Quantifying animal phenology in the aerosphere at a continental scale using NEXRAD weather radars

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Abstract. One of the primary ecological manifestations of climate change is a shift in the timing of events in a species' annual cycle. Such phenological shifts have been documented in numerous taxa, but data for animals have been derived primarily from human observers rather than networks of instruments used for remote sensing. The potential to use the network of weather radars in the United States (NEXRAD) to remotely sense animal phenologies could advance our understanding of the spatiotemporal scaling of phenologies in relation to shifts in local and regional climate. We tested the utility of NEXRAD radar products for quantifying the phenology of the purple martin (*Progne subis*) at summer roost sites in the United States. We found that the maximum radar reflectivity value in the hour before local sunrise above purple martin roost sites contained a strong phenological signal of significantly increased radar reflectivity during June, July, and August 2010. The seasonal pattern in this radar signal matched our expectation of the timing of formation and dissipation of these seasonal roosts. Radar reflectivity was greater and less variable when considering roosts close to NEXRAD stations (<25 km) than when including all 358 documented roosts; there was a negative relationship between maximum reflectivity and the distance between a roost and the nearest NEXRAD. Our results suggest that: (1) mosaicked NEXRAD radar products are a valuable source of information on the phenology of bioscatter in the aerosphere; (2) citizen scientists who document the locations of roosts on the ground are providing critical information for advancing our understanding of animal phenology and aeroecology; and (3) ongoing research that examines spatiotemporal relationships among radar-derived phenologies in airborne organisms, climate, and land cover change are likely to provide further insights.

Key words: aeroecology; continental scale; NEXRAD; phenology; remote sensing.

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INTRODUCTION

Changes in the Earth's annual mean temperature are causing range shifts and changes in the timing of seasonal events (phenology) in the life cycles of a wide variety of organisms (Walther et al. 2002, Morisette et al. 2009, Forrest and Miller-Rushing 2010, Chen et al. 2011). Phenological

analyses of plant and animal life cycles have revealed patterns of earlier spring arrival (Van Buskirk et al. 2009), emergence (Roy and Sparks 2000), and reproduction (Winkler et al. 2002) in north temperate regions correlated with earlier onset of spring. There is also evidence that the end of the growing season is delayed (Dragoni et al. 2011). These phenological shifts are well-documented symptoms of anthropogenically driven climate change (Solomon et al. 2007).

A limitation of many datasets on phenology is that sparse records limit the capacity to down-scale the results for interpretation of regional and local environments that may differ from broader geographic patterns (Ibáñez et al. 2010). Moreover, to link phenological patterns to biological processes directly affected by climate change, it is necessary to document phenologies across the range of spatial and temporal scales that match species-specific behaviors, population dynamics, community structure and ecosystem function. Most existing analyses of animal phenology are based on observations made by humans in the field. While there is good evidence of temporal and spatial patterns within these datasets (Hodgson et al. 2011), the potential for investigating a wide range of spatial and temporal scaling relationships is limited by the relatively low spatial and temporal frequency of data collection, particularly in historical archival data.

Remotely sensed data, such as the Moderate Resolution Spectroradiometer (MODIS) derived Normalized Difference Vegetation Index (NDVI), often have higher spatial and temporal sampling frequencies than data derived from human observers. Remotely-sensed data also have limitations owing to uncertainty in ascribing precise biological meaning to trends in data (e.g., Garrity et al. 2010), relatively small archives available for exploring historical patterns, and the constraint that remote sensing from satellites detects only changes in primary production or vegetation characteristics and not higher trophic level dynamics. Satellite-based radar data as a measure of plant phenology is well established (Zhang et al. 2003), and significant progress has been made in matching ground-based observations to satellite-derived data (Cleland et al. 2007), but the use of these sensors for understanding animal phenologies is still in its infancy (Pettorelli et al. 2011). For these reasons, robust datasets on animal phenologies that can be used to examine interactions of animals with environmental factors over a broad range of temporal and spatial scales are uncommon. Moreover, we expect that such data will provide new insights into how animal phenologies respond to climate change.

