Chapter 27: Using WSR-88 weather radar to identify patterns of nocturnal avian migration in the offshore environment
Final Report to the Department of Energy Wind and Water Power Technologies Office, 2015

Evan M. Adams[1], Phillip B. Chilson[2], and Kathryn A. Williams[1]

[1]Biodiversity Research Institute, Portland, ME
[2]University of Oklahoma, Norman, OK

Project webpage: *www.briloon.org/mabs*

Chapter 27 Highlights

Estimating offshore nocturnal migratory activity of birds and bats using weather radar

Context[1]

While there is evidence of passerine and shorebird migration over the northwestern Atlantic for some species, oceanic flyways and migrant use of these offshore regions are poorly known. In part, this is because migration occurs over a broad spatial scale, and varies at a fine temporal scale, so efforts such as this project's boat and aerial surveys (conducted 7-8 times a year) may do a poor job of documenting migratory activity. Effective monitoring is particularly difficult for many terrestrial species that migrate at night.

An alternative approach is to use WSR-88D weather radar (also known as NEXRAD) to document migratory activity in the atmosphere. Migratory animals, from songbirds to waterfowl, are detected by these radar units over broad spatial areas. There are limitations to the distance and altitude at which migratory activity can be measured offshore, but the modeling approaches utilized in this chapter address these limitations and allow for less biased predictions of migratory activity levels at varying distances from shore. Precipitation events can interfere with the documentation of animal activities using radar, but our new analytical techniques provide the most accurate assessment of nocturnal migratory activity in the region to date.

Study goal/objectives

Examine the utility of NEXRAD weather radar for studying migration off the Atlantic coast of the U.S. from New York to North Carolina, assess offshore areas for consistent migratory activity, and determine how weather influences overwater migrations.

Highlights

- NEXRAD monitoring was successful in describing migratory activity at low altitudes over the ocean; often the units could detect birds 82 m above sea level. Sampling sites were located up to 80 km offshore.
- Weather interference was successfully removed from the NEXRAD data so that we could monitor offshore migration in a wider range of environmental conditions.
- Offshore activity was much higher in fall than spring. Areas south of Long Island had consistently high migratory activity in fall; activity offshore of the Carolinas was high in both fall and spring.
- Westerly winds promoted offshore activity in the fall, but not in spring. In fall, effects of wind changed with latitude: offshore activity in the northern part of the radar coverage area was highly dependent on westerlies, while offshore activity in the south was high regardless of winds.

Implications

There is good evidence that birds are regularly migrating overwater up to 80 km out on the mid-Atlantic Outer Continental Shelf. Given the levels of migratory activity predicted in offshore locations, regulators for offshore wind energy development may want to consider potential impacts to migrants in development scenarios, particularly in locations with consistently higher levels of migratory activity, such as the New York Bight and areas offshore of North Carolina.

---

[1] For more detailed context for this chapter, please see the introduction to Part VI of this report.

Abstract

Developed as a tool to monitor meteorological phenomena, weather surveillance radar regularly detects volant animals in the atmosphere, and is being increasingly incorporated into biological studies of migration patterns and movements. Understanding these patterns in open water environments is of increasing interest to regulators of offshore wind energy development, but these areas often have poor radar coverage in comparison to terrestrial areas of the United States. In this study, we aimed to create a robust statistical model that can be used to predict offshore migratory activity. Initially, we examine the utility of WSR-88D (NEXRAD) weather radar for studying migration offshore, specifically off the mid-Atlantic coast of the U.S. from New York to North Carolina. Then we compare migratory activity at sites over land and up to 80 km out to sea, controlling for variables that could affect measured levels of migratory activity, and we identify the environmental variables correlated with offshore activity.

After controlling for biases in measured levels of migratory activity, we found that in fall, there was no significant difference in migratory activity at offshore vs. terrestrial sites across the radar coverage area. This suggests that migration over open water areas may be quite common during this season. During fall, offshore activity was particularly high with west winds in the northern part of the study area (e.g., New York to New Jersey). There was less migratory activity offshore in spring than in fall, though there was some in the southern part of the radar coverage area (the Carolinas). There were high levels of daily variation in migratory activity related in part to wind conditions, but some offshore areas had consistently higher predicted activity levels, most notably the New York Bight (south of Long Island) and offshore of North Carolina.

Introduction

Weather radars such as the WSR-88Ds (also known as Next Generation Radar, or NEXRAD) are designed to detect the presence of hydrometeors such as rain drops, ice pellets, snowflakes, or hail stones in the atmosphere. These radars transmit radio waves (typically with wavelengths between about 3 and 10 cm) and receive electromagnetic energy scattered by these particles (Rinehart 2004). The time delay between when a pulse of energy is transmitted and the echo returns provides information about the distance, or range, of the hydrometeor from the radar. The power amplitude of echo signal is then used to calculate a product called the radar reflectivity factor (Z), which relies on several assumptions concerning the size, distribution, number of the hydrometeors along with their phase (liquid or solid; Chilson et al. 2012a). The bulk velocity of the collection of samples taken along the path of the transmitted and received radio wave is calculated by finding the change in phase angle of the electromagnetic signal with time.

Although developed as a tool to facilitate the monitoring of meteorological phenomena, weather surveillance radars regularly detect "bioscatter," or reflectivity caused by biological entities in the atmosphere, such as birds, bats, and insects (Chilson et al. 2012a), and are being increasingly incorporated into biological studies (Bridge et al. 2011; Buler et al. 2012; Gauthreaux and Belser, 2003; Shamoun-Baranes et al. 2014). A discussion of how these radars detect bioscatter and how the resulting backscatter can be used to make meaningful biological inferences has occurred in the open literature (Bridge et al., 2011; Chilson et al. 2012; Chilson et al. 2012a; Robinson et al., 2010).

Migration is a difficult phenomenon to study, in part due to the large geographic scale at which it occurs. The long-distance migration of many passerines, shorebirds, and other avian taxa also occurs at night and often at high altitudes, making visual observations difficult or impossible. For these reasons, weather radar can be an attractive approach for studying large-scale migratory movement patterns in volant taxa. Monitoring can be conducted at any time of day or night (weather permitting), which is a clear advantage for studying nocturnal phenomena, including migration and bat emergence from roosts (Chilson et al. 2012; Frick et al. 2012). As weather radar measures collective reflectivity of biomass in the aerosphere, it is also an effective way of monitoring populations whose individuals are too small-bodied to effectively track via satellite telemetry or similar approaches. Though they lack the fine scale resolution of traditional marine radar (e.g., Harmata et al, 1999, Brabant et al. 2012), NEXRAD data allow for efficient monitoring of spatial and temporal patterns in migration on a broad scale (Gauthreaux and Belser,2003), and may prove useful for developing a better understanding of environmental factors affecting migration and for identifying major migration routes.

Recently, methods have been developed to analyze NEXRAD data to estimate the relative abundance, direction of movement, speed, and altitude of migrants based on radar reflectivity data (Diehl et al. 2003; Horn and Kunz 2008). When multiple animals are present, radar reflectivity values express cumulative reflectivity per volume of sampled air. The size of an individual migrant can affect cumulative reflectivity; a goose, for instance, reflects back more microwaves than a warbler, so without knowing the identities of migrants, reflectivity alone cannot be directly translated to abundance of animals. However, reflectivity is directly correlated with biomass density (a combination of the number of individuals present in a given airspace multiplied by the average body size of those individuals) in the atmosphere, and as such can be regarded as an index of migratory activity at the measured altitude (Buler and Diehl 2009; Chilson et al. 2012a). It should be noted that with distance from the radar station, the average height of the volume of air sampled by the radar beam increases in altitude, and the power of the beam weakens. Thus it becomes increasingly difficult to detect low altitude and low density bioscatter with increasing range from the radar.

NEXRAD radars are located throughout the United States in order to provide comprehensive coverage for monitoring of meteorological phenomena (Maddox et al. 2002). However, monitoring of offshore areas is limited to coastal radars whose coverage partially extends into the marine environment. Perhaps as a result, the utility of NEXRAD data for predicting migratory patterns in the marine environment is relatively unstudied, though it has been examined in the Great Lakes, where radar coverage is more comprehensive (Diehl et al. 2003). One of the only studies to examine this topic was focused on areas offshore of New Jersey, as part of a baseline study of offshore wildlife in relation to future offshore wind energy development (Geo-Marine Inc. 2010). Data from the KDIX radar, located in Mount Holly, New Jersey, indicated that migratory activity was substantially greater in coastal than offshore areas, although this study did not fully account for the relatively poor and high altitude-biased coverage available offshore (since those areas were located farther from the radar). Migratory activity in coastal areas of New Jersey was highly variable from year to year, but was two to three times greater during fall migration than in spring (Geo-Marine Inc. 2010).

Based on this and other studies of NEXRAD radar and migration, we suggest that the variables that influence migratory activity at a given site (or our ability to detect that activity using radar) include:

- Site characteristics, such as the distance and of the site from the coast, and whether the site is on- or offshore;
- Relationship of the site with the NEXRAD station, such as the distance of the site from the nearest radar unit, and which unit that site is closest to;
- Temporal variables, such as time of year, season, and year; and
- Weather, such as wind speed and direction.

In this study, we examine the utility of NEXRAD data for studying migration offshore, and specifically off the Atlantic coast of the U.S.; we compare NEXRAD migratory activity at land and water sites, controlling for variables that could affect measured levels of migratory activity; and we identify potential offshore migration pathways and timing, as well as the environmental and temporal variables correlated with these patterns. The study area for this effort, hereafter referred to as the "radar study area," includes locations from New York to North Carolina, a broader geographic range than the mid-Atlantic study area discussed in previous chapters. This expanded area was examined due to poor NEXRAD coverage of the Outer Continental Shelf (OCS) offshore of Maryland and Virginia. Because direct assessment of some habitats in the mid-Atlantic study area was impossible, we chose to describe offshore migration more broadly along the mid-Atlantic eastern seaboard. The objective of this analysis is to create a robust model that can be used to predict offshore migratory activity across the radar study area in relation to topography and environmental conditions. This model may prove useful for understanding the potential interactions between nocturnal migrants and offshore wind energy development along the Atlantic coast of the United States.

A short primer on weather radar and uses in aeroecology
Radar data used for this study were stored at the National Oceanic and Atmospheric Administration's National Severe Storms Laboratory database, housed at the National Weather Center on the University of Oklahoma (OU) campus. Radar reflectivity factor (Z) data from all WSR-88D sites in the NEXRAD network for the contiguous United States (CONUS) are combined to create a mosaic GeoTIFF file for each of six subdomains (tiles)[2]. The mosaicked data are stored as both "quality-controlled" (reflectivity values believed to have originated from non-meteorological sources have been removed) and "un-quality-controlled" files (all sources of radar backscatter are present, including bioscatter). The quality-controlled data are available as 3-D fields and as 2-D raster projections onto the Earth's surface. When constructing the projections, the maximum available reflectivity value in height for a particular raster element in the 2-D projection is used. This is called a composite reflectivity (CREF). Composite reflectivity projections consisting of the un-quality-controlled data are also available ("UNQC_CREF" data), though no 3-D data are stored for the un-quality-controlled fields. CREF and UNQC_CREF have a spatial resolution of 0.01° x 0.01°. Prior to mid-2013, they were stored every 5 minutes; since that time period, CREF and UNQC_CREF have been stored every 2 minutes.

---

[2] http://nmq.ou.edu/

Figure 27-1 and Figure 27-2 show UNQC_CREF data for 2000, 2300, 0200, and 0500 EDT for May 1, 2011 and September 1, 2011, respectively. For both months, 2000 EDT corresponds approximately to the time of sunset along the Atlantic coast of the United States. This can be seen by the strobes of high reflectivity directed roughly towards the west. These are "sun spurs" created by the radars' detection of radiation from the setting sun. In the September image, the sun spurs occur further west, indicating that the sun had already set along the coast at 2000 hours. Other spurious echoes can also be seen in the radar images; as the UNQC_CREF data have not been quality controlled, they contain such effects as sun spurs, radio interference, ground clutter, sea clutter, and bioscatter, as well as precipitation features. For bioscatter, one expects to see the signal diminish with range from the radar, since the biological entities are predominantly near the earth's surface. The bulk of the reflectivity data seen in Figure 27-1 and Figure 27-2, especially at night (2300 and 0200 hours) is the result of nocturnal migrants in the atmosphere.

Generally speaking, the minimum height of the atmosphere that can be probed by a fixed location radar increases as a function of range from the radar for a given antenna elevation angle. There are five primary contributing factors to the minimum height of the radar beam above ground level: 1) antenna elevation angle; 2) antenna beam width; 3) curvature of the Earth; 4) thermodynamic properties of the atmosphere, which affects refraction; and 5) the local topography. The culmination of the first four effects is depicted in Figure 27-3. Since biological scatter is expected to primarily occur near the Earth's surface, only the lowest elevation angle (0.5°) is depicted in the figure. The sample volume for weather radar is usually based on the 3-dB (half power) width of the beam (Figure 27-3). However, biological scatterers can have relatively large cross sections, making them quite "bright" to the probing radar, and thus correspondingly easily detected at lower powers (Chilson et al. 2012a). Therefore, we elected to use the 6-dB point when assigning the beam width for this study.

Methods

Radar data collection

CREF and UNQC_CREF data from the National Severe Storms Laboratory were transferred to a computing cluster at OU explicitly dedicated to processing and analysis of radar data for aeroecological applications. Six WSR-88D sites along the east coast of the United States were selected for this study (Figure 27-4):

- KOKX (Upton, NY: 40.8656 N, 72.8647 W)
- KDIX (Mt. Holly, NJ: 39.9469 N, 74.4111 W)
- KDOX (Dover Air Force Base, DE: 38.8256 N, 75.4400 W)
- KAKQ (Wakefield, VA: 36.9839 N, 77.0025 W)
- KMHX (Morehead City, NC: 34.7761 N, 76.8767 W)
- KLTX (Wilmington, NC: 33.9892 N, 78.4292 W)

Twenty-four sampling sites were chosen around each radar, for 144 sampling sites in total. Data processing for these sites was initialized according to the workflow outlined in Figure 27-5. Sites were located in three concentric rings, centered at the radar, with radii of 30, 60, and 90 km (similar to Williams et al. 2013).

Along each ring a sampling site was located on the eight cardinal and intercardinal compass positions (Figure 27-4). This configuration of sampling sites allowed us to examine potential differences in biological activity at sites that had approximately the same radar beam height (because they were the same distances from the radar), but had differing characteristics in other respects (such as location over land vs. water). The non-uniform distribution of NEXRAD units across the eastern coast of North America led to coverage gaps in the mid-Atlantic OCS, particularly off the coast of Maryland and Virginia.

