

# Chapter 24: Using state-space models to identify areas of persistent winter activity and their associated environmental covariates in Northern Gannets

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## Chapter 24 Highlights

*Using telemetry data to determine environmental drivers of foraging activity in Northern Gannets*

### **Context<sup>1</sup>**

The project team investigated the spatial patterns, temporal patterns, and environmental variation in offshore bird migration and winter habitat use through a combination of satellite telemetry data and remotely collected environmental covariate information. Northern Gannet telemetry data are analyzed in three chapters: Chapter 22 (focused on wintering habitat use of Northern Gannets in the mid-Atlantic), Chapter 23 (inclusion of a temporal component in models of habitat use, to improve our understanding of the species' use of the landscape through time), and this chapter, which is focused on individual-scale movements and foraging patterns. Northern Gannet interactions with offshore wind energy development are hypothesized to largely occur as a result of their foraging behaviors, which include a large proportion of time spent soaring at or near the altitude of the rotor-sweep zone for offshore wind turbines. Being able to differentiate between foraging and other behaviors in telemetry data will allow us to better determine areas of potential conflict between offshore wind energy development and Northern Gannet habitat use, and could inform the siting and permitting of offshore wind energy development.

### **Study goal/objectives**

Identify the locations of foraging Northern Gannets during the non-breeding season, and determine how bathymetry and sea surface temperature fronts are related to these patterns.

### **Highlights**

- Used satellite tracking data in a state-space model to describe locations where Northern Gannets were conducting foraging behavior in the mid-Atlantic.
- Foraging locations were more common in and around bays, but tended to be in deeper areas.
- The number of nearby sea surface temperature fronts in the week prior to a Northern Gannet observation was the strongest predictor of foraging behavior. As the number of fronts in the area increased, so did the chances of foraging. These fronts are likely aggregating food for Northern Gannets.
- Coastal sea surface temperature fronts showed both annual and daily variability. To predict locations of gannet foraging activity in the future, we will need to be able predict the locations of these fronts.

### **Implications**

Predictions of the effects of offshore wind energy development on Northern Gannets in the mid-Atlantic must consider exposure (e.g., whether they are present in an area in large numbers) as well as whether they are foraging in the area. Within their range, gannets are preferentially foraging in deeper waters with high numbers of temperature fronts. Sea surface temperature front locations change on a daily and annual basis, and exposure to offshore development activities may vary at those same scales.

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<sup>1</sup> For more detailed context for this chapter, please see the introduction to Part V of this report.

## Abstract

Satellite telemetry data provide an understanding of the spatial ecology as well as the individual movement behavior of birds. In seabird ecology, movement behavior can be an indicator of whether an animal is foraging at a location and even what kind of prey the animal is pursuing. In this study, we used three years (2012 – 2014) of satellite telemetry data from Northern Gannets (*Morus bassanus*) wintering on the Atlantic coast of North America to build a state-space model in the Bayesian modeling environment. This model was designed to: (1) use all telemetry data acquired to determine the most likely daily position of an individual, and (2) employ a correlated random walk model with a behavioral switching component to identify whether a given location was part of a transient or stationary behavioral pattern. The objective was to identify areas where gannets are likely to be foraging (i.e. conducting area restricted searching, or ARS), and determine the environmental covariates that were associated with that behavior.

Using data from 34 individuals tracked over three winters, positions were classified as foraging behavior 67% of the time. ARS locations were associated with deeper water and locations with persistent sea surface temperature fronts, suggesting that both static and dynamic environmental variables can influence foraging behavior. These behavioral – environmental associations are likely related to increased prey availability. Movement behavior was highly variable among individuals, with some birds moving over long distances, while others focusing on foraging at a single site. Given the strong relationship between temperature fronts and Northern Gannet foraging behavior, accurate projections of ocean temperatures and fronts with climate change will be critical to successfully predicting the locations of Northern Gannet foraging activity.

## Introduction

Understanding animal associations with dynamic environmental conditions is an important behavioral and ecological concern (Nathan 2008), and these relationships can be difficult to quantify in marine environments (Weimerskirch 2007). There are some known general distributional patterns, such as greater abundance in nearshore areas, and greater productivity in estuaries and upwellings (Small and Menzies 1981), but spatial and temporal variance at small spatial scales and short temporal scales can also alter animal distributions and behavior and are not as well understood. Water temperature likely influences animal distributions in several ways. Many marine animal distributions are strongly limited by temperature because ectothermic species like fishes and sea turtles cannot function outside of a given temperature range (Houde 1989, Portner 2001). Changes in ocean temperature can also affect distributions more indirectly, as sea surface temperature (SST) fronts, or abrupt thermal gradients, are mechanisms for generating currents that can aggregate plankton and other passively propelled marine life (Bost et al. 2009), which in turn can aggregate species at higher trophic levels (Benoit-Bird and McManus 2012, Woodson and Litvin 2015). Because ocean temperature can change over multiple temporal scales, it plays a large role in determining the dynamism we see in marine predator behavior and distribution.

Seabirds are adapted to this environmental dynamism and have developed behavioral strategies to deal with the issues of highly clustered and volatile foraging opportunities (Weimerskirch 2007, Miramontes et al. 2012), including methods to predict the occurrence of prey (Pettex et al. 2010). Due to this, seabird foraging behaviors and population parameters have proven to be reliable indicators of prey distributions in the marine environment (Cairns 1987, Santora et al. 2009), and even can be diagnostic to prey species (Elliot et al. 2008). Many seabird species employ wide-area searches followed by area restricted search (ARS) patterns once a location with suitable foraging opportunities is identified (Weimerskirch et al. 2007, Hamer et al. 2009, Pavia et al. 2010). Thus, seabird foraging activity can indicate areas of high prey abundance.

