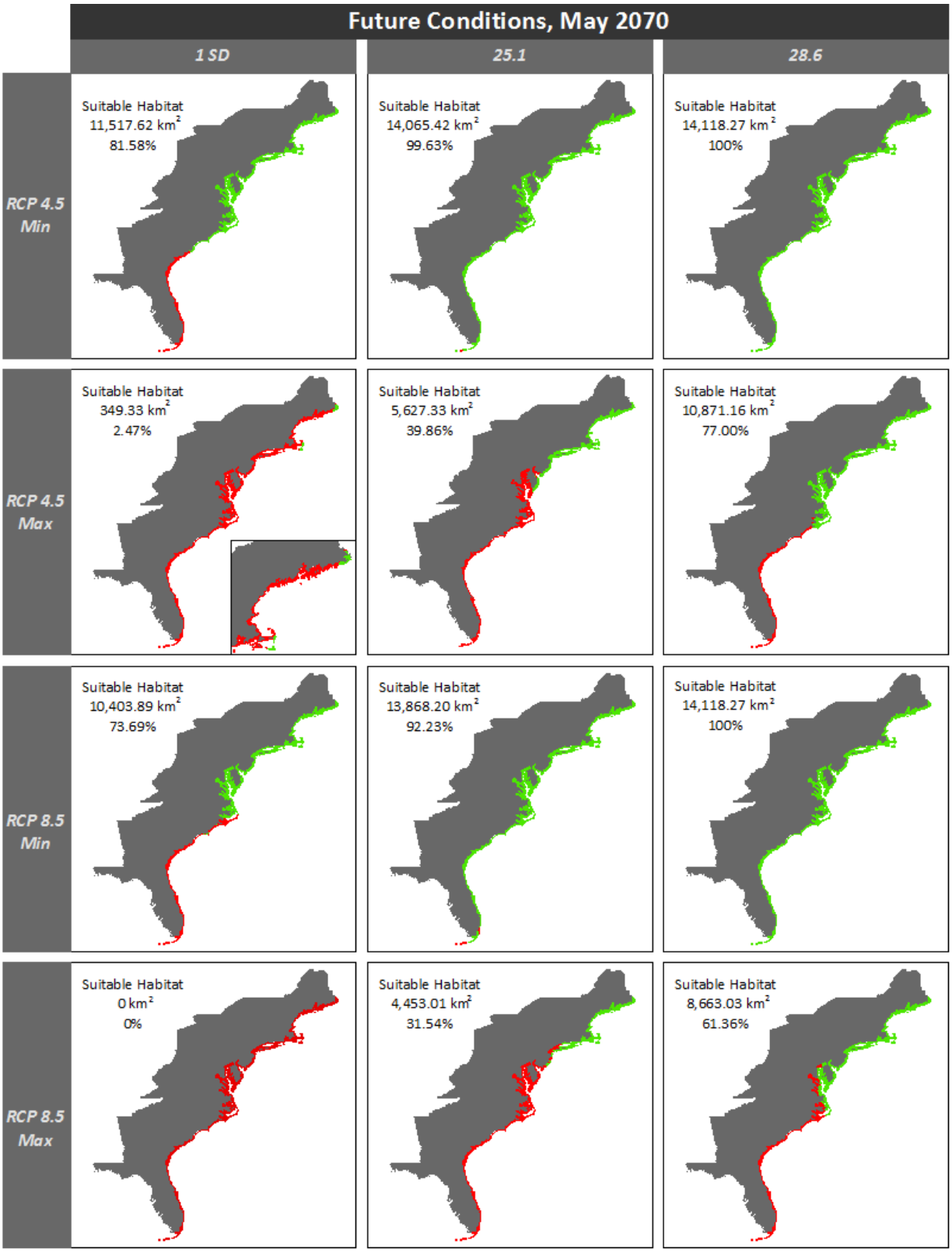


*Figure 7. Future conditions in May 2070 based on RCP 4.5 and 8.5 scenarios, using the minimum and maximum ambient temperatures coupled with the three metrics of interest: current preferences, thermal limit of juveniles, and thermal limit of adults.*

