Filecode 2658-2006-2008-F

Evaluation of Relative Risk of Co-Occurrence of North Atlantic Right Whales and Vessels in the Southeastern United States (SEUS) Calving Grounds

Final Report submitted to the National Fish and Wildlife Foundation by The Florida Fish and Wildlife Conservation Commission, Fish and Wildlife Research Institute

Introduction

For the North Atlantic right whale (*Eubalaena glacialis*), one of the most endangered large whales in the world, was once an abundant inhabitant of coastal waters in both the western and eastern Atlantic Ocean. Whaling in earlier centuries critically reduced population levels in this and other whale species (Reeves and Mitchell 1986), however the right whale was especially desirable to whalers, largely because they traveled slowly and close to shore while yielding large quantities of oil and baleen. Right whales first received international protection from commercial harvest by the League of Nations in 1935. Today, North Atlantic right whales are additionally protected by the Marine Mammal Protection Act of 1972 and the Endangered Species Act of 1973 in the United States. Additionally, United States federal regulation requires boats and aircraft to stay a minimum of 460 m (500 yards) from right whales (Federal Register, 50 CFR 224.103, 2004). The recovery of the species is still uncertain and increased protective measures are under consideration.

The current major impediments to right whale population recovery include mortalities from vessel strike and fishing gear entanglement (Knowlton and Kraus 2001, NMFS 2005). Of the documented right whale mortalities, vessel strike dominates the confirmed cause of death (Moore *et al.* 2005). It has been estimated that the prevention of as few as two reproductive female mortalities per year could improve growth rates, potentially preventing or at least slowing the extinction of the species (Fujiwara and Caswell 2001). Reducing the risk of mortality to the North Atlantic right whale through improvements in protection from vessels, therefore, could make the difference in survival of this species.

The coastal nature of the species increases its vulnerability to anthropogenic impacts today, as in the historical whaling era. Both summer feeding habitat along the northeastern U. S.

coastline and winter calving habitat along the southeastern U. S. coastline (SEUS) occur in areas of very high commercial shipping traffic (Ward-Geiger *et al.*, 2005). While migrating between northern and southern habitats, the whales' proximity to shore places them in high traffic areas, passing directly through busy mid-Atlantic ports (Figure 1). Several high intensity ports (e.g., Brunswick, Georgia, and Fernandina and Jacksonville, Florida) are found within the SEUS, the only known calving area for the species (Kraus *et al.* 1986*b*).

When planning effective protection for endangered species it is crucial to develop a broad understanding of their spatial distribution and habitat use (Austin 2002, Lehmann *et al.* 2002, Gibson *et al.* 2004, Redfern *et al.* 2006). Understanding the ecology, especially those factors that drive spatial and temporal variability in abundance, may enable ecologists to feasibly predict potential habitats in un-surveyed areas or animal distribution with shifts of environmental conditions (Hamazaki 2002, Redfern *et al.* 2006). Habitat prediction is essential for developing effective conservation strategies particularly for dynamic marine environments (Guisan and Zimmerman 2000, Austin 2002, Scott *et al.* 2002). Our right whale habitat model, based on aerial survey data and associated spatial covariate data, will demonstrate overall dynamics of habitat throughout the calving season and will serve as a basis for evaluating risk of ship strike to right whales within the SEUS region.

In an effort to develop conservation strategies to reduce ship strikes on right whales, National Oceanic and Atmospheric Administration (NOAA) Fisheries (Kraus *et al.* 2005), the federal agency charged with protection of the right whales, contracted a report on recommendations for vessel strike reduction management measures. NOAA used the report (Russell 2001) as a baseline for developing a proposed protection strategy to reduce vessel strikes of right whales. Measures in the strategy call for reducing the overlap between vessels and whales to reduce the likelihood of vessel strikes with minimized adverse impacts to vessel operations. Initial research required for implementation of the Strategy, including a Port Access Route Study (PARS) performed by the U.S. Coast Guard in which a variety of scenarios for shipping lanes were examined. For the SEUS, the PARS study was followed-up by a risk assessment for co-occurrence of vessels and whales during the winter calving season using five shipping lane scenarios (Fonnesbeck *et al.* in 2008). Fonnesbeck *et al.* estimated risk associated with observed traffic patterns and compared this with a set of candidate routes. They reported

that alternative routes reduced estimated risk by 27% to 44% relative to the estimated risk of observed traffic.

In 2007, NOAA Fisheries proposed its final rule for ship management in critical areas to right whales along the east coast, which called for both speed restrictions and recommended shipping routes to pilot buoys, where mariners pick up and drop off pilots familiar with narrow shipping channels leading to port. The final rule will be implemented in December 2008 however, both voluntary speed restrictions and recommended shipping routes, based in part on the previous risk assessment, were implemented in December 2006 in the SEUS.

The spatial resolution of all data used in the previous risk assessment (Fonnesbeck *et al.*, 2008) was limited by the coarse resolution of available shipping data. Shipping data available for that study came from the Mandatory Ship Reporting System (MSRS). The MSRS system required self-propelled commercial vessels of 300 gross tons or more to report their locations and intended routes into port to a shore-based station when entering the designated MSRS zone (Figure 1) surrounding federally designated right whale critical habitat (Ward-Geiger *et al.* 2005). More recently, a new improved method for collecting vessel traffic data, the Automated Identification System (AIS), was implemented in the southeast by the Florida Fish and Wildlife Conservation Commission in partnership with NOAA.

The AIS provides high-resolution, real-time data on the location of vessels entering or leaving ports along with identification data about the vessel itself. Vessels (greater than 65') are now required to be equipped with broadcast antennas that continually send out a signal with identifying and locational information received by an onshore antenna, where data are downloaded to an automated server for real-time visualization and storage. Onshore antennae are located at Jacksonville and Brunswick, providing consistent data to the boundary of the MSRS zone. Although signals ranging to Savannah, Georgia, are often collected, reception was not consistent for the time-period of data collection used here and so was not included in comparative, quantitative analyses. AIS criteria apply to a broader range of vessels than MSRS criteria. In addition to more inclusive range of vessel types, improvements with AIS include data on outbound as well as inbound trips, a nearly-continual (updated every 30 seconds) stream of precise, real-time locational data rather than self-reported, minimal information, and detailed data describing the vessel and its characteristics. These advances in vessel monitoring allow a revised risk analysis based upon more accurate vessel data at a finer spatial resolution.

For this study, we have updated the previous risk assessment, using the new vessel traffic data from the first year of AIS implementation in the SEUS (2006/2007), the same season that recommended shipping routes were implemented, and a dynamic model of SEUS right whale distribution. Right whale spatial distribution in the SEUS varies temporally within the four-month calving season. Previous analyses have found strong relationships of right whale distribution in the SEUS with sea surface temperature (SST) and bathymetry (a.k.a. depth) (Keller *et al.* 2006). Unlike the previous risk assessment, we have restricted our analysis to reproductive females because of their importance to the population (Fujiwara and Caswell 2001) and their relationship to habitat variables may differ from that of other demographic groups.

We first develop a Bayesian hierarchical logit model to relate probability of reproductive right whales (hereafter referenced as right whale) occurrence to habitat variables. Application of the model to spatially- and temporally-explicit habitat variables in a geographic information system provides a predictive model of right whale distribution. Predictive models are important for developing effective conservation strategies in shifting environments, such as the SEUS where variations in SST in space and time may strongly affect right whale intra- and inter-seasonal distribution (Hamazaki 2002, Redfern *et al.* 2006). The spatial prediction model then enables an evaluation of relative risk of right whale co-occurrence with vessels and whales for examining spatial and temporal patterns in relative risk. We examine the spatial variation in risk across a simulated right whale seasonal distribution, as well as biweekly simulations. We then compare risk quantitatively among biweeks, as well as within designated regions of the study area. These comparisons provide managers with important information for developing effective vessel management strategies in the SEUS, as well as for developing efficient mitigation strategies, such as right whale aerial survey programs.

Methods

Calving Right Whale Sightings

For this project, we included a total of 660 sightings of pregnant females or mom-calf pairs recorded during surveys matching the standardized effort criteria (observers formally "on-watch," Beaufort Sea State nominally ≤3, altitude<305 m, and visibility of at least 3.7 km) from 1992 to 2003. The boundaries of the study area encompassed the spatial extent of the aerial

search area (Figure 1). Pregnant females were identified using the North Atlantic right whale photo-identification catalog maintained by the North Atlantic Right Whale Consortium and curated by the New England Aquarium. Identified females with calves were presumed to be pregnant in previous sightings for the season. Whale sightings, which represent groups rather than individuals, were used because most sightings were mother/dependent calf pairs. Photo-identification records were only available through the 2002/2003 season.

Aerial Survey and Environmental Data

The known calving ground off the coast of northern Florida and Georgia has been surveyed by air intensively during the winter months (December through March). The effort level (1992 through 2003) varied over the survey area (Figure 2), but included the latitudinal range from Savannah, GA (32° 09' N) to Ormond Beach, FL (29°34' N). Positions along the trackline were sequentially recorded, allowing spatial and temporal compilation of survey effort for effort-corrected whale sighting data. Upon observing a whale group, the plane broke track to determine a more accurate location and record data and photographs for scientific use. For this analysis, only those sightings gathered under on-watch conditions were used.

The study area was divided into 4-km^2 grid cells in ArcGIS for spatially aggregating data. Aggregating data (including effort data and right whale sightings, as well as environmental variables included in the habitat model) is important for relating right whale distribution to co-variates at appropriate spatial and temporal scales. Environmental data used in map analysis included SST and bathymetry. For additional explanation of aerial survey and environmental data specifications and handling, see Keller *et al.* (2006).

Preliminary Analysis - Sensitivity of Resolution

The spatial resolution (4-km by 4-km cell size) used in the previous risk assessment was suited to the precision of the available vessel and environmental data used in the model. However, the refined AIS data provided reasons to evaluate the spatial resolution for this updated risk assessment. A sensitivity analysis was performed to compare the distributions and relationships of the data when aggregated at both 16-km^2 and 4-km^2 resolutions.

A subsample of the data (1997/1998 and 2000/2001 seasons) was used to perform the sensitivity analysis. The environmental variables, bathymetry and SST, were each averaged

within cells of both sizes. Whale sighting data included the average effort (e.g., the number of observation days per cell, averaged across an original resolution of 100 x 100 m) and the number of whale-group sightings per cell per biweek.

Of interest is whether aggregating (e.g., averaging) environmental variables, SST and bathymetry) at the coarser resolution masks within-cell variability. If so, then distributions of environmental variables at the 4-km^2 resolution should reveal variability that was hidden at the 16-km^2 resolution. The scatter plots (Figure 3) show clumping along on the 45 degree line, indicating that little variability was masked at the coarser resolution. Scattering of points at lower bathymetry (between 0 and 15-20 m) may indicate that the 4-km^2 data may be more precise than the 16-km^2 at shallow depths.

Sightings-per-unit-effort (SPUE) declined in relation to mean aerial effort per biweek within each of the two cell sizes (Figure 4), likely owing to the rarity of species sightings over space. Because SPUE was 0 for cells without sightings, these diagrams represent only those cells with at least one whale group (each group constitutes a single sighting). The separation of series of points, especially in the 16-km^2 cell size, resulted from additional group sightings in a cell for any given biweek. The reduced number of cells with more than one group-sighting in the 4-km^2 data indicates that data are suitable for a logit modeling framework, where presence/absence of whale sightings is modeled.

Although no major differences were observed between the data sets at the two resolutions for either environmental or whale-sighting data (including both effort and sightings), there were some subtle but potentially valuable differences among the data sets. The 4-km^2 data were suitable for a logistic regression modeling framework, whereas the 16-km^2 data were not as well suited to either Poisson or logistic analysis. Although the Poisson or negative-binomial distribution are often used for count data such as right whale groups, neither can accommodate the large number of '0' counts in this data set. At the finer resolution, rarely was more than a single right whale group seen in a cell per biweek, so a model such as a logit model in which data correspond to a binomial distribution (0 or 1, absent or present, etc.) should well represent observed data.

Data Specifications

Model data included average effort, SST, and bathymetry, as well as the presence of a group that included reproductive females per cell per biweek. Data were spatially aggregated into the 4-km^2 cell size grid over the study area and temporally aggregated into biweekly periods: from the 1st to the 15th day of the month, and from the 16th to the last day of each month. The study area comprised a total of 6625 4-km^2 cells. The division of the sampling area into 6625 spatial cells, 8 biweekly time intervals, sampled over 12 seasons results in 636,000 potential sampling units, or cells. Following elimination of cells with no effort or no available SST per biweek, the final data set comprised 237,404 4- km^2 sampling units (but see *Autocorrelation* below).