Satellite telemetry provides opportunity to understand the space use and movement behavior of seabirds at scales useful for elucidating relationships with dynamic environmental conditions (Camphuysen et al. 2012). Analytical approaches have been developed to translate spatial information into an understanding of rules that govern the movement of individuals. For example, sequential position data can be used in a correlated random walk model in a Bayesian state-space modeling framework (Jonsen et al. 2003, 2005, 2006, 2007, Patterson et al. 2008). In these models, vector velocity and direction dictates movement from one point to the next. By using more complex correlated random walk models that allow the individual to switch among different behavioral patterns, we can identify how that animal is using marine habitats for different purposes (Jonsen et al. 2007). For example, a bird employing ARS foraging behaviors would be expected to show a high turn rate and little forward movement, as they try to use a limited amount of space in the ocean to maximize foraging success (Hamer et al. 2009, Pavia et al. 2010).

For a seabird species like the Northern Gannet (*Morus bassanus*), foraging behavior is also related to anthropogenic development and activity in the marine environment. Northern Gannet interactions with

offshore wind energy development are hypothesized to largely occur as a result of their foraging behaviors, which include a large proportion of time spent soaring at or near the altitude of the rotor-swept zone of offshore wind turbines (Garthe et al. 2000, Langston 2010, Johnston et al. 2014). These interactions have been suggested to include collision risk during foraging (e.g., Furness et al. 2013, Johnston et al. 2014), though such has not been observed to date. However, displacement or avoidance behaviors have been observed in this species at several offshore wind energy facilities in Europe (Lindeboom et al. 2011, Vanermen et al. 2014). Being able to differentiate between foraging and other behaviors will allow better determinations of areas of potential conflict between offshore wind energy development and Northern Gannet habitat use, and could inform the siting and permitting of offshore wind energy development.

The objectives of this study are 1) to determine how Northern Gannets use marine habitat during the non-breeding season and 2) identify the environmental conditions associated with changes in an individual's movement strategy. Using positional data from satellite transmitters deployed on Northern Gannets during the nonbreeding season, we used a behavioral state switching state-space model (SSSM) in a Bayesian modeling framework to identify when these seabirds were employing ARS foraging behavior versus transient behavior in the mid-Atlantic U.S. This analysis provides information on locations that are consistently used by Northern Gannets for foraging, and the habitat characteristics (e.g., water depth, SST front density) that define these foraging areas. Understanding marine habitat most important to foraging Northern Gannets will provide key conservation information for the species, and better inform species distribution models as well as marine spatial planning.

## Methods

Satellite transmitters were deployed on Northern Gannets in the winters of 2012-14 at several locations in the mid-Atlantic U.S., as well as in autumn 2012 at a breeding colony in Canada (Chapter 22). We include a third year of data (2014 deployments) that are not included in Chapter 22, which were funded by the Bureau of Ocean Energy Management (BOEM) as part of the project, *Determining Offshore Use of Diving Bird Species in Federal Waters of the Mid-Atlantic United States Using Satellite Tracking*.

### ***Satellite transmitter deployment***

We deployed 55 satellite transmitters on Northern Gannets at several locations. These techniques are described in detail in Chapter 22. Most individuals were captured on the wintering grounds in the mid-Atlantic, using a night-lighting technique in which birds were approached at night in a small vessel, briefly disoriented with a spotlight, then captured with a dip net. A metal USGS bird band was attached and morphometric measures were taken. Northern Gannets were also captured at a breeding colony in Newfoundland during the fledging period, using a telescoping noose pole. Individuals captured at this location were given a USFWS metal band.

Satellite transmitters were deployed either by external attachment or internal implantation. At the breeding colony, transmitters were attached by tape to the underside of the central retrices of nine birds (Chapter 22). On the wintering grounds, transmitters were either taped as above at the capture location (n=3 in 2011-12) or were surgically implanted in the abdominal cavity by a veterinarian onshore

(n=3 in 2011-12, n=20 in 2013, n=20 in 2014). After being cleared by the veterinarian, birds were released on the water the following morning.

Two different duty cycles were used during the winter period. The tail-mounted transmitters were set to be on for 4 hours then off for 9, while the implanted transmitters were on for 4 hours and off for 13. Tail-taped transmitters were expected to not last as long as implanted devices and so we increased the data collection period per day trading finer temporal scale for decreased battery life. Satellite transmitter data were collected from the ARGOS service and included the estimated position of the individual and the quality of that positional estimate (ranked in qualitative categories). The beginning and end of winter were defined by assessing each individual track for rapid transient movements to or from the breeding grounds. Once each bird stopped making such long distance flights, the winter period was said to begin.

### ***State-space modeling***

Using the raw position data from 30 of the satellite transmitters (not all deployed transmitters collected useful data during the winter), including three tail-mounted and 31 implanted transmitters, we parameterized a SSSM to predict movement behavior and daily position. Two main components of the state-space model include a first order correlated random walk with a behavioral state switching function that describes the overall movement pattern of the animal, and a positional estimation model that gives the most likely daily location for the animal. This analysis is modeled after similar work with marine mammals that was effective at determining the most likely position of the animal and identifying periods where the animal was exhibiting foraging behavior versus transiting behavior (Jonsen et al. 2007). Here we predefined two behavioral states: (1) an ARS state where spatial autocorrelation is high, turning angle is high and distance traveled is low, and (2) a transient state where spatial autocorrelation is low, turning rate is low and distance traveled is high. While more details are provided in Jonsen et al. (2007), we briefly describe how this type of model works. The movement behavior portion of the model is described by a switching correlated random walk:

$$\mathbf{d}_t \sim N_2[\gamma_{bt} \mathbf{T}(\theta_{bt}) \mathbf{d}_{t-1} \boldsymbol{\Sigma}]$$

Where,  $\mathbf{d}_t$  is the difference between locations  $x_t$  and  $x_{t-1}$ ,  $\mathbf{d}_{t-1}$  is the difference between locations  $x_{t-1}$  and  $x_{t-2}$ ,  $\mathbf{T}(\theta)$  is a transition matrix that provides the rotational component ( $\vartheta$ ) required to move from  $\mathbf{d}_{t-1}$  to  $\mathbf{d}_t$ , where  $\theta$  is the mean turning angle, and  $N_2$  is a bivariate Gaussian distribution with the covariance matrix  $\boldsymbol{\Sigma}$ , with  $\gamma$  controlling variability in the autocorrelation of direction and speed. The subscript  $b$  designates which behavioral state the animal is currently using (in this case, either ARS or transient) and the subscript  $t$  designates the time step. This model is based on our estimates of position from this equation:

$$\mathbf{y}_{t,i} = (1 - j_i)x_{t-1} + j_i x_t + \boldsymbol{\varepsilon}_t$$

Where,  $\mathbf{y}_{t,i}$  is the  $i$ th observed position during the time interval  $t-1$  to  $t$ ,  $j_i$  is the fraction of time spent at the location for the  $i$ th observation, and  $\boldsymbol{\varepsilon}_t$  is a random variable representing the error involved in estimating the positions of the individuals using Doppler-based satellite telemetry.