The existing network of weather surveillance radar (WSR) is a remote sensing platform that routinely detects animals directly. These radars have been used to study movements of airborne animals for more than 60 years (Lack and Varley 1945, Gauthreaux 2006). The US network of WSRs, often referred to as NEXRAD (Crum and Alberty 1993, Serafin and Wilson 2000), has been used for biological investigations of animal distributions and movements almost since its inception (Gauthreaux and Belser 2003). Nonetheless, there has been almost no application of NEXRAD radar data to questions regarding phenology and climate change (however, see Horn and Kunz 2008). The timing, direction, and duration of animal flights are all critical components to understanding the life histories of many airborne arthropods, bats, and birds. Many of these events have marked seasonal phenologies that should be subject to the same climate drivers proposed as explanations of broader patterns in phenological data (e.g., Both et al. 2006, Parmesan 2006, Tottrup et al. 2010)

Documenting the size and dynamics of animal aggregations has been one of the most productive uses of WSR radars in the biological sciences (e.g., dispersal of bat colonies, Horn and Kunz 2008; bird roosts, Harper 1959.; and migratory stopover locations Diehl et al. 2003). Our analysis focuses on the purple martin (*Progne subis*), which forms aggregations during most of the year (Brown 1997). Several studies (Russell and Gauthreaux 1998, Russell et al. 1998, Russell and Gauthreaux 1999) have demonstrated the capability of NEXRAD for locating and monitoring roosts of purple martins. Detection of purple martin roosts using NEXRAD is accomplished in part by examining reported values of radar reflectivity, which is related to the total scattering area of the entities (e.g., number of martins) in a radar sampling volume (Rinehart 2004). Changes in radar reflectivity values associated with a geo-referenced biological aggregation can be used as an index of aerial density of biological scatterers.

Previous studies that used radar to study purple martins also highlight a number of considerations with NEXRAD reflectivity data that include: (1) data acquisition and processing requirements for broad spatial extents and long time series, and (2) the potential for animal aggregations to go undetected by radar due to local topographic factors and atmospheric conditions (Russell and Gauthreaux 1998). Because of this foundational work on purple martins, we chose to evaluate whether advances made in accessing and processing of data from the national network of radars might make them valuable for monitoring the phenology of animal aggregations over space and time.

In the US and Canada, the purple martin is the only common member of its genus. This species is relatively common east of the 100th meridian, in the plains of Alberta and Saskatchewan, in the Chihuahuan and Sonoran Deserts, and along the Pacific coast (Brown 1997). During the breeding and post-breeding season, March through August, this species is particularly abundant in the southeastern and south-central US (Brown 1997). The purple martin is typical of its genus with respect to its habits of: (1) aerial insectivory, (2) secondary cavity nesting, and (3) roosting communally in large aggregations throughout the non-breeding season. This species is exceptional in that nearly all individuals in the core of its range nest in colonies in structures provided by humans. After nesting, adult males and females and their young begin to gather in nightly aggregations (at roost sites) that can number in the hundreds of thousands of martins (Russell and Gauthreaux 1999). The purple martin is by far the most migratory member of the genus, traveling to a South American winter range that is centered in Bolivia (Brown 1997).

The primary hypothesis that we tested is that patterns in radar reflectivity (specifically, non quality-controlled composite reflectivity, or UnQC'd CREF, see Methods) were a direct measure of the phenology of purple martin aggregations. For this specific case, we predicted; (1) that seasonal patterns of radar reflectivity from locations of documented martin roosts would be significantly greater than those from random locations; (2) reflectivity values of purple martins emerging from roost sites would increase through summer, peaking between late July and

mid August, and declining through September in a curvilinear fashion; and (3) there would be no seasonal pattern in the reflectivity returned from randomly selected points. There are numerous reasons why these predictions might not be supported, which include: (1) the distance between roosts and radars is too great and therefore height of the lowest radar scan above the earth exceeds the flight altitude of purple martins; (2) the location data we obtained for purple martin roosts may have been too inaccurate to be useful; (3) radar scanning (volume coverage pattern) and processing is optimized for meteorological detections rather than biological detections.