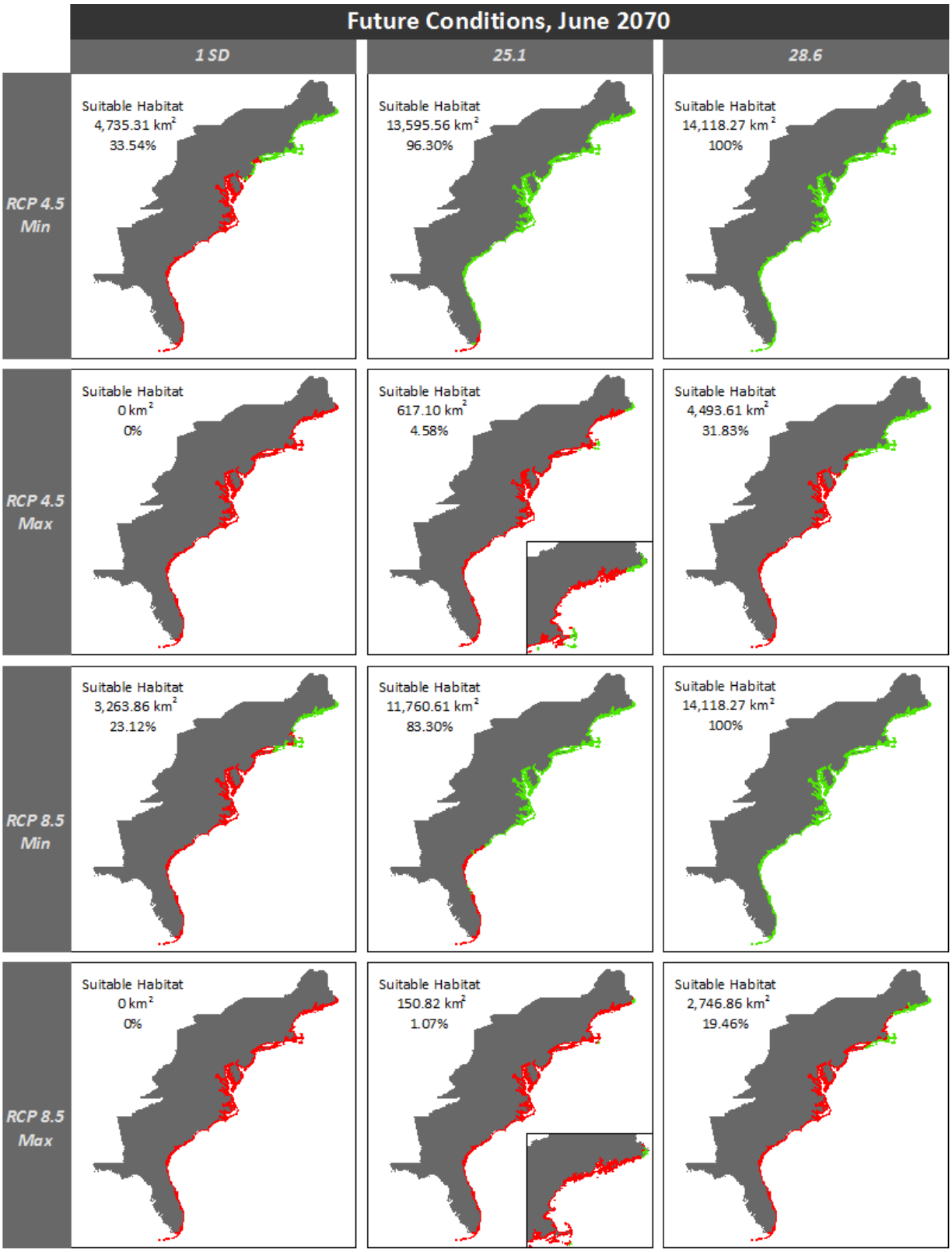


*Figure 8. Future conditions in June 2070 based on the RCP 4.5 and 8.5 scenarios, using the minimum and maximum ambient temperatures and the three metrics of interest: current preferences, thermal limit of juveniles, and the thermal limit of adults.*