For all reported data, radar reflectivity factor values (Z), which are used for hydrometeors (e.g., for weather detection), were converted to the more biologically relevant metric of reflectivity η ("eta"), or scattering area per unit of volume (cm^2 per km^3; Chilson et al. 2012b). Log transformations of reflectivity data are common practice in the field of radar aeroecology to normalize reflectivity data for analyses (Chilson et al. 2012b). When values of η are log-transformed with a reference value of $\eta_o = 1$ cm^2 per km^3, the resulting quantity is known as dB η. The log-transform follows the relationship: dB η = $10*\log_{10}(\eta/\eta_o)$, so a value η = 1000 cm^2/km^3 is equivalent to a dB η of 30.

We developed tools in MATLAB and open-source Geographic Information System (GRASS GIS[3]) to process four years of May, September, and October NEXRAD reflectivity radar data, weather data, and the vector images for the 144 sites (2010-2013). Data used for the analysis were the raster CREF and UNQC_CREF files. For each of the 144 sample sites, a localized collection of raster elements were extracted (Figure 27-6), and the combined data were averaged in time across a six hour time period centered around midnight for each sampling date. These averages were used when calculating the spatial univariate statistics of dB η (e.g., the minimum value to reduce the chance of spurious high reflectivity radar interference in the 5 minute interval) for both CREF and UNQC_CREF data for each site and time step. The results were written to a CSV file (Figure 27-7). Dedicated computer resources for aeroecological applications with multi-core processing capabilities were assigned to this processing-intensive task. When no other processes were running on these computer resources, it required 2-3 days to process one month of radar data for a single file type (CREF or UNQC_CREF).

To the extent that the quality control procedures developed by the National Ocean and Atmospheric Administration (NOAA) are accurate, the CREF data should only contain reflectivity signals created by weather. Since weather signals generally mask or obscure the presence of bioscatter, it is common to only use weather radar during clear conditions when conducting biological studies. Often, researchers will discount entire radar scans if any precipitation is present within any spatial region or time of the scan (e.g., Geo-Marine Inc. 2010). As an alternative, we developed a method in MATLAB which the CREF data were used to "mask" the times and locations corresponding weather from the UNQC_CREF data, allowing preservation of the remainder of these scans for analysis (Figure 27-8). The resulting combined data (univariate outputs for each site and each time step after masking) were used for the remainder of data processing.

---

[3] http://grass.osgeo.org/

Covariates

For each site, we identified four static explanatory variables (radar unit, distance from radar unit, site type, and distance from shore). Each site's latitude and longitude were included as continuous variables. Sites were located in sets of eight, at 30 km, 60 km, or 90 km from each radar, with distance band and radar unit included as a categorical variable for each. Each site was classified as to whether it was over water or over land (site type), and how far away it was from the coastline, using the National Land Cover Database (2011) in ArcGIS 10.3 (ESRI, Redlands, CA). Negative values indicated the site was over land (inland from the coast) and positive values indicated the site was over the ocean.

Weather covariate data were collected and compiled from airports and buoys located in proximity to the 144 study sites for the spring and fall migration seasons from 2010-2013. Using package 'weatherData' (Narasimhan 2014) in the R Statistical Computing Environment (R Core Team 2014) we gathered weather data from 1900-2400 EDT each day from a weather station at each of the NEXRAD units. For each day, we collected wind speed and wind direction data, and linearized the circular direction data into two vector components: U wind (East/West, with westerlies, or eastward winds, taken as positive) and V wind (North/South, with northerlies, or southward winds, taken as positive). We then used the median U and V value for each evening. The 24 sites associated with each radar unit were assigned values of dynamic variables from the weather station at that radar unit. Calendar date and year were also included in models.

Generally, we included a variable in a model because (1) it was involved in a hypothesis that explained migratory activity, or (2) it was a variable that confounded our ability to understand the biological explanations for these patterns. Variables of the second type, or "nuisance" variables, included year, calendar date, elevation (the ground can clutter radar reflectivity and alter migratory patterns), and distance from the radar unit (as previously discussed, the beam has lower reflectivity and increased elevation with distance). Site type was also included as an explanatory variable in weather models, specifically to allow weather patterns over land and water to lead to different kinds of radar interference. All other variables were used to explore how time of year, weather and distance from shore influenced migratory activity.

Modeling bioscatter

To determine where animals migrated offshore in the mid-Atlantic region, and the conditions under which they migrated, we used a total of four different general linear mixed models (two each for the spring and fall migration seasons). Average reflectivity (dB η) was paired with static and dynamic explanatory variables for each site and date. Reflectivity is a normally distributed variable (as it is already converted to the logarithmic dB scale to normalize the data), so the Gaussian family was used with an identity link using package "lme4" in the R Statistical Computing Environment (Bates et al., 2014). Each model was tested for overall fit by withholding 20% of the data, and comparing predicted responses using the model to actual responses in the withheld data.

We used two different models to describe migratory activity: a "spatial" model designed to examine general patterns of migratory activity at sites across the radar study area (in relation to static covariates), and a "weather" model that explored the day-to-day variation in migratory activity across all

sites. The spatial model was designed to quantify the geographic variation in dB η across the 144 sites. Calendar date, year, and site were used as random variables to account for unexplained variation in reflectivity across space and time. The fixed effects in the model were the radar unit, distance to shore (modeled as continuous), distance to the radar hub (a categorical variable, as sites were located in three distinct distance bands), and the average elevation of the site. We added interactions between radar and distance to shore to account for potential differences in inland versus open water migration patterns for each radar unit (e.g., to help account for differences in migration patterns related to local topography and sites' positions relative to the coast). Once we controlled for nuisance variables like distance to radar and elevation, we then used this model to predict the average dB η values for each site in both seasons.

In the weather model, we wanted to focus on how weather was influencing the amount of bioscatter over the ocean across the radar study area. Site and year were included as random effects (the inclusion of date as a random effect over parameterized this model). Radar unit, distance from the radar hub, elevation, and site type were used as fixed effects. We also included two high level interactions, and all of their parent base effects and interactions, to predict the effects of winds on offshore dB η at various latitudes in the study region: 1) two-way interactions between east/west wind, distance to shore, and latitude; and 2) two-way interactions between north/south wind, distance to shore, and latitude. These interactions allowed us to explore variation in the numbers of animals over the ocean with regards to both the local winds during migration and to sites' positions along the coast. Longitude was also included as a base effect, but was not interacted with other variables due to a correlation with latitude and distance to shore in our models. To test for significance, we calculated the 95% confidence intervals of the individual parameters using a parametric bootstrapping method in package "lme4" and a likelihood ratio test for groups of effects (e.g., radar unit).

Results

Assessment of the utility of radar data for measuring migratory activity offshore
We calculated the predicted beam height as a function of distance from a given radar unit (Figure 27-3). This plot assumes that the Earth is perfectly round (which is not accurate, but provides a reasonable approximation of the earth's curvature) and takes into account the effect of refraction as the beam propagates through the atmosphere (assuming standard atmospheric conditions). We projected predicted beam height values onto the radar study area, and used digital elevation maps with ArcGIS and GRASS to calculate the lowest detectable beam heights for all 24 points at each of our six focal NEXRAD stations (Figure 27-9). While water sites tended to be farther away than land sites (because the radar units are positioned over land), the minimum beam height did not appear to be high enough to be a limiting factor in analyses; the average minimum beam height at which we could expect to detect bioscatter at our 144 sites was 82 m (Figure 27-9), and the highest minimum beam height for our sites was 226 m. There was little variation in minimum beam height among the six units, likely because there are few major elevation changes in this region of the United States.

To test our ability to detect bioscatter at the selected NEXRAD stations, we selected a particularly active night in spring migration (May 1, 2011). On this night, migratory activity erupted at sunset and tapered off

as the night progressed (Figure 27-1). Weather was mild on this evening, though rain showers appeared in the final two frames at 06 and 09 UTC (0200 and 0500 EDT). Bioscatter was clearly detectable throughout the night. Reflectivity decreases with distance from the NEXRAD unit, due to decreasing beam power, and this remains a confounding factor in this visualization. However, biological scatter was detected at least 60 km from the radar over land on this date, so we expect that bioscatter would also be detected over water if it occurred within this range (at least within the range of beam heights defined in Figure 27-3 and Figure 27-9). Indeed, during a night of fall migration (September 1, 2011), bioscatter clearly occurred over the ocean to the south of KMHX (Figure 27-2).

We compared migratory activity over land and water at sites that were the same distance from the radar unit on the same date (May 1, 2011) for the two North Carolina radars (Figure 27-1). Bays and inlets were treated as "land" in this analysis, rather than being lumped with open ocean locations. The KLTX unit had more activity overall than the KMHX unit on this date, and migratory activity was consistently higher over land than water for both these radar units. The innermost eight sampling points for each of the units showed a rapid increase of activity at sunset over land sites (also called "migratory exodus") as migrants left terrestrial habitats to begin their nocturnal flights (Gauthreaux and Belser, 2005); this exodus activity did not occur at water sites (Figure 27-10). Where there was activity over water, it occurred later in the evening. While activity over the open water was low on this particular night in 2011, our analysis suggests that this was due to a lack of overwater bioscatter rather than to biases in detection.

Analysis of migratory activity offshore: Fall
The spatial and weather models had 0.71 and 0.63 Pearson correlations, respectively, between the known response and predicted response in the withheld data, which indicated a reasonable model fit. Residuals for both models also qualitatively appeared to be randomly distributed, suggesting good overall fit.

In the spatial model, we found that radar unit and distance to the radar unit were important to predicting dB η levels, as well as the interaction between radar unit and distance of the site to the coast (Table 27-1). The random effect of date explained 17.9% of the total variance in the model, while site was less important, only explaining 5% of the variance. dB η decreased at 60 km (β=-6.6; 95% Confidence Interval=-7.0, -6.2) and 90 km (β=--6.0; 95% CI: -6.4, -5.6) away from the radar hub when compared to sites in the 30 km band (where β is the estimated effect of the variable on reflectivity and the confidence interval is the range in which we are 95% certain that this parameter value is contained). Radar unit was also important (F_5=6.7), with KLTX showing more activity (β=1.0; 95% CI: 0.3, 1.7) than the other units. Distance to shore was not significant as a single effect or in an interaction with radar; effectively, the model could not distinguish between sites on- or offshore in terms of reflected bioscatter during fall, suggesting that migratory activity was similar onshore and offshore within the radar coverage area. Elevation of the site had a positive effect on dB η (β=7.3E-3; 95% CI: 4.9E-5, 1.5E-2).

After correcting for biases due to elevation, radar unit, and distance to the radar, the model predicted considerable migratory activity offshore in the fall (Figure 27-11). There was no apparent decrease in bioscatter signal over the ocean on average, though there was wide variation in migratory activity levels between locations along the coast. Sites offshore of Long Island and coastal North Carolina appeared to

have higher levels of migratory activity over water, on average, than locations off the New Jersey and Delaware coasts.

In the fall weather model, we found that in addition to radar unit and distance to the radar, weather and relative spatial position was also important to determining when birds were migrating offshore (Table 27-2). Site and year only made up 6% of the total variance in the model. Radar reflectivity was influenced by significant interactions between U wind and latitude (β=2.1E-3; 95% CI: 8.7E-3, 2.6E-2), U wind and distance to shore (β=1.1E-7; 95% CI: 8.1E-7, 2.3E-6), and V wind and latitude (β=-9.1E-3; 95% CI: -1.5E-2, -3.9E-3). Westerly winds led to more offshore activity at all latitudes, but particularly in the northern part of the radar study area (New York/New Jersey). In the southern part of the radar study area (the Carolinas), offshore activity was equally high in westerlies and easterlies, but activity levels varied in terrestrial areas (Figure 27-12). The positive effect of northerly winds on reflectivity at higher latitudes was primarily true onshore (Figure 27-13); offshore levels of bioscatter were predicted to be the same regardless of North-South winds. The opposite was true at lower latitudes within our radar study area, where strong northerlies led to decreases in offshore activity relative to onshore activity.

Analysis of migratory activity offshore: Spring
Model fit during the spring was good, with the spatial model showing a 0.78 Pearson correlation between known and predicted response for the withheld data, and the weather model showing a 0.69 Pearson correlation. Both models were above average in predicting within-study bioscatter.

The spatial model predicted there to be little activity over the ocean during the spring in the mid-Atlantic (Figure 27-14). The one location of high activity was offshore of the border between North and South Carolina, and was primarily due to unexplained random effects. The spatial model suggested that radar unit, distance from the radar, distance to shore, elevation, and the interaction between radar and distance to shore were all important to predicting bioscatter (Table 27-3), with distance from radar by far the most important. Date and site each made up 37% of the total variance, leaving fixed effects to explain no more than 26% of the total variance. Most radar stations were similar in activity except KMHX in NC, which was below average (β=-1.9; 95% CI: -3.5, -0.33). Reflectivity was positively correlated with elevation (β=1.9E-2; 95% CI: 2.7E-3, 3.5E-2). There was a decrease in bioscatter with distance to the radar hub; sites at 60 km were 5 dB η less (95% CI: -5.9, -4.1) and sites at 90 km were 5.5 dB η less (95% CI: -6.5, -4.5) than sites located 30 km away. Bioscatter alone did not show a strong decrease with distance from shore (β=-9.5E-6; 95% CI: -4.1E-5, 2.4E-5; F_1=22.5), but it was important in interactions with radar unit, showing particularly significant declines at KDIX (β=-5.6E-5; 95% CI: -9.9E-5, -1.3E-5) and KDOX (β=-6.4E-5; 95% CI: -1.3E-4, -9.9E-6). In areas around Delaware and New Jersey migratory activity was highest at inland sites, and we documented higher migratory activity on or near the shoreline than in areas farther offshore.

The most important terms in the weather model, aside from nuisance variables like distance from radar and elevation, were interactions between latitude and distance to shore, both wind vectors and distance to shore, and the base effect of east/west winds (Table 27-4). As a random variable, site made up 16.7% of the total variance. The predictions from this model suggest a differing process for overwater activity in different subregions of the radar study area. Overall, there was less activity in more eastern

longitudes (β=-2.3; 95% CI: -3.0, -1.6), even when controlling for distance from shore. Westerly winds generally led to more migratory activity over land but less over water (β=-1.8E-6; 95% CI: -2.8E-6, -7.9E-7; Figure 27-15). Similarly, southerly winds increased onshore activity and decreased offshore activity with no variance by geography (β= -2.0E-6; 95% CI: -3.0E-6, -1.2E-6; Figure 27-16). Unlike fall, there were significant differences in reflectivity offshore by latitude (β=-1.2E-5; 95% CI: -1.6E-5, -7.5E-6); the southern part of the region (the Carolinas)had significantly more activity over water than over land, while in the central and north regions (the mid-Atlantic and New York/New Jersey, respectively), offshore and onshore levels of migratory activity were similar (Figure 27-17).