This model was fit using a Bayesian hierarchical framework using JAGS (Just Another Gibbs Sampler; [mcmc-jags.sourceforge.net](http://mcmc-jags.sourceforge.net)) and package ‘rjags’ in the R Statistical Computing Environment (R Core Team 2015). To achieve convergence, we ran the model in adaptive mode for 200,000 iterations, ran a 100,000 iteration burn-in, then analyzed the last 100,000 iterations, thinning one out of every five iterations to reduce autocorrelation, while monitoring three separate chains. We used visual evaluation and the Heidel test—a method for determining if sufficient model iterations had been run to achieve convergence for each parameter—to determine that chains were appropriately converging for each model and could be included in the next stage of analysis. In order to map the locations where individuals were exhibiting ARS or transient behavior, we mapped all points where that behavioral state was observed in greater than 75% of the model runs, then conducted a kernel density estimation (KDE) analysis in ArcGIS 10.3.1 (ESRI, Redlands, CA) to document the locations where many individuals expressed these behaviors. If the point did not meet those criteria then the behavioral state at that location was said to be uncertain. To control for the effect of variable individual sample sizes on KDE, we subsampled the data for each individual down to 20 total points (for individuals with fewer than 20 points we left their data as is) to generate an activity plot for each behavioral state over the mid-Atlantic portion of the study area.

### ***Deriving environmental covariates***

Water depth data was used from standard ocean bathymetry layers and sea surface temperature (SST) using the Marine Geospatial Ecology Tools (MGET<sup>2</sup>) in ArcGIS 10.3.1. SST was collected from the NASA JPL satellite across the globe. For each of the daily position estimates generated by the state-space model, we related both water depth and a daily SST values.

In addition to SST, we also used the NASA JPL dataset to import 1° Centigrade Cayula-Cornillon (1992) sea surface temperature fronts and then MGET to calculate Cayula-Cornillon SST fronts (an algorithm designed to identify 1° C in SST changes over space) across the entire study area for each day of the study. To make these more useful for our analysis, we created a composite raster (with 1.2 km<sup>2</sup> grid cells) for all the temperature fronts for the seven days around the day of interest. When a raster pixel was identified as having a front for one day in the study week it was assigned a score of one; if it was a front in two days, then it was assigned a score of two, etc. Finally, an equal weight spatial smoother was used such that each raster pixel was assigned the sum total of all the front scores in an 11 by 11 grid (149 km<sup>2</sup>). So, for each day, we smoothed the data over space and time to create a weekly SST front density variable that reduces the chance that strong fronts might not match perfectly with the satellite tracking data and to emphasize locations with consistent fronting.

### ***Correlates to gannet behavioral state***

Using the state-space model output of behavioral state, we specified a generalized linear mixed model to determine how behavioral state was influenced by environmental factors. First, we defined when the animal was in the ARS foraging state as any point where it was identified as such in at least 75% of the JAGS model runs. This was treated as a categorical variable, where all points that were defined as ARS were given a one, and all other points (both transient and uncertain) a zero. The model also accounts for

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<sup>2</sup> <https://code.env.duke.edu/projects/mget>

individual variation in behavioral state as a random variable, which creates a repeated measures analysis. Lastly, we added year (e.g., winter of 2011-12, 2012-13, or 2013-14), capture year (a categorical variable with two designations: First Winter, which are data from the winter of capture for birds caught at the wintering grounds and the winter after capture for birds caught at the breeding grounds; and Second Winter, which only applies to birds caught at the wintering grounds are data from the next full winter after the winter of capture), water depth, and sea surface front density to the model as fixed effects. We included capture location (a categorical variable that divided individuals into one of seven broad locations of capture on both the wintering and breeding grounds), attachment type (a binary categorical variable that covers the two attachment methods), and SST (a continuous variable) into early modeling efforts, but these variables were not found to improve model fit and were removed from the final model for clarity and to increase the precision of the model parameter estimates. This analysis was conducted using package “lme4” in the R Statistical Computing Environment (Bates et al. 2014). Confidence intervals of model coefficients were calculated using the “profile” method from this package.

## Results

### *Assessment of behavioral state*

Movement models from 30 individuals passed the convergence tests and were used in subsequent analyses. Among all 30 individuals, ARS behavior occurred 69% of the time, uncertain behavior 26% of the time, and transient behavior 5% of the time. Northern Gannets appeared to be utilizing local marine resources the majority of time during winter, punctuated by periods of transient behavior in which they made linear movements to the next location (e.g., Figure 24-1). Individual Northern Gannets varied in their behavioral assessment; while the median individual showed ARS behavior 75% of the time, the first quartile was at 33%, and the third quartile at 93%. Similar variability was seen in transient behavior, with the median percentage at 5%, the first quartile at 0%, and the third quartile at 11%. In the mid-Atlantic region, we found that many individuals were in the ARS behavioral state when they were located in large bays, such as Chesapeake Bay (Figure 24-2A). Transient behavior, while still occurring in many of the bays (Figure 24-2B), was more equitably distributed, with areas on the continental shelf outside of the bays also being consistently used for this behavior.

### *Environmental correlates to foraging behavior*

The generalized linear model was a significant improvement over the null model with a random effect ( $\chi^2=32.3$ ,  $p<0.001$ ), with most modeling terms significantly contributing to an improved overall fit (below). The random effect of individual was important to predicting foraging behavior. Overall, the term had a variance estimate of 3.5 (SD=1.9), which suggests large variation in how often individuals utilized ARS or transient behaviors compared to the fixed effects portion of the model.