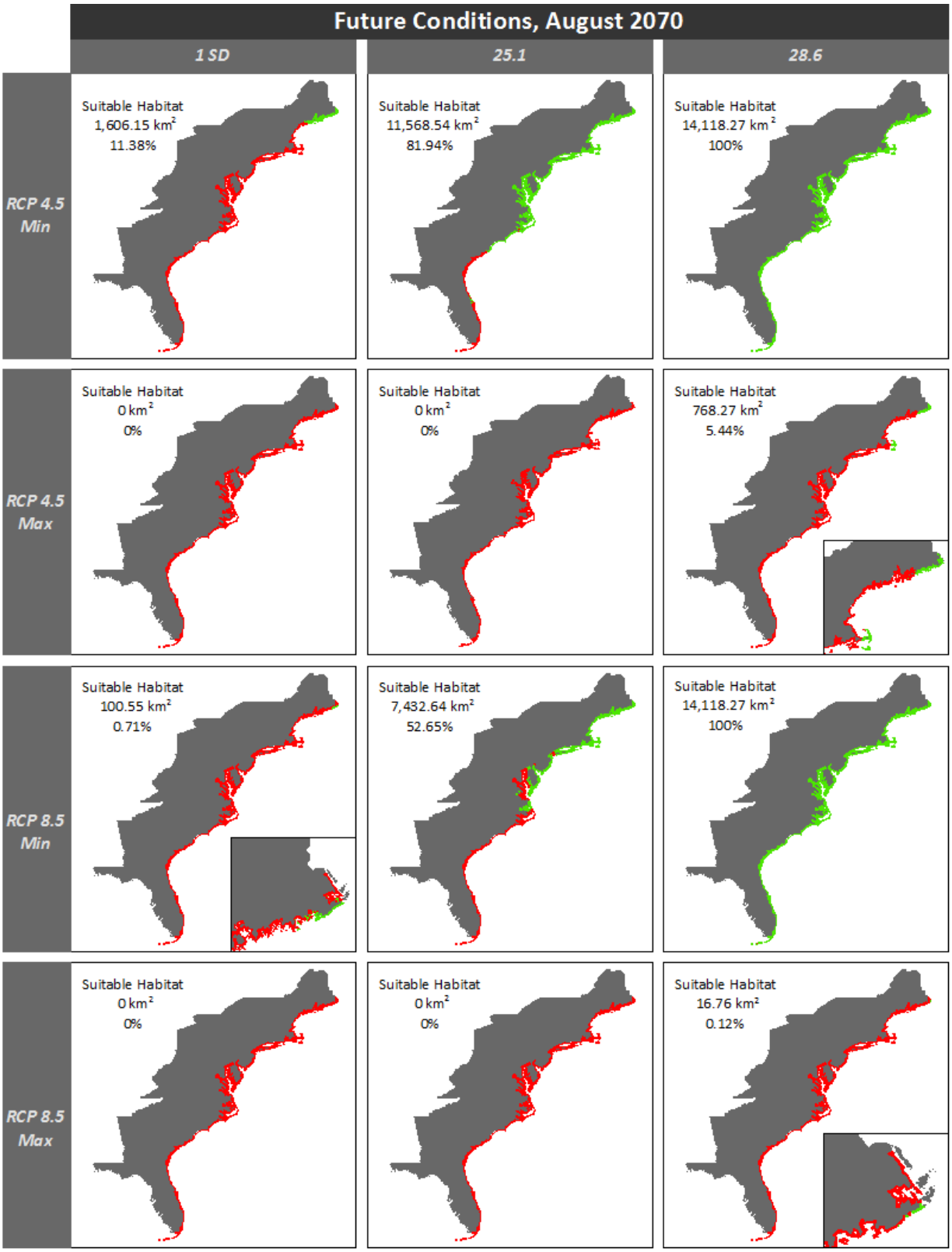


*Figure 9. Future conditions in August 2070 based on RCP 4.5 and 8.5 scenarios, using the minimum and maximum ambient temperatures and the three metrics of interest: current preferences, thermal limit of juveniles, and thermal limit of adults.*

**Discussion**

Our study focuses solely on the role upper critical temperatures play on the distribution of both harbor seal juveniles and adults. Extensive research, which was performed by Hansen et al. (1995) and Hansen and Lavigne (1997), has provided us with the thermal limits for juvenile and adult harbor seals. Despite our research focusing on the southern most limits of harbor seals, further research regarding the northern limits of harbor seal juveniles and adults may provide worthwhile information. Just as we used the upper critical temperature, the study could be performed using the lower critical temperatures found in Hansen's research to assess the northern expansion of harbor seals with warming ambient temperatures. In places where sea ice and other factors may limit their northern distribution, we suspect that a northern trend may follow due to rising temperatures.

