Using climate change scenarios to project loggerhead turtle distributions in the US Mid-Atlantic

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Executive Summary

The proposed project directly addressed research needs outlined under **2018 S-K Priority #2: adapting to environmental changes and other long-term impacts in marine ecosystems.** Specifically, this project characterized sea surface temperature (SST) conditions encountered by loggerheads in the Mid-Atlantic Bight (MAB) using a large, long-term satellite tagging dataset. Geostatistical mixed effects models (Thorson et al. 2016) were applied to identify SST associated with loggerhead habitat usage using data obtained from satellite SST composites (Hazen et al. 2012). These models are rooted in generalized linear mixed modeling techniques, but explicitly account for spatial and/or temporal autocorrelation using Gaussian random fields (Lindgren et al. 2011). Models were based upon existing code developed to estimate spatial variation in monthly loggerhead densities in the MAB for each year with data available (2009 – 2018; Winton et al. 2018). The thermal habitat model was used to project how loggerhead distributions in the MAB may shift in response to climate change over long-term (i.e., 80-100 year) time scales to show impacts over the lifetime of an individual turtle (Crouse et al. 1987). Projections were based on a climate change scenario based on National Oceanic and Atmospheric Association’s (NOAA’s) high-resolution global climate model (i.e., CM2.6) as described by Saba et al. (2016).

Due to their protected status, federal regulations limit the number of interactions (often referred to as “takes”) that can occur annually between loggerheads and fishing vessels; the seasonal presence of loggerheads can restrict commercial fishing operations through the implementation of gear modifications (e.g., the Turtle Deflector Scallop Dredge, Smolowitz et al. 2012) or closures if the number of allowable interactions is exceeded (Swimmer et al. 2017). Northward shifts or the prolonged seasonal presence of loggerheads may result in increased bycatch of loggerheads in the MAB, which may substantially impact commercial fishing in the region, both economically and ecologically.

The specific goals of this project were: A) determine the fundamental thermal niche of loggerheads in the MAB by fitting a geostatistical mixed effects model to temperature data collected from turtle-borne loggers and satellite-derived sea surface temperature composites; B) use the fitted models to incorporate projections from climate models to evaluate possible changes in loggerhead distribution in the MAB under differing sea surface temperature forecasts and in relation to existing sea turtle conservation measures; C) disseminate results to local stakeholders through various formats to increase viewership and accessibility. This includes materials distributed online, through presentations and directly at the docksides.

Project Overview and Purpose

The proposed project directly addressed research needs outlined under **2018 S-K Priority #2: adapting to environmental changes and other long-term impacts in marine ecosystems.** The specific goals of this project were: A) determine the fundamental thermal niche of loggerheads in the Mid-Atlantic Bight (MAB) by fitting a geostatistical mixed effects model to temperature data collected from turtle-borne loggers and satellite-derived sea surface temperature composites; B) use the fitted models to incorporate projections from climate models to evaluate likely changes in loggerhead distribution in the MAB under differing sea surface temperature forecasts and in relation to existing sea turtle conservation measures; C) disseminate results to local stakeholders through various formats to increase viewership and accessibility. This includes materials distributed online, through presentations and directly at the docksides.

This project characterized sea surface temperature (SST) conditions favored by loggerheads in the MAB using a large, long-term satellite tagging dataset. Geostatistical mixed effects models (Thorson et al. 2016) were applied to identify SST associated with loggerhead habitat usage using data obtained from satellite SST composites (Hazen et al. 2012). These models are rooted in generalized linear mixed modeling techniques, but explicitly account for spatial and/or temporal autocorrelation using Gaussian random fields (Lindgren et al. 2011). Models were based upon existing code developed to estimate spatial variation in monthly loggerhead densities in the MAB for each year with data available (2009 – 2018; Winton et al. 2018). The thermal habitat model was used to project how loggerhead distributions in the MAB may shift in response to climate change over long-term (i.e., 80-100 year) time scales to show impacts over the lifetime of an individual turtle (Crouse et al. 1987). Projections were based on a climate change scenario based on NOAA's high-resolution global climate model (CM2.6) as described by Saba et al. (2016).

Background

Attempts to mitigate bycatch of highly migratory protected species such as loggerhead sea turtles (*Caretta caretta*) are often based on an understanding of when and where a species occurs over time. The MAB of the northwest Atlantic is home to a seasonal aggregation of juvenile through adult loggerhead turtles (**Figure 1**). These turtles migrate into the Mid-Atlantic in the late spring to forage and return to overwintering grounds south of Cape Hatteras, North Carolina, in the fall (Ceriani et al. 2012; Griffin et al. 2013; Winton et al. 2018). Similar to other sea turtle populations throughout the world, loggerheads in this region are known to be susceptible to climate and ecosystem changes because 1) their distribution AND behavior are both heavily influenced by temperature (Hawkes et al. 2007; Mansfield et al. 2009), and 2) their diet includes gelatinous zooplankton (Smolowitz et al. 2015), which are directly influenced by changes in the ecosystem (Richardson 2008). Using a minimum habitat usage threshold of 15° C for Atlantic loggerheads, Witt et al. (2010) predicted that this population would continue to gain accessible habitat further north as ocean temperatures warmed. However, loggerheads are already found in colder Canadian waters, and have even recently gained protection under the Species at Risk Act of Canada (SARA 2017). This indicates a need for a closer examination of the impact temperature has on loggerhead distribution and the potential consequences that shifts to the NW Atlantic thermal environment will have on this turtle population.

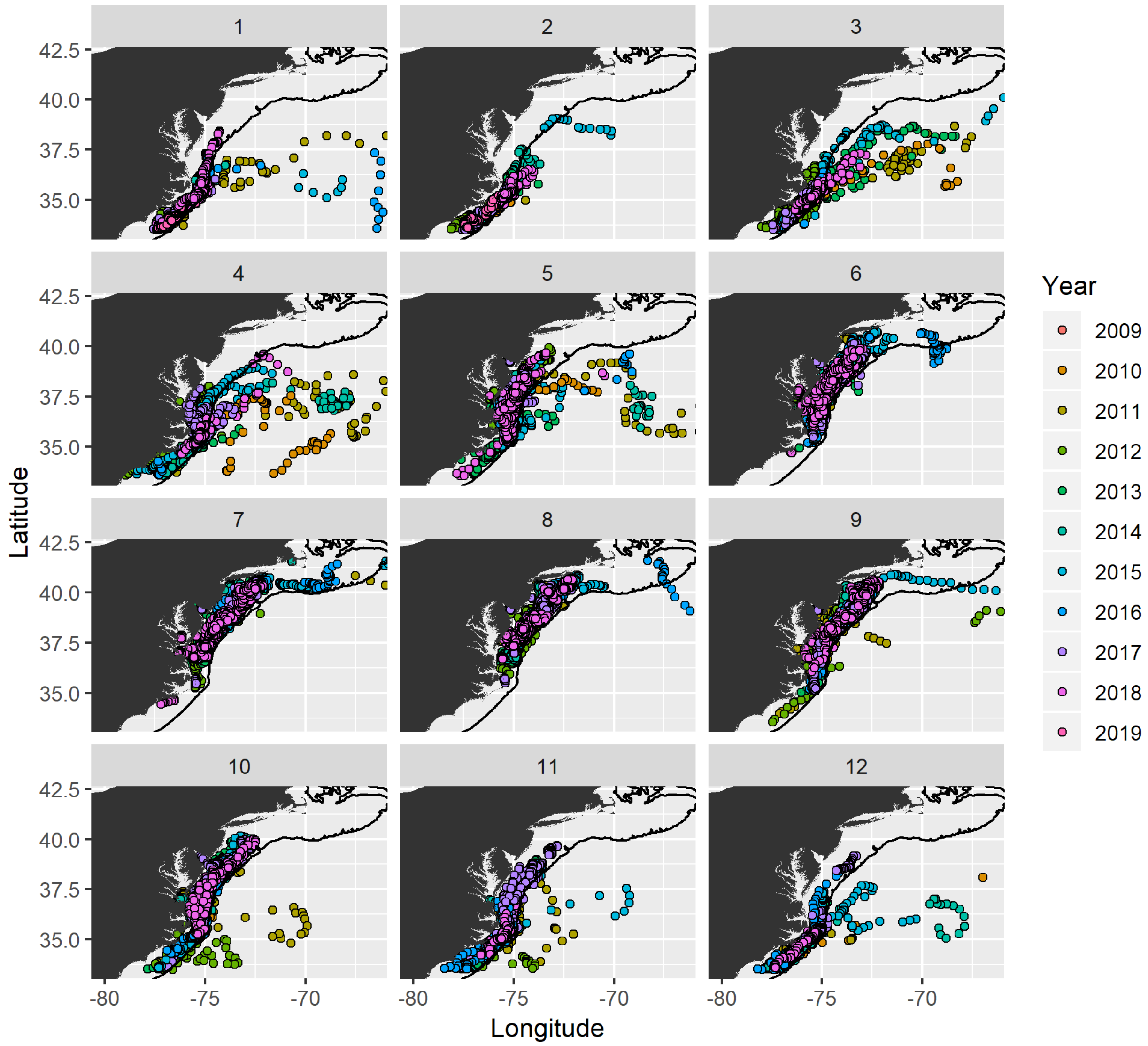


Figure 1: *Locations of tagged loggerheads by month and year within the NW Atlantic.*

Due to their protected status, federal regulations limit the number of interactions (often referred to as "takes") that can occur annually between loggerheads and fishing vessels. The seasonal presence of loggerheads can restrict commercial fishing operations through the implementation of gear modifications (e.g. the mandatory use of Turtle Deflector Dredges in the commercial scallop fishery in the MAB; Framework 23 NOAA-NMFS-2011-0255) or closures if the number of allowable interactions is exceeded (Swimmer et al. 2017). In the Pacific, interactions with loggerheads have resulted in temporary area closures, and vessels must comply with stringent regulations to prevent the incidental capture of loggerheads (Howell et al. 2008). While these regulations have resulted in reduced bycatch of both loggerhead and leatherback sea turtles (Swimmer et al. 2017), they are not sufficient for avoiding incidental takes altogether. In Hawaii, the TurtleWatch program has been developed to forecast thermal habitats where turtle interactions are most likely to occur in order to help fishermen avoid bycatch. This type of program is the first step to projecting long term shifts in thermal habitat range for the species in an effort to reduce bycatch (https://oceanwatch.pifsc.noaa.gov/turtlewatch.html)).