Methods

Data from 159 WSRs in the United States are regularly collected, processed, and archived in a standardized manner and made available to the public through the National Climate Data Center (www.ncdc.noaa.gov). The temporal sampling frequency is typically ≤ 10 minutes depending on the volume coverage pattern chosen for an individual WSR at a given time. In addition to detecting precipitation in the atmosphere, these radars also detect flying animals, such as birds, bats and volant arthropods (Chilson et al. 2011). Recent advances in processing of data from networked radars into mosaics that map radar reflectivity onto a Cartesian grid spanning the entire continental US (Zhang et al. 2004, Zhang et al. 2005, Langston et al. 2007, Vasiloff et al. 2007) greatly increases the potential to use these radar data for continental-scale analyses.

The mosaic composite radar product that we analyzed is generated from raw reflectivity data collected by individual WSRs and processed through the National Severe Storms Laboratory's (NSSL) National Mosaic and Multi-Sensor QPE (NMQ) interface (Zhang et al. 2011). Before applying 'quality-control' algorithms to eliminate biological scatter, ground clutter, and other non-meteorological signals, raw radar products in spherical coordinates are mapped onto a Cartesian grid to generate so-called un-quality controlled composite reflectivity (UnQC'd CREF) products. This composite process takes the maximum reflectivity value for a given azimuth angle and range and maps it to a spatial location

on the Earth's surface in 0.1 degrees in Cartesian space; that is a 2-dimensional (2-D) spatial grid. The UnQC'd CREF maps from individual radars are then merged using a distance-weighted mean to produce a Continental US radar mosaic with a grid size of approximately 1 km^2 (Zhang et al. 2005). National mosaic radar products of 2-D UnQC'd and 3-dimensional (3-D) QC'd data among others are produced and maintained by NSSL. These products can be viewed in near real time on a national scale (http://soar.ou.edu/).

On 3 October 2010, we obtained latitudinal and longitudinal coordinates for 358 post-breeding roost sites of purple martins listed on the web page of the Purple Martin Conservation Association (www.purplemartin.org). Many of these locations are a direct result of the citizen science efforts by the Purple Martin Conservation Association (PMCA), which provides a web interface where observers can record locations of roosts and updates to their status. Thus, our study represents, in part, a test of the quality of the data reported by citizen scientists. We queried the mosaicked radar archive for two values: (1) maximum composite 2-D radar reflectivity (UnQC'd CREF in dBZ) of a 3 km × 3 km grid (i.e., maximum of the values of 9 adjacent, 1-km^2 cells) surrounding each of the 358 points for every 5 minute interval from 1 June 2010 through 29 September 2010 UTC; and (2) the maximum rainfall rate estimated from radar data in mm/h. Here we used radar reflectivity to detect the presence of purple martins; with larger values of Z corresponding to larger numbers of animals (Russell and Gauthreaux 1998). Russell and Gauthreaux (1998) found that the most reliable time to detect purple martins with WSRs at roost sites was in the hour before sunrise; therefore, we defined our temporal window as the hour before sunrise local time. We also censured all reflectivity data from time periods when radar products indicated that the rainfall rate was >0 mm/h in the 9 kms^2 from which we obtained radar data. From the filtered data, we then calculated the maximum radar reflectivity value for each roost on each day of the study period within the 9 km^2 grid centered at each roost location. To calculate the arithmetic mean of reflectivity values across all roosts for each day during the summer period, we converted maximum radar reflectivity values from a logarithmic scale (dBZ) to linear scale for

averaging and then rescaled the resulting means back to a logarithmic scale in dBZ. The means and confidence intervals we present represent all sites in a particular sample (e.g., random vs. roost sites) for a given day. We interpret instances where the 95% confidence limits of means do not overlap as evidence of significant difference between means, which is a relatively conservative approach for assigning statistical significance.