Under current maximum temperatures, we found May to be most hospitable month to both juveniles and adults. Our analysis revealed that 9,574.39 $km^2$ of the United States coastline should be suitable habitat for pups, while Adults would be able to access 12,751.88 $km^2$. However, in the month of June and August the gap widens and temperatures rise. In June, maximum temperatures constrain harbor seal pups to the upper most portion of Maine down to Cape Cod, Massachusetts. Under these circumstances, pups are only able to make use of half of the coastline available to adult harbor seals and in August these numbers deteriorate further. In August, pups are limited to the upper most portion of Maine, which constitutes only 1,317.40 $km^2$ of the coast, while adults may utilize 5,330.85 $km^2$.

When we examine conditions in the future, we find that minimum temperatures under the RCP 4.5 and 8.5 scenario are conducive to both juveniles and adult harbor seals with very little difference in the overall area available to each. For example, in the year 2050 using the RCP 4.5 scenario, harbor seal pups should be able to make use of 12,168.59 $km^2$ of the shore, while suitable adult habitat should hover around 14,118.27 $km^2$, which happens to be the entirety of the United States coastline. However, maximum temperatures, particularly in 2070, constrained adults to a very small percentage, 16.76%, of the United States coastline, while pups were unable to survive in the United States all together and likely would have to migrate to more northern, cooler habitats in Canada. Due to the fact that older, larger bodied seals are more heat tolerant,

we found that juveniles will be particularly susceptible to increasing ambient temperatures under these future scenarios.

The world is on trend with the RCP 8.5 scenario, but we examined the fate of both juveniles and adult harbor seals in the event that global $CO_2$ emissions declines over the years with the help of technology and more environmental management. Our results indicate that if we stay on trend with the RCP 8.5 scenario and fail to cut $CO_2$ emissions drastically, the health and wellness of adult, but particularly juvenile harbor seals will be threatened. When we compare the availability of coastline using the RCP 4.5 and 8.5 scenario based on maximum temperatures, we found that juveniles could access 19.98 $km^2$ in August 2070, which is characterized as the warmest month of the year. Meanwhile, adult in the same month and year should be able to use 1963.86 km2 of the United States coastline. In the event that we are unable to reduce global $CO_2$ emissions, we would expect that under the RCP 8.5 scenario in August 2070 that 0 $km^2$ of United States coastline could be used by juvenile harbor seals to haul out. However, 756.03 $km^2$ of coastline should be available to adult harbor seals. These findings show that a reduction in $CO_2$ emissions could drastically impact the future of harbor seals along the United States coast and likely many other trophic levels that are intertwined with pinnipeds.

Although Hansen and Lavigne (1997) found that both older and larger harbor seals have a higher heat tolerance when it comes to warm air compared to the same individuals in their first year, it should be noted that other environmental factors, such as solar insulation, may affect their ability to thermoregulate. Indeed, McGinnis (1975) revealed that an adult harbor seal could not regulate its internal body temperature during calm sunny conditions despite the fact that ambient temperatures were only 20°C. Under this scenario, even conditions that fell within our current preferences metric, which were one and two standard deviations from the current mean ambient temperatures in which we see harbor seals today, may not accurately represent suitable habitat under specific environmental conditions.

We used only ambient temperature to predict possible terrestrial habitat for both harbor seal juveniles and adults. However, there are a plethora of other possible environmental variables that could impact their distribution and abundance along the coast. Some of these other variables could be sea surface temperatures, abundance of prey, tidal height, wind, and precipitation. Tidal height impacts the area on land that is available to seals for hauling out. The

time in which seals typically haul out is also drastically reduced in the presence of strong winds and heavy precipitation (Watts 1991).

In conclusion, our findings demonstrate that rising ambient temperatures will greatly impede the distribution of harbor seals along the United States coastline. We expect juvenile harbor seals to be most effected by rising air temperatures due to differences in relative body mass. Due to the fact that juvenile harbor seals are most susceptible to rising air temperatures, we would expect that the historic areas where adult harbor seals tend to pup will move northward with unprecedented air temperatures. These findings demonstrate that a more conscious effort to reduce global $CO_2$ emissions needs to be made in order to save coastal ecological diversity because seals are greatly intertwined with the success of other organisms.