The MAB supports a range of large commercial fisheries, including the Atlantic sea scallop fishery and the lobster fishery, that each annually earn ~$500 million. As mentioned previously, the scallop fishery modified their gear to reduce the severity of takes of turtles; however, turtles are still incidentally caught in gillnets, trawls and long lines throughout the region. Unfortunately, modifications to fishing gear do not always successfully balance reducing turtle bycatch while maintaining high target-catch (Epperly, 2003), and a more thorough investigation into the at-sea behavior of sea turtles is required (Smolowitz et al. 2015). Since 2009 Coonamessett Farm Foundation (CFF), in collaboration with Northeast Fisheries Science Center, has been studying this sub-population through boat surveys, underwater videography and satellite telemetry. This has yielded tag deployments on over 200 turtles, with nearly all of them spending a large portion of their time within the MAB. With this large assemblage of data, we proposed to model the distribution and identify the thermal niche of loggerheads, which has not previously been quantified within the region. Based on those results, we used modern climate change models to project shifts in the available thermal habitat over the next 80+ years. Due to the unique case of having telemetry data covering nearly a decade within the same region and from such a large number of turtles, we expected to generate an accurate representation of the thermal habitat in which this subpopulation of loggerheads is most likely to be encountered. Once complete, we disseminated relevant results for public consumption through online resources at the CFF website (www.cfarm.org). We plan to present results and distribute literature at upcoming managements meetings and scientific conferences.

Project Objectives and approaches

A) Determine the fundamental thermal niche of loggerheads in the MAB by fitting a geostatistical mixed effects model to temperature data collected from turtle-borne loggers and satellite-derived sea surface temperature composites.

To develop the fundamental thermal niche, we first had to smooth the data to ensure spatiotemporal cross compatibility between turtle locations, historical SST data and climate change projections. All turtle tag location data were filtered to create daily position estimates for each turtle. This yielded ~50,000 locations within the MAB (**Figure 2**). Speed filtering first removed errant locations and then, based on remaining locations, daily positions were estimated. This allows for a less temporally biased dataset, as telemetry data is not always sent at a consistent rate. Raw telemetry data can be skewed when data are transmitted irregularly, and this can yield an inaccurate conclusion on when and where animals spend their time. Additionally, by creating consistent time-step position estimates, this allows for easier comparison with oceanographic data that are typically distributed in daily to monthly composites. For analysis

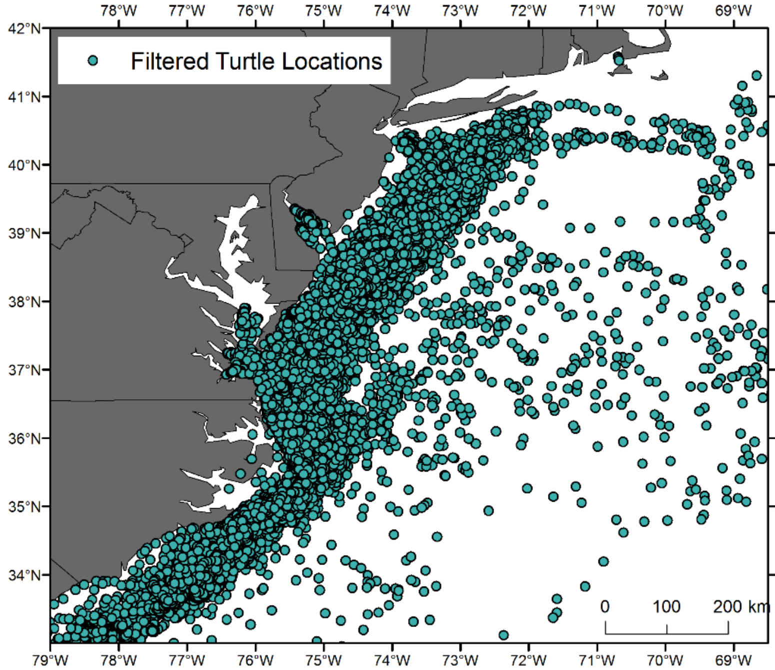


***Figure 2**: Filtered locations for tagged loggerheads within the MAB.*

purposes, daily loggerhead locations were binned by month (the time step we have found most often requested by managers) and aggregated over the 10-km resolution Atlantic Marine Assessment Program for Protected Species (AMAPPS) spatial grid. We used this grid to remain consistent with existing programs designed to understand the overlap between protected species and anthropogenic impacts within the region.

The next step was to decide which SST product to use. We originally planned on using the SST data from Geostationary (GOES) satellite imagers; however, these data do not extend into the Atlantic Ocean for 2018. As a result, we chose the Optimum Interpolation Sea Surface Temperature (OISST) product, which is a combination of observations from different platforms (satellites, ships, buoys) and is produced at a 1/4° resolution. Daily OISST images were downloaded and then averaged together within a month to create monthly composites. Monthly composites were then up-sampled to align with the AMAPPS grid by simple averaging (**Figure 3**).

For model fitting, we slightly refined the data and used the daily loggerhead location estimates from continental shelf waters (depths < 200 m) between 33.5°N - 41.6°N, which encompasses the Mid-Atlantic as delineated by National Marine Fisheries Service statistical areas, and corresponds to the area traversed by satellite-tagged loggerheads. Locations were binned by month to match the resolution of climate projections and year and aggregated over the 10-km resolution AMAPPS spatial grid (areas = 100 km^2) corresponding to the specified area. The AMAPPS grid was bounded by the coastline to constrain the loggerhead's space use to the ocean.

To characterize the thermal niche of loggerheads in the mid-Atlantic, we modeled the occurrence, y_{it}, (0 = absent, 1 = present), of tagged turtles in grid cell i during time step t as the outcome of a Bernoulli random variable:

$$y_{it} \sim \text{Bernoulli}(p_{it}),$$

where p_{it} is the probability a tagged turtle was present in grid cell *i* during time step *t*. We modeled the probability tagged loggerheads were present as a function of SST and depth as:

$$\text{logit}(p_{it}) = \beta_{0,} + \beta_1 \text{SST}_{it} + \beta_2 SST_{it}^2 + \beta_3 Depth_{it} + \beta_4 Depth_{it}^2,$$

where the logit link function constrains P_{it} from 0 to 1, β_0 is an intercept term; β_1 and β_2 represent a quadratic effect of SST (which allows for a non-linear relationship); β_3 and β_4 a quadratic effect of bottom depth. Ideally, we would have included spatial and a spatiotemporal autocorrelation terms to represent variation not accounted for by the included covariates (Thorson et al. 2017). However, the results of preliminary model fits including spatial random effects were indicative of spatial confounding with the included covariates. Given that our ultimate goal is to project loggerhead distribution under climate change scenarios, we omitted spatial random effects from final model fitting.

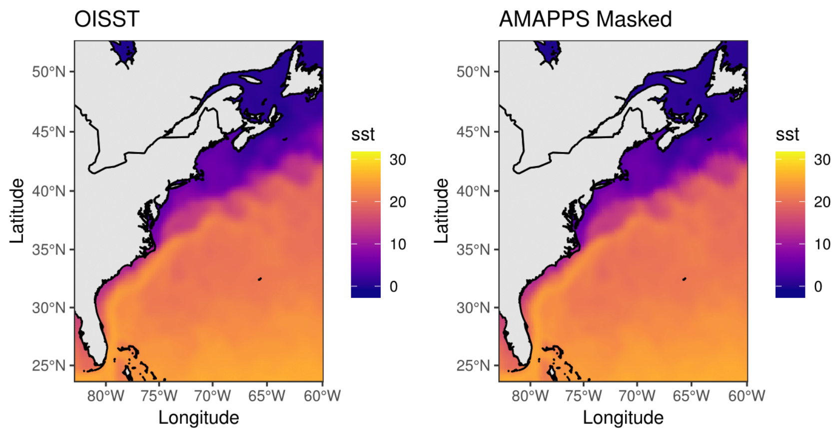


Figure 3*: Comparison of OISST (left) with up-sampled version to match AMAPPS grid resolution (right).*

B) Use the fitted models to incorporate projections from climate models to evaluate likely changes in loggerhead distribution in the MAB under differing sea surface temperature forecasts and in relation to existing sea turtle conservation measures.

SST projections from a high-resolution global climate model (CM2.6) developed by the Geophysical Fluid Dynamics Laboratory (GFDL) were used to evaluate likely changes in probability of loggerhead presence in the NW Atlantic. The projected SST output from the CM2.6 represents a monthly deviation from a historical average derived from control simulations (i.e., deltas). The CM2.6 output was rasterized onto a 0.1° x 0.1° mesh and then warped to the AMAPPS grid. The SST deltas were then added to monthly climatologies created by taking an average over OISST images from 1982 - 2018 to produce monthly projections of SST (**Appendix 2**). Along with depth, the modelled SST was used to project the probability of loggerhead presence in the MAB and north for 80 years conditioning on the fitted model. Probability of presence was then averaged across season and years. All ten years of observed data were averaged by season and projected data were averaged seasonally across 10 and 20 years.