Each fixed effect was found to be both statistically and ecologically important. The effect of capture year was large, with birds in their first winter showing less ARS behavior than birds in their second winter ( $\beta=0.8$ , 95% CI: 0.2, 1.4; Figure 24-3). There was no significant effect of year itself once we accounted for this variable ( $F_2=1.9$ ). As water depth increased, the probability of ARS foraging behaviors also increased ( $\beta= 0.47$ , 95% CI: 0.17, 0.94; median depth = 15 m and maximum depth = 862 m; Figure 24-4). The

largest effect was that of SST front density, which increased the probability of Northern Gannets using ARS foraging behavior ( $\beta=0.28$ , 95% CI: 0.09, 0.49; Figure 24-5). There was considerable variation in the locations of SST fronts at the annual scale during our study, as relatively higher front density extended further from shore in the winter of 2012-13 compared to the other years (Figure 24-6). The correlation between SST front density and ARS behavior suggests that Northern Gannet foraging locations were also varying on an annual scale.

## Discussion

Our model indicates that Northern Gannets often engaged in ARS behaviors during winter, punctuated by transient movements to the next primary foraging area. Similar behavior has been found in Northern Gannets during the breeding season when they exhibit central place foraging (Hamer et al. 2009, Scales et al. 2014, Thiebault et al. 2014), but this is the first time that this behavior has been documented during the non-breeding season. Water depth and the density of SST fronts were both correlated with behavioral state; individuals were most likely to engage in ARS behaviors where the waters were relatively deep and frontal density was relatively high. Sea surface temperature fronts have been long known to correlate with seabird densities (Haney and McGillivray 1985), but our results suggest that Northern Gannets were not only occupying these spaces, but using them consistently for foraging opportunities. Temperature front density was a very strong predictor of foraging activity, which indicates that Northern Gannets were dynamically responding to either the change in water temperature itself, or to the increase in prey availability that is likely occurring in areas with high front density (Bost et al. 2009, Benoit-Bird and McManus 2012).

Passively moving marine species, such as plankton, are often aggregated in the frontal areas between two water masses (Bost et al. 2009), which propagates up through the pelagic community and results in greater relative abundance of higher trophic level species (Benoit-Bird and McManus 2012). Predatory fish, such as tuna, are seen in high abundance at areas of cold water intrusion into warmer waters (Andrade 2003). Capture rates for some species (Pacific Herring, *Clupea pallasii*, and Northern Anchovies, *Engraulis mordax*) have been found to be greater close to SST fronts on the U.S. Pacific coast (Reese et al. 2011). In the South Atlantic Bight, such fronts are associated with increased plankton and planktivorous birds, though forage fish are also likely to occur in such conditions (Haney and McGillivray 1985). Fronts in different locations vary in their capacity to aggregate marine biomass (Bost et al. 2009), and we lack direct evidence regarding the species that SST fronts are aggregating in the mid-Atlantic. Further research on the distribution of plankton and pelagic forage fishes in this region, particularly around temperature fronts, is warranted. During the breeding season, Northern Gannets primarily forage on near-surface schooling pelagic mackerel, capelin, sand lance, squid, saury, and herring (Montevecchi and Myers 1997). Given the size and ecology of those species, we suspect menhaden and shad constitute large proportions of gannets' diet in the non-breeding season, but little is known about their diet during this period. This uncertainty makes it even more difficult to confirm that SST fronts are aggregating prey fish for this species, though there is strong overall evidence suggesting that SST fronts in the region may act in this manner.

The results of this study suggest slightly different environmental drivers of gannet distributions than we have seen in other chapters in this report, for several reasons. The first is a matter of scale: unlike boat or aerial surveys (Parts II-IV) or other telemetry analyses (Chapters 20-23) in this report, this analysis focuses on individual foraging decisions, which are necessarily made at an individual scale, rather than a population scale. We do not attempt to describe the overall distribution of Northern Gannets, but rather to understand, within that broader distribution where the species has been observed, why individuals forage in some locations over others. Utilization distributions and survey data for Northern Gannets indicated that while they were wide-ranging across the Outer Continental Shelf (OCS), they were most common in shallower waters and closer to shore (Chapters 12, 17, and 22). This analysis suggests that, within the areas close to shore where they were abundant, Northern Gannets preferred to use ARS behaviors in areas of deeper water. This likely indicates the habitat preferences of their prey or increased competition in nearshore areas. Sea surface temperature fronts were not assessed in previous studies in this report, making it difficult to draw further comparison, though we should note that this chapter assesses front densities at a daily scale (using a sliding weekly window) while Chapter 22 looks at annual and seasonal patterns in climate data (climatologies) for inference. A third year of tracking data (from birds captured in the winter of 2013-2014) was also included in this analysis, which may have further affected the observed relationships with environmental covariates relative to the analysis in Chapter 22.

Several limitations of this study should be noted. First, we have based this analysis on data from only three winters. Given the variance described in this study, it seems likely that winter conditions could vary even more than we observed, which could influence the accuracy of our predictions. Second, our modeling methodology allowed us to assess ARS and foraging behavior at the daily scale in this study. Previous studies on Northern Gannets and other seabirds that used higher-accuracy GPS data loggers have assessed ARS at finer temporal and spatial scales. While our results have some similarity to these other studies (Hamer et al. 2009, Pavia et al. 2010), our satellite telemetry technology did not allow inference at a sub-daily scale, and any differences in ARS behavior that may be occurring at smaller time scales could not be analyzed here.