Discussion

By using currently available NEXRAD radar technology, we assessed the migratory activity levels of aerofauna in the mid-Atlantic region and in a broader area along the eastern seaboard, both on- and offshore. While radar coverage of areas offshore of Virginia and Maryland was limited due to the placement of NEXRAD radars in the region, this analysis represents a broad assessment of offshore migration over much of the OCS for the eastern United States. As with a previous study in the region (e.g., Geo-Marine Inc., 2010), our analysis indicated that there was more migratory activity over the ocean during the fall than during the spring. Unlike this previous study, we corrected for bias in measured values based on distance from the radar, elevation, and other nuisance variables, then quantified the patterns of migratory activity in space relative to distance from shore, and determined the influence of weather on migratory activity offshore. These corrections, along with the broader geographic range examined in this study, led to different findings from the previous work in New Jersey. In particular, after correcting for nuisance variables we found that migratory activity did not decrease with increasing distance from shore in the fall (within our radar study area, at least, which included locations up to 80 km from the shoreline). There was a decrease in migratory activity with distance from shore in the spring, but only offshore of Delaware and New Jersey. While NEXRAD has limited range offshore in some areas, and we had few sampling points in the Delaware, Maryland, and Virginia Wind Energy Areas, using multiple radar stations allowed us to survey a broad area for patterns in nocturnal migratory activity over multiple years. Pairing this study with other recent advances in our understanding of overwater migration in the region (DeLuca et al., 2015; Johnson and Connors, 2010; Williams and Williams, 1990; Chapters 19-24), these data suggest a consistent pattern of overwater aerofauna migration during fall.

Evaluating the usefulness of NEXRAD for detecting overwater bioscatter

Based on beam geometry, the Earth's curvature, and standard atmospheric models of radio-wave refraction, at a range of 90 km away from the radar unit, bioscatter resulting from nocturnally migrating birds should be detected above ~300 m altitude with a quarter power beam, and above 500 m with a half-power beam. Consequently, much of the aerosphere where nocturnal avian migration occurred could be surveyed by weather radar. Not all radar units are close enough to the coast to survey over the ocean, but those that are located in coastal areas should have no issues doing so (though an increasingly large portion of the lower aerosphere will go unsurveyed in places farther from the NEXRAD unit).

Most of the 144 sites surveyed for this study had a minimum beam height similar to the altitude of the potential rotor-swept zone for offshore wind turbines. The rotor-sweep zone of offshore wind turbines varies by turbine size and type, but may include altitudes between approximately 20 m and 200 m (Willmott et al., 2013). The rotor-sweep zone for a Siemens 3.6 MW offshore turbine is approximately 22-142 m in altitude, while a larger Siemens 6 MW turbine's rotors reach between about 25 m and 179 m in altitude. Larger turbines for offshore deployment are currently in development, and the altitude of the rotor-swept zone will continue to increase as the technology develops; a prototype Vestas 8 MW turbine, for example, reaches 222 m in altitude. The highest minimum beam height in this study was 226 m, and 73% of the sites had a minimum beam height that overlapped with the height of current commercially available technology (about 180 m in height). While we corrected for distance from the radar in this study, thus theoretically negating the effects of distance from radar on predicted migratory activity levels, this assumes that bioscatter is linearly correlated across altitudes, which may not always be the case. The high level of altitudinal overlap between our measurements and turbines heights, however, suggests that our predictions of bioscatter levels in the offshore environment are likely to be highly relevant to migration occurring at rotor-sweep heights in the mid-Atlantic.

Patterns of migration along the Atlantic coast of the United States
Migratory activity was highest in the fall, particularly off the coast of the Long Island and North Carolina. Topography and weather patterns could be consistently facilitating overwater migration in these areas. Alternatively, these locations around Pennsylvania and the Carolinas may be where breeding populations from northwest and northeastern North America converge (e.g., the many boreal-breeding warblers), leading to more birds being present in these areas in general during migration. Bioscatter was generally high in the southern part of the radar study area, suggesting that this second explanation may have some merit.

Tailwinds are crucial for successful migrations in birds (Alerstam et al. 1990, Jenni et al. 2003). In the present study, we found that offshore activity in fall was higher under westerlies, particularly in the northern parts of the radar study area. In the New Jersey/Long Island areas, westerly winds either caused birds to drift over the ocean or were used as a cue for birds to attempt an overwater migration. In the south, offshore activity was similar in all wind conditions. Perhaps this geographic position is so effective for beginning an overwater journey that birds are willing to make this trip under a wide variety of conditions. Migratory activity onshore showed strong influences of tailwinds as well; northerlies promoted migratory activity in the north and westerlies in the south.

In the spring, there was considerably less migration over water than in fall, with high levels of offshore activity only predicted in a small area off the coast of North Carolina. Animals still migrated over water, but our spring reflectivity mapping suggests these migrants stay closer to shore, rather than attempting the long offshore trips seen in fall. In the central and northern parts of the radar study area, we did not see more birds over water under tailwind conditions (southerlies and westerlies), so birds did not appear to be crossing the ocean during peak migratory conditions. This might indicate that birds fly overwater as a mistake during this time period, where headwinds perhaps force a mid-flight redirection. While migrants are known to cross water barriers during the spring (including a substantial migration of a wide range of species across the Gulf of Mexico; Moore et al. 1990), they did not appear to do so in

the radar study area. The lack of consistent southerlies in spring may preclude this from being an evolutionarily stable strategy, as without reliable tailwinds, the risk of an overwater crossing may overwhelm the reproductive benefit of arriving early at the breeding grounds.

Sources of uncertainty

Distance from the radar was associated with a non-linear decrease in reflectivity. As the reduction of beam strength and the increase in sampling volume with distance from the radar is already accounted for in the calculation of dB η (Chilson et al. 2012b), this suggests that other processes are affecting our understanding of migratory activity at longer distances from the radar unit. When interpreting the backscattered signal from a collection of scatterers, one assumes that the scatterers are uniformly distributed throughout the sampling volume. Clearly this condition becomes increasingly difficult to fulfill as the size of the sampling volume increases (as with increased distance from the radar unit). This is particularly true in the case of migration, which is not evenly distributed throughout the airspace. Although birds are relatively "bright" to a weather radar compared to hydrometeors, the number and density of birds is much less than that for precipitation. Consequently, the loss of sensitivity due to clumped distribution within the sampling volume could be a significant source of the decrease in reflectivity at 60 and 90 km from the radar unit.. There is also a potential biological explanation for this decreased reflectivity. While minimum beam height was only ~200m above sea level at 90 km from the radar unit, it is possible that large numbers of birds were migrating below that altitude, and we were unable to sample most of the migrating population in these areas. In this analysis we assume that the data from the 30 km distance band is the least biased due to the smaller sampling area and lower beam height at this distance from the radar; we correct values in the other distance bands such that they display data as if they were sampled at 30 km. This correction allows for an "apples to apples" comparison of average reflectivity values between locations (as in Figures 27-11 and Figure 27-14), but our uncertainty about the biological or physical mechanism behind these differences makes it difficult to ensure that we are completely correcting for these disparities.

Future areas of research should include a focus on the efficacy of weather radar for detecting bioscatter over open water. "Ground-truthing" the weather radar data with vertical marine radar (if possible offshore) and passive acoustic detection would go a long way towards confirming the patterns we have seen in this study. As radar technology improves, the ability to analyze overwater data by elevation band will be an interesting means of describing the altitudinal distribution of migrants, and may allow for better modeling of activity in low altitude areas far from radar units. Individual radars often have slightly different settings or other factors that could influence measured reflectivity values, and more detailed studies of the spatial and temporal variation in migratory activity between individual radar units would also be useful for understanding the limitations of each unit's efficacy in surveying the ocean. Lastly, gathering data from marine habitat offshore of Virginia and Maryland would be helpful for confirming patterns of migratory activity in this area. While we can assume that migratory activity there is similar to areas north and south of it (as animals would have to migrate over the site to get to the next location), direct measurement of migratory activity at these locations was lacking due to the inland locations of nearby NEXRAD units.

Implications for development along the eastern seaboard
While we have known for some years that birds and bats migrate over the northwest Atlantic Ocean (Williams et al. 1977, Gauthreaux and Belser 2005), this study identified areas that were consistently used by migrants in both spring and fall, as well as the conditions under which offshore migration was most likely to occur in various locations along the eastern seaboard. Our findings suggest that there is more nocturnal migratory activity offshore than predicted by past studies. We suspect the newer methods employed in this study, including controlling for distance from the radar and other nuisance variables, improved our ability to obtain accurate estimates of migratory activity offshore. Migratory activity levels were quite variable, and it is also possible that we merely chose a four-year period with higher than normal levels of offshore activity. But the geographic variability in these predicted values, and the consistency of these patterns in certain locations along the eastern seaboard, particularly in fall, suggest that there may be substantial offshore migration pathways that begin with "jumping off points" along the coast.

Overwater activity is much more widespread in the fall than in spring. Paired with data collected from our shipboard surveys (Chapter 26), these data suggest that an overwater migration strategy may be utilized by many species, particularly songbirds and shorebirds. Trans-oceanic migrations, once thought to be extreme events only undertaken by few individuals or species with extreme physiological adaptations (e.g., DeLuca et al. 2015, Delingat et al. 2008), are perhaps more commonplace than previously thought in this region. Given the levels of migratory activity predicted in offshore locations, regulators for offshore wind energy development may want to consider potential impacts to nocturnal migrants, including terrestrial species (passerines, shorebirds, bats, etc.) in offshore wind development scenarios. This may be particularly important in locations with consistently higher levels of migratory activity, such as the New York Bight and areas offshore of North Carolina. Predicted levels of bioscatter in many other parts of the radar study area were also intermittently high, however, suggesting that offshore migration is a widespread phenomenon, and should be regarded as such during planning activities.

Our work here suggests that weather radar systems can be effective in describing overwater migration, and that there are parts of the ocean that are consistently being used by migratory aerofauna. In particular, our findings demonstrate a strong pattern of overwater migration in aerofauna during fall, and the variation in overwater migration activity in relation to weather patterns suggests that overwater migration may be facultative for many taxa. More research into these areas will allow us to better describe this phenomenon, and inform decision making regarding the anthropogenic utilization of the marine environment.

Literature cited

Alerstam, T., & Lindström, Å. (1990). Optimal bird migration: the relative importance of time, energy, and safety. Pp. 331-351 in: Gwinner,E. (Ed.) Bird migration. Springer Berlin Heidelberg.

Bates, D., Maechler, M., Bolker, B., & Walker, S. (2014). _lme4: Linear mixed-effects models using Eigen and S4_. R package version 1.1-7. http://CRAN.R-project.org/package=lme4.

Brabant, R., Vigin, L., Stienen, E. W. M., Vanermen, N. & Degraer, S. (2012). Radar research on the impact of offshore wind farms on birds: Preparing to go offshore. pp. 111-126 in: Degraer, S., Brabant, R. & Rumes, B. (Eds.) Offshore wind farms in the Belgian part of the North Sea: Heading for an understanding of environmental impacts. Royal Belgian Institute of Natural Sciences, Management Unit of the North Sea Mathematical Models, Marine ecosystem management unit. 155 pp. + annexes.

Bridge, E. S., Thorup, K., Bowlin, M. S., Chilson, P. B., Diehl, R. H., Fleron, R. W., Hartl, P., Kays, R., Kelly, J. F., Robinson, W. D., & Wikelski, M. (2011). Technology on the move: recent and forthcoming innovations for tracking migratory birds. Bioscience, 61, 689 - 698.

Buler, J. J., & Diehl, R. H. (2009). Quantifying Bird Density During Migratory Stopover Using Weather Surveillance Radar. IEEE Transactions on Geoscience and Remote Sensing, 47(8), 2741-2751. doi: 10.1109/Tgrs.2009.2014463

Buler, J., Randall, L., Fleskes, J., Barrow, W., Bogart, T., & Kluver, D. (2012). Mapping wintering waterfowl distributions using weather surveillance radar. PLoS ONE, 7, e41571.

Chilson, P. B., Bridge, E., Frick, W. F., Chapman, J. W., & Kelly, J. F. (2012). Radar aeroecology: exploring the movements of aerial fauna through radio-wave remote sensing. Biology Letters, 8(5), 698-701. doi: 10.1098/rsbl.2012.0384

Chilson, P. B., Frick, W. F., Kelly, J. F., Howard, K. W., Larkin, R. P., Diehl, R. H., Westbrook, J. K., Kelly, T. A., & Kunz, T. H. (2012a). Partly Cloudy with a Chance of Migration Weather, Radars, and Aeroecology. Bulletin of the American Meteorological Society, 93(5), 669-686. doi: 10.1175/Bams-D-11-00099.1

Chilson, P. B., Frick, W. F., Stepanian, P. M., Shipley, J. R., Kunz, T. H., & Kelly, J. F. (2012b). Estimating animal densities in the aerosphere using weather radar: To Z or not to Z? Ecosphere, 3(8), art72. doi: 10.1890/ES12-00027.1

DeLuca, W. V., Woodworth, B. K., Rimmer, C. C., Marra, P. P., Taylor, P. D., McFarland, K. P., Mackenzie, S. A., & Norris, D. R. (2015). Transoceanic migration by a 12 g songbird. Biology Letters, 11.

Delingat, J., F. Bairlein, and A. Hedenstrom. (2008). Obligatory barrier crossing and adaptive fuel management in migratory birds: the case of the Atlantic crossing in Northern Wheatears (*Oenanthe oenanthe*). Behavioral Ecology and Sociobiology 62:1069-1078.

Diehl, R. H., Larkin, R. P., & Black, J. E. (2003). Radar observations of bird migration over the Great Lakes. Auk, 120(2), 278-290. doi: 10.1642/0004-8038(2003)120[0278:Roobmo]2.0.Co;2

Frick, W. F., Stepanian, P. M., Kelly, J. F., Howard, K. W., Kuster, C. M., Kunz, T. H., Chilson, P. B. (2012). Climate and weather impact timing of emergence of bats. PLoS One 7, e42737. doi:10.1371/journal.pone.0042737

Gauthreaux, S. A. Jr., & Belser, C. G. (2003). Radar ornithology and biological conservation. Auk, 120, 266 - 277.

Gauthreaux, S. A. Jr., & Belser, C. G. (2005). Radar Ornithology and the Conservation of Migratory Birds. USDA Forest Service Gen. Tech. Rep. PSW-GTR-191. pp 871-875.