C) Disseminate results to local stakeholders through various formats to increase viewership and accessibility. This includes materials distributed online, through presentations and directly at the docksides.

In developing tools to make the results accessible to local stakeholders, we created an animation of the availability of the suitable habitat within the MAB, Southern New England (SNE) and Georges Bank (GB) shelf waters from the monthly images and a flyer to be distributed dockside (**Appendix 3**). This animation displays the seasonal and yearly shifts in available thermal habitat for loggerheads within these NW Atlantic regions. This includes both the historical available

***Table 1**: Model selection results.*

Forward selection of presence predictors	k	nLL	Deviance	dev exp	AIC	delta AIC	BIC	delta BIC	Hessian
Null	1	50855	101710	-	101712	20452	101722	20411	yes
Step 1									
Temperature	3	43005	86009	15.4	86015	4755	86046	4734	yes
Depth	3	48761	97523	4.1	97529	16268	97559	16248	yes
Step 2									
Temperature + Depth	**5**	**40625**	**81250**	**20.1**	**81260**	**0**	**81312**	**0**	**yes**

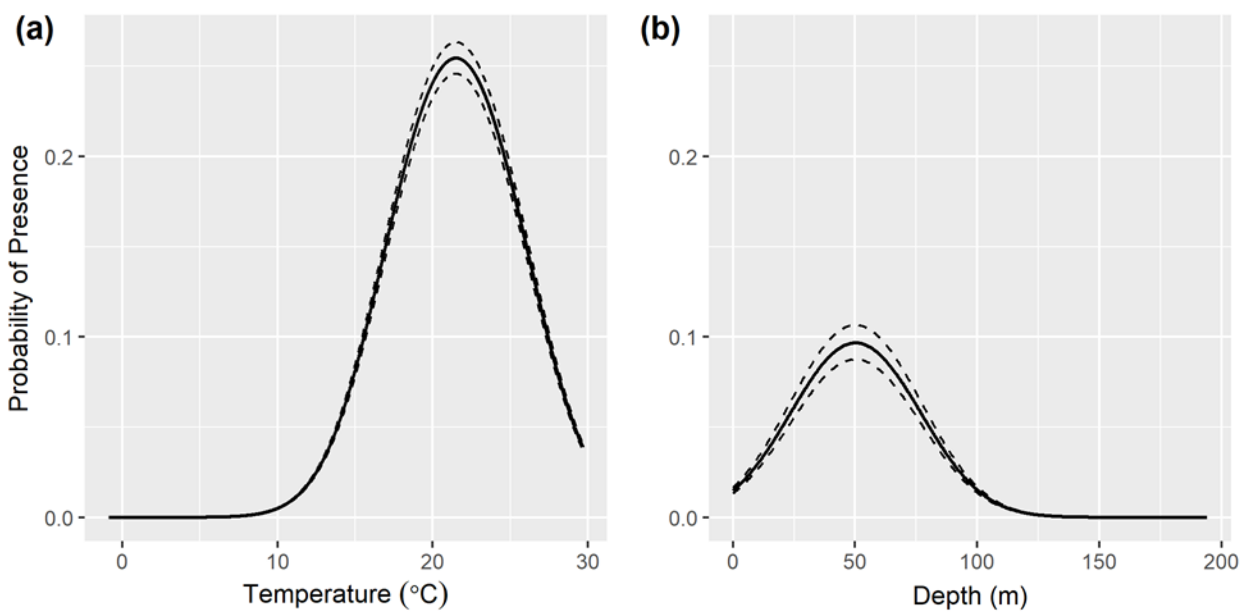


***Figure 4:** a) Historical probability of presence of loggerheads as associated with SST. b) Historical probability of presence of loggerheads as associated with bottom depth.*

thermal habitats and the projected available thermal habitats over the next 80 years. This animation is available online at the CFF website, and will be presented, when appropriate, at relevant management meetings and scientific conferences.

Results and Discussion

Model selection results supported a relationship between loggerhead presence, SST, and depth. Of the considered covariates, the inclusion of SST improved model fit most (in terms of both AIC and BIC value reductions and increases in the deviance explained; **Table 1**). Combined, temperature and depth explained ~20% of the variability in loggerhead presence. Historically, loggerheads resided in regions with SST between ~15° - ~28° C and at depths between 10 – 90 m (**Figure 4a, b**). This matched well with previous research also attempting to establish the habitat envelope for loggerheads in the region (Hawkes et al. 2011). They found that tracked turtles spent the majority of their time in temperatures between 18.2° – 29.2° C, at depths between 3 – 89 m (Hawkes et al. 2011).

Based on the fitted model, historical turtle probability of presence in the NW Atlantic is highest from May through October (**Figure 5**). The model found that portions of SNE and GB would have a higher probability of presence than the MAB in July – Sept. This does not match well with the actual loggerhead tracking data (Winton et al. 2018), but rather is an indicator that these regions have temperature and depth conditions highly suitable for loggerheads. Previous research has found that sea turtles spend time in SNE and GB; however, with likely lower densities (Griffin et al. 2019, Winton et al. 2018). We suspect that as turtles are travelling north during their spring migration, they remain in the MAB because this is an established successful foraging ground, rather than an inability to continue north. Furthermore, the historical data indicates that SNE and GB are thermally-suitable for a shorter period of the summer/early fall months, while the MAB is suitable for the entire late spring through early fall. Overall, we suspect that temperature and depth alone have limited explanatory value due to the foraging capacity of the region. It seems likely that the availability of prey resources is driving turtle abundance and

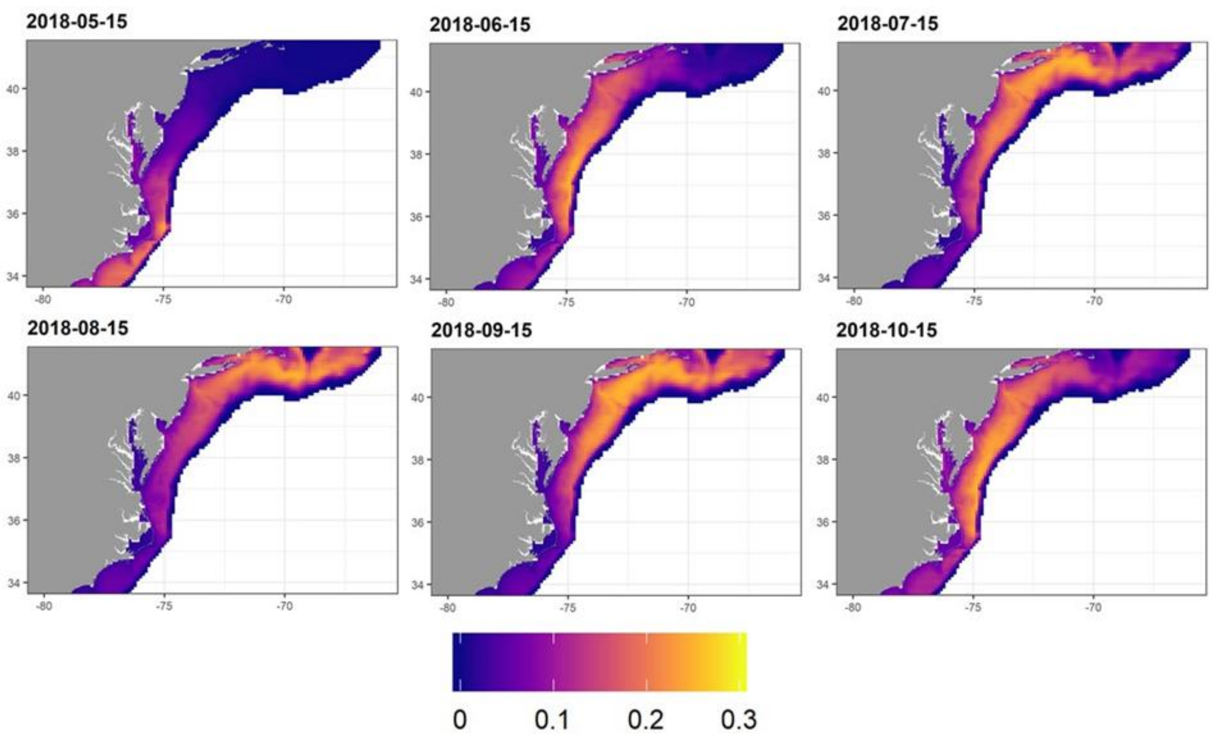


Figure 5: *Examples of probability of turtle presence in the NW Atlantic for loggerheads based on historical SST, loggerhead locations and depth as determined by the fitted model. Yellow is the highest probability of turtle presence and dark purple is the lowest.*

presence in the MAB in addition to temperature and depth. However, the current best approach for projecting habitat change is through temperature, which will impact both loggerheads and their prey resources.

Using climate change model CM2.6, we projected that the probability of presence for loggerheads in the NW Atlantic will expand from the historical May – October season, to an April – December season within 20 – 60 years (**Figure 6**). Based on temperature and depth alone, we projected that loggerheads could not only continue to forage in the MAB, SNE and GB, but that they will likely remain within these regions beyond the historical season (**Figure 7**). Additionally, with the northern regions (SNE and GB) having expanded seasons of warmer temperatures, we expect loggerheads to more readily venture into these waters and stay longer. This would likely require changing many fisheries regulations. For example, the scallop fishery requires the use of Turtle Deflector Dredges (TDD) from May 1 – Nov 30 in areas west of -71° longitude due to a historically high bycatch of loggerheads (Murray 2011; Smolowitz et al. 2012). If turtles become longer-term residents of the MAB, and their potential of being caught in a dredge remains equal throughout the year, then the regulation would likely need to be changed to accommodate for this shift in loggerhead seasonality.