There are several potential explanations for the effect of capture year on our results. Birds could employ ARS behavior less often in their first winter as an effect of satellite tag deployment. A recent meta-analysis suggests a range of effects to birds caused by transmitter attachment, including changes in foraging duration and food consumption (Barron et al. 2010) and diving behavior in King Penguins (Ropert-Coudert 2000). Implanted transmitters have been shown to cause mortality in seabirds (reviewed in Burger and Shaffer 2008) but few studies using implants have specifically examined foraging behavior. A study on Adélie Penguins found no effect of transmitter implantation on foraging duration (Ballard et al. 2001) but this study's relevance specifically to the Northern Gannet foraging behavior is tenuous. While we think it is unlikely that birds would respond to capture by exhibiting more transient behavior, it remains possible that this is a short-term response to capture and handling. Alternatively, the SSSM could be under-predicting rare transient behavior in the second winter, when we typically had fewer data points per individual. A third possibility is that foraging behavior may vary seasonally; winter capture efforts were centered in the middle of the winter season, so data from the

winter of capture was limited to late winter periods, while data from the winter after capture were generally from early winter, before tags began to fail.

Northern Gannets spent considerable time using ARS foraging behavior in relatively deep parts of the OCS, where there are high densities of SST fronts. Given the strong relationship to SST fronts that we observed, we would expect that as the locations of SST fronts change over time, the locations of consistent foraging activity in Northern Gannets will change with them. Frontal patterns have changed during periods of climate change in the past (Chavez et al. 2003, Hoegh-Guldberg and Bruno 2010), but the scientific community is currently uncertain about how SST fronts will change specifically on the mid-Atlantic OCS in the coming years or decades. The variation could look similar to differences between El Niño and La Niña years that are currently observed, which would make predictions of future changes relatively simple. However, the possibility of generating no-analog communities—and their difficult to predict conditions—also exists (Williams and Jackson 2007). Under this scenario, climate change modifies environmentally conditions in an ecosystem to an arrangement that has not been documented by science, thus making ecosystem difficult to impossible to predict.

Offshore wind energy development could potentially affect Northern Gannets in several ways: by increasing mortality due to direct collision, displacing them from high-quality foraging areas, or increasing energy expenditures through added flight costs to avoid turbines (Fox et al. 2006, Furness et al. 2013, Johnston et al. 2014, Vanermen et al. 2014). Foraging birds are suggested to be at greater risk to collision with wind turbines (Furness et al. 2013). Thus, for assessing the potential for both collisions and displacement of Northern Gannets in relation to offshore wind energy development, it will be important to understand the locations of foraging areas, and to develop accurate predictions of SST fronts, both now and in the future, when changing ocean temperatures could alter the distribution of seabird foraging locations.