## Appendix

| Period | Statistic | Month | Metrics | Percent | Area ($km^2$) |
|---|---|---|---|---|---|
| Current (1950 to 2000) | Minimum | May | 1 Standard Deviation | 91.44 | 12910.43 |
| | | | 2 Standard Deviations | 96.78 | 13663.24 |
| | | | Pups | 100.00 | 14118.27 |
| | | | Adults | 100.00 | 14118.27 |
| | | June | 1 Standard Deviation | 67.95 | 9593.72 |
| | | | 2 Standard Deviations | 88.66 | 12517.28 |
| | | | Pups | 99.98 | 14115.05 |
| | | | Adults | 100.00 | 14118.27 |
| | | August | 1 Standard Deviation | 41.58 | 5870.31 |
| | | | 2 Standard Deviations | 75.48 | 10656.54 |
| | | | Pups | 99.14 | 13997.10 |
| | | | Adults | 100.00 | 14118.27 |
| | Mean | May | 1 Standard Deviation | 59.66 | 8422.62 |
| | | | 2 Standard Deviation | 80.41 | 11351.98 |
| | | | Pups | 95.57 | 13493.08 |
| | | | Adults | 100.00 | 14118.27 |
| | | June | 1 Standard Deviation | 21.95 | 3099.51 |
| | | | 2 Standard Deviation | 36.10 | 5096.24 |
| | | | Pups | 81.50 | 11506.66 |
| | | | Adults | 100.00 | 14118.27 |
| | | August | 1 Standard Deviation | 3.53 | 498.86 |
| | | | 2 Standard Deviation | 21.12 | 2982.21 |
| | | | Pups | 63.74 | 8999.47 |
| | | | Adults | 99.65 | 14068.64 |
| | Maximum | May | 1 Standard Deviation | 21.25 | 3000.25 |
| | | | 2 Standard Deviation | 34.90 | 4926.73 |
| | | | Pups | 67.82 | 9574.39 |
| | | | Adults | 90.32 | 12751.88 |
| | | June | 1 Standard Deviation | 0.00 | 0.00 |

| | | | | | |
|---|---|---|---|---|---|
| | | | 2 Standard Deviation | 3.63 | 512.40 |
| | | | Pups | 29.08 | 4105.61 |
| | | | Adults | 62.23 | 8786.13 |
| | | August | 1 Standard Deviation | 0.00 | 0.00 |
| | | | 2 Standard Deviation | 0.00 | 0.00 |
| | | | Pups | 9.33 | 1317.40 |
| | | | Adults | 37.76 | 5330.85 |

| Period | Scenario | Month | Metrics | Percent | Area ($km^2$) |
|---|---|---|---|---|---|
| Future Conditions in 2050 | RCP 4.5 Minimum | May | 1 Standard Deviation | 81.73 | 11539.53 |
| | | | 2 Standard Deviation | 92.22 | 13019.36 |
| | | | Pups | 99.78 | 14087.33 |
| | | | Adults | 100.00 | 14118.27 |
| | | June | 1 Standard Deviation | 35.80 | 5054.35 |
| | | | 2 Standard Deviation | 72.68 | 10260.80 |
| | | | Pups | 97.13 | 13713.51 |
| | | | Adults | 100.00 | 14118.27 |
| | | August | 1 Standard Deviation | 14.71 | 2077.30 |
| | | | 2 Standard Deviations | 34.97 | 4937.04 |
| | | | Pups | 86.19 | 12168.59 |
| | | | Adults | 100.00 | 14118.27 |
| | RCP 4.5 Maximum | May | 1 Standard Deviation | 3.61 | 509.82 |
| | | | 2 Standard Deviation | 21.40 | 3021.52 |
| | | | Pups | 40.90 | 5774.28 |
| | | | Adults | 78.06 | 11020.69 |
| | | June | 1 Standard Deviation | 0.00 | 0.00 |
| | | | 2 Standard Deviation | 0.00 | 0.00 |
| | | | Pups | 6.10 | 861.73 |
| | | | Adults | 33.18 | 4684.39 |
| | | August | 1 Standard Deviation | 0.00 | 0.00 |
| | | | 2 Standard Deviations | 0.00 | 0.00 |
| | | | Pups | 0.14 | 19.98 |
| | | | Adults | 13.91 | 1963.86 |