Model Selection and Fitting

Cow/Calf Whale Habitat Model

Because more than one group sighting per cell per biweek occurred very rarely, the probability of encountering a whale group was modeled as a Bayesian logit model with a Bernoulli distribution for the distribution of the response variable, y. The inverse of the logit response y, $(\exp(y) / (1+\exp(y))$, yields a probability of a group sighting per cell per biweek. Effort was used as an offset in the model to scale results to a rate per unit effort to minimize bias due to variability of effort in space and time.

Previous habitat models (Keller *et al.* 2006, Keller *et al.* in prep) have narrowed the field of potential co-variates for investigation, and we preliminarily investigated a short list that included normalized SST and bathymetry, as well as polynomials (a.k.a., squared terms), an interaction term, or all of the above. Model fit was preliminarily assessed using Akaike's Information Criterion (AIC) which is based upon the deviation of observations from predictions, along with a penalty term for the number of parameters in the model. A lower criterion generally indicates a better fit of the model to the data. For these models, the model with an interaction term provided a model with the lowest AIC value (AIC = 2594). The model using polynomials of both variables had a slightly higher AIC value (AIC = 2611). Adding the interaction term to a model with polynomials provided no AIC reductions. Graphical evaluation and visualization in

GIS of model output indicated that the polynomial model provided a better description of whale sighting data.

So the Bayesian, hierarchical model of whale habitat was developed using the polynomial, logit model:

$$(\pi_{it}) \sim \text{Bernoulli distribution}$$
$$\text{logit}(\pi_{it}) = e_{it} + \theta_t + \beta_1 b_i + \gamma_1 s_{it} + \beta_2 b_i^2 + \gamma_2 s_{it}^2$$

where π_{it} is the probability of encountering a group of right whales per cell (i) per biweek (t), e_{it} is the average effort per cell i per biweek t , θ_t is the random effect of biweek t, b_i is the average bathymetry per cell i and s_{it} is the average SST in the cell i per biweek t. Both bathymetry and SST were normalized by subtracting the mean to reduce effects of variable magnitudes in the model. The response of whales to bathymetry and SST is expected to remain the same during the calving period, and so the mean variable θ_t reflects the variability in the number of whales, and therefore the probability of sighting groups, over the course of biweekly periods in the study. The mean variable θ_t provides for random variation around the mean by biweek, thereby yielding a mean value per biweek.

Bayesian hierarchical modeling involves the use of prior distributions on parameters for the model, which in this model includes the biweek effects, θ_t as well as coefficients, β_1, β_2, γ_1 and γ_2. Vague priors can be used to minimize their influence on the outcome when strong evidence for the form of the priors is lacking. The modeling was performed using WinBUGS software (through a call from R using R2WinBUGS) and Monte Carlo chains. Initial values and prior distribution are provided to initiate the model run. The Monte Carlo algorithm is an iterative process of sampling from a prior distribution, which becomes modified over time as the most recent sample value replaces the last accepted value as a better estimate of the parameter (a.k.a. mean of the distribution) through a rejection/acceptance algorithm. Generally, model exploration is run using more than a single chain (often 2-3), because the convergence of all chains to similar values (e.g., mean parameter estimates) provides an indication of model fit. Convergence is measured by an Rhat value, which is 1 at convergence. Because the earlier iterations are often exploring less likely areas of the posterior distribution, a 'burn-in' period is specified before successive samples are included in the posterior distribution. Likewise,

successive sample values may be autocorrelated due to the algorithm used to explore the 'prior' distribution, and so are generally 'thinned' (e.g., including every *n*th value). Quartiles of the posterior distribution of parameter estimates comprise Bayesian credible intervals. Bayesian credible intervals can be interpreted as a 95% chance of including the actual value (Gelman *et al.* 2004).

Bayesian hierarchical modeling was performed with vague priors for 2000 iterations with a 500 iteration burn-in. Although this was a relatively short number of iterations, the large number of observations included in the study allowed the Monte Carlo chains to converge quickly and the convergence of the 3 chains came to 1 or very nearly so.

Posterior predictions of the response value, y, were provided through the application of the model to environmental and effort data using the mean of the Bayesian credible intervals for the parameter estimates. The inverse-logit of the predictions provides an estimate of the probability of seeing a whale group per cell per biweek. Model output, when depicted spatially, provides a spatial and temporal (e.g., comparison of distribution across biweeks) simulation of right whale intra-seasonal dynamics of distribution. To evaluate the probability of sighting a whale group per cell across the entire season, probabilities for the eight biweeks were then summed by cell. This habitat model then provided the underlying basis for evaluating the risk of co-occurrence with vessels in time and space.

Autocorrelation

Each 4-km^2 cell may not represent an independent degree of freedom because of spatial and temporal dependence between cells that are close in space or time. Ecological data usually contain positive spatial autocorrelation, where similarity of measurements varies inversely with distance in space and time (Legendre 1993). Positive spatial autocorrelation generally results from social factors that cause animals to be located closer together than expected. Spatial autocorrelation may inflate the importance of parameters but deflate standard errors in habitat niche models (Segurado *et al.* 2006), although the consequences for model output depend upon the goals and objectives of the study, model choice, and spatial characteristics of the environment and the species distribution (Segurado and Araujo 2004).

We evaluated whether the data exhibited spatial autocorrelation effects by developing a generalized mixed model using a single biweek of data (Jan 16-31, 2001, $n = 57$). We chose this

biweek because it had the highest number of sightings and therefore provided the greatest potential for measurement should autocorrelation be present. Using a generalized random effects mixed model (PROC GLIMMIX in SAS) with restricted cubic splines (rcs - Poisson link - 3 knots), we used parametric techniques to estimate fine-scale spatial autocorrelation, the type that induces non-independent errors (Lichstein *et al.* 2002). Comparing rcs models in combinations with and without variables or spatial autocorrelation as a random effect, we determined if spatial autocorrelation impacted the model on any level. There was no evidence of any type of positive spatial autocorrelation in the data aggregated at the scale of this analysis. Because we accounted for groups of right whales as the unit of response, we precluded social factors as a potential for confounding the relationships to environmental variables.

Shipping Data

The shipping data for the 2006/2007 calving season was summarized spatially and temporally at the 4-km^2 cell size and per biweek, respectively. Vessels for which ship length was greater than 65' were included in the final data set (although Coast Guard requirements only apply to vessels $\geq$ 65', some mariners with smaller vessels opt to broadcast for safety reasons). Vessel types were categorized as cargo, tankers, utility, and other. Utility included towing, tugs, pilot vessels and port tenders. The 'other' category includes a variety of ship types greater than 65' (Table 1). Tracks without length or vessel type were excluded from the analysis unless vessel type was either cargo or tanker because they were extremely unlikely to be less than 65'. Tracklines from AIS data were summed per cell per biweek and an overall frequency for each cell was developed by dividing by the sum of the total trackline across the entire season. The frequency distribution (per cell) was a single value for each vessel type (cargo, tankers, utility boats, and other), as well as a total of the vessel types per cell for the entire season, representing the total frequency of tracklines for the season. Most of the data comprised cargo vessels, with smaller contributions from the other 3 types of vessels. Although the vessel locational data are not as reliably received outside the MSRS zone (reception through the AIS system may vary with distance, weather, etc.), the overall frequency outside the MSRS

Table 1. Types of ships categorized as 'other' in the AIS vessel data included in this study. Only vessels that included the length field and were greater than 65' were included in the analysis.

Vessel Type
WIG (Wing-In-Ground)
Fishing
Vessel engaged in dredging or underwater operations
Vessel engaged in diving operations
Vessel engaged in military operations
Sailing
Pleasure craft
Reserved for future use
HSC(High Speed Craft)
Search and rescue vessels
Vessels with anti-pollution facilities or equipment
Law enforcement vessels
Medical Transports
Passenger ships
Other ships
Unreported
Unknowns

boundary reflects a minimum. Data were evaluated biweekly, but for this particular study, we aggregated the data across the season as it is unknown whether temporal trends across the season will be repeated in subsequent years. The data herein serve as a representation of potential scenarios, which may be evaluated for temporal trends as additional years of shipping data are collected.

Calculation of the Relative Risk Index

Relative risk index per cell was evaluated as the product of the normalized (divided by the sum of probabilities for the whole season) probability of whale sighting and the normalized frequency of vessels for a season. This product provided an index of co-occurrence (e.g., relative risk) for right whales with vessels, which provided a basis for evaluating relative risk across space (among port regions – Figure 1) and time (per biweek or for an entire season). This index does not represent a direct 'probability' of collision, in part because it is an index and in part because it does not and cannot account for fine-scale interactions between ships and whales,

such as whale behavior near an oncoming vessel. The risk of collision itself is also dependent upon other factors, including the vessel speed, the hydrodynamic forces related to vessel type, vessel weight, and numerous other factors. We have, therefore, chosen to describe risk at a coarser scale over space and time.

The relative risk index was evaluated at two temporal scales: biweekly and seasonally. The biweekly average of the frequency of total vessels was used to evaluate risk intra-seasonally across biweeks. Changes in risk across biweeks reflected biweekly differences in simulated whale distribution through the season. Risk evaluated near the port of Jacksonville provides an illustration of a comparison of risk between the lowest biweek of the season (the first biweek in December) to the highest risk period (the second biweek in January). To temporally compare the overall risk among biweeks, cumulative risk for the entire study area per biweek was used. Spatial comparison of biweekly risk was compared among the three of the port regions: Brunswick, Fernandina, and Jacksonville. Savannah was not included in the comparison because AIS data were less reliable in that area than in ports closer to the receiving antennae.

Total risk index for an entire season was calculated as the sum of the biweekly probabilities of sighting a whale group per cell – the sum represents the probability of a whale sighting over an entire season. The final probability was normalized by dividing by the sum of the probabilities. The risk index for the season was computed by multiplying the normalized frequency of vessels for the full season by the normalized probability of sighting a whale per cell over a season.

Results

Whale Sighting Probability for Entire Season

Spatial simulation of the model of normalized seasonal probability of observing right whales (Figure 5) indicates that the greatest probabilities occur in an area extending from the northern portion of the study area to the southern, with the distribution extending closer to the shoreline from approximately Jacksonville and southward. The two highest categories (ranging from > 0.00021 to 0.00029) represent the highest 20% of sighting probabilities. The reduction in whale sighting probabilities eastward likely reflects increased depth as well as the edge of the

warmer Gulf Stream current that flows northward along the outer continental shelf in the region (Keller *et al.* 2006). This surface reflects an average within and among seasons. Variability among seasons would occur based on overall SSTs for the year as well as numbers of migrating whales.

The strip of lower probability enveloped by higher probability, slightly south of Jacksonville, represents an area of decreased depth that is clearly visible in the original bathymetry data. The overall surface represents a generalized pattern of habitat use for whales, the whales may not respond to the presence of this small area and it may be a simply artifact of model building.

Frequency of Vessels

The 2006/2007 AIS data set shows a higher intensity of traffic around port entrances (Figure 6), with port of Jacksonville having the highest overall traffic. Higher use areas into and out of Jacksonville are identified in the frequency distribution. Reduced vessel frequencies outside the MSRS boundary is the result of more diffuse distribution of vessels as they leave ports and reduced reception from AIS broadcasting.

The major component of total vessel traffic in the AIS data includes cargo vessels (Figure 7) with the other three categories comprising a minority. Approximately 80% of the total trackline included in AIS data is cargo vessels. Tankers comprise approximately 13%. Of the included vessels types, only cargo vessels and tankers have been requested to use recommended lanes. Utility boats (4%) and others (3%) are not included in the recommendations.

Risk Index for Entire Season

The spatial distribution of the relative risk index for the entire right whale calving season strongly reflects the distribution of vessels. The highest risk occurs around the port of Jacksonville, where the confluence of a large number of vessels near the port entrance coincides with the more shoreward distribution of right whales. The intensity of vessel use of the port indicates higher risk along all of the areas utilized by mariners for access to and from Jacksonville. Likewise, areas heavily used by vessels accessing other ports are evident in the risk surface.