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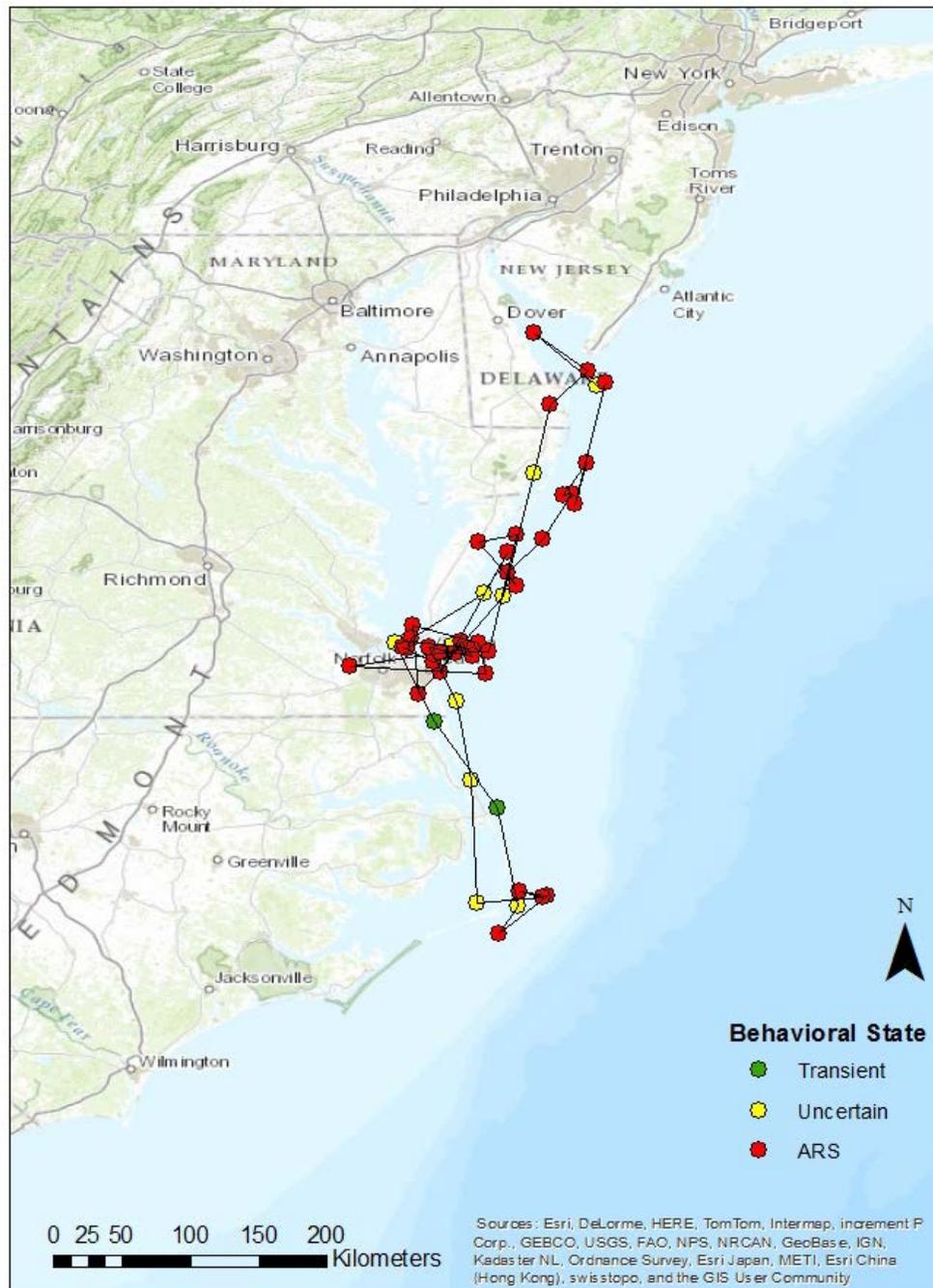
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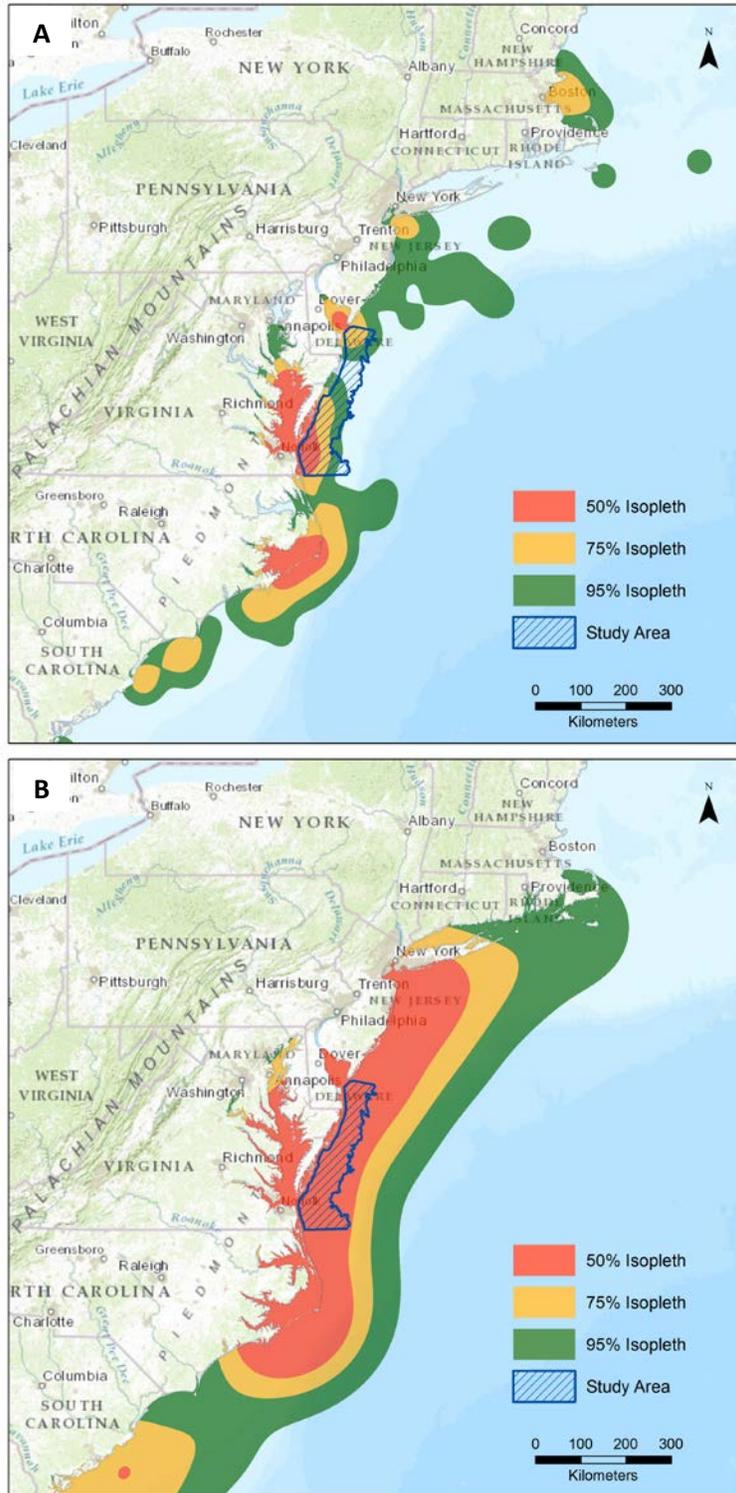
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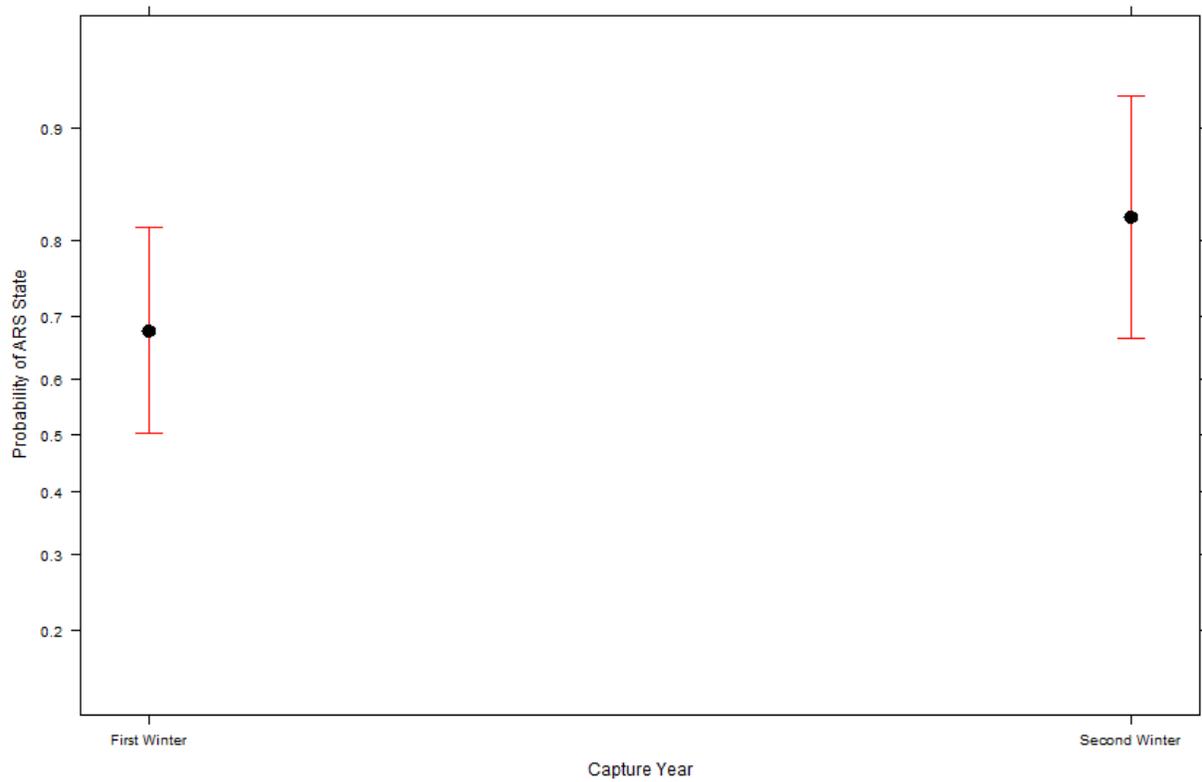
## Figures