Geo-Marine, Inc. (2010). New Jersey Department of Environmental Protection Baseline Studies. Final Report Vol II: Avian Studies. www.nj.gov/dep/dsr/ocean-wind/report.htm

Harmata, A. R., Podruzny, K. M., Zelenak, J. R., & Morrison, M. L. (1999). Using marine surveillance radar to study bird movements and impact assessment. Wildlife Society Bulletin, 27: 44-52.

Horn, J. W., & Kunz, T. H. (2008). Analyzing NEXRAD doppler radar images to assess nightly dispersal patterns and population trends in Brazilian free-tailed bats (*Tadarida brasiliensis*). Integrative and Comparative Biology, 48(1), 24-39. doi: 10.1093/icb/icn051

Jenni, L. and M. Schaub. (2003). Behavioral and physiological reactions to environmental variation in bird migration: a review. Pp. 331-351 in: Berthold, P., Gwinner,E., and Sonnenschein E. (Eds.) Bird migration. Springer Berlin Heidelberg.

Johnson, O. W. & Connors, P. G. (2010). American Golden-Plover (*Pluvialis dominica*), in: Poole, A. (Ed.), The Birds of North America Online. Cornell Lab of Ornithology, Ithaca, New York. doi:10.2173/bna.201

Maddox, R. A., Zhang, J., Gourley, J. J., & Howard, K. W. (2002). Weather radar coverage over the contiguous United States. Weather and Forecasting, 17(4): 927–934.

Moore, F. R., Kerlinger, P., & Simons, T. R. (1990). Stopover on a gulf coast barrier island by spring trans-gulf migrants. Wilson Bulletin, 102:487-500.

Narasimhan, R. (2014). weatherData: Get Weather Data from the Web. R package version 0.4.1. http://CRAN.R-project.org/package=weatherData

R Core Team 2014. (2014). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org.

Rinehart, R. E. (2004). Radar for Meteorologists (4th ed.). Colombia, MO.

Robinson, W. D., Bowlin, M. S., Bisson, I., Shamoun-Baranes, J., Thorup, K., Diehl, R. H., Kunz, T. H., Mabey, S., & Winkler, D. W. (2010). Integrating concepts and technologies to advance the study of bird migration. Frontiers in Ecology and the Environment, 8, 354 - 361.

Shamoun-Baranes, J., Alves, J. A., Bauer, S., Dokter, A. M., Hüppop, O., Koistinen, J., Leijnse, H., Liechti, F., van Gasteren, H., & Chapman, J. (2014). Continental-scale radar monitoring of the aerial movements of animals. Movement Ecology, 2(1), 9.

Williams, K. A., Adams, E. M., Fiely, J., Yates, D., Chilson, P. B., Kuster, C., & Evers, D. C. (2013). Migratory Bird and Bat Monitoring in the Thousand Islands Region of New York State: Final Report, March 2013. Report to the U.S. Fish and Wildlife Service Columbus, Ohio Field Office. Report BRI 2013-11, Biodiversity Research Institute, Gorham, Maine.

Williams, T. C., Williams, J. M., Ireland, L. C., & Teal, J. M. (1977). Autumnal bird migration over the western North Atlantic Ocean. American Birds, 31:251:267.

Williams, T. C., & Williams, J.M. (1990). The Orientation of Transoceanic Migrants, in: Gwinner, E. (Ed.), Bird Migration: Physiology and Ecophysiology. Springer-Verlag, Berlin, Germany, pp. 7–21.

Willmott, J. R., G. Forcey, and A. Kent. (2013). The Relative Vulnerability of Migratory Bird Species to Offshore Wind Energy Projects on the Atlantic Outer Continental Shelf: An Assessment Method and Database. Final Report to the U.S. Department of the Interior, Bureau of Ocean Energy Management, Office of Renewable Energy Programs. OCS Study BOEM 2013-207.

Figures and tables
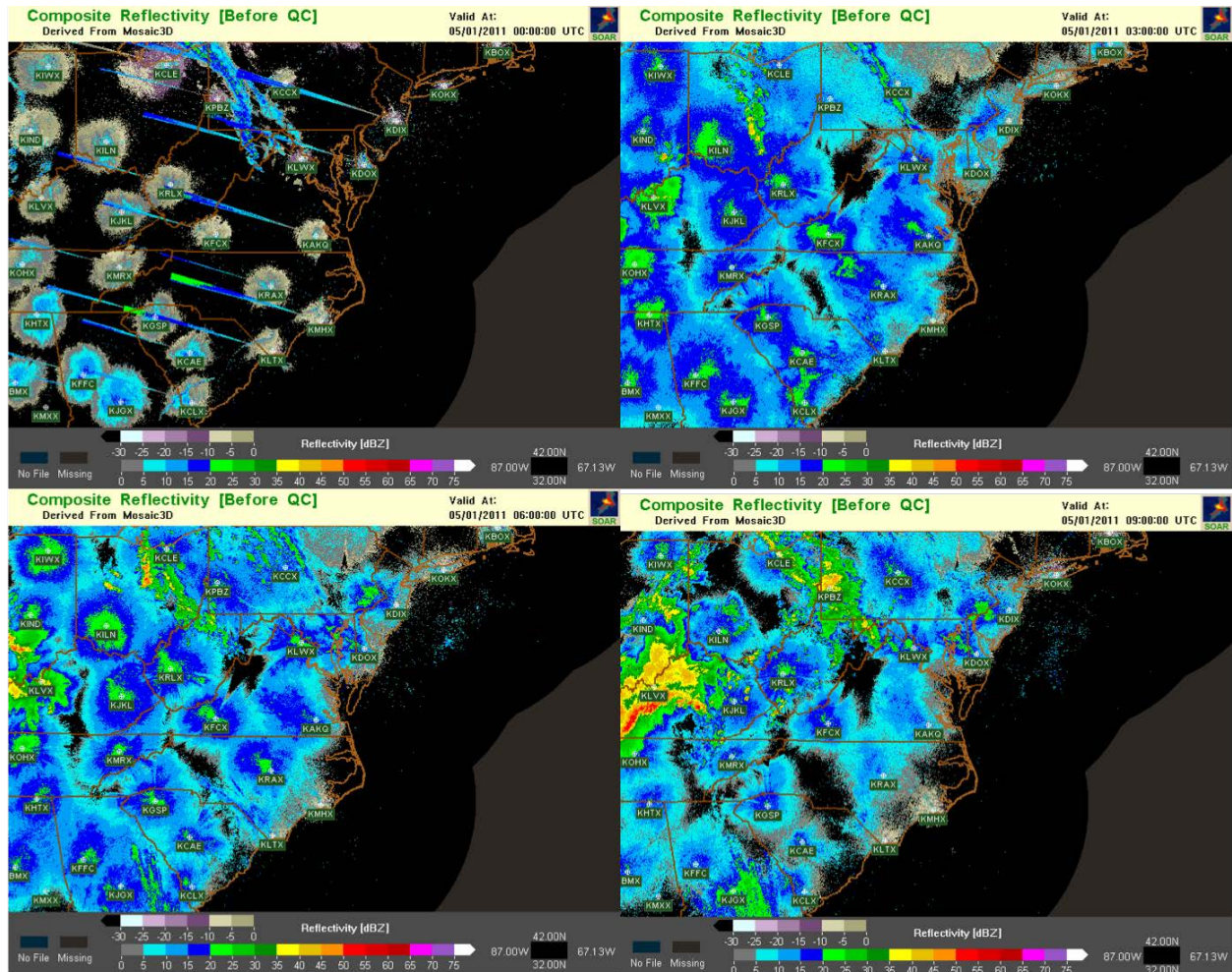
Figure 27-1. Composite radar data (expressed in dB Z) for May 1, 2011. The radar has not been quality controlled to remove biological scatter, radio interference, or anomalous propagation. The four panels correspond to times of 00, 03, 06, and 09 UTC (2000, 2300, 0200, and 0500 hours EDT). Typical precipitation features are seen (irregular green, yellow and red areas), as well as the onset of nocturnal migration (round "blooms" around the radar units). 00 UTC (2000 EDT) also shows "sun spurs" caused by the setting sun (see text).
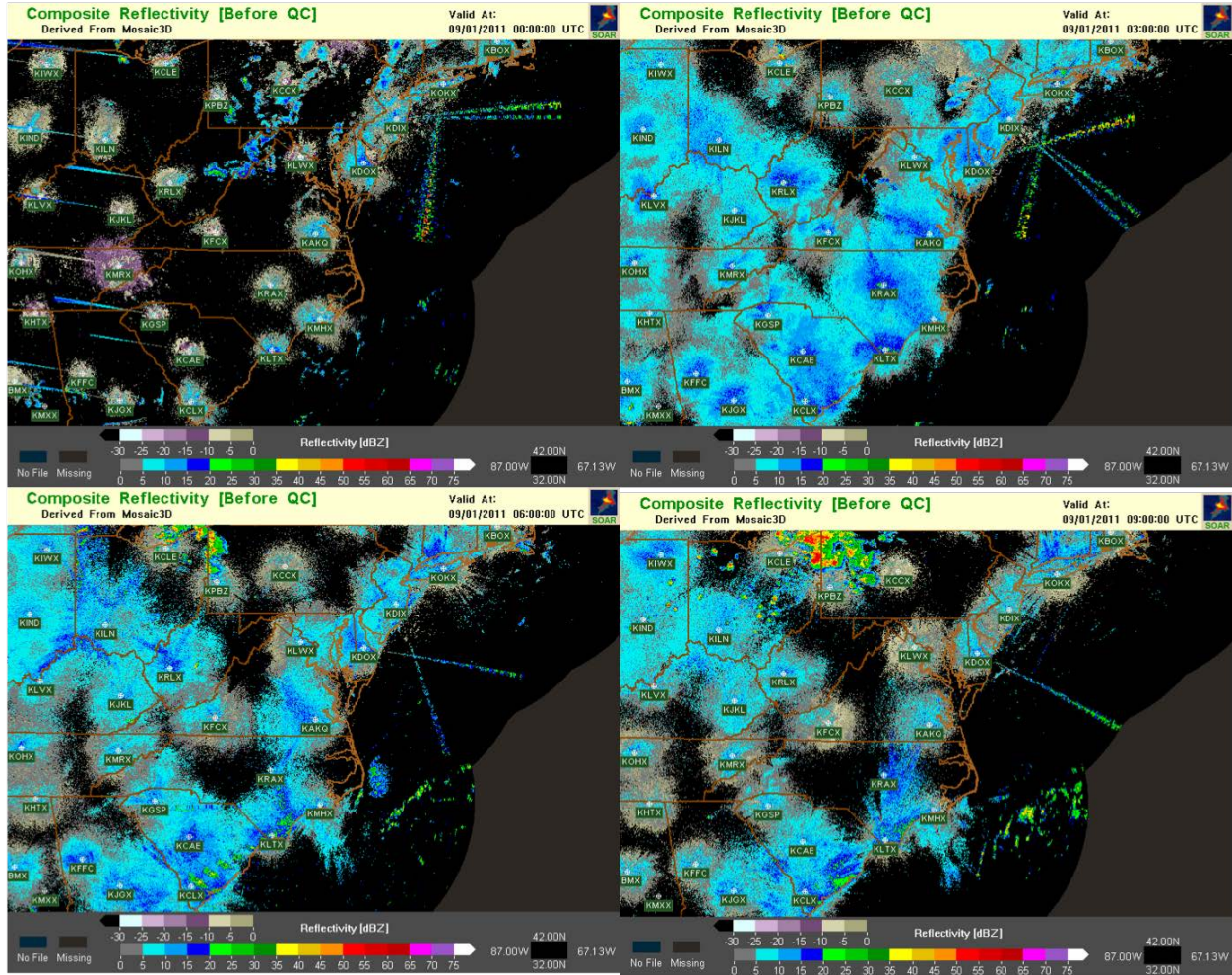
Figure 27-2. Composite radar data (expressed in dB Z) for September 1, 2011. See caption for Figure 27-1.
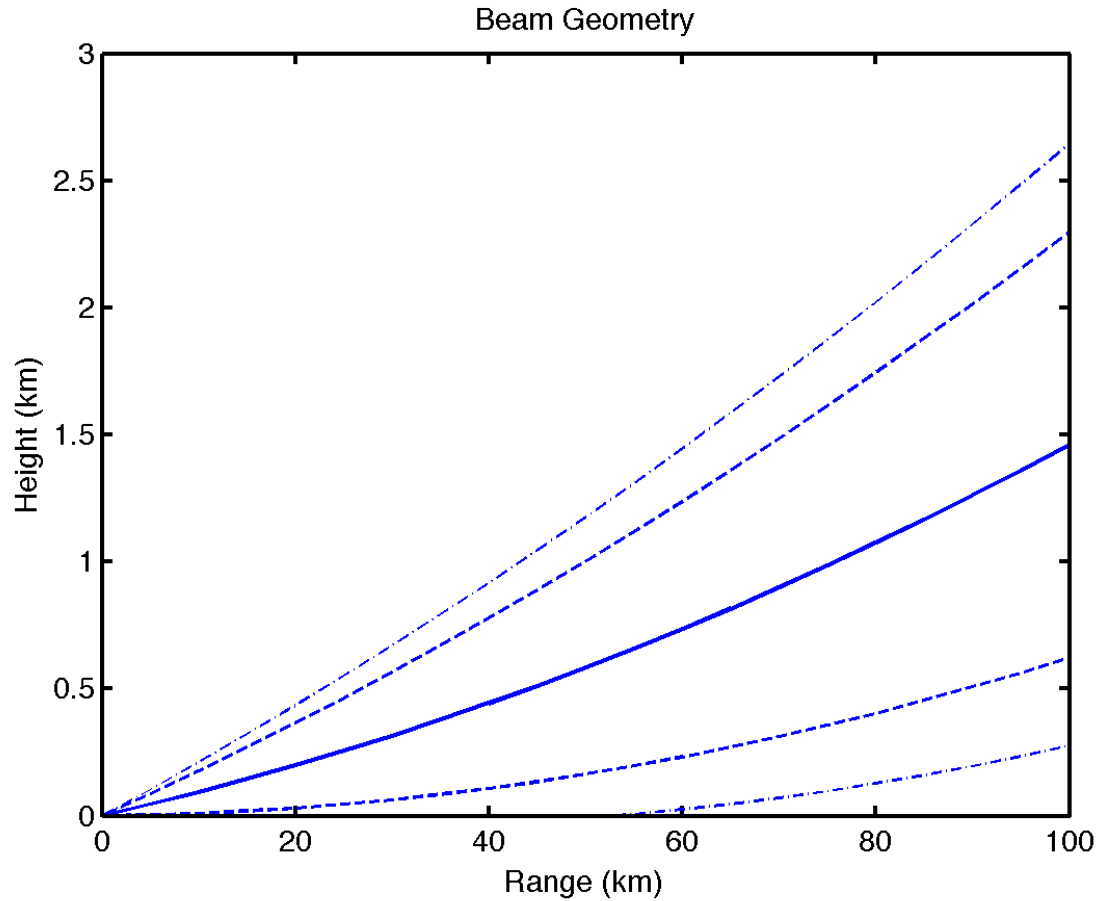
Figure 27-3. Depiction of the sampling heights of NEXRAD as a function of range for a radar beam with an elevation angle of 0.5°. Here the effects of the Earth curvature and the refraction of radio waves through a standard atmosphere have been taken into account. The bold solid line marks the center of the beam. The dashed line represents the beam's half-power (3 dB) point and the dashed-dotted line represents the beam's quarter-power (6 dB) point.
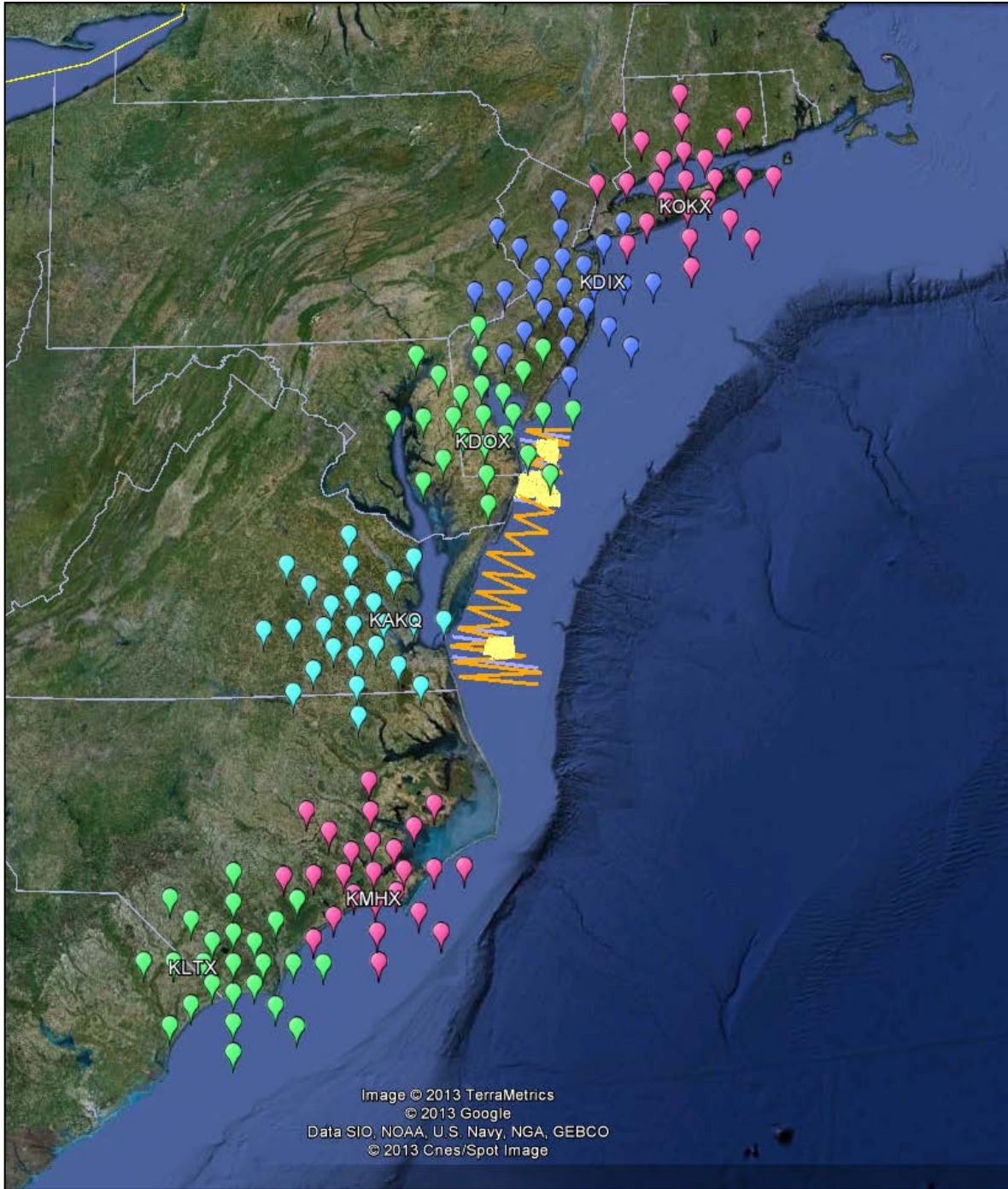
Figure 27-4. The six NEXRAD radar units (KOKX, KDIX, KDOX, KAKQ, KMHX, and KLTX) used for analyses. Each radar station had 24 comparison locations located at standardized distances from the unit, which were used for landscape-scale analyses of migratory activity patterns. Aerial survey transects delineating the radar study area are shown in yellow and orange.
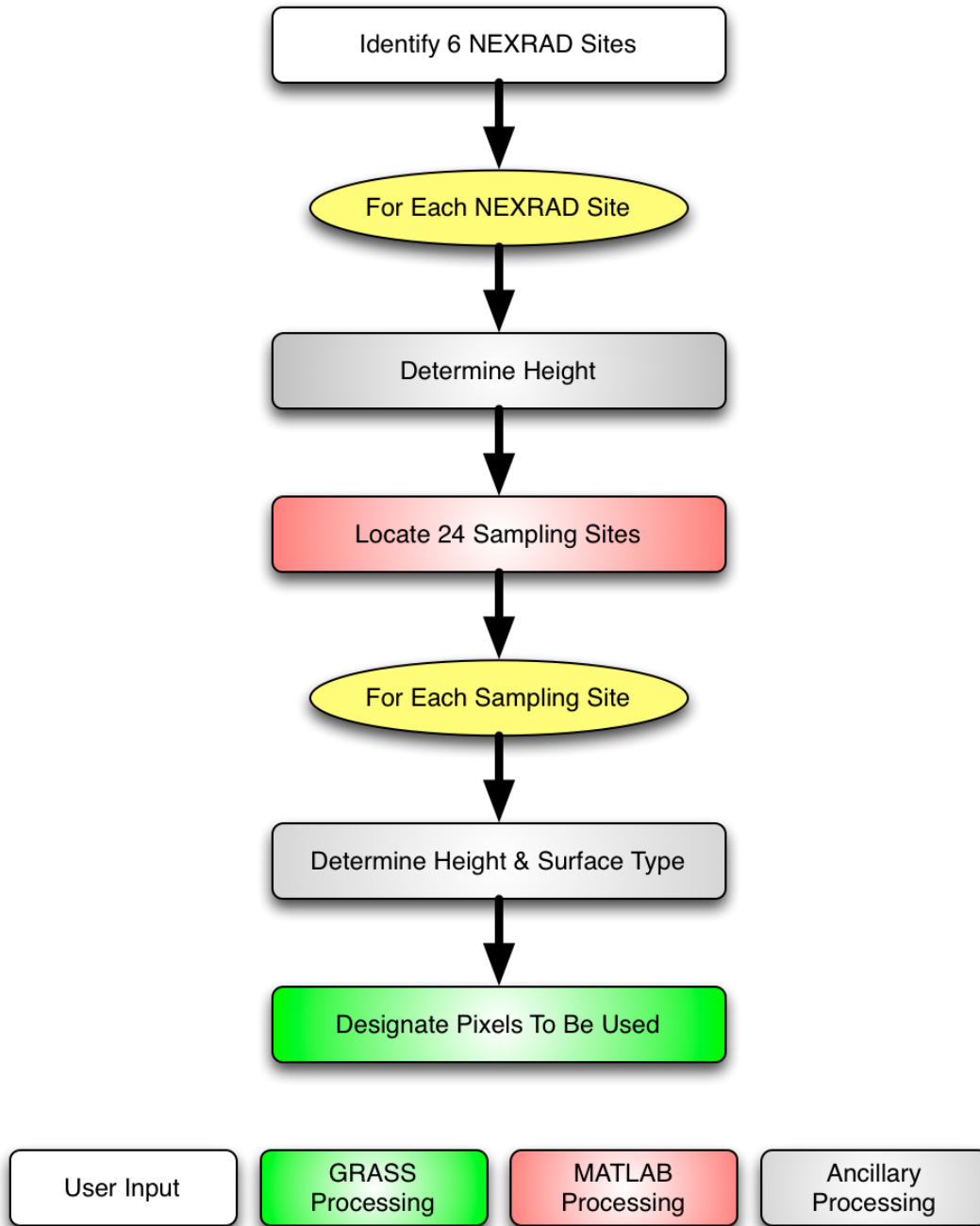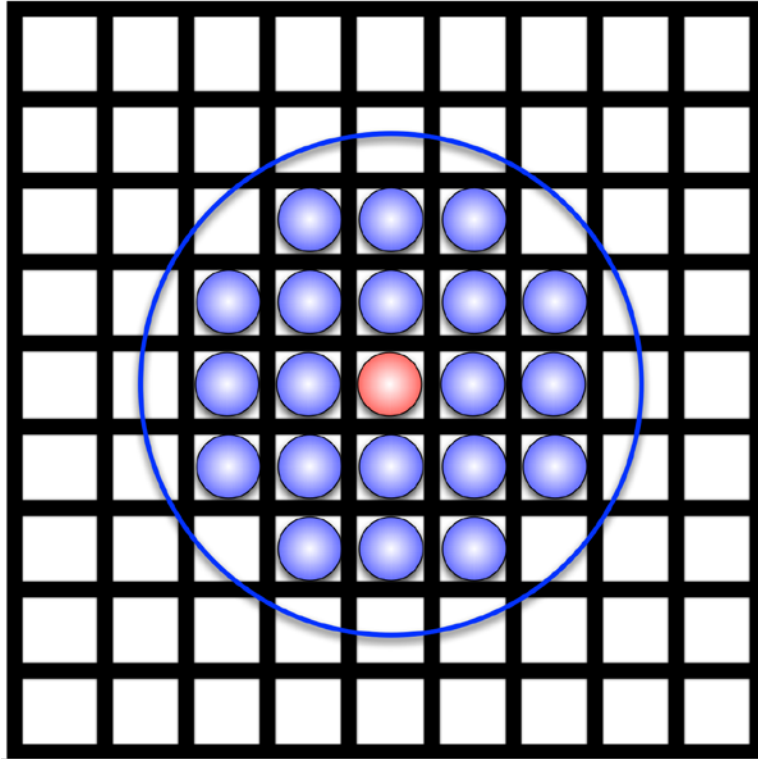
Figure 27-5. Workflow showing the initialization steps conducted as part of the data processing.