The sum of the relative risk index falling within the current recommended lanes was compared to the sum of the relative risk for the entire study area. Approximately 58% of all risk occurred within the recommended lanes given current levels of use.

Biweekly Habitat for Right Whales

Maps showing the probability of whale group sightings among the eight biweekly periods simulate the typical pattern of whale arrival, occupation, and departure from the SEUS during winter season (Figure 9). Generally, the progression begins early in December with an influx of pregnant females and mothers already with calves from the north, with arrivals getting more numerous in the latter half of the month. The number of right whale sightings in the SEUS continues to increase throughout January, with most females having borne their calves by this time. The distribution of whales extends further south into the end of the month. February generally has high numbers, with some retraction toward the north beginning to show during the second biweek. The progression of the whales back toward the north is evident through March, with few remaining by the end of the month.

The results of the Bayesian analysis of the right whale probabilities for biweekly averages across season are shown in Table 2. For logit models, the coefficients relate environmental variables to the log odds of the probability; however, the progression of the θ's does reflect the progression of the right whale probabilities throughout the season. The Bayesian model output provides the posterior distribution for each of the parameters, and so the standard deviation of the parameter values is derived from the distribution.

Biweekly Cumulative Relative Risk

A comparison of cumulative risk per biweek, based upon the progression of whales and the average vessel frequencies (not accounting for variance in vessels) is shown in Figure 10. The first biweek in December and the last biweek in March are equally low in total risk. The intermediate biweeks, the second in December and the first of March, are nearly equal, although risk in the second week in December is slightly higher. The middle two months, January and February, differ only slightly. The maximum cumulative index for the riskiest biweek, late January, is over three times that of early December and late March.

Table 2. Posterior means and standard deviations for parameters of the logit model for probability of whale sighting. θ_1 through θ_8 represent biweekly means for the logit model – although coefficients of the logit model relate to the log odds rather than probability, the progression of the mean relates to the progression of the whale distribution. The standard deviations of the posterior distributions are small, likely owing to the large amount of data used to inform the model. The 95% credible interval has a 95% chance of including the true parameter value.

Parameter	Mean of posterior distribution	Standard deviation of the posterior distribution	95% credible interval
θ_1 (December 1st – 15th)	-7.43	0.22	-7.85 — -7.07
θ_2 (December 15th – 31st)	-6.97	0.11	-7.02 — -6.76
θ_3 (January 1st – 15th)	-6.84	0.10	-7.06 — -6.66
θ_4 (January 15th – 31st)	-6.74	0.09	-6.93 — -6.54
θ_5 (February 1st – 15th)	-6.83	0.11	-7.05 — -6.62
θ_6 (February 15th – 28th (or 29th)	-6.81	0.10	-7.01 — -6.62
θ_7 (March 1st to 15th)	-7.30	0.13	-7.55 — -7.05
θ_8 (March 16th to 31st)	-7.64	0.23	-8.12 — -7.26
β_1	0.23	0.09	0.06 — 0.39
β_2	-0.64	0.09	-0.80 — -0.47
γ_3	-0.29	0.06	-0.40 — -0.18
γ_4	-0.59	0.08	-0.75 — -0.45

Changes in the relative risk index near the port of Jacksonville for a low and high biweek are illustrated in Figure 12. Relative risk is still highest near the port entrance when compared across the study region in early December (Figure 12a), but over the season, risk increases near the port, reaching a peak during the second biweek of January (Figure 12b). By January, high risk extends beyond the aid-to-navigation pilot buoy and risk near the port has nearly doubled.

To clarify the evaluation of changes in total relative risk, the study area was divided into four regions based loosely on port areas: Savannah, Brunswick, Fernandina, and Jacksonville (Figure 1). These sections were partially based upon traffic patterns associated with ports as well

as the recommended lanes, but are not meant to assign risk levels to any specific port. The sections provide a means of examining overall patterns of changes in relative risk both spatially and temporally within the study area. The sum of the relative risk index per biweek for each region is shown (Figure 13). Changes in total relative risk occur most dramatically in the southernmost, Jacksonville region, increasing three-fold from the temporal boundaries of the season to the highest right whale density periods January and February.

Discussion

Using the model of probability of right whale occurrence during the calving season and a representative year of AIS vessel data, we have developed a spatial and temporal simulation of risk of co-occurrence of whales and vessels in the SEUS. The overall habitat model provides a simulation of seasonal distribution of right whales, and clearly demonstrates their movements in and out of the SEUS during the calving season. Relating right whale distribution to habitat use, rather than an effort-corrected distribution, enabled the simulation of risk for this analysis because AIS vessel data were not contemporaneous with available whale sighting data (the most recent photo-identification data were from 2003 while the first year of AIS vessel tracking data was 2006). The spatiotemporal dynamic model produced here also enables researchers to predict future right whale distribution in the event of changes in the environment, such as may be associated with climate change.

Relating whale distribution to habitat variables also enabled us to simulate intra-seasonal changes in distribution for right whales in the SEUS. The overall seasonal distribution represents an average among the 12 seasons included in the study, as well as the variable distribution found throughout the eight biweekly periods. The intra-seasonal changes in distribution exhibited in the model contributed to increased risk during January and February, when typically the highest densities of right whales occur.

Spatial modeling enables assessment of spatiotemporal patterns in risk throughout a typical calving season. The greatest increase in risk toward the middle of the calving season occurs in the southern section of the study area, in the region encompassing the Jacksonville port. Because of the high intensity of the Jacksonville shipping traffic, the relative risk index is

high in the vicinity of the port entrance, even during the early and late part of the season when fewer whales are found in this area.

The AIS provides a greatly improved method for characterizing vessel traffic in the SEUS. The previous risk assessment (Fonnesbeck *et al.*, 2008) using the less precise MSRS data and coarse temporal (monthly) and spatial resolution (16 km^2), also found that risk was highest in the Jacksonville port area and, in general, at port entrances. However, although Fonnesbeck *et al.* accounted for annual and monthly variation in encounters in their estimates, temporal changes in risk (specific bi-weeks) were not compared and spatial aspects of risk included an assessment of current patterns (MSRS data) compared with estimates of risk from a set of hypothetical routes. The largest marginal gains in risk reduction were attained by restricting traffic on all ports, especially Jacksonville.

Because the AIS data used in this analysis represent the first year of the implementation of recommended shipping lanes (and speed reductions), use of these lanes may be lower in this data set (especially earlier in the 2006-2007 season) than in future years, as more mariners learn of the recommendations and become accustomed to using these lanes. At the present level of use, most of the relative risk in the study area occurred within the recommended lanes as expected. This research did not evaluate the changes in risk that would be associated with increased use of recommended lanes beyond the status quo, and may be better assessed with more than a single season of data. The concentration of risk in a small area would allow managers to focus greater aerial survey surveillance within a smaller area. The recommended lanes represent less than 6% of the study area. Concentrating aerial survey efforts in these areas when flight time is limited would envelope nearly 60% of the estimated risk within the study area at levels of use exhibited in this data set. Future risk assessments, as additional AIS data are collected, can be conducted using the same framework as developed here for comparison. Various proposed scenarios, such as the effects of increased use of recommended lanes, could be evaluated using this model.

Other trends observed in this study may not be consistent in future years. Intraseasonal temporal trends were averaged out of the data as we have no evidence that these trends would be similar among years. Other trends, such as the greater intensity of shipping traffic at the Jacksonville port, and greater intensity at port entrances are likely to be consistent among years.

Cargo vessels will likely continue to comprise a large portion of the vessel traffic, and therefore pose the greatest risk of co-occurrence with whales.

Although the whale habitat model simulates whale distribution throughout and across seasons, it cannot account for variability in whale numbers during a season. Relative risk of co-occurrence may be lower than estimated in the simulation model during years when fewer females are calving. During warmer years, calving females may spend more time along the mid-Atlantic shelf and may not make the entire migration to the SEUS. Future seasons will likely vary around averages produced by the model, depending upon additional factors which influence the number of animals that travel to the southeast in the winter from their northeastern feeding grounds and affect the population trajectory. Additionally, although survey effort was accounted for in the model, low effort in some areas could contribute to greater uncertainty of model parameters for the whale probability surface. Using the posterior distribution from the Bayesian hierarchical model allows us to postulate the uncertainty in the data, such as that would be associated with inter-seasonal differences, when predicting the averages on a biweekly basis.

Summing of the vessel tracks and using a frequency of vessels within the cells, allows us to create an index of relative risk to the right whale, but does not enable us to account for the uncertainty of vessel distribution for developing a predictive model with variance. Using the average as a hypothetical future surface does allow us to derive information that will be useful to management, such as for purposes of allocating aerial survey effort in areas of high risk.

Although cells of high relative risk were concentrated around pilot buoys, these areas may not entail the level of risk implied simply by the level of traffic. Traffic around pilot buoys may be moving at a reduced speed in order to pick up the harbor pilot or navigate into narrow channels, which may mitigate risk to whales. Reduced speeds likely reduce the severity of injuries to whales in the case of strike, however, reduced speed could potentially increase the risk of co-occurrence because of the increased time spent in the vicinity (Vanderlaan and Taggart 2006).

Pace and Silber (2005) and Vanderlaan and Taggart (2006) attempted to compare vessel strike speeds from a large whale vessel strike database (Jensen and Silber 2003) to non-strike vessel speeds from the Mandatory Ship Reporting data in the northeast. The most scientifically rigorous studies to date regarding the effects of speed, these probabilistic models investigated the severity of impacts to large whales with increasing vessel speed (Pace and Silber 2005,

Vanderlaan and Taggart 2006). In both studies, the probability of serious injury or mortality increased rapidly between speeds of 9 -10 knots and 14 -15 knots, and continued to increase slowly above that. Two corroborating studies provide the most convincing evidence available that reducing vessel speed may increase protection to whales by reducing severity of impacts. However, the sources of the two data sets (e.g., the large whale ship strike database and the MSRS data) are disparate on many levels, they do not provide metrics for goodness of fit, nor do they compare their models with alternative models (particularly a "no-effect" model). Nonetheless, careful interpretation of available literature does implicate speed as a factor in the severity of impacts to whales, and the threshold at which the rise in probability becomes steep is approximately 9-10 knots.

Our analysis does not address aspects of vessels or behavior of whales that may contribute to an actual collision in the event of co-occurrence of them both. No one is really sure why whales, at least is some cases, do not successfully evade oncoming vessels (Terhune and Verboom 1999). Right whales may be so frequently exposed to noise from vessels that they have become habituated to sounds (Nowacek *et al.* 2008), and may not recognize the significance until a vessel is too close for evasive maneuvers to be effective (Richardson *et al.*1995, Laist *et al.* 2001). Sound propagation underwater is complicated (Urick 1983, Nowacek *et al.* 2008,), and may contribute to collisions although right whales should be able to hear on-coming vessels (Richardson *et al.* 1995, Ketten 1998).

The two major alternative methods for reducing risk to right whales include re-routing vessels to avoid high density areas, and to reduce vessel speed in areas where whales may occur. Vanderlaan *et al.* (2008) showed that in northeastern habitats for right whales, significant reductions in risk of co-occurrence should result from proposed re-routing of vessels in that region. The extensive area right whales occupy along the southeastern coast in winter make it impossible to re-route vessels in the SEUS to completely avoid areas of high whale density. However, recommended routes were established to minimize risk and likely contribute to refining mitigation efforts, such as aerial surveys.

This analysis provides managers with baseline information for spatiotemporal evaluation of risk in the SEUS calving area. This framework will enable managers to plan future vessel management scenarios, explore effects of changes in environmental factors and shipping characteristics, and to more effectively design aerial surveys for effective and efficient vessel

strike mitigation. Average speed per cell per biweek would also contribute to the potential for evaluating risk in the SEUS, and work is ongoing to characterize speed data and incorporate it into the risk assessment.

Future work on this modeling approach should include additional whale-sighting, especially in under-represented areas of the area (i.e., northern Georgia) and additional AIS data. AIS data collection efforts near Savannah are underway and will enable us to collect consistent traffic information for that area. This will enable modeling of vessel traffic for improved prediction of future traffic scenarios, accounting for uncertainty in the analysis of vessel traffic and overall risk.

References Cited

Austin, M. P. 2002. Spatial prediction of species distribution: an interface between ecological theory and statistical modeling. Ecological Modelling 157:101-118.