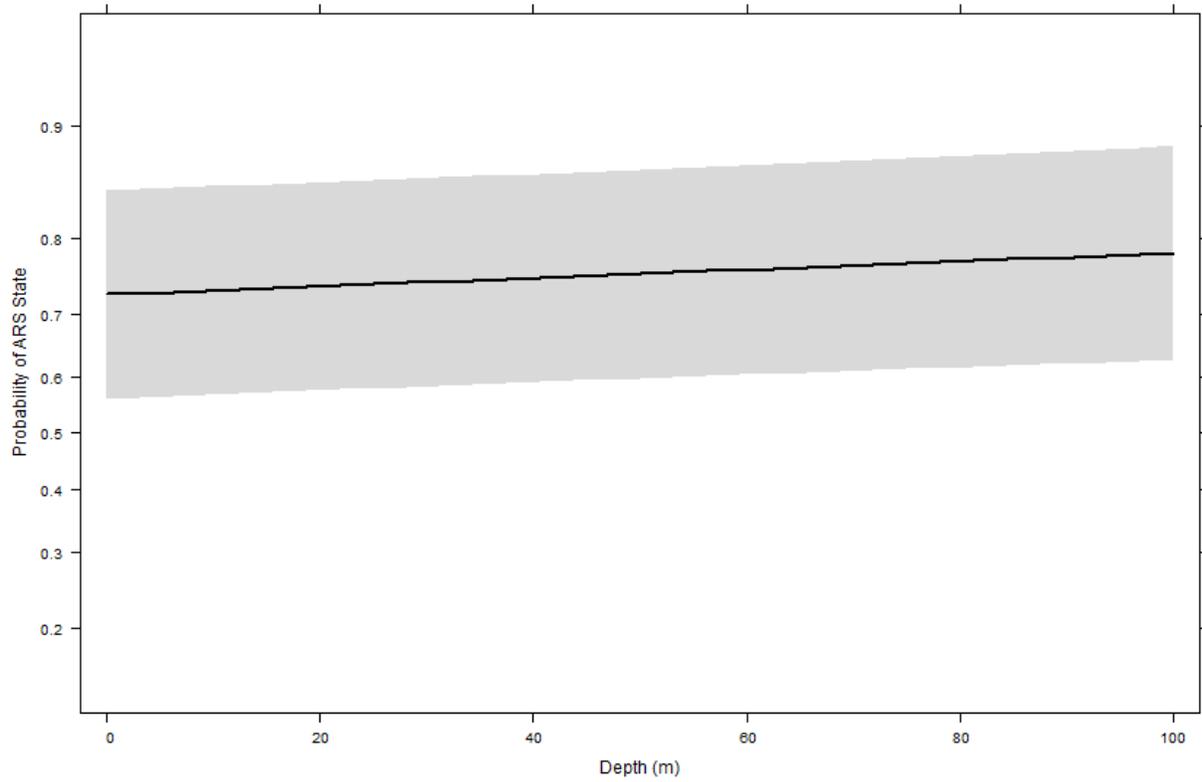
**Figure 24-1. Examples of ARS and transient movements from a Northern Gannet with a satellite transmitter.** Points represent the most likely daily position of one Northern Gannet estimated by the state-space model, and the lines connect points sequentially in time. The color of the point indicates what type of behavior was occurring at that point: transient behavior (green), uncertain (yellow), or area-restricted search behaviors (red).



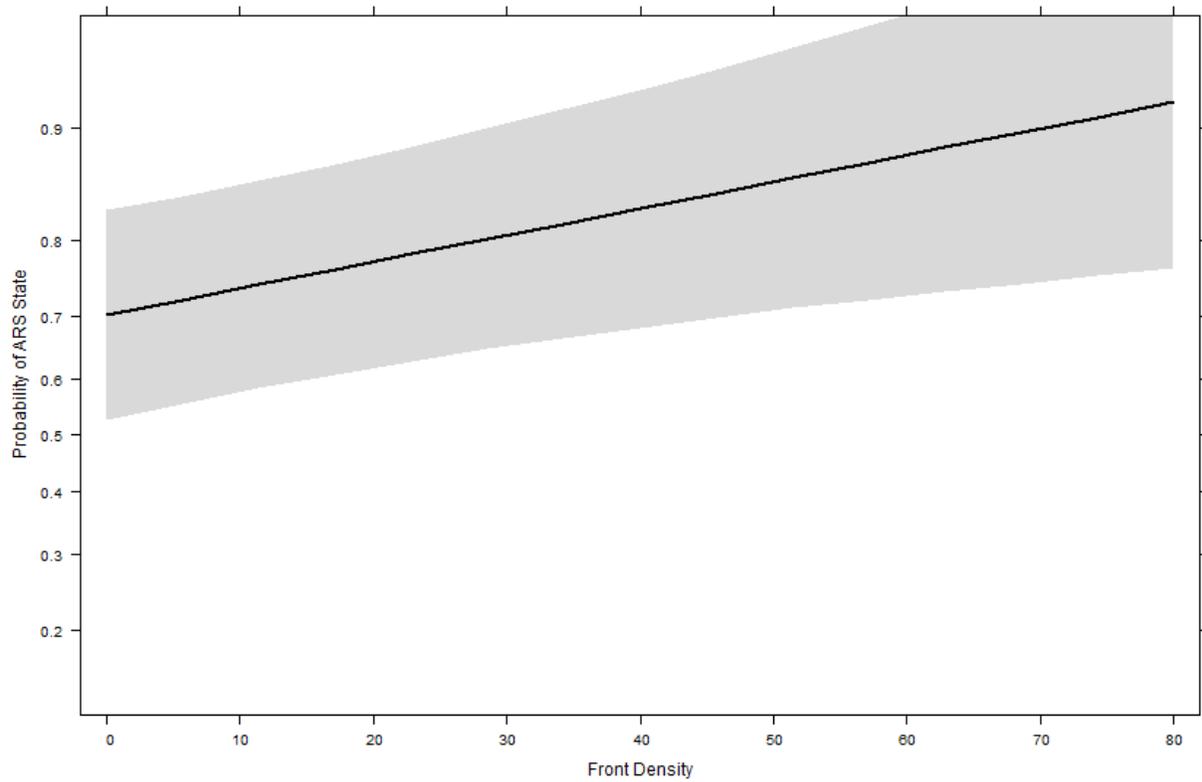
**Figure 24-2. Kernel Density Estimates of Northern Gannets exhibiting area-restricted search (ARS) foraging behavior (A) and transient behavior (B) in the mid-Atlantic.** Redder colors (and high density levels) indicate that more individuals in that area are exhibiting the respective behavioral state. This analysis sums activity across years and individuals.