Figure 27-6. Illustration of the process used to select the raster elements used when evaluating the univariate statistics of the CREF and UNQC_CREF data for each of the sampling sites. The red dot corresponds to the coordinate of one of the 24 locations placed around the radar site. Using GRASS, the area to be considered is "grown" radially outward from the point. Those raster elements fully contained within the circle are designated as those to be considered. For each of the sampling sites, 21 raster elements were chosen using this process.
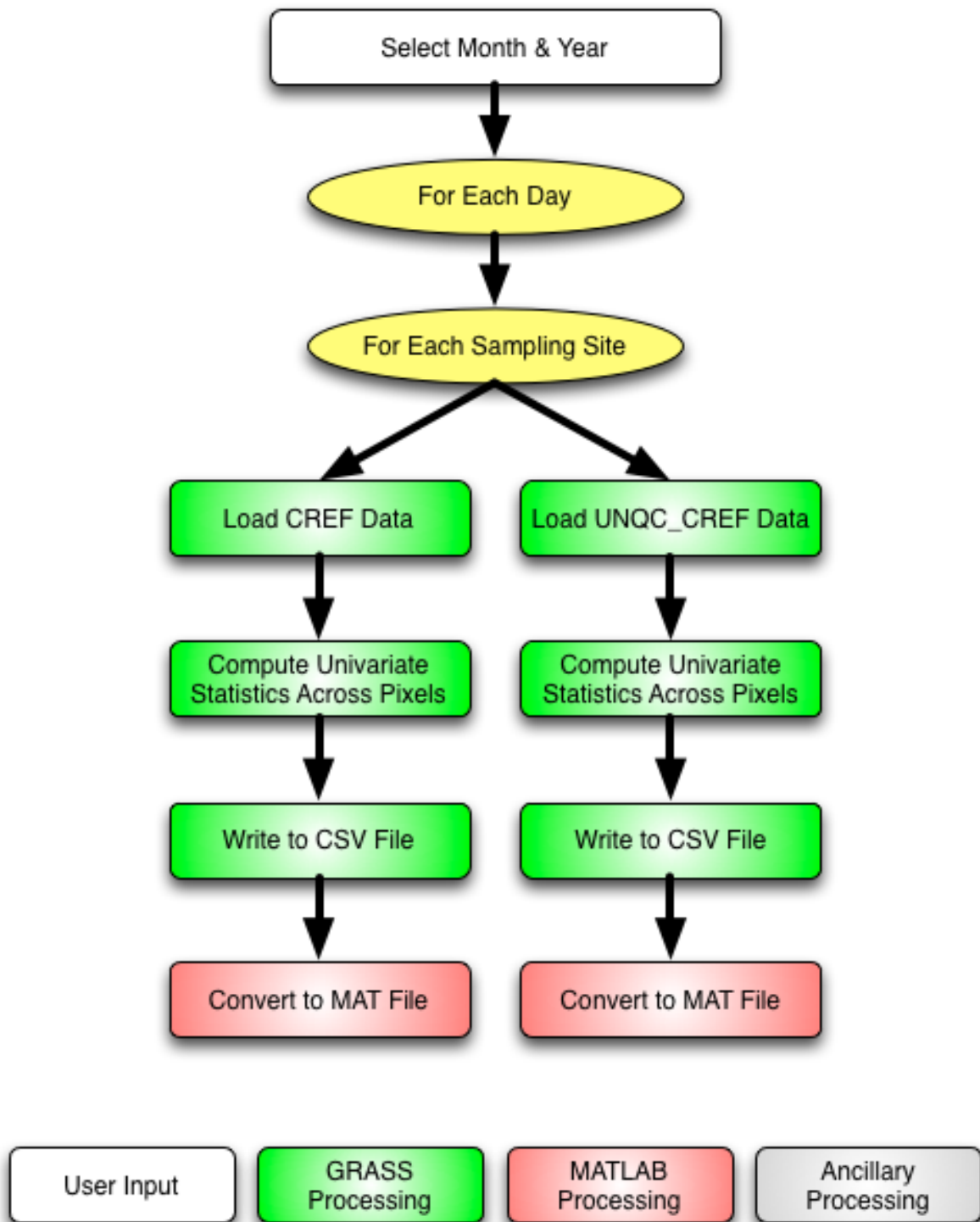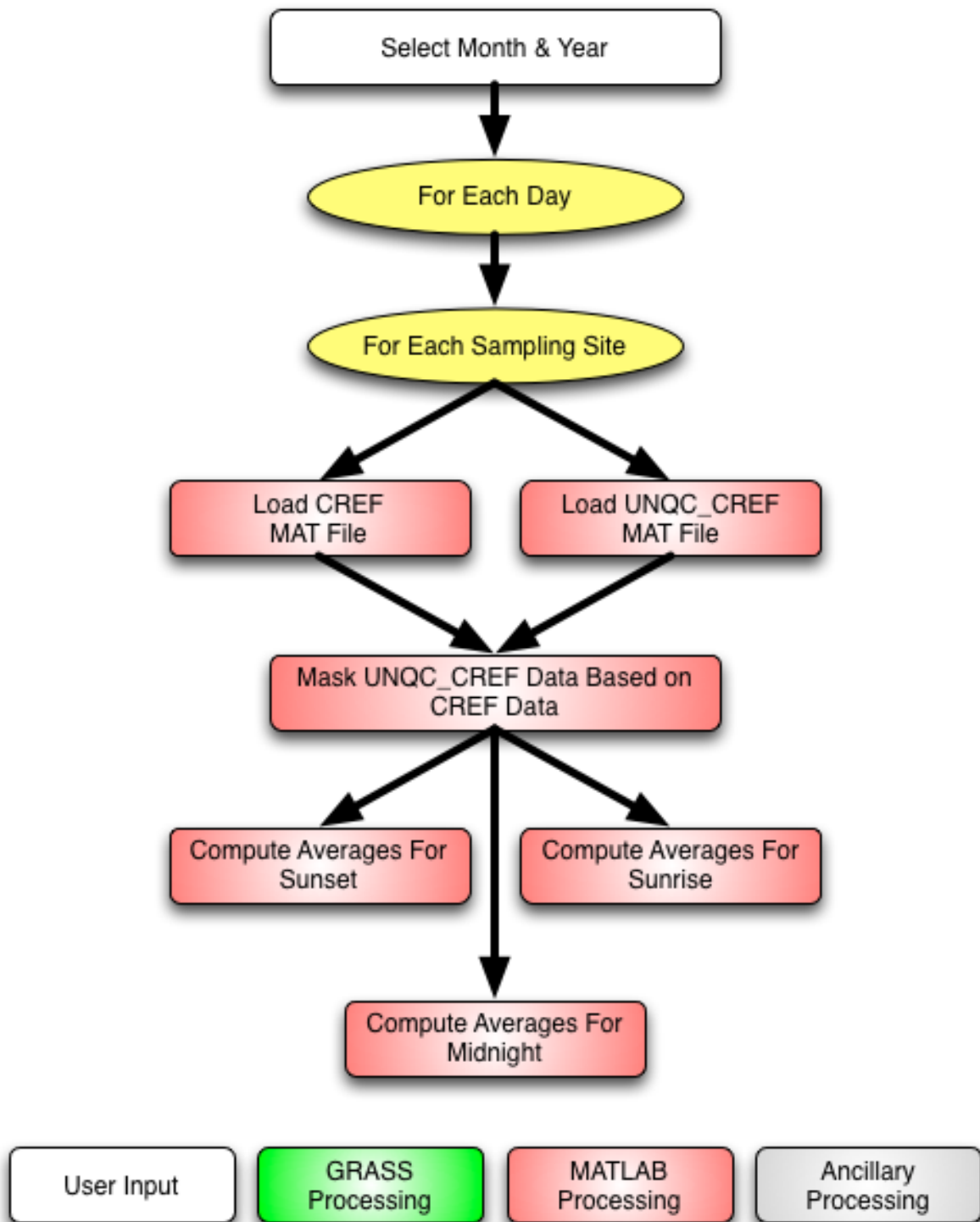
Figure 27-7. Workflow showing the radar processing conducted primarily using GRASS when analyzing the CREF and UNQC_CREF GeoTIFF files.