Fonnesbeck, C. J., L. Garrison, L. Ward, and R. Baumstark. 2008. A Bayesian hierarchical model for evaluating the risk of vessel strikes on North Atlantic right whales in the southeastern United States. Endangered Species Research 6:87-94.

Fujiwara, M., and H. Caswell. 2001. Demography of the endangered North Atlantic right whale. Nature 414(6863):493-494.

Gelman, A., J. B. Carlin, H. S. Stern, and D. B. Rubin. 2004. Bayesian Data Analysis. 2nd Ed. Chapman & Hall/CRC.

Gibson, L. A., B. A. Wilson, D. M. Cahill, and J. Hill. 2004. Spatial prediction of rufous bristlebird habitat in a coastal heathland: a GIS-based approach. Journal of Applied Ecology 41:213-223.

Guisan, A., and N. Zimmerman. 2000. Predictive habitat distribution models in ecology. Ecological Modelling 135:147-186.

Hamazaki, T. 2002. Spatiotemporal prediction models of cetacean habitats in the mid-western North Atlantic Ocean (from Cape Hatteras, North Carolina, U.S.A. to Nova Scotia, Canada). Marine Mammal Science 18:920-929.

Jensen, A. S. and G. K. Silber. 2003. Large Whale Ship Strike Database. U.S. Department of Commerce, National Oceanic and Atmosphere Administration Technical Memorandum. NMFS-OPR-25.

Katona, S., and S. D. Kraus. 1999. Efforts to conserve the North Atlantic right whales. Conservation Management of Marine Mammals. J. R. Twiss, Jr., and R. R. Reeves (eds.). Pp. 311-331. Smithsonian Press, Washington DC.

Keller, C. A., L. I. Ward-Geiger, W. B. Brooks, C. K. Slay, C. R. Taylor, B. J. Zoodsma. 2006. North Atlantic right whale distribution in relation to sea-surface temperature in the southeastern United States calving grounds. Marine Mammal Science 22:426-445.

Keller, C.A., L. Garrison, R. Baumstark, L. I. Ward-Geiger, and E. Hines. in prep. Defining Calving Habitat for the North Atlantic Right Whale in the southeastern United States: An

Application of a Habitat Model.

Ketten, D. R. 1998. Marine mammal ears: an anatomical perspective on underwater hearing. In Joint Meeting of the Acoustical Society of America and the International Acoustical Society, Plenary Lecture. Seattle, WA.

Knowlton, A. R., and S. D. Kraus. 2001. Mortality and serious injury of northern right whales (*Eubalaena glacialis*) in the western North Atlantic Ocean. Journal of Cetacean Research and Management (Special Issue 2):193-208.

Kraus, S. D., K. E. Moore, C. E. Price, M. J. Crone, W. A. Watkins, H. E. Winn, and J. H. Prescott. 1986*b*. The use of photographs to identify individual North Atlantic right whales (*Eubalaena glacialis*). Pages 145-151 *in* R. L. Brownell, Jr., P. B. Best and J. H. Prescott, eds. Right Whales: Past and Present Status. International Whaling Commission, Cambridge, U.K.

Kraus, S.D., M. W. Brown, H. Caswell, C. W. Clark, M. Fujiwara, P. K. Hamilton, R. D. Kenney, A. R. Knowlton, S. Landry, C. A. Mayo, W. A. McLellan, M. J. Moore, D. P. Nowacek, D. A. Pabst, A. J. Read, and R. M. Rolland. 2005. North Atlantic right whales in crisis. Science 309:561-562.

Laist, D. W., A. R. Knowlton, J. G. Mead, A. S. Collet, and M. Podesta. 2001. Collisions between ships and whales. Marine Mammal Science 17:35-75.

Legendre, P. 1993. Spatial autocorrelation: trouble or new paradigm? Ecology 74:1659-1673.

Lehmann, A., J. McC. Overton, and J. R. Leathwick. 2002. GRASP: generalized regression analysis and spatial prediction. Ecological Modelling 157:189-207.

Lichstein, J. W., T. R. Simons, S. A. Shriner, and K. E. Franzreb. 2002. Spatial autocorrelation and autoregressive models in ecology. Ecological Monographs 72:445-463.

Moore, M. J., A. R. Knowlton, S. D. Kraus, W. A. McLellan, and R. K. Bonde. 2005. Morphometry, gross morphology and available histopathology in North Atlantic right whale (*Eubalaena glacialis*) mortalities (1970-2002). Journal of Cetacean Research and Management 6(3):199-214.

National Oceanic and Atmospheric Administration (NOAA), National Marine Fisheries Service. 2005. Recovery plan for the North Atlantic right whale (*Eubalaena glacialis*). National Marine Fisheries Service, Silver Spring, MD.

National Oceanic and Atmospheric Administration (NOAA), National Marine Fisheries Service.

2007. Proposed Rule to Implement Speed Restrictions to Reduce the Threat of Ship Collisions with North Atlantic Right Whales. Vol 71. Fed. Reg. 36299-36313 (to be codified at 50 CFR p. 224).

Nowacek, D. P., M. P. Johnson, and P.L. Tyack. 2004. North Atlantic right whales (*Eubalaena glacialis*) ignore ships but response to alerting stimuli. Proceedings of the Royal Society of London, B 271:227-231.

Pace, R. M. and G. K. Silber. 2005. Abstract. Simply analyses of ship and large whale collisions: Does speed kill? Sixteenth Biennial Conference on the Biology of Marine Mammals, San Diego, December 2005.

Redfern, J. V., M. C. Ferguson, E. A. Becker, K. D. Hyrenbach, C. Good, J. Barlow, K. Kaschner, M. F. Baumgartner, K. A. Forney, L. T. Balance, P. Fauchald, P. Halpin, T. Hamazaki, A. J. Pershing, S. S. Quian, A. Read, S. B. Reilly, L. Torres, and F. Werner. 2006. Techniques for cetacean-habitat modeling. Marine Ecology Progress Series 310:271-295.

Reeves, R. R., and E. Mitchell. 1986. American pelagic whaling for right whales in the North Atlantic. Report of the International Whaling Commission (Special Issue 10):201-220.

Richardson, W. J., C. R. Greene, C. I. Malme, and D. H. Thomson. 1995. Marine Mammals and Noise. San Diego, CA: Academic.

Russell, B. A. 2001. Recommended Measures to Reduce Ship Strikes of North Atlantic Right Whales. submitted to the National Marine Fisheries Service in partial fulfillment of NMFS contract 40EMF9000223. 31 pp. http://www.nero.noaa.gov/whaletrp/

Scott, J. M., P. J. Heglund, M. L. Morrison, J. B. Hauffer, M. G. Raphael, W. A. Wall, and F. B. Samson (eds). 2002. Predicting Species Occurrences: Issues of Accuracy and Scale. Island Press, Washington, DC. 868 pp.

Segurado, P., and M. B. Araújo. 2004. An evaluation of methods for modeling species distributions. Journal of Biogeography 31:1555-1568.

Segurado, P., M. B. Araújo, and W. E. Kunin. 2006. Consequences of spatial autocorrelation for niche-based models. Journal of Applied Ecology 43:433-444.

Terhune J. M. and W. C. 1999. Right whales and ship noise. Marine Mammal Science 15:256-258.

Urick, R. J. 1983. Principles of underwater sound. New York: McGraw-Hill.

Vanderlaan, A. S. M., and C. T. Taggart. 2006. Vessel collisions with whales: the probability of lethal injury based upon vessel speed. Marine Mammal Science 23:144-156.

Vanderlaan, A. S. M., C. T. Taggart, A. R. Serdynska, R. D. Kenney, and M. W. Brown. 2008. Reducing the risk of lethal encounters: vessels and right whales in the Bay of Fundy and on the Scotian shelf. Endangered Species Research 4:283-297.

Ward-Geiger, L. I., G. K. Silber, R. D. Baumstark, and T. L. Pulfer. 2005. Characterization of ship traffic in right whale critical habitat. Coastal Management 33:263-278.

Filecode 2658-2006-2008-F

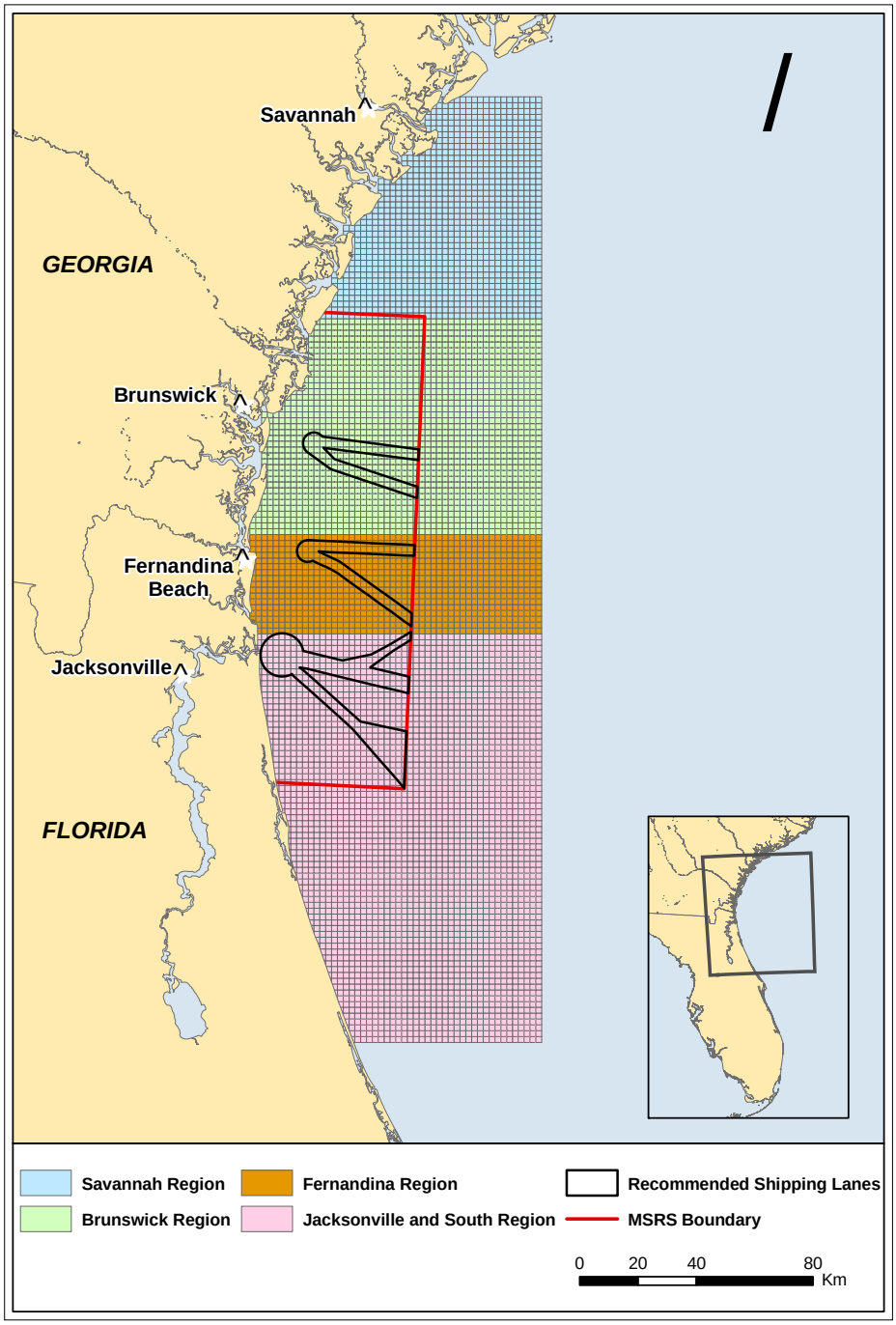


Figure 1. The Study Region and Area. Recommended shipping lanes are shown for Jacksonville, Fernandina, and Brunswick. Currently, Savannah has no recommended lanes. Port regions encompass recommended shipping lanes; Vessel traffic data used for this analysis also influenced regional determinations.