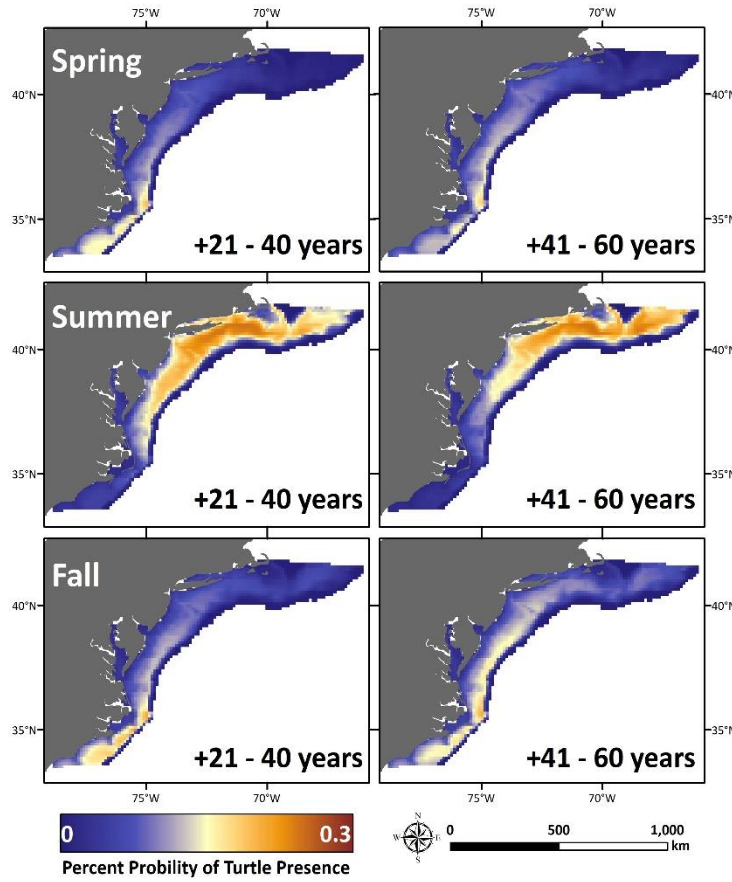


Figure 6: *Projections of probability of turtle presence within the NW Atlantic during Spring, Summer and Fall. Full sets of seasonal probability maps from observed data and CM2.6 model can be found in* ***Appendix 1****.*

In the past ten years of observed data, we have already started to notice a subtle trend of turtles remaining within the MAB during months outside of the TDD requirements (**Figure 8**). Furthermore, if the more northern habitats, SNE and GB, become utilized more regularly by loggerheads, the spatial requirements for the TDD will also likely need to be expanded north and east. The scallop fishery may be one of the least negatively impacted by this shift in loggerhead habitat usage, as the fishery already has in-use many gear modifications to maintain high scallop

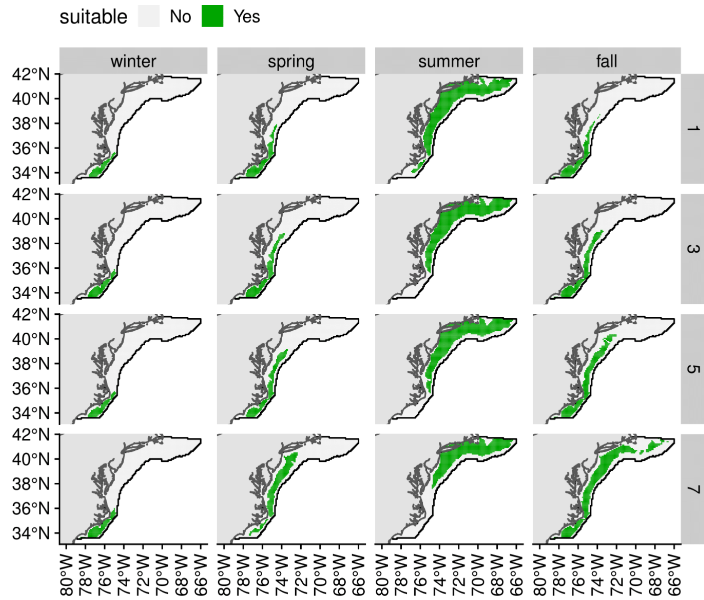


__Figure 7:__ Simplified habitat suitability projections for each season and a subset of future decades (decade on the right of each map set).

catch and limit deadly interactions with turtles. Fisheries like pelagic long lines and gillnets, however, will likely see a substantial uptick in bycatch if management doesn't adjust to these projected environmental changes. In both of these fisheries, in response to protected species bycatch, seasonal and area closures can last years and may be prompted within the fishing season (Murray 2009; Swimmer et al. 2017). As mentioned previously, in the Pacific, to avoid loggerhead bycatch, a program called TurtleWatch was created to continuously update pelagic long line fishers of the locations of SST bands most likely to have turtles present. While TurtleWatch is based on the temperature ranges with the highest percentage of fisheries interactions with loggerheads, our model is based on the temperatures and depths with the highest probability of turtles present based on satellite telemetry data. In our scenario, we are assuming that if more turtles are present, the likelihood of fisheries interactions will increase. Swimmer et al. (2017) identified that loggerheads in the NW Atlantic were most often caught in long lines when SST ranged between 22° - 27° C and hooks were set shallower than 50 m depth. Our model found that turtle presence is likeliest in waters that reach 50 m, and SST is ~22°C. Gillnet bycatch occurred within a much broader range of SST (8.6° – 27.8°C), with a slightly higher likelihood across a

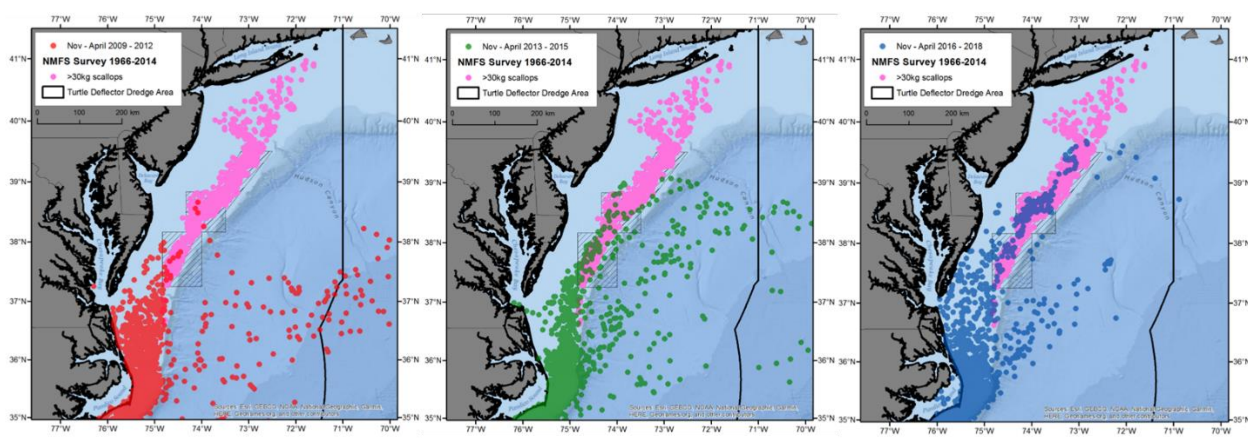


__Figure 8:__ Loggerhead locations (red, green and blue dots) between Nov through April overlaid on NOAA fisheries survey locations (1966 – 2014) with >30kg scallops caught (pink dots). Left map is locations from 2009 – 2012, center map is locations from 2013 – 2015, right map is locations from 2016 – 2018.

broader spatial range in warmer temperatures (Murray 2009). This again matches well with our loggerhead presence data, as they tend to be more broadly distributed within the MAB during the warmer months. This similar representation of loggerhead distribution in the MAB based on both fisheries-dependent and fisheries-independent surveys has been confirmed by Murray and Orphanides (2013).

Conclusions

Temperature and depth explained 20% of the variability in location for satellite tagged loggerheads within the MAB. Specifically, turtle presence was most likely associated with SST ranging between ~15° - ~28° C and at depths between 10 – 90 m. Based on the GFDL CM2.6 climate model, this temperature range is expected to occur further north throughout a larger portion of the year. Using this combined information, within the next 20 – 60 years, we projected that loggerhead probability of presence will increase further north outside of the traditional May – Oct foraging months. Specifically, we projected that loggerheads will likely enter the MAB in April, migrate north, and have increased presence in SNE and GB before returning south in December. From January – March, we projected minimal presence of loggerheads within the MAB, SNE and GB, nearly identical to the historical data. Fisheries bycatch of sea turtles was particularly high within these temperature ranges, indicating that loggerhead susceptibility to being caught in fishing gear will remain unchanged as they shift habitat range and seasonality. Furthermore, as currently the expectations of catching sea turtles for many of the fisheries in SNE and GB are extremely low, few tools exist for these fisheries to accommodate to a shift in loggerhead habitat usage. As a result, both fisheries and management will quickly need to develop strategies to reduce sea turtle interactions as the regions' climate warms.

Dissemination of Project Results

Project results have been disseminated through grant reports and on the CFF website, and will be highlighted through social media (Twitter, Instagram, and Facebook). A copy of the final report will be sent to the Northeast Fisheries Management Council and Mid-Atlantic Fisheries Management Council, and we will present results at relevant council meetings upon request and scientific conferences. We intend to publish the results of the project in a peer-reviewed journal to reach a wider audience.