| | | | | | |
|---|---|---|---|---|---|
| | RCP 8.5 Minimum | May | 1 Standard Deviation | 81.53 | 11511.18 |
| | | | 2 Standard Deviation | 91.71 | 12948.46 |
| | | | Pups | 99.46 | 14042.22 |
| | | | Adults | 100.00 | 14118.27 |
| | | June | 1 Standard Deviation | 32.77 | 4626.38 |
| | | | 2 Standard Deviation | 67.66 | 9553.12 |
| | | | Pups | 95.96 | 13547.87 |
| | | | Adults | 100.00 | 14118.27 |
| | | August | 1 Standard Deviation | 11.65 | 1644.18 |
| | | | 2 Standard Deviation | 50.60 | 7143.25 |
| | | | Pups | 80.24 | 11328.78 |
| | | | Adults | 100.00 | 14118.27 |
| | RCP 8.5 Maximum | May | 1 Standard Deviation | 1.68 | 237.18 |
| | | | 2 Standard Deviation | 13.45 | 1899.41 |
| | | | Pups | 38.60 | 5448.15 |
| | | | Adults | 75.33 | 10634.62 |
| | | June | 1 Standard Deviation | 0.00 | 0.00 |
| | | | 2 Standard Deviation | 0.00 | 0.00 |
| | | | Pups | 4.51 | 637.43 |
| | | | Adults | 31.13 | 4395.65 |
| | | August | 1 Standard Deviation | 0.00 | 0.00 |
| | | | 2 Standard Deviation | 0.00 | 0.00 |
| | | | Pups | 0.00 | 0.00 |
| | | | Adults | 5.35 | 756.03 |

| **Period** | **Scenario** | **Month** | **Metrics** | **Percent** | **Area ($km^2$)** |
|---|---|---|---|---|---|
| Future Conditions in 2070 | RCP 4.5 Minimum | May | 1 Standard Deviation | 81.58 | 11517.62 |
| | | | 2 Standard Deviation | 91.89 | 12972.95 |
| | | | Pups | 99.63 | 14065.42 |
| | | | Adults | 100.00 | 14118.27 |
| | | June | 1 Standard Deviation | 33.54 | 4735.31 |
| | | | 2 Standard Deviation | 68.64 | 9691.04 |
| | | | Pups | 96.30 | 13595.56 |

| | | | | |
|---|---|---|---|---|
| | | Adults | 100.00 | 14118.27 |
| | August | 1 Standard Deviation | 11.38 | 1606.15 |
| | | 2 Standard Deviation | 28.83 | 4070.81 |
| | | Pups | 81.94 | 11568.54 |
| | | Adults | 100.00 | 14118.27 |
| RCP 4.5 Maximum | May | 1 Standard Deviation | 2.47 | 349.33 |
| | | 2 Standard Deviation | 17.57 | 2480.77 |
| | | Pups | 39.86 | 5627.33 |
| | | Adults | 77.00 | 10871.16 |
| | June | 1 Standard Deviation | 0.00 | 0.00 |
| | | 2 Standard Deviation | 0.00 | 0.00 |
| | | Pups | 4.58 | 647.10 |
| | | Adults | 31.83 | 4493.61 |
| | August | 1 Standard Deviation | 0.00 | 0.00 |
| | | 2 Standard Deviation | 0.00 | 0.00 |
| | | Pups | 0.00 | 0.00 |
| | | Adults | 5.44 | 768.27 |
| RCP 8.5 Minimum | May | 1 Standard Deviation | 73.69 | 10403.89 |
| | | 2 Standard Deviation | 84.41 | 11917.22 |
| | | Pups | 98.23 | 13868.20 |
| | | Adults | 100.00 | 14118.27 |
| | June | 1 Standard Deviation | 23.12 | 3263.86 |
| | | 2 Standard Deviation | 41.07 | 5793.77 |
| | | Pups | 83.30 | 11760.61 |
| | | Adults | 100.00 | 14118.27 |
| | August | 1 Standard Deviation | 0.71 | 100.55 |
| | | 2 Standard Deviation | 12.19 | 1720.88 |
| | | Pups | 52.65 | 7432.64 |
| | | Adults | 99.91 | 14105.38 |
| RCP 8.5 Maximum | May | 1 Standard Deviation | 0.00 | 0.00 |
| | | 2 Standard Deviation | 4.14 | 583.94 |
| | | Pups | 31.54 | 4453.01 |
| | | Adults | 61.36 | 8663.03 |

| | | | | |
|---|---|---|---|---|
| | June | 1 Standard Deviation | 0.00 | 0.00 |
| | | 2 Standard Deviation | 0.00 | 0.00 |
| | | Pups | 1.07 | 150.82 |
| | | Adults | 19.46 | 2746.96 |
| | August | 1 Standard Deviation | 0.00 | 0.00 |
| | | 2 Standard Deviation | 0.00 | 0.00 |
| | | Pups | 0.00 | 0.00 |
| | | Adults | 0.12 | 16.76 |

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