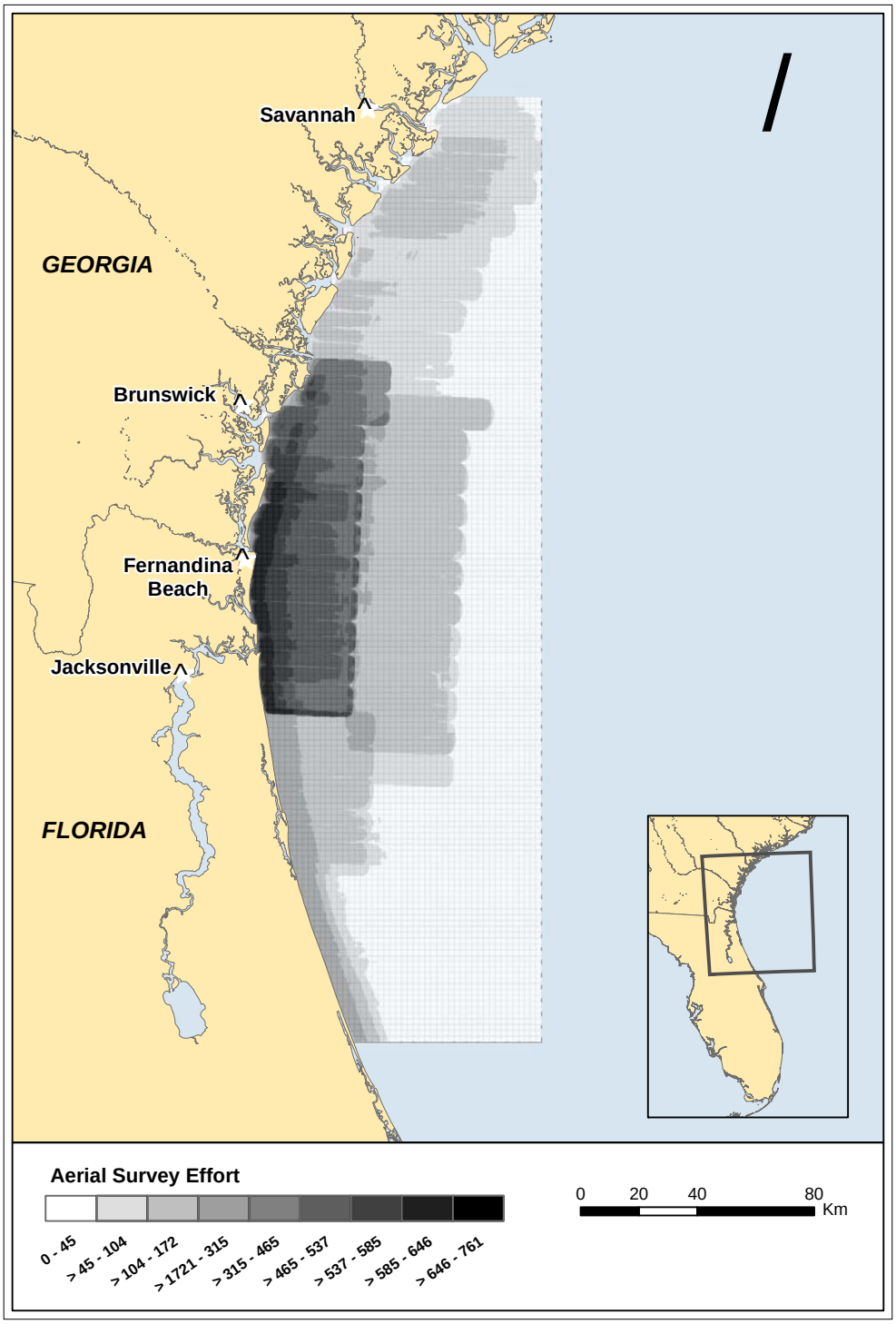


Figure 2. Total aerial effort for the study period from 1991 through 2003. Total aerial survey effort spatially varies within the study region. This was accounted for in the model using effort as an offset in the model.

a) b)

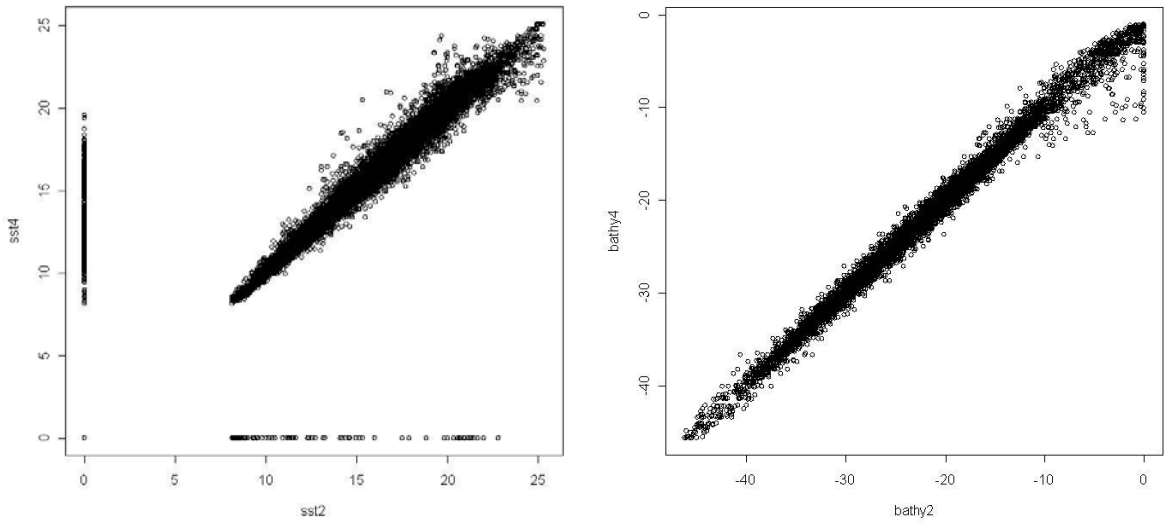


Figure 3. Scatter plots of environmental variables: a) sst and b) bathymetry of mean values per cell (and per biweek for sst) for 2x2-km resolution (x-axes) and 4x4-km resolution (y-axes). Most values correspond closely between the two data sets, however, scattered cells differ for sst between the two data sets throughout the most of the range of sst values and differ for bathymetry in the shallower depths.

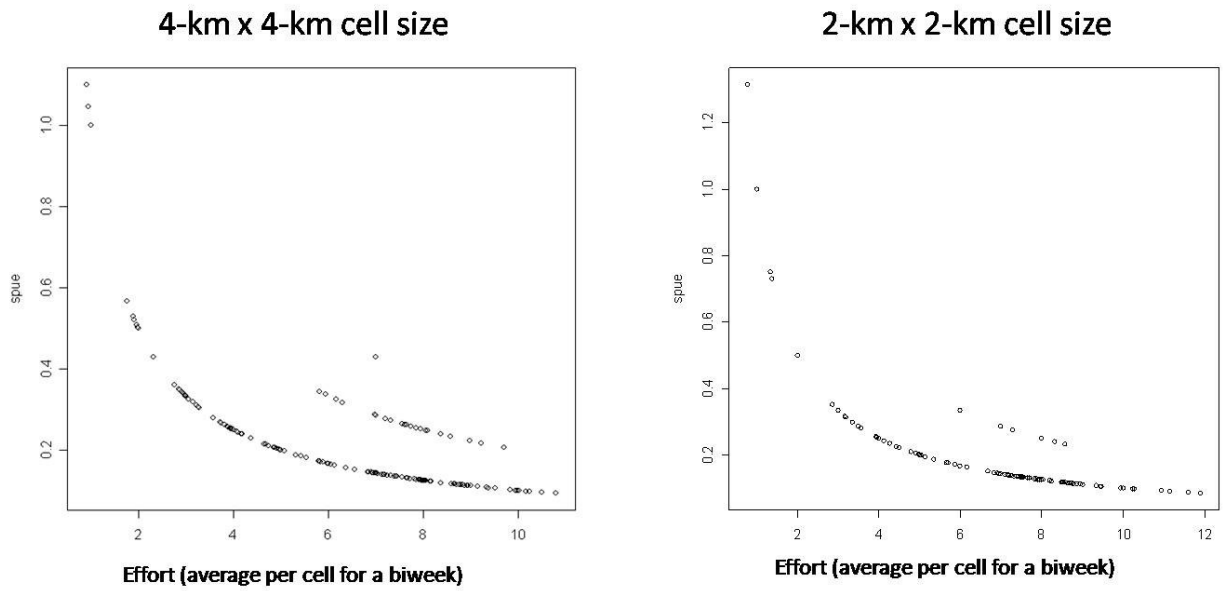


Figure 4. Scatter diagrams showing the relationship of sightings-per-unit-effort (spue) against the average effort aggregated at the two spatial cell sizes. Although the maximum spue is higher at 2x2-km cell size, the decline is smoother. The 2x2-km data appears to have fewer cells in which more than one group sighting occurs for a given biweek, indicated by the fewer number of points higher than the main trend line, which represents single group sightings per biweek per cell.

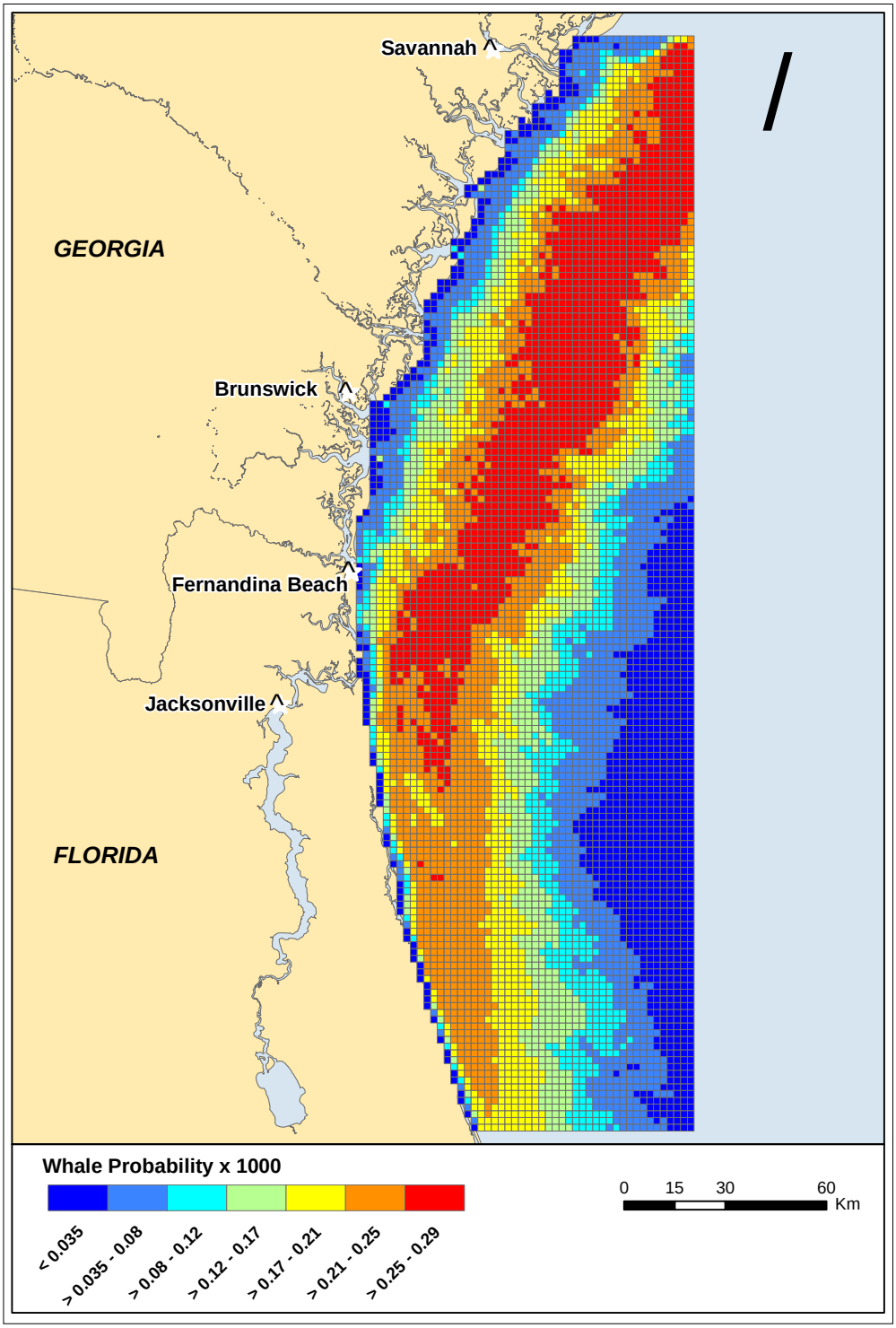


Figure 5. Probability of observing a whale group over season. Probabilities comprise the sum of probabilities (based upon mean covariates in the model) across seasons for all biweeks, normalized by the sum of all probabilities.