Figure 27-8. Workflow showing the radar processing conducted using MATLAB when conducting such steps as data masking and temporal averaging. Averages for sunset and sunrise were not used in this analysis. The "midnight" period included six hours centered around midnight for each night of sampling.
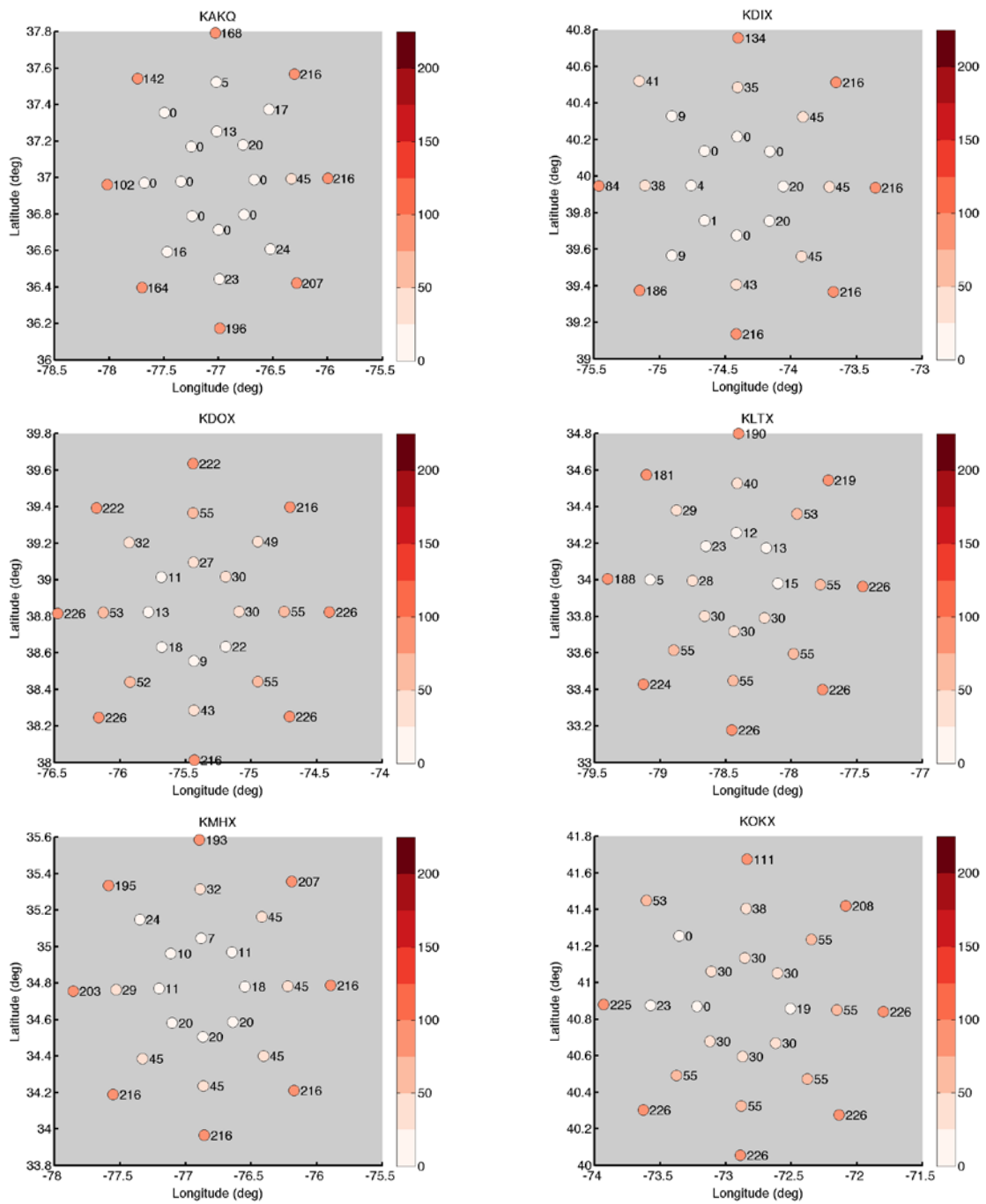
Figure 27-9. Representation of the lowest detectable heights (m) for the 144 different sampling sites used in the study for each radar location. Since biological entities have relatively large radar cross-sections, the 6-dB points in the beam have been used. The height of the radar and elevation of each sampling site have been factored into the calculation.
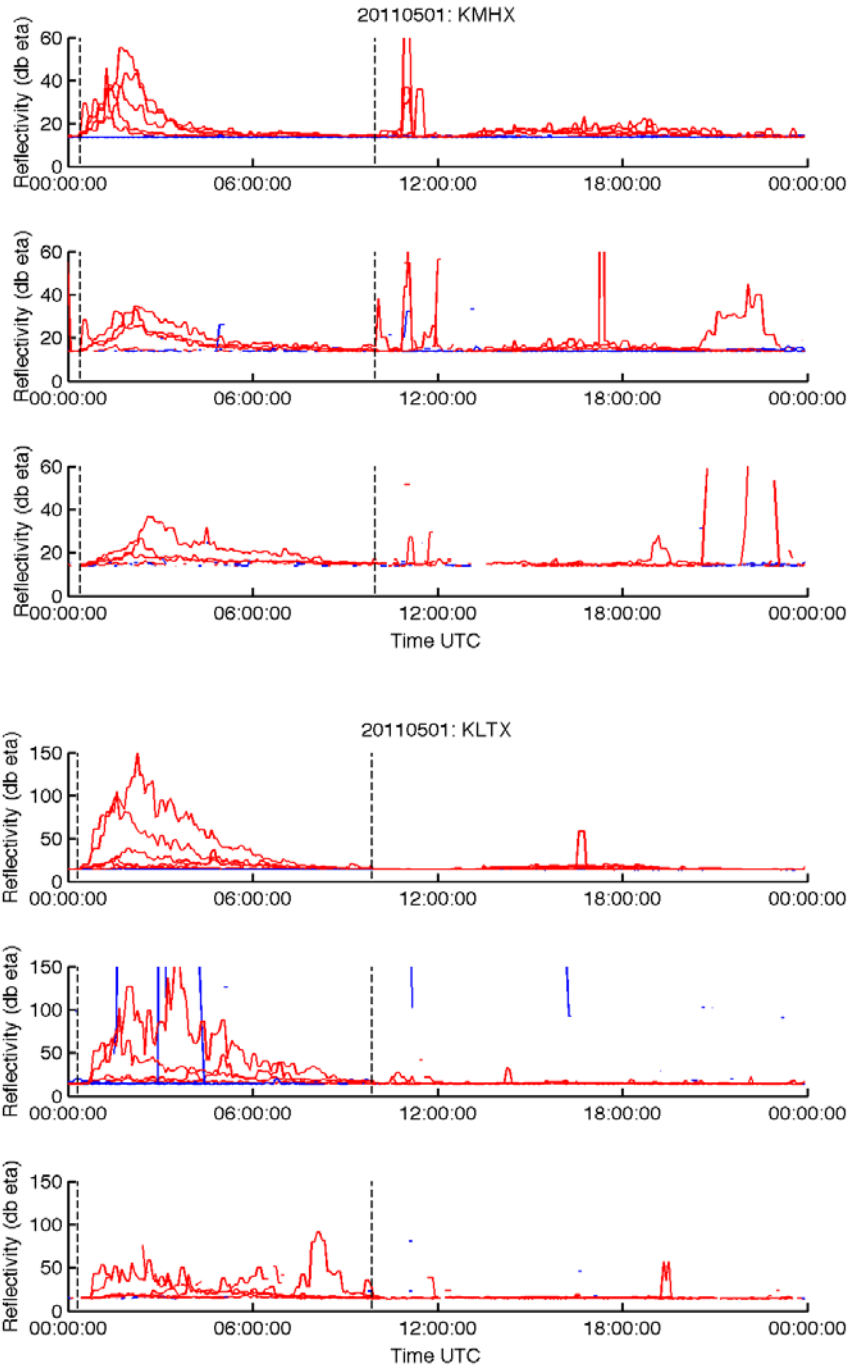
Figure 27-10. Plots of the radar reflectivity in dBη for KMHX (upper 3 panels) and KLTX (lower 3 panels) for May 1, 2011. The upper panels for a given radar show sampling locations 1-8 (30 km from radar), the middle panels show sites 8-16 (60 km), and the lower panels show sites 17-24 (90 km). Plots in red and blue are for locations over land and water, respectively. Sunset and rise times are indicated by vertical dashed lines (sunset is around 00 UTC, or 2000 hours in EDT; sunrise is around 10 UTC, 0r 0600 EDT). Sites over land (particularly in areas closer to the radar, since these values do not include a correction for this nuisance variable) show a pattern of "exodus" as migrants leave terrestrial stopover locations after sunset and begin their nocturnal flights. As expected, sites over water do not show this exodus pattern, and overall show lower dB η reflectivity values for this date.
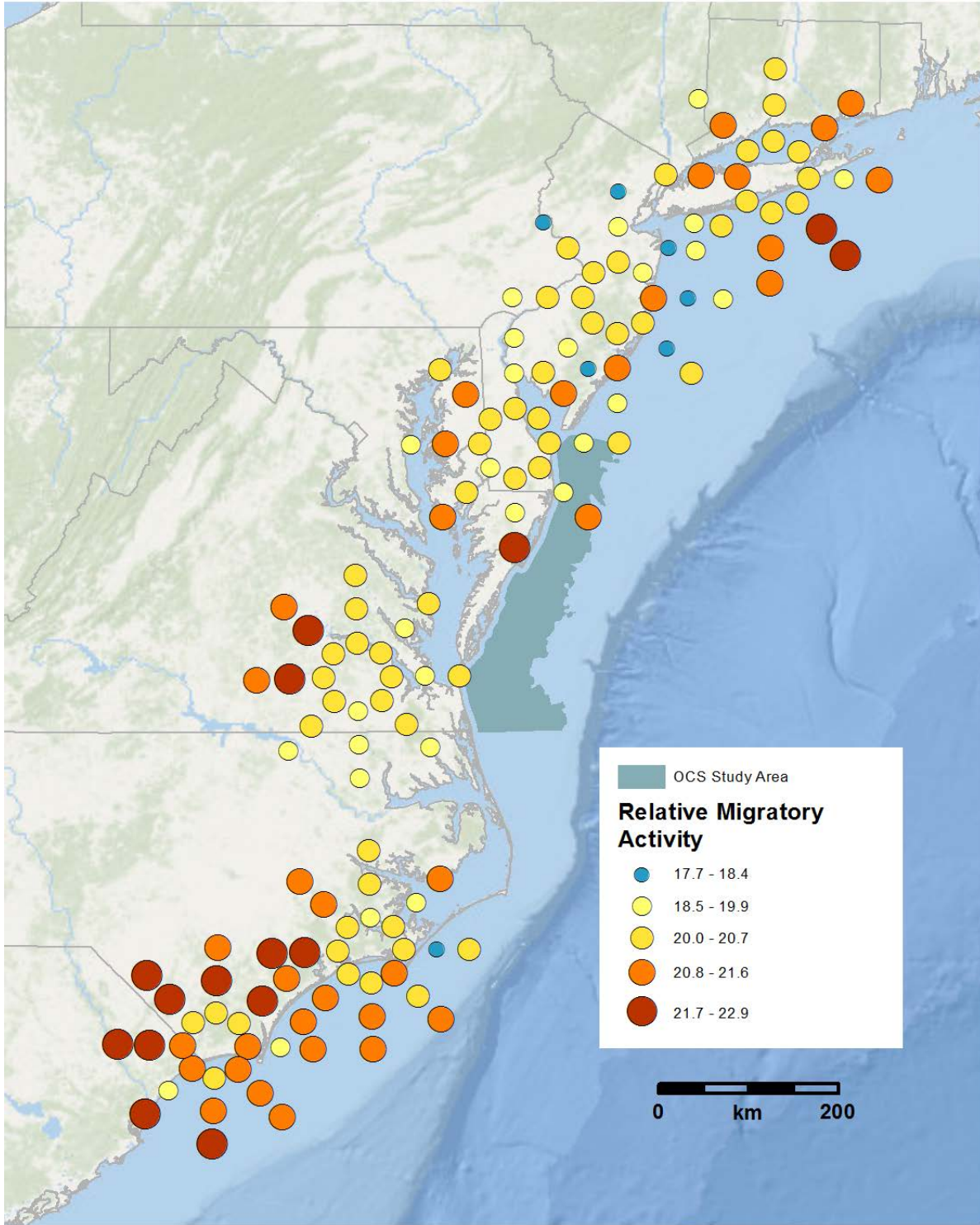
Figure 27-11. Map of predicted levels of bioscatter across the radar study area for fall, averaged across all dates and years. Elevation, radar unit, site type, and distance to the radar were standardized for each point so we could control for those nuisance variables and focus on the spatial factors that lead to differences in bioscatter. Relative migratory activity estimates are in values of dB η; the "OCS study area" is the mid-Atlantic study area referenced in other chapters in this report.