Literature Cited

Ceriani SA, Roth JD, Evans DR, Weishampel JF, Ehrhart LM. 2012. Inferring foraging areas of nesting loggerhead turtles using satellite telemetry and stable isotopes. PLoS One. 7(9):e45335.

Crouse D, Crowder L, Caswell H. 1987. A stage-based population model for loggerhead sea turtles and implications for conservation. Ecology 68: 1412-1423.

Epperly SP, 2003. Fisheries-related mortality and turtle excluder devices (TEDs). The biology of sea turtles, 2: 339-353.

Griffin LP, Griffin CR, Finn JT, Prescott RL, Faherty M, Still BM, Danylchuk AJ. 2019. Warming seas increase cold-stunning events for Kemp's ridley sea turtles in the northwest Atlantic. PloS one. 14(1):e0211503.

Griffin DB, Murphy SR, Frick MG, Broderick AC, Coker JW, Coyne MS, Dodd MG, Godfrey MH, Godley BJ, Hawkes LA, Murphy TM. 2013. Foraging habitats and migration corridors utilized by a recovering subpopulation of adult female loggerhead sea turtles: implications for conservation. Marine biology. 160(12): 3071-86.

Hawkes LA, Broderick AC, Coyne MS, Godfrey MH, Godley BJ, 2007. Only some like it hot—quantifying the environmental niche of the loggerhead sea turtle. Diversity and distributions 13(4): 447-457.

Hawkes LA, Witt MJ, Broderick AC, Coker JW, Coyne MS, Dodd M, Frick MG, Godfrey MH, Griffin DB, Murphy SR, Murphy TM. 2011. Home on the range: spatial ecology of loggerhead turtles in Atlantic waters of the USA. Diversity and Distributions. 17(4):624-40.

Hazen EL, Jorgensen S, Rykaczewski RR, Bograd SJ, Foley DG, Jonsen ID, et al. 2013. Predicted habitat shifts of Pacific top predators in a changing climate. Nature Climate Change 3(3): 234-238.

Howell EA, Kobayashi DR, Parker DM, Balazs GH, Polovina JJ. 2008. TurtleWatch: a tool to aid in the bycatch reduction of loggerhead turtles *Caretta caretta* in the Hawaii-based pelagic longline fishery. Endangered Species Research. 5(2-3): 267-78.

Lindgren F, Rue H, Lindström J. 2011. An explicit link between Gaussian fields and Gaussian Markov random fields: the stochastic partial differential equation approach. Journal of the Royal Statistical Society Series B 73: 423-498.

Mansfield KL, Saba VS, Keinath JA, Musick JA. 2009. Satellite tracking reveals a dichotomy in migration strategies among juvenile loggerhead turtles in the Northwest Atlantic. Marine Biology 156: 2555–2570.

Murray KT. 2009. Characteristics and magnitude of sea turtle bycatch in US mid-Atlantic gillnet gear. Endangered Species Research. 8(3): 211-24.

Murray KT. 2011. Interactions between sea turtles and dredge gear in the US sea scallop (*Placopecten magellanicus*) fishery, 2001–2008. Fisheries Research. 107(1-3): 137-46.

Murray KT, Orphanides CD. 2013. Estimating the risk of loggerhead turtle Caretta caretta bycatch in the US mid-Atlantic using fishery-independent and-dependent data. Marine Ecology Progress Series. 477: 259-70.

Richardson A. 2008 In hot water: zooplankton and climate change. ICES Journal of Marine Science 65: 279 – 295.

Saba VS, Griffies SM, Anderson WG, Winton M, Alexander MA, Delworth TL, et al. 2016. Enhanced warming of the Northwest Atlantic Ocean under climate change. Journal of Geophysical Research: Oceans 121: 118-132.

Species at Risk Act. 2017. Threat Assessment for loggerhead sea turtle (*Caretta caretta*), Northwest Atlantic Population. Canada Division of Fisheries and Oceans.

Smolowitz R, Milliken HO, Weeks M. 2012. Design, evolution, and assessment of a sea turtle deflector dredge for the US Northwest Atlantic sea scallop fishery: impacts on fish bycatch. North American journal of fisheries management. 32(1): 65-76.

Smolowitz R, Patel S, Haas H, Miller S. 2015. Using a remotely operated vehicle (ROV) to observe loggerhead sea turtle (*Caretta caretta*) behavior on foraging grounds off the mid-Atlantic United States. Journal of Experimental Marine Biology and Ecology 471: 84 – 91.

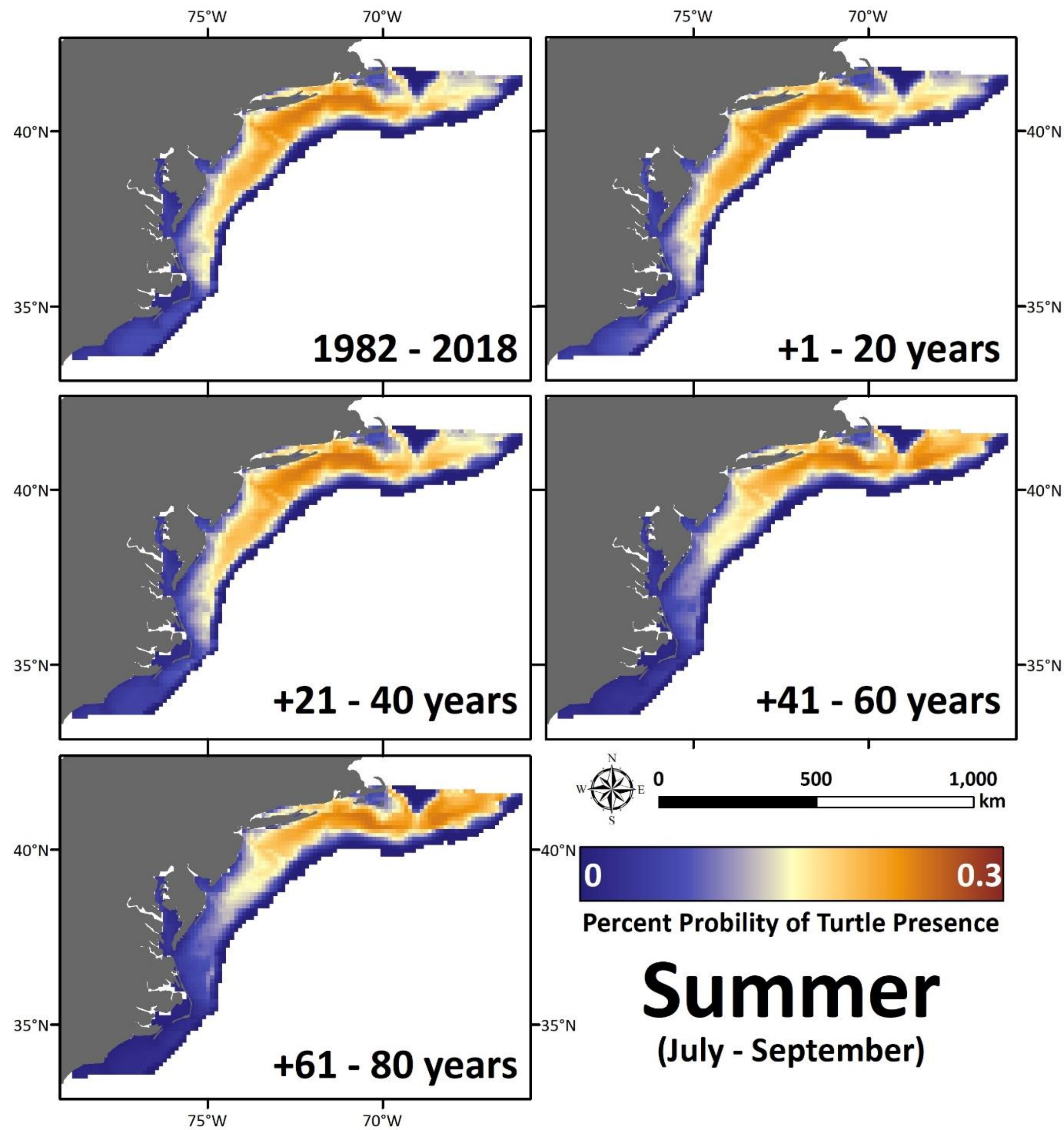
Swimmer Y, Gutierrez A, Bigelow K, Barceló C, Schroeder B, Keene K, Shattenkirk K, Foster DG. 2017. Sea turtle bycatch mitigation in US longline fisheries. Frontiers in Marine Science. 4:260.