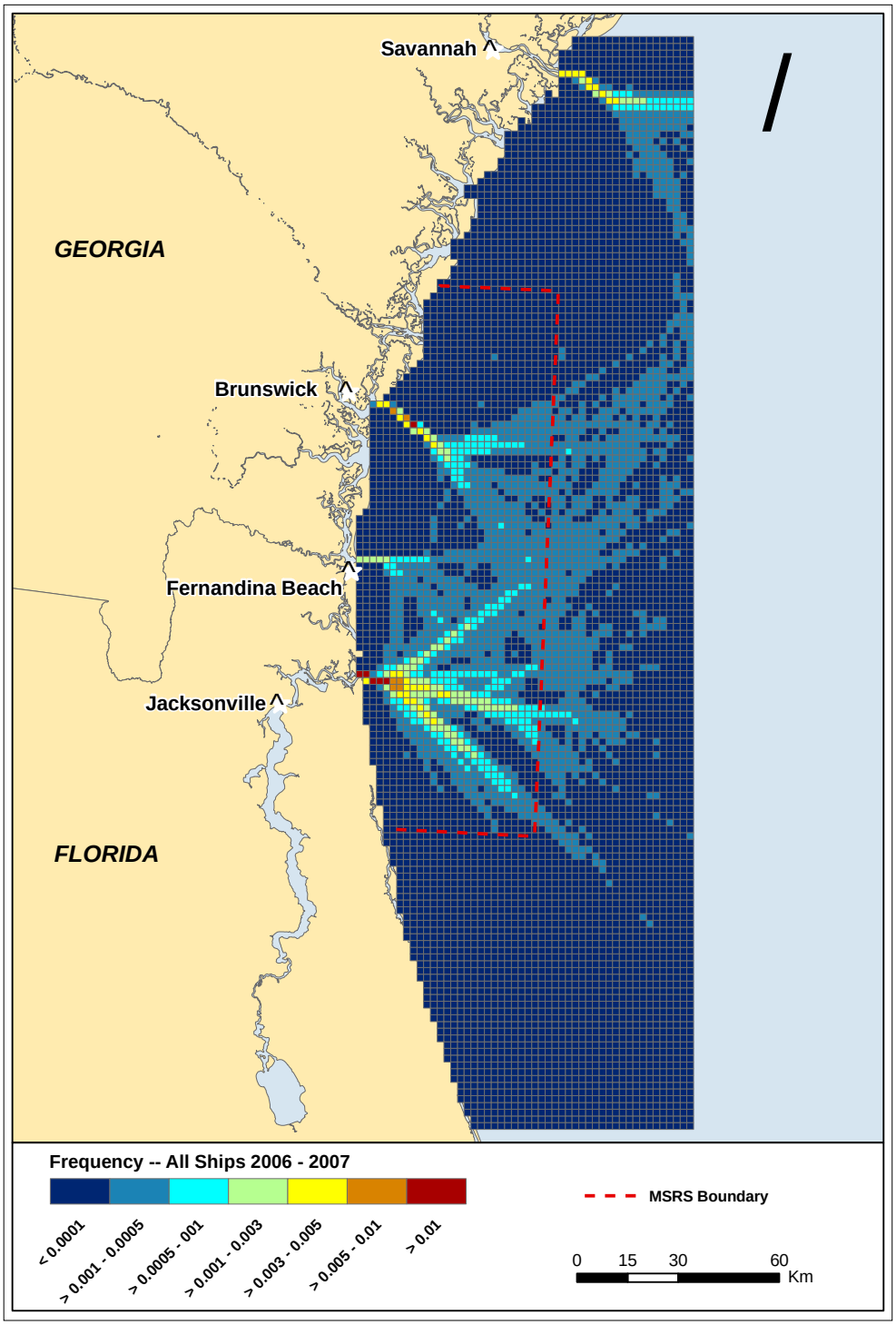


Figure 6. Overall frequency of ships of all types (greater than 65') within the study area for 2006-2007 right whale calving season. Maximum frequencies occur around pilot buoys and river entrances. Generally, higher risk occurs in proximity to the shipping lanes that receive the greatest use.

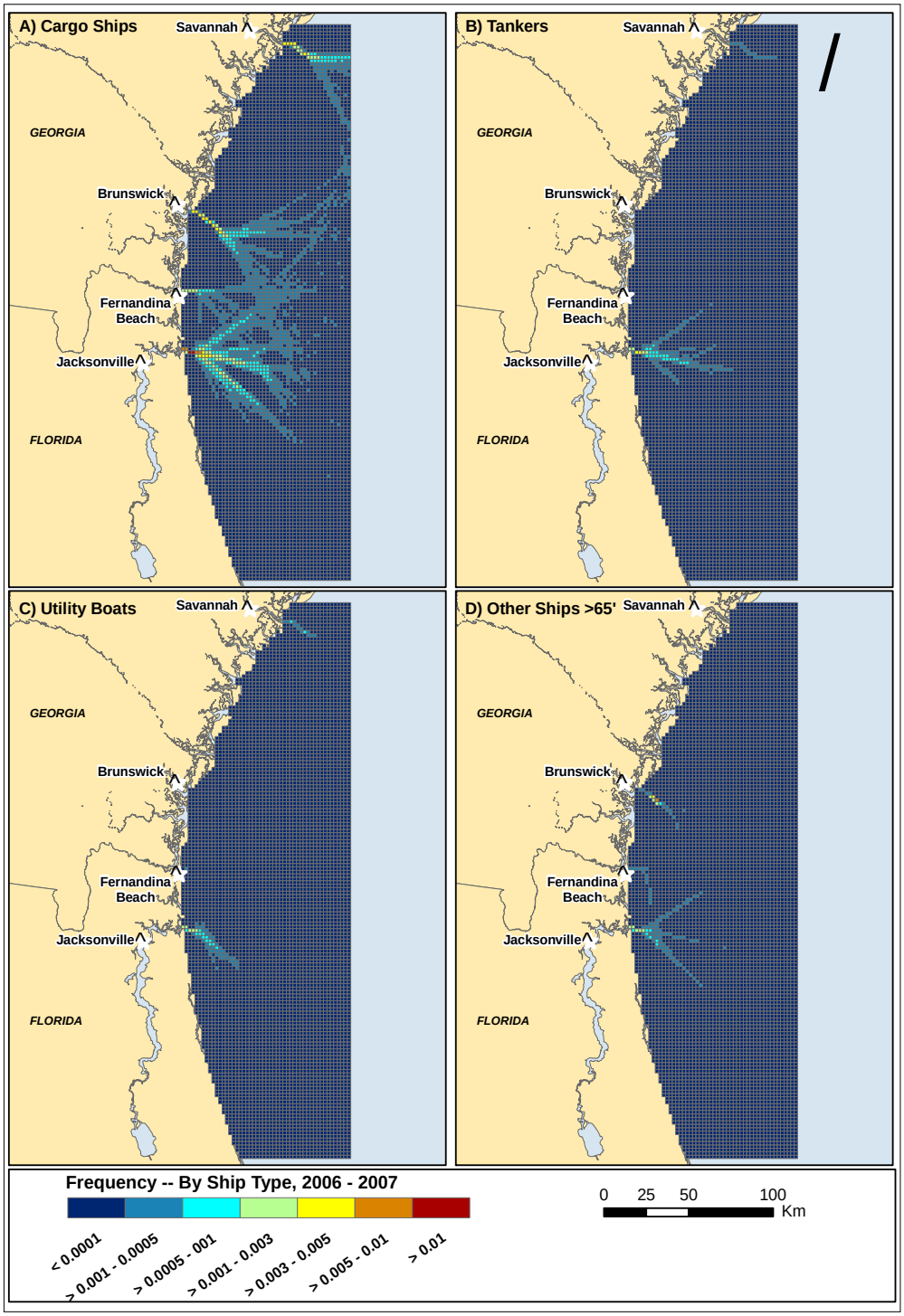


Figure 7. Frequency distribution of ships by type: A) Cargo, B) Tankers, C) Utility Boats, and D) Others > 65'. The greatest proportion of the total vessels in the data comprise cargo ships. Utility boats and others make up a very small percentage. Although recommended shipping lanes apply to cargo and tankers only, these data indicate that utility boats and others utilize shipping lanes as well.

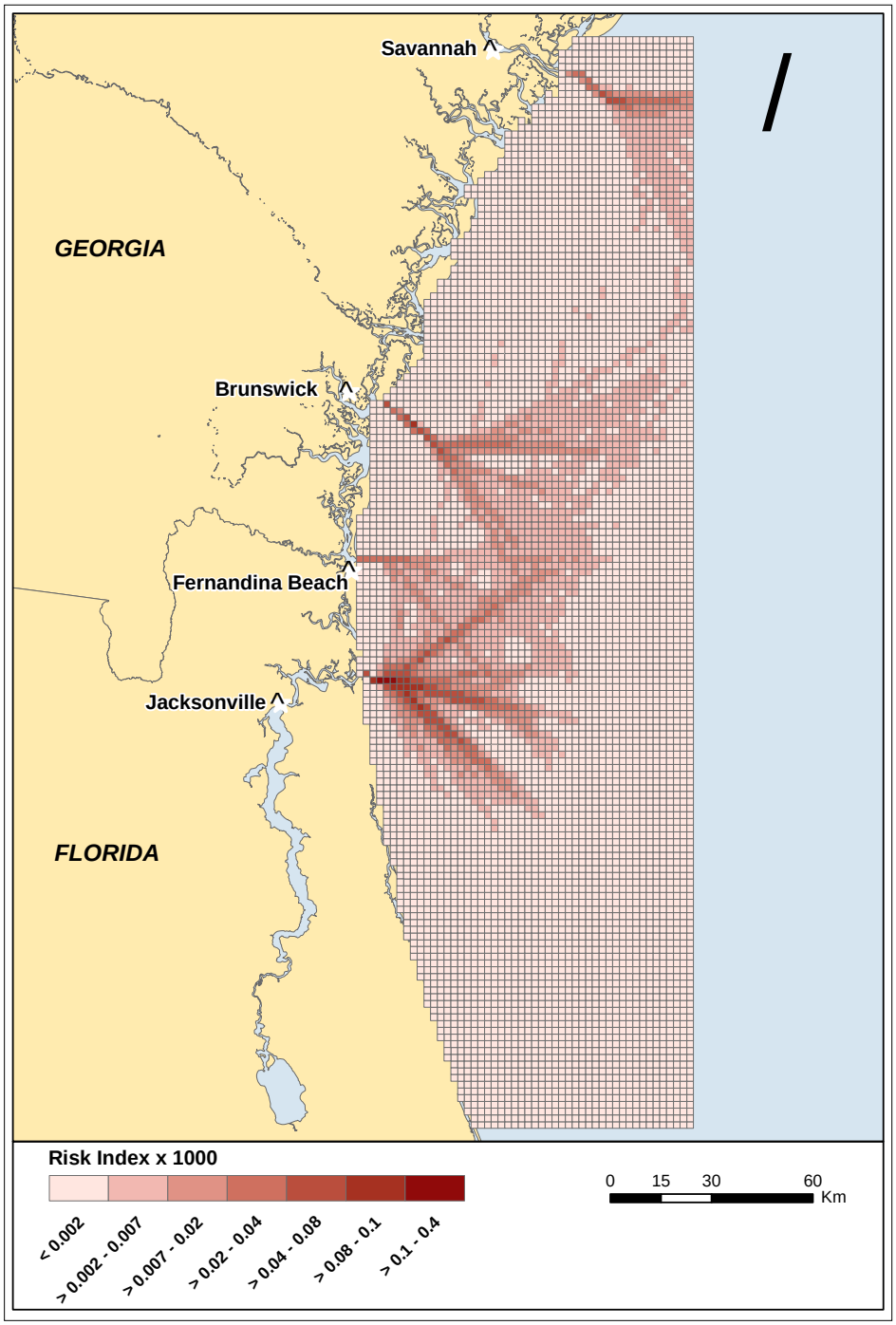
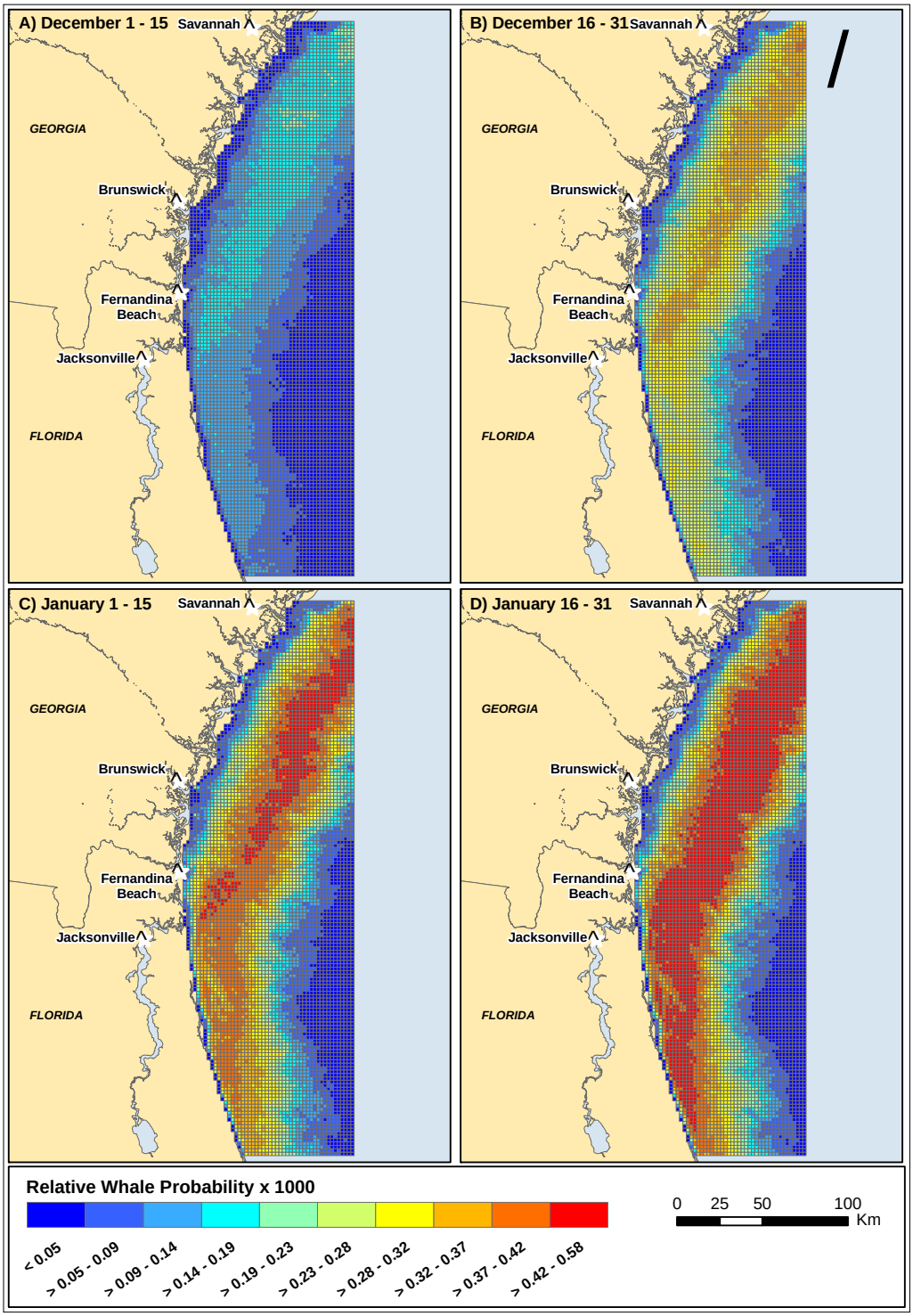