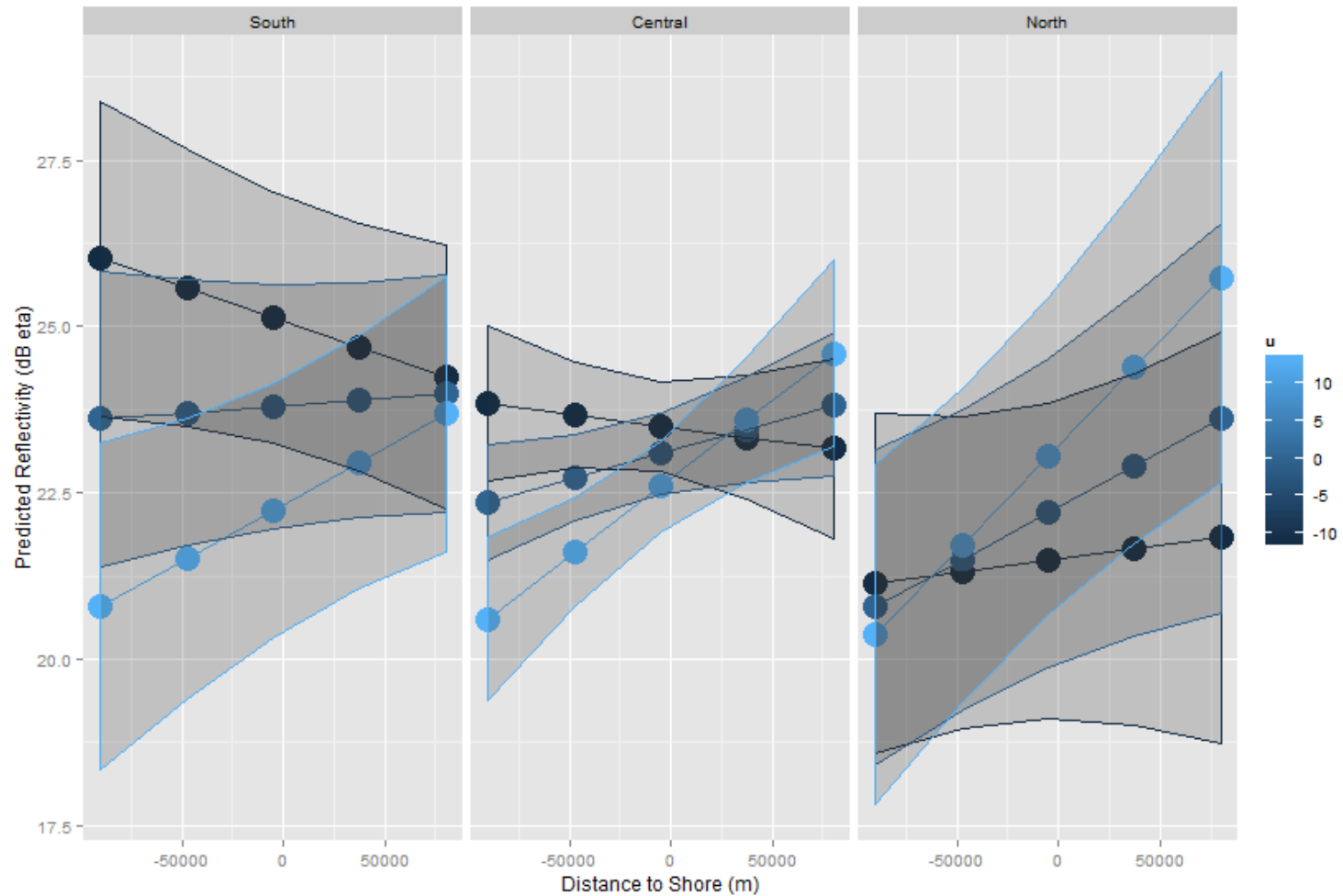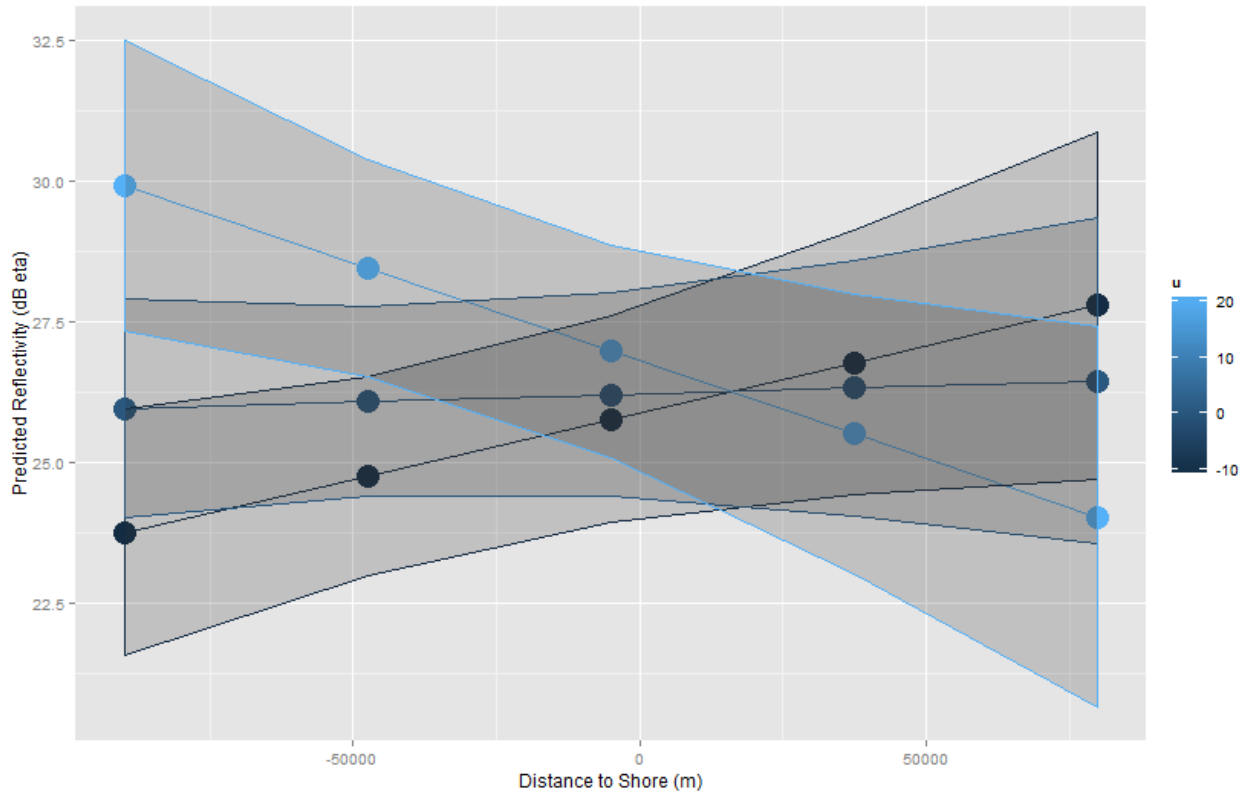
Figure 27-12. The effects of fall East-West winds on bioscatter in relation to distance to shore. Effects are shown separately for different latitudes within the radar study area, where South = the Carolinas, Central = Delaware, Maryland and Virginia, and North = New Jersey and New York. Wind direction is indicated by color, where easterlies are dark blue and westerlies and light blue. Zero is the shoreline, while positive values indicate locations further offshore and negative values are further inland. Shaded areas indicate the estimated 95% confidence interval of the prediction (when accounting only for variation in the model's fixed effects).
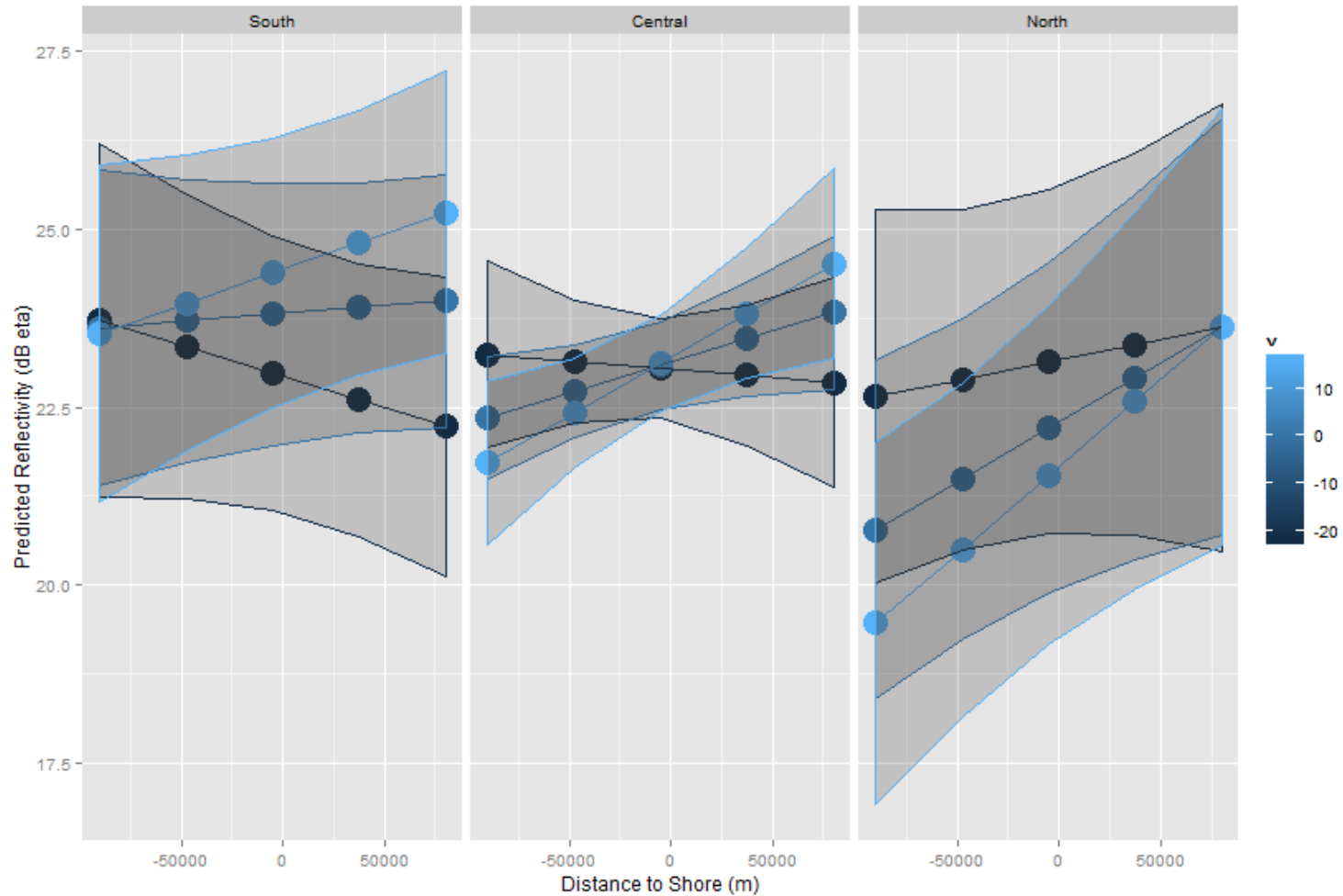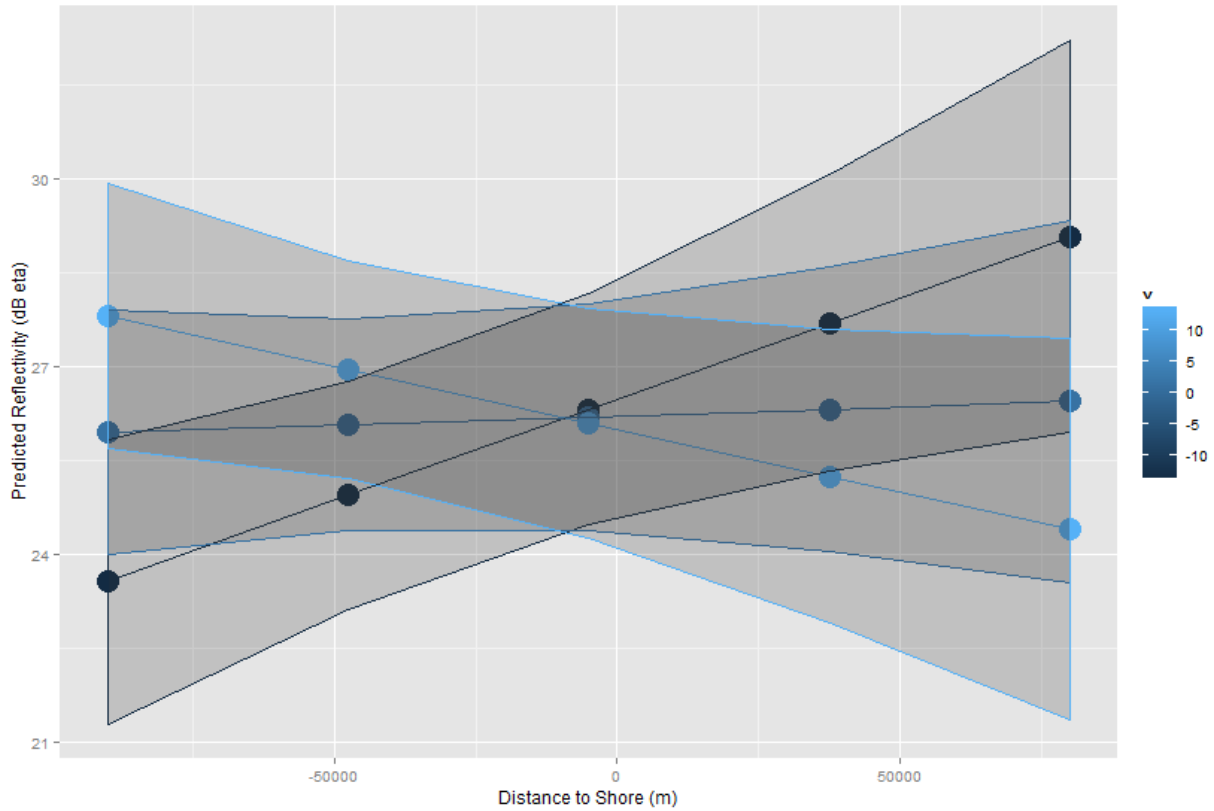
Figure 27-13. The effects of fall North-South winds on bioscatter in relation to distance to shore. Effects are shown separately for different latitudes within the radar study area, where South = the Carolinas, Central = Delaware, Maryland and Virginia, and North = New Jersey and New York. Wind direction is indicated by color, where northerlies are dark blue and southerlies and light blue. Zero is the shoreline, while positive values indicate locations further offshore and negative values are further inland. Shaded areas indicate the estimated 95% confidence interval of the prediction (when accounting only for variation in the model's fixed effects).
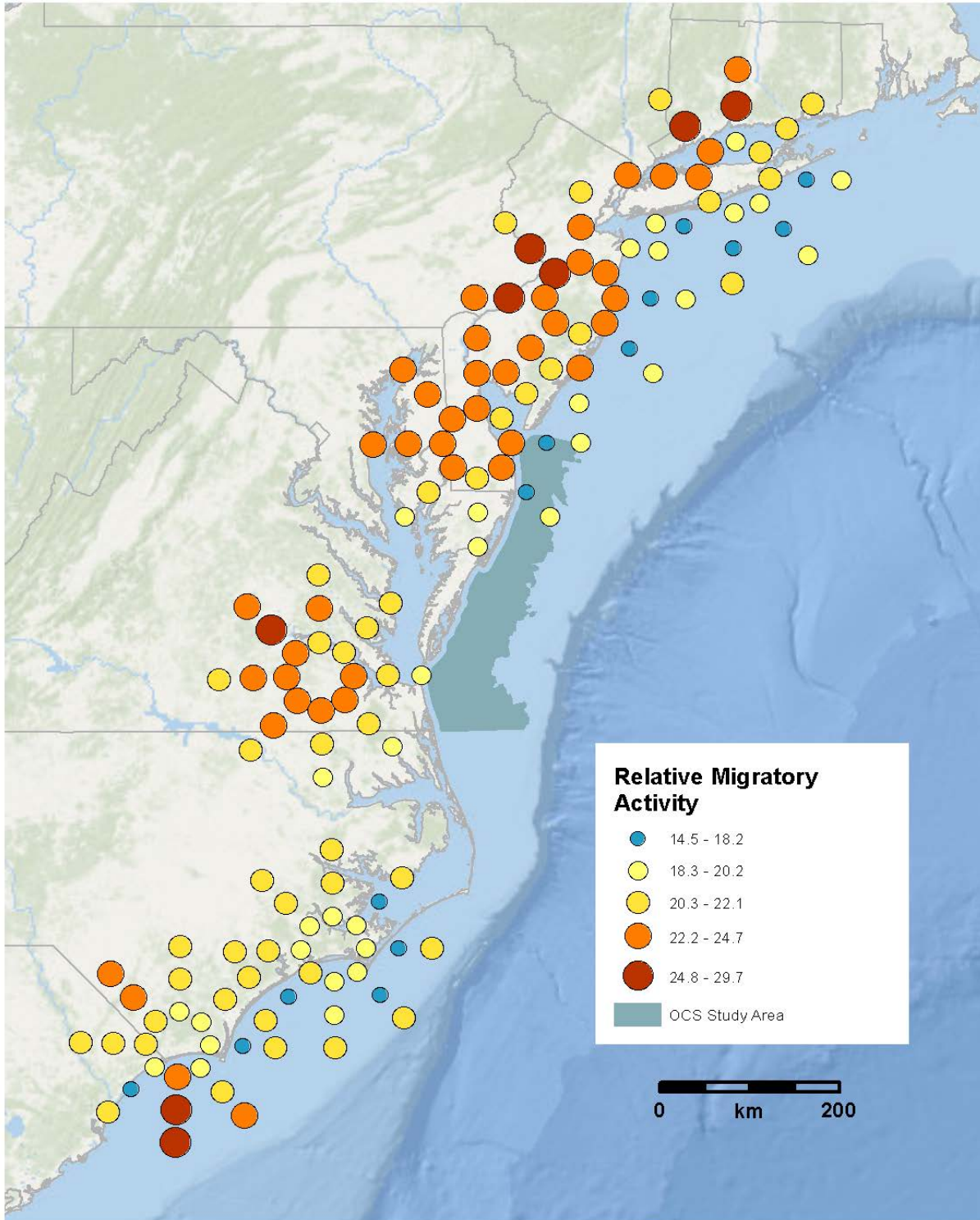
Figure 27-14. Map of predicted levels of bioscatter across the radar study area for spring, averaged across all dates and years. Elevation, radar unit, site type, and distance to the radar were standardized for each point so we could control for those nuisance variables and focus on the spatial factors that lead to differences in bioscatter. Relative migratory activity estimates are in values of dB η; the "OCS study area" is the mid-Atlantic study area referenced in other chapters in this report.