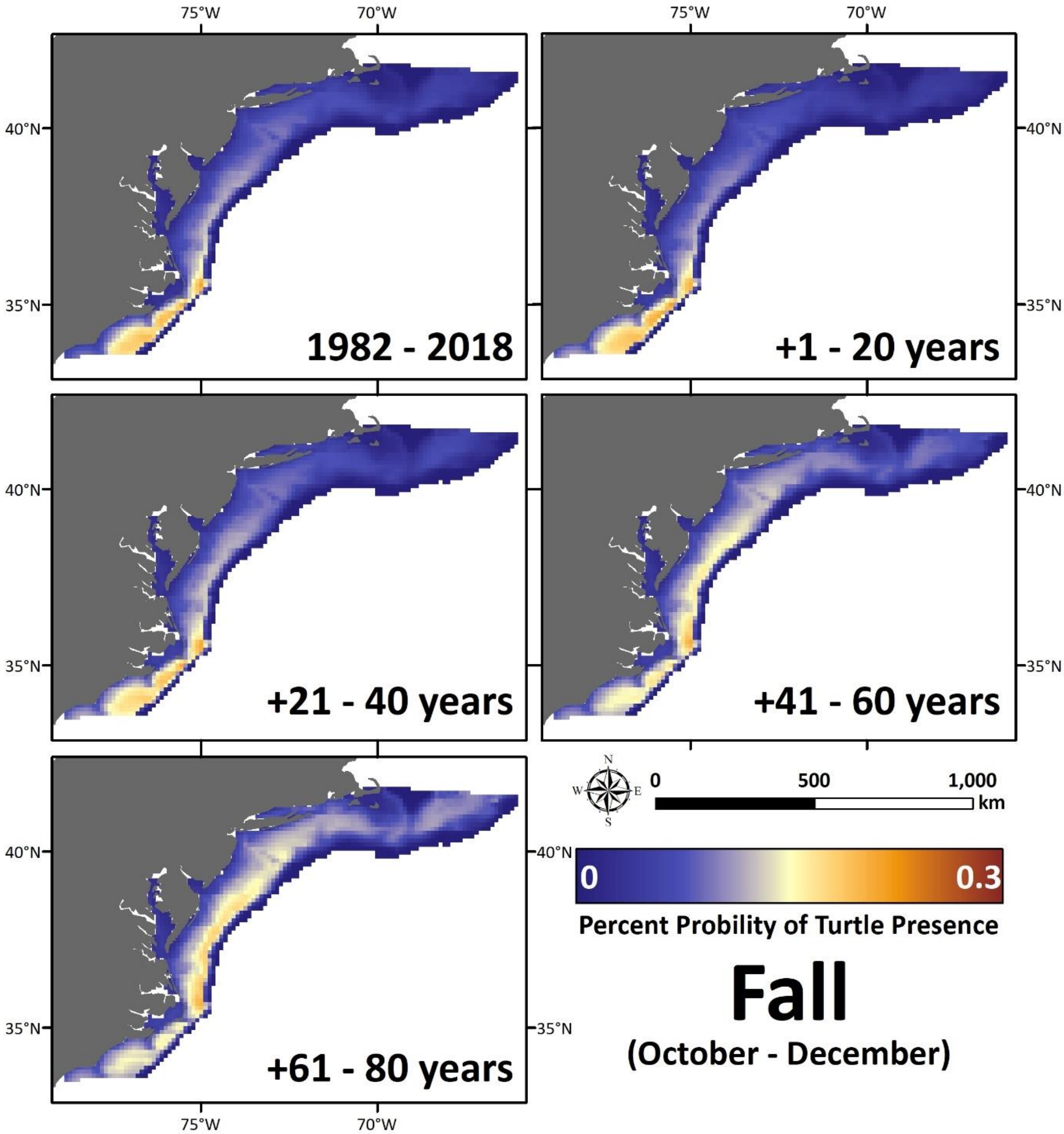
Thorson JT, Jannot J, Somers K. 2017. Using spatio-temporal models of population growth and movement to monitor overlap between human impacts and fish populations. Journal of Applied Ecology 54(2): 577-587.

Winton MV, Fay G, Haas HL, Arendt M, Barco S, James MC, Sasso C, Smolowitz R. 2018. Estimating the distribution and relative density of satellite-tagged loggerhead sea turtles using geostatistical mixed effects models. Marine Ecology Progress Series. 586: 217-32.

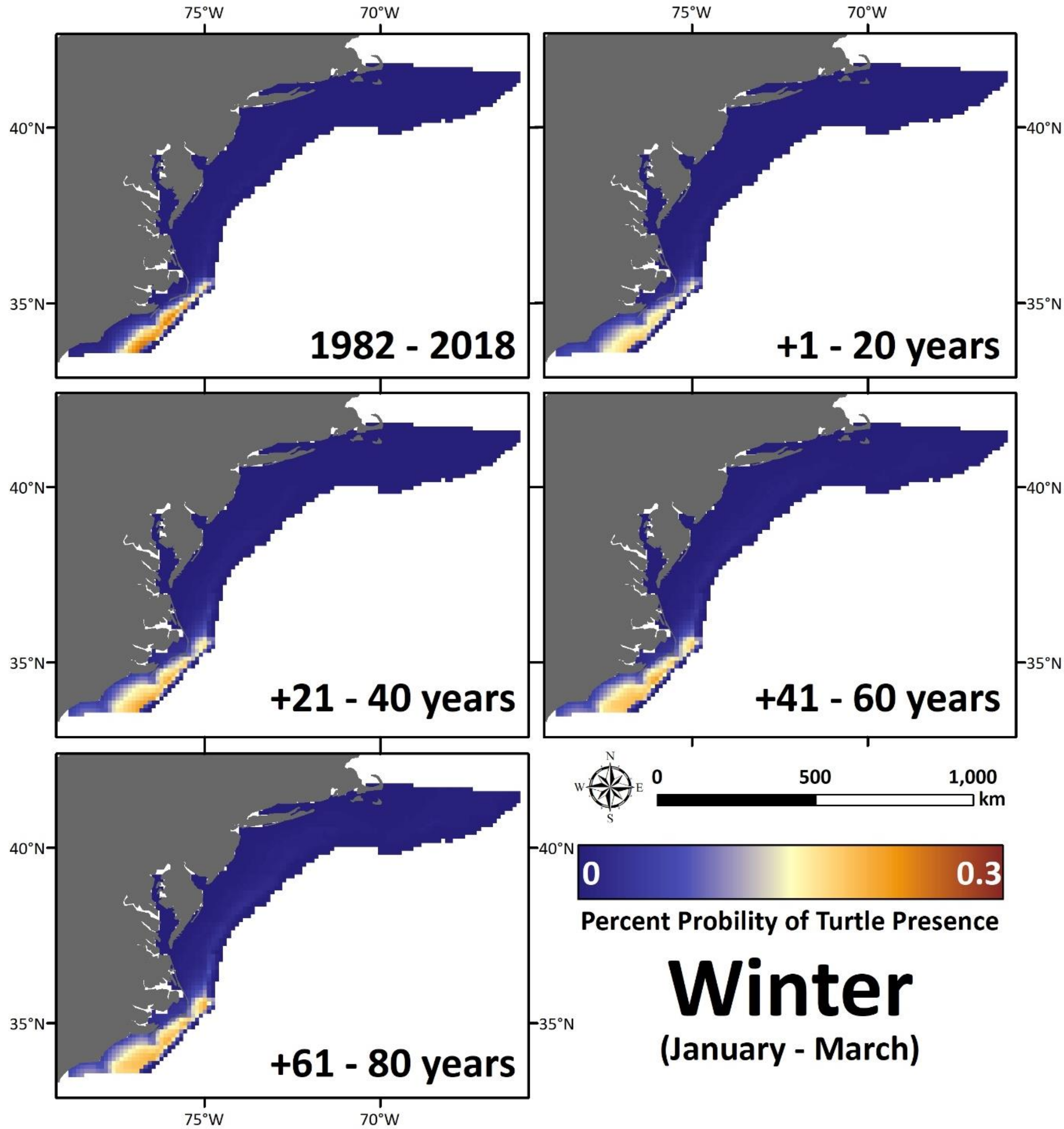
Witt MJ, Hawkes LA, Godfrey MH, Godley BJ, Broderick AC. 2010. Predicting the impacts of climate change on a globally distributed species: the case of the loggerhead turtle. Journal of Experimental Biology 213: 901 – 911.

Appendix 1: Seasonal maps of probability of turtle presence based on observed data and projected using the CM2.6 model.