Figure 8. Relative Risk Index for Simulated Season. Relative risk index is the product of the sum of biweekly normalized probability of observing a whale group per cell multiplied by the total normalized frequency of ships during the 2006/2007 season. For any port, the highest risk, by far, occurs near the pilot buoy at the entrance to the port. Jacksonville represents the busiest port entrance in the SEUS Region.


A) December 1 - 15
B) December 16 - 31
C) January 1 - 15
D) January 16 - 31
Savannah
Brunswick
Fernandina Beach
Jacksonville
GEORGIA
FLORIDA
Relative Whale Probability x 1000
< 0.05
> 0.05 - 0.09
> 0.09 - 0.14
> 0.14 - 0.19
> 0.19 - 0.23
> 0.23 - 0.28
> 0.28 - 0.32
> 0.32 - 0.37
> 0.37 - 0.42
> 0.42 - 0.58
0 25 50 100
Km

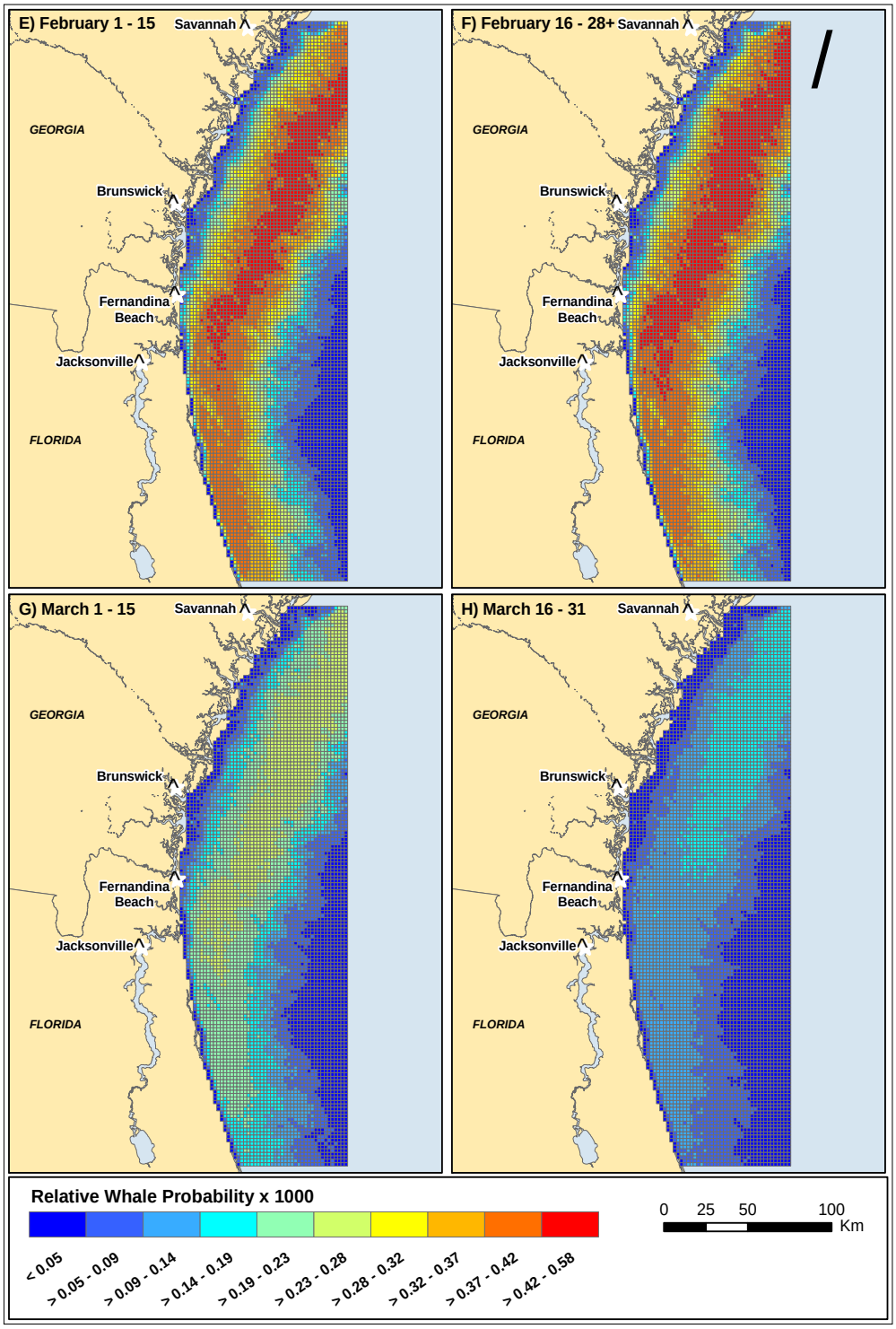

E) February 1 - 15
F) February 16 - 28+
G) March 1 - 15
H) March 16 - 31
Savannah
Brunswick
Fernandina Beach
Jacksonville
GEORGIA
FLORIDA
Relative Whale Probability x 1000
< 0.05
> 0.05 - 0.09
> 0.09 - 0.14
> 0.14 - 0.19
> 0.19 - 0.23
> 0.23 - 0.28
> 0.28 - 0.32
> 0.32 - 0.37
> 0.37 - 0.42
> 0.42 - 0.58
0 25 50 100
Km

Figure 9. The intra-seasonal progression of normalized probabilities for right whale distribution in the SEUS. Figures A) through H) shows the simulated progression of right whale distribution in biweekly increments throughout the four month calving season. Normalized probability is shown in percentiles. The influx of right whales throughout the month of December is exhibited by the low but increasing probability of observation throughout the month. In March, the progression of migrating whales to the north is also evident. The highest intensity occurs on average in the second biweek of January.

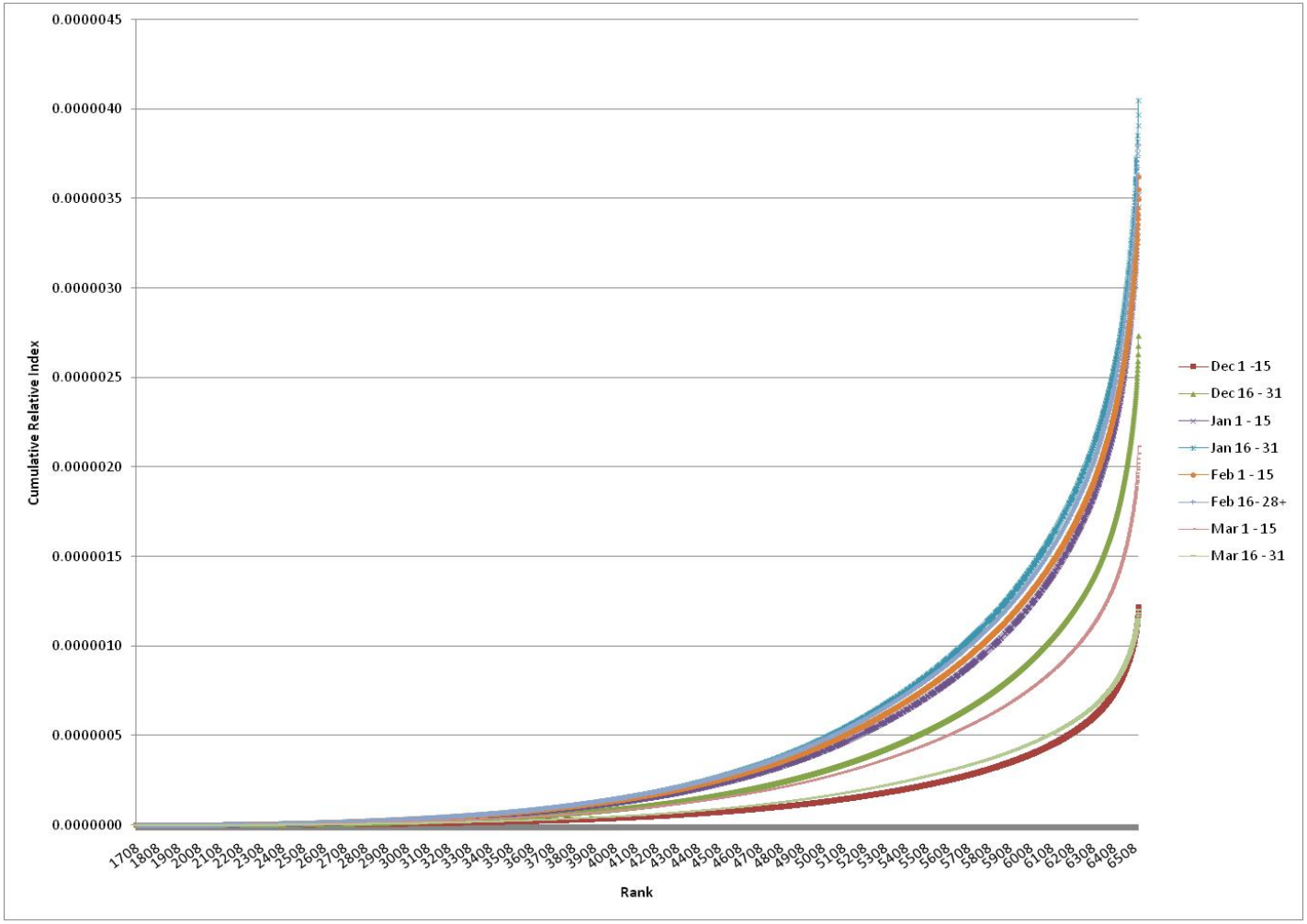


Figure 10. Cumulative Risk Index by biweeks. The first biweek of December and the last biweek of March each have the lowest levels of risk. The second biweek of December and the first biweek of March are lower than the all biweeks in January and February, with December slightly higher risk than March. The middle four biweeks are similar, exhibiting high cumulative risk. The last biweek of January exhibits the highest cumulative risk.