Figure 27-15. The effects of spring East-West winds on bioscatter in relation to distance to shore. Zero is the shoreline, while positive values indicate locations further offshore and negative values are further inland. Shaded areas indicate the estimated 95% confidence interval of the prediction (when accounting only for variation in the model's fixed effects).

Figure 27-16. The effects of spring North-South winds on bioscatter in relation to distance to shore. Zero is the shoreline, while positive values indicate locations further offshore and negative values are further inland. Shaded areas indicate the estimated 95% confidence interval of the prediction (when accounting only for variation in the model's fixed effects).
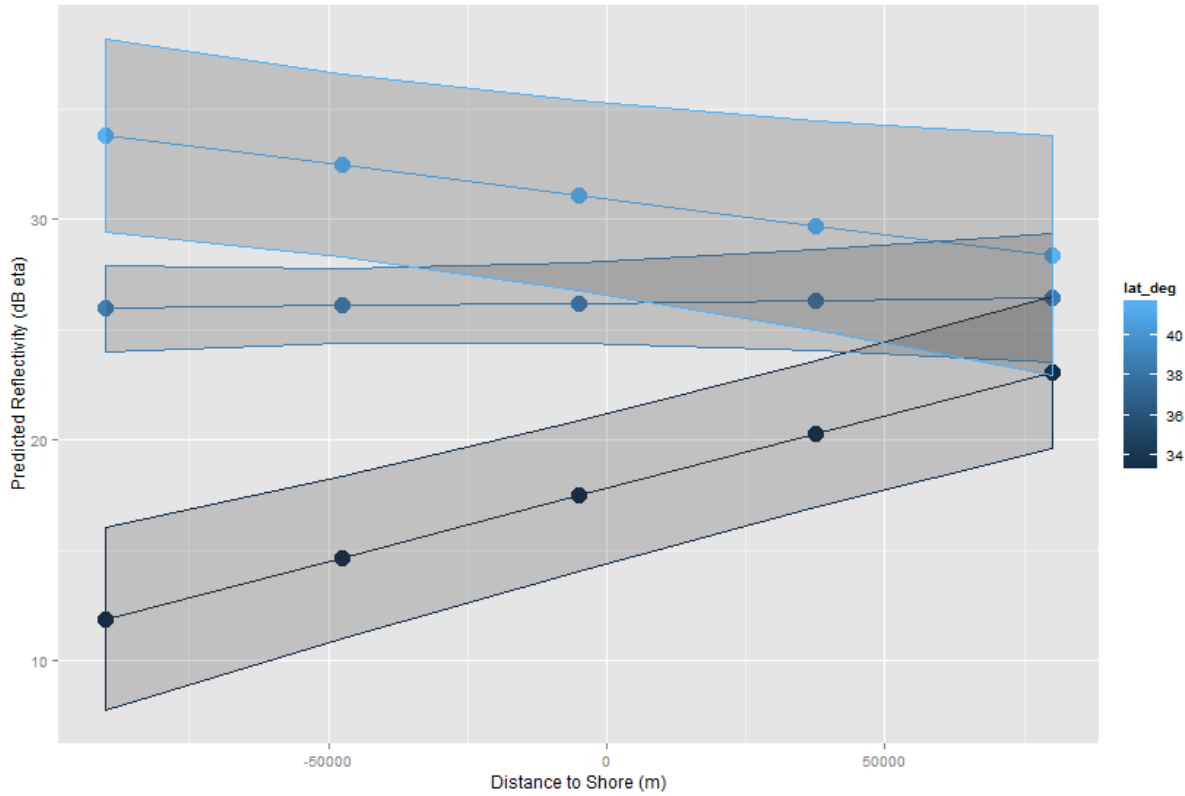
Figure 27-17. The effects of spring latitude on bioscatter with distance to shore. Zero is the shoreline while positive values indicate further away from the coast and negative values indicate further inland. Shaded areas indicate the estimated 95% confidence interval of the prediction when account only for variation in the model's fixed effects.

Table 27-1. Analysis of Variance Table for the Fall Spatial Model. Date, site and year were included as random variables. DF is degrees of freedom for the term, SSE is the sum squared error, MSE is the mean squared error and the F-value is a test to determine statistical significance on the F distribution.

Model Term	DF	SSE	MSE	F value
Radar Unit	5	358.6	71.7	6.6577*
Distance to Radar	2	14809.1	7404.5	687.3636*
Distance to Shore	1	28.8	28.8	2.6736
Elevation	1	30.5	30.5	2.8283*
Radar X Distance to Shore	5	57.7	11.5	1.071

*Indicates the 95% confidence interval of at least one of the parameters in this term does not overlap zero

Table 27-2. Analysis of Variance Table for the Fall Weather Model. DF is degrees of freedom for the term, SSE is the sum squared error, MSE is the mean squared error and the F-value is a test to determine statistical significance on the F distribution.

Model Term	DF	SSE	MSE	F value
Radar Unit	5	654.6	130.9	10.3178*
Distance to Radar	2	19413.5	9706.8	764.9804*
Land Cover	1	85.6	85.6	6.7447*
U Wind	1	71.7	71.7	5.6541*
V Wind	1	13.9	13.9	1.0981
Elevation	1	7	7	0.5481
Latitude	1	55.9	55.9	4.4035
Longitude	1	46.7	46.7	3.683*
Distance to Shore	1	23.7	23.7	1.8705
U Wind X Distance to Shore	1	150.3	150.3	11.8426*
U Wind X Latitude	1	251.3	251.3	19.8031*
V Wind X Distance to Shore	1	42.4	42.4	3.34
V Wind X Latitude	1	124.2	124.2	9.7847*
Distance to Shore X Latitude	1	32.4	32.4	2.5502

*Indicates the 95% confidence interval of at least one of the parameters in this term does not overlap zero

Table 27-3. Analysis of Variance Table for the Spring Spatial Model. DF is degrees of freedom for the term, SSE is the sum squared error, MSE is the mean squared error and the F-value is a test to determine statistical significance on the F distribution. A star in the "significance" column indicates that the 95% confidence interval for β does not overlap zero.

Model Term	DF	SSE	MSE	F value
Radar unit	5	286.17	57.23	4.9257*
Distance to Radar	2	2551.95	1275.98	109.8139*
Distance to Shore	1	261.18	261.18	22.4776
Elevation	1	223.23	223.23	19.2116*
Radar X Distance to Shore	5	274.44	54.89	4.7238*

*Indicates the 95% confidence interval of at least one of the parameters in this term does not overlap zero

Table 27-4. Analysis of Variance Table for the Spring Weather Model. DF is degrees of freedom for the term, SSE is the sum squared error, MSE is the mean squared error and the F-value is a test to determine statistical significance on the F distribution. A star in the "significance" column indicates that the 95% confidence interval for β does not overlap zero.

Model Term	DF	SSE	MSE	F value
Radar Unit	5	261.9	52.38	3.3612
Distance to Radar	2	5068.4	2534.21	162.6332*
Land Cover	1	1051.2	1051.16	67.4586*
U Wind	1	214.4	214.42	13.7605
V Wind	1	0.6	0.63	0.0406
Elevation	1	214.6	214.58	13.7707
Latitude	1	16.7	16.67	1.07*
Longitude	1	405.3	405.27	26.0084*
Distance to Shore	1	214.5	214.45	13.7627*
U Wind X Distance to Shore	1	325.1	325.07	20.8616*
U Wind X Latitude	1	27.7	27.69	1.7767
V Wind X Distance to Shore	1	271.1	271.05	17.3947*
V Wind X Latitude	1	13.3	13.29	0.853
Distance to Shore X Latitude	1	481.5	481.54	30.9026*

*Indicates the 95% confidence interval of at least one of the parameters in this term does not overlap zero