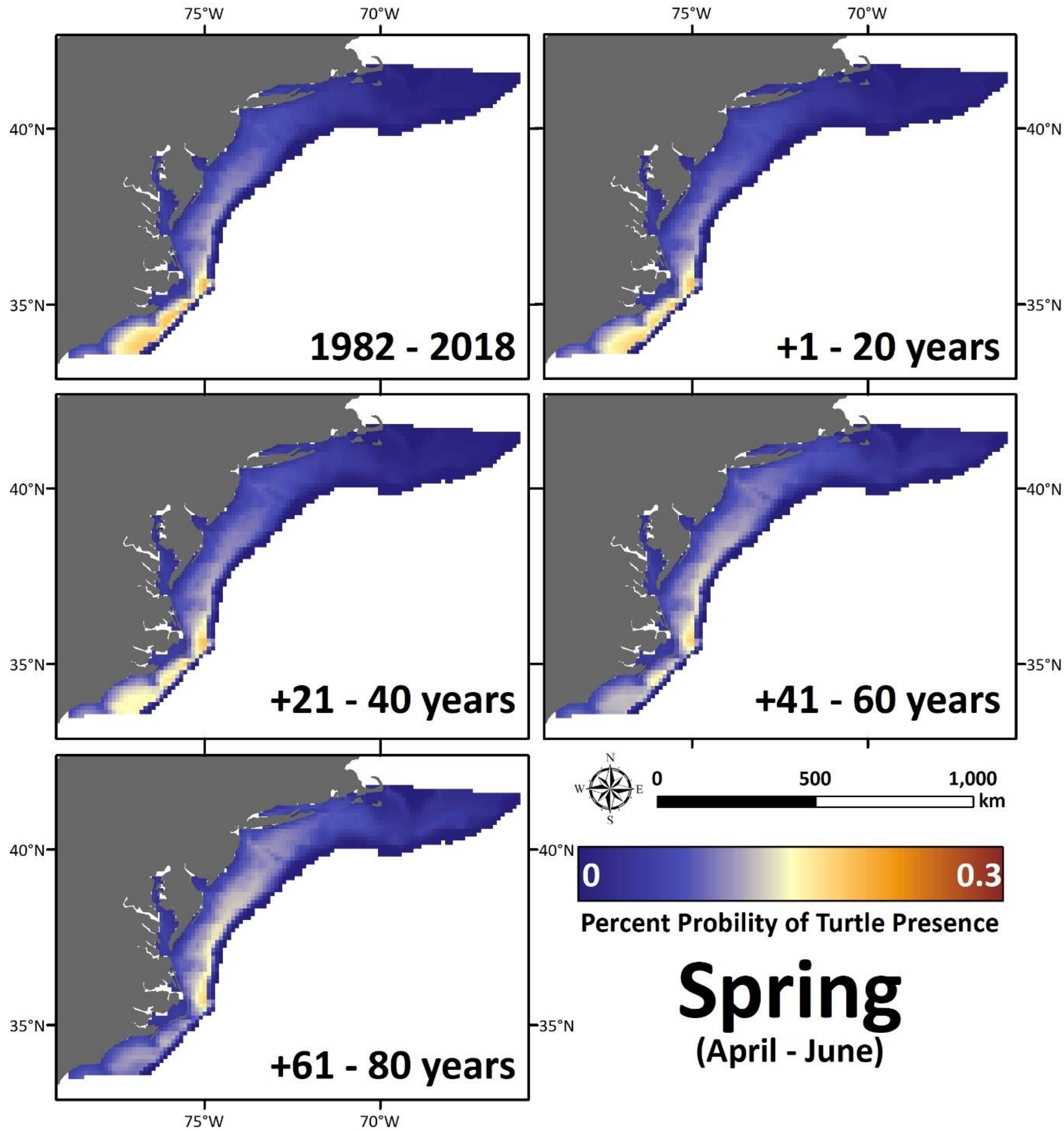




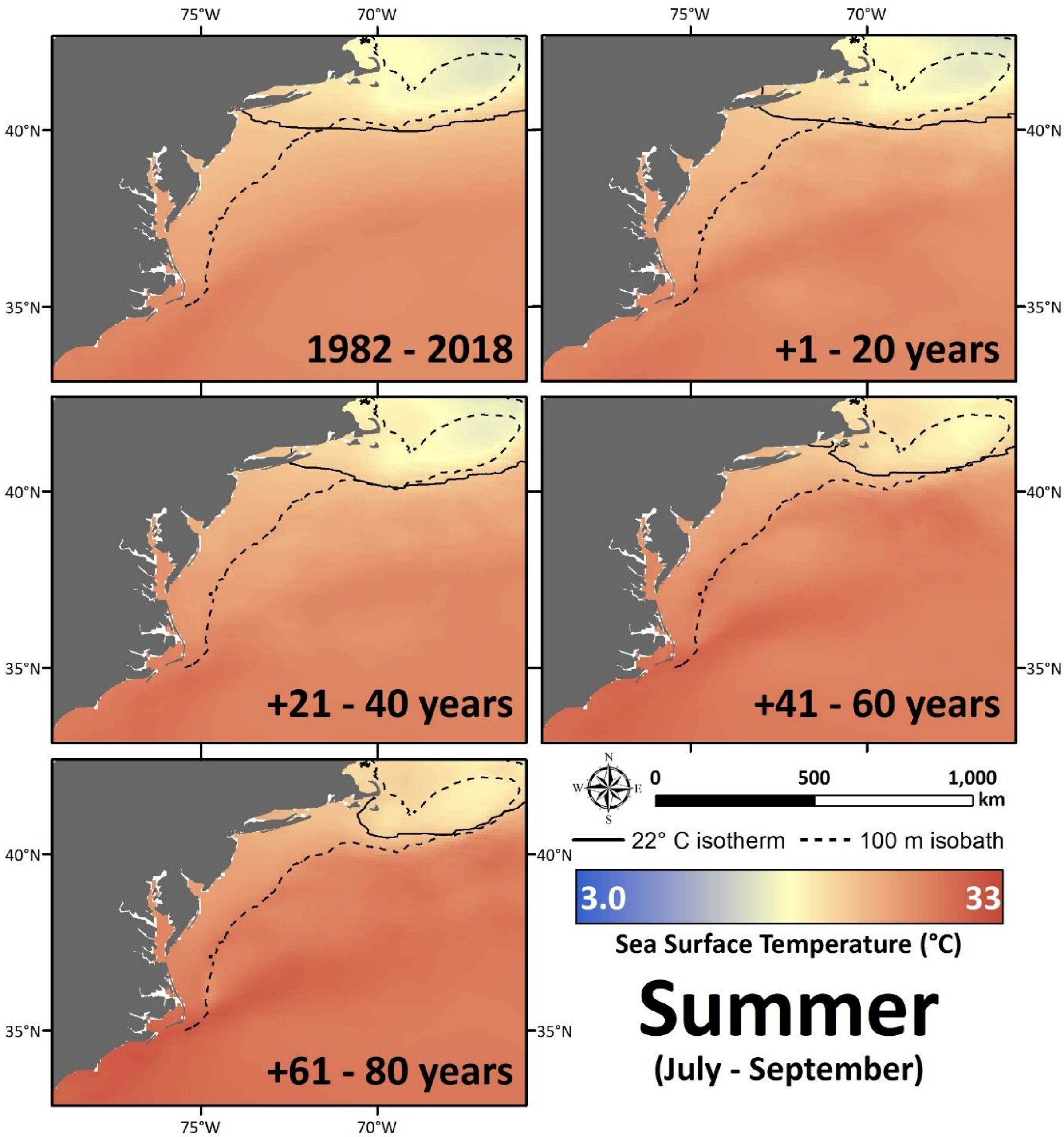
75°W
70°W
40°N
35°N
1982 - 2018
+1 - 20 years
+21 - 40 years
+41 - 60 years
+61 - 80 years
N
S
E
W
0
500
1,000
km
0
0.3
Percent Probility of Turtle Presence
Fall
(October - December)

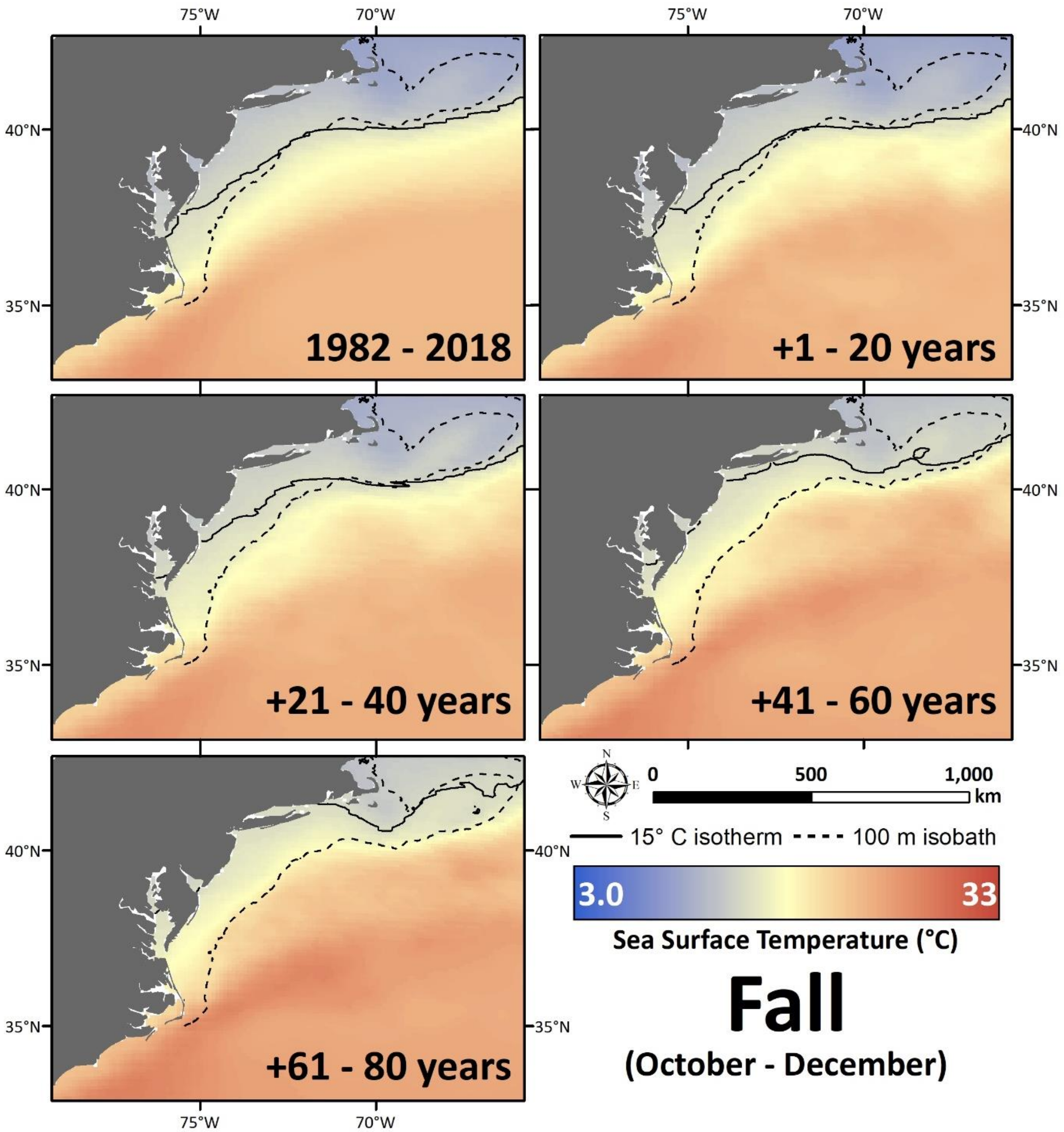


75°W
70°W
40°N
35°N
1982 - 2018
+1 - 20 years
+21 - 40 years
+41 - 60 years
+61 - 80 years
N
S
E
W
0
500
1,000
km
0
0.3
Percent Probility of Turtle Presence
Winter
(January - March)