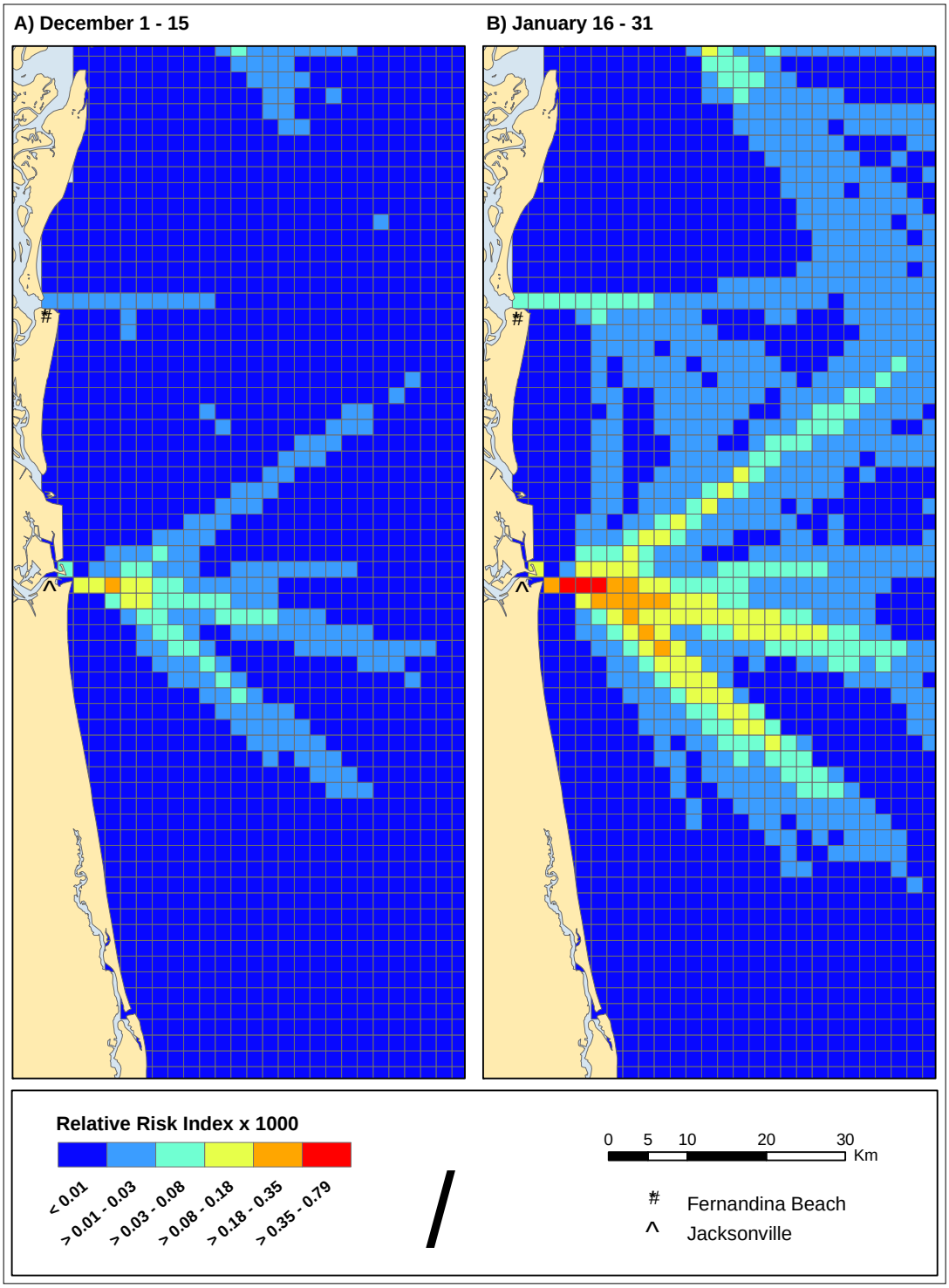


Figure 11. Inset of Port of Jacksonville, showing temporal changes in Relative Risk Index for December 1st – 15th as representing low risk and for January 16th to 31st, when risk of co-occurrence is at its highest.

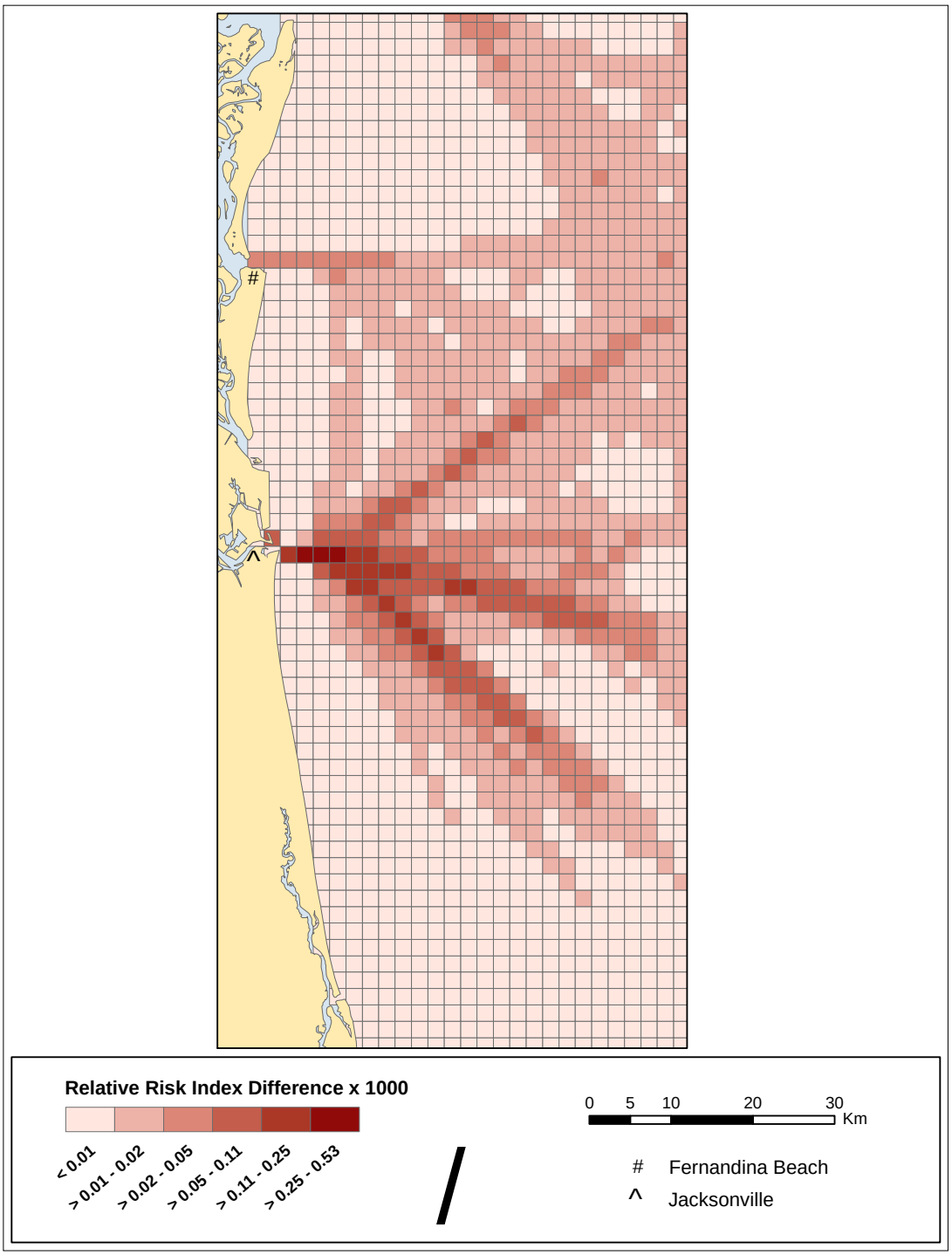


Figure 12. The increase in relative risk index from the first biweek in December to the second biweek of January based upon the simulated probability distribution of right whales on a biweekly basis and average biweekly frequency of vessel traffic.

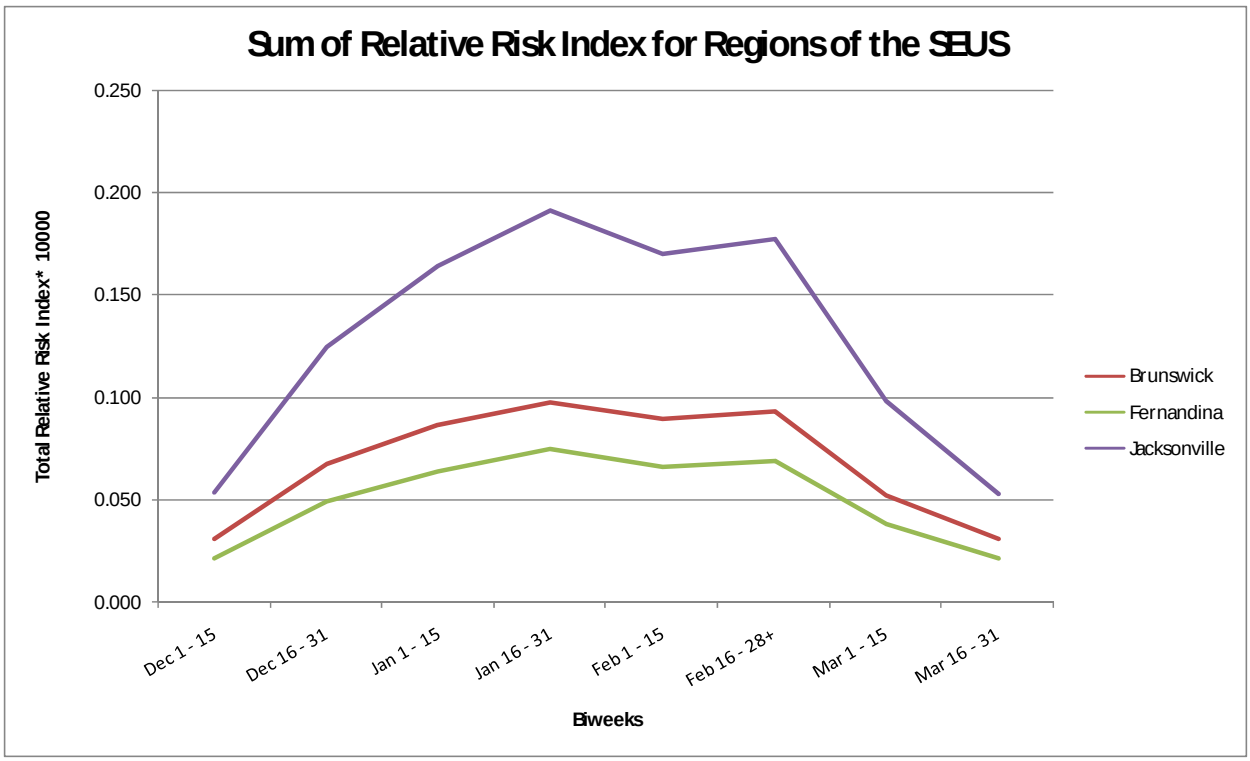


Figure 13. Changes in total relative risk index within regions throughout the season. Jacksonville is highest at all times of the season despite its southerly location where whale probabilities are relatively low in the early and late times of the season. The Jacksonville region shows the greatest increase in total relative risk index during middle months of the season when right whales are most numerous and concentrated further south than other times.