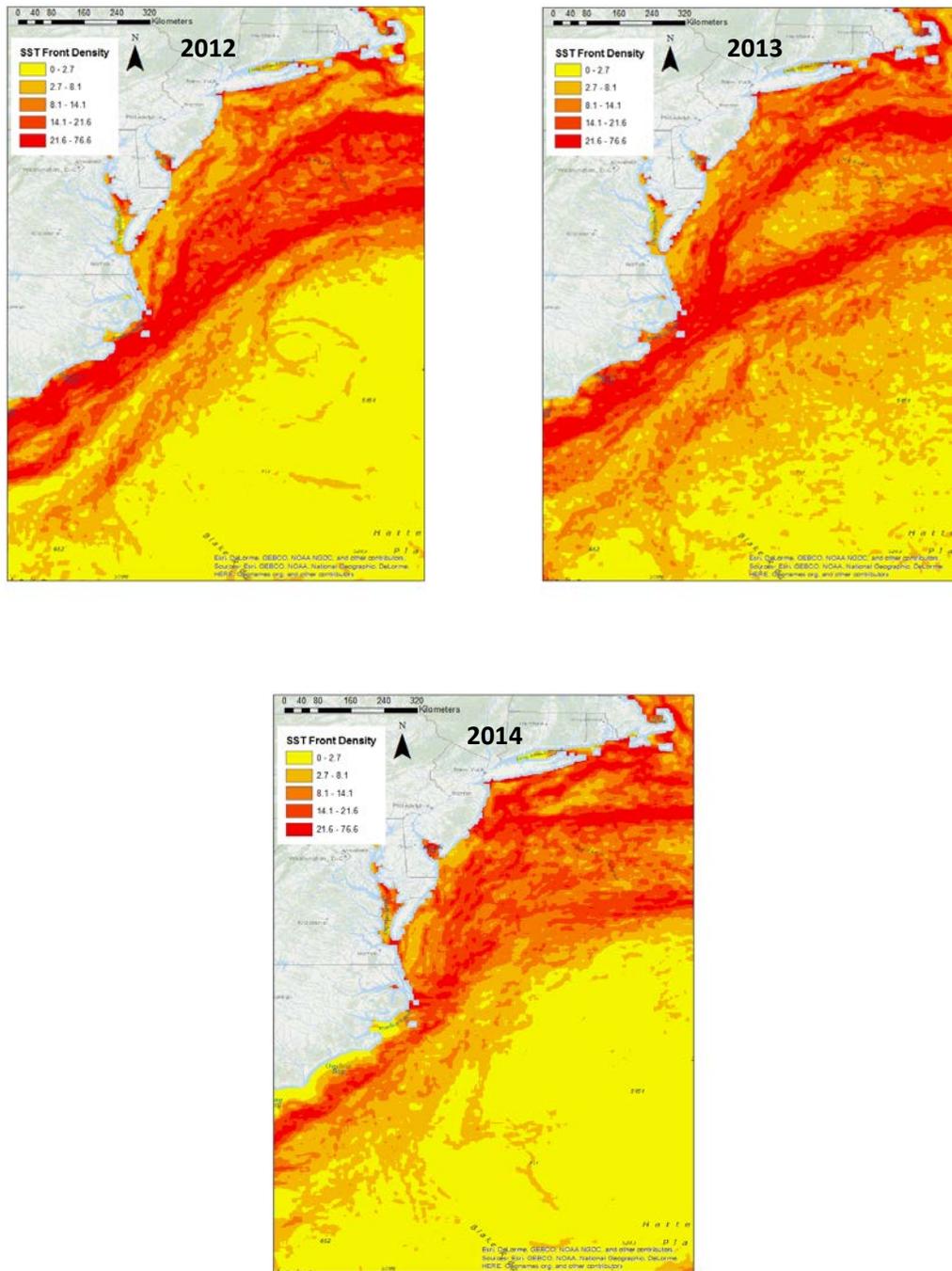
**Figure 24-3. The predicted effect of capture year on the probability of Northern Gannets being in an ARS state during the winter they were captured (First Winter) and the winter immediately after (Second Winter).** Individuals demonstrated a significantly higher ratio of ARS to non-ARS behaviors in the second winter. Error bars indicate the 95% confidence interval of the mean.



**Figure 24-4. The predicted effect of water depth (m) on the probability of Northern Gannets being in an ARS state during winter (across all years and individuals). The shaded area indicates the 95% confidence interval of the prediction.**



**Figure 24-5. The effect of sea surface temperature front density (number of fronts for each position estimate) on the probability of Northern Gannets being in ARS state during winter (across years and individuals). The shaded area indicates the 95% confidence interval of the prediction.**



**Figure 24-6. Maps of daily SST front density averaged for three winters (2012-14) in the mid-Atlantic region. Color shifts from yellow to red as the number sea surface temperature fronts in the past week around each point increases.**