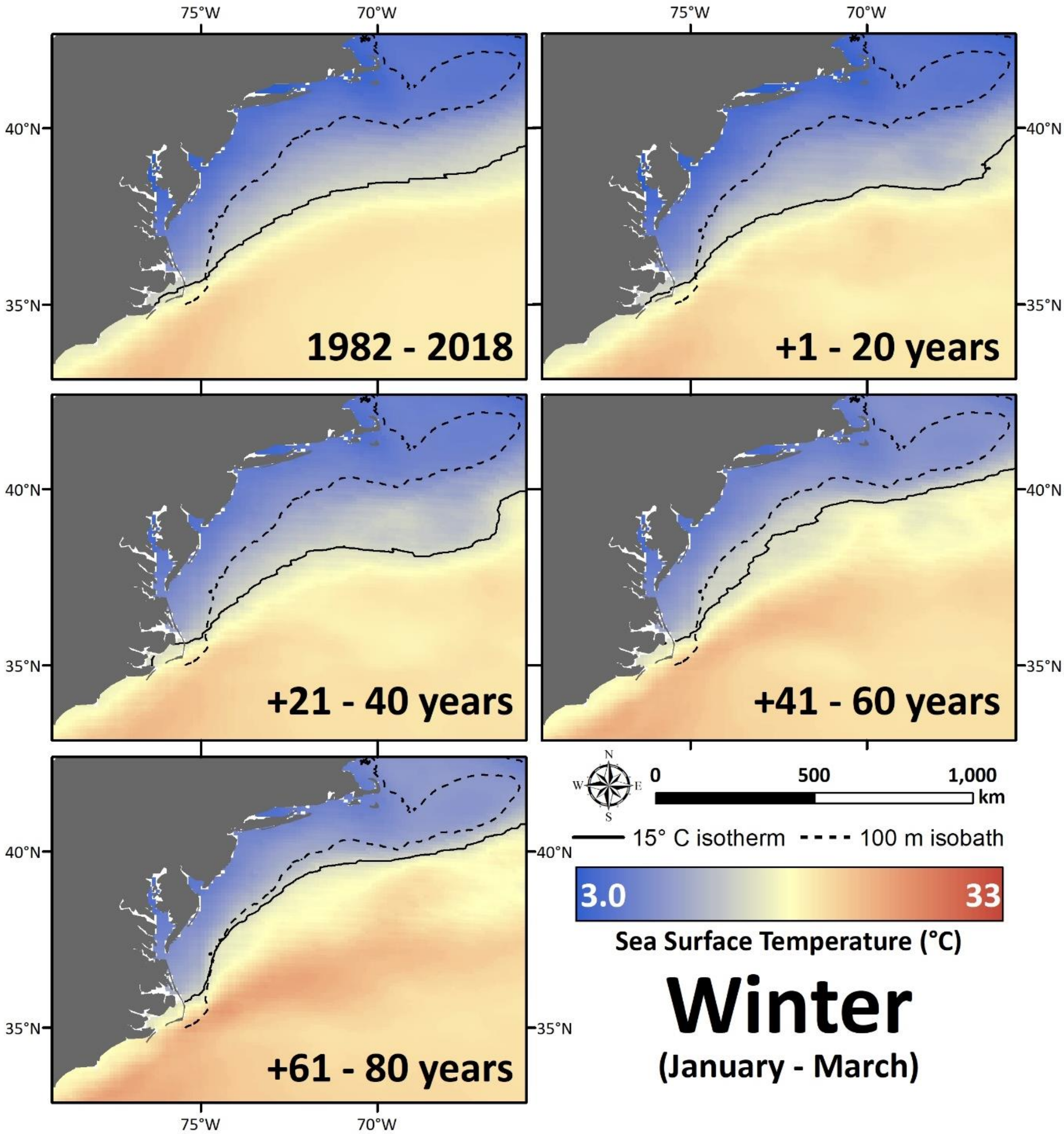

75°W
70°W
40°N
35°N
1982 - 2018
+1 - 20 years
+21 - 40 years
+41 - 60 years
+61 - 80 years
N
W
E
S
0
500
1,000
km
0
0.3
Percent Probility of Turtle Presence
Spring
(April - June)

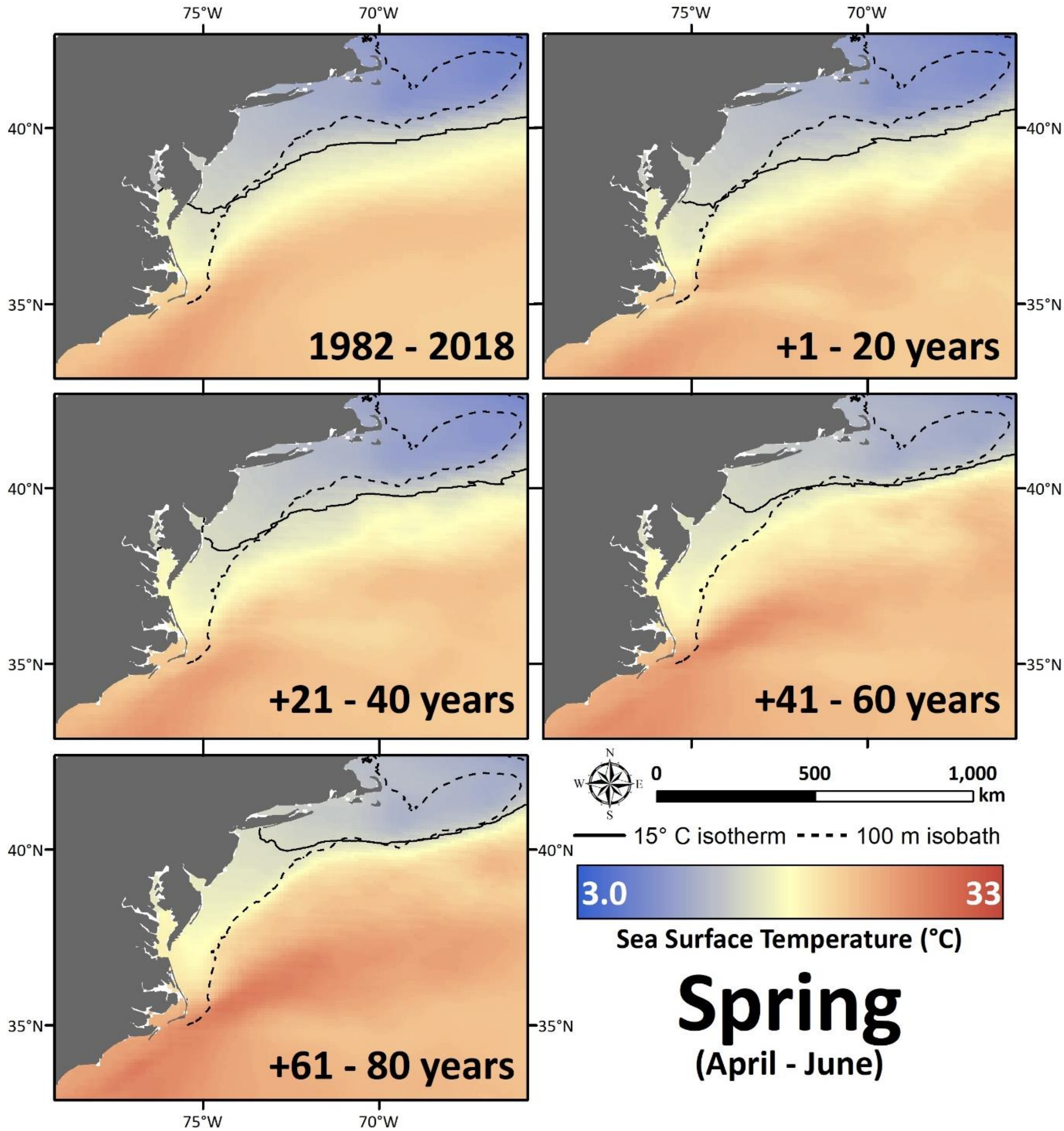
Appendix 2: Seasonal maps of historical and projected SST.





75°W
70°W
40°N
35°N
1982 - 2018
+1 - 20 years
+21 - 40 years
+41 - 60 years
+61 - 80 years
N
S
W
E
0
500
1,000
km
15° C isotherm
100 m isobath
3.0
33
Sea Surface Temperature (°C)
Fall
(October - December)


75°W
70°W
40°N
35°N
1982 - 2018
+1 - 20 years
+21 - 40 years
+41 - 60 years
+61 - 80 years
N
S
W
E
0
500
1,000
km
15° C isotherm
100 m isobath
3.0
33
Sea Surface Temperature (°C)
Winter
(January - March)


75°W
70°W
40°N
35°N
1982 - 2018
+1 - 20 years
+21 - 40 years
+41 - 60 years
+61 - 80 years
N
S
E
W
0
500
1,000
km
15° C isotherm
100 m isobath
3.0
33
Sea Surface Temperature (°C)
Spring
(April - June)

Appendix 3: Dockside flyer to demonstrate to fishermen the projected changes in loggerhead presence within the NW Atlantic.

Loggerhead sea turtles are a protected species integral to the health of the oceans.

Currently, from May – October, loggerheads are common in the Mid-Atlantic Bight.

Due to climate change, within 20 – 60 years, loggerhead probability of presence is projected to increase within the region from April – December.