The height of the radar beam above the Earth's surface is a function of distance from the nearest radar station and atmospheric conditions. The lowest tilt angle typically used by WSR stations is 0.5 degrees above horizontal. This upward tilt of the radar beam means that the minimum elevation that can be detected by the radar increases with distance from the radar antenna; curvature of the earth also contributes to increasing elevation of the radar beam with distance from the antenna (Rinehart 2004). Because purple martins departing from a roost site can increase elevation slowly, they may be within several hundred meters of the ground when they are within the 3 km × 3 km grid that we sampled and thus are less likely to be routinely detected by radars if their roosts sites are far from a WSR. For example, at 100 km from a WSR station the lowest elevation of the bottom of the radar beam would typically be about 700 m. For these reasons, we used two approaches to evaluate the effects of distance between a roost site and the nearest WSR station on reflectivity measured by the radar. First, we repeated the analyses described above for all roost with the exception of removing roost sites from the analysis if they were further than 100, 50, and 25 km from a NEXRAD in successive steps. Second we calculated a mean for each roost site for the 31 days between 15 July and 15 August, when reflectivity at roost sites was high. Means were again calculated by converting to linear scale and then back converting to dBZ as described above. These mean values were then regressed against the distance between the roosts sites and the nearest NEXRAD.

Results

Mean maximum radar reflectivity averaged over all 358 martin roosts increased through July,

peaked in August and then declined in September (Fig. 1). This pattern was predicted if the roost locations we obtained were accurate and the daily emergence of purple martins from roosts sites was detectable with NEXRAD. There was no such pattern in the data from random locations. However, we discovered a linear increase in reflectivity at the random sites across the season that we did not predict. This increase does not appear to be associated with purple martins (Fig. 1). Seasonal patterns in reflectivity at roost sites were better described by a quadratic relationship than by a line while the converse was true for the reflectivity at random sites (Table

1). Reflectivity at the roost sites was significantly greater than that returned at random points from 17 June through 3 September 2010 (Fig. 2). Radar reflectivity measured at purple martin roosts increased successively and significantly when sites were filtered to include only those that were nearest to NEXRAD stations (Fig. 3). Sites within 100 km of the radar had reflectivity significantly greater than that at random sites from 15 June through 10 September, roosts within 50 km differed from random from 11 June through 22 September, and roosts within 25 km of a NEXRAD differed from random from 2 June through 25 September. This distance effect was also evident in analysis of all roosts, which demonstrated that there was a significant negative relationship between mean maximum reflectivity measured at roosts between 15 July and 15 August and the distance between a roost and a NEXRAD (Fig. 4).

Discussion

Our results suggest that at a continental scale, reflectivity data from WSRs are a valuable source of phenological information in respect to purple martins. Radar reflectivity from martin roost sites was both greater than that at random points and obviously seasonal in nature (Fig. 1, Table 1). These patterns matched well with the seasonal patterns reported by Russell and Gathreaux (Russell and Gauthreaux 1998) for one large martin roost in South Carolina as well as that of purple martins in the US more generally, peaking in late July and early August (Brown 1997).

Future analyses will likely include more sophisticated use of the mosaicked radar data. Indeed, we have a number of spatial tools under development that build substantially on our initial analysis presented here including 3 dimensional characterizations of bioscatter in the aerosphere. Our finding that the distance between the WSR and martin roost location was an important component of the magnitude of radar reflectivity detected at roosts means that this distance-effect will need to be a consideration for use of the WSR data in monitoring phenology over space and time. For example, our data suggest that selecting roosts within a 25–50 km distance to a WSR station may increase the quality of observations with respect to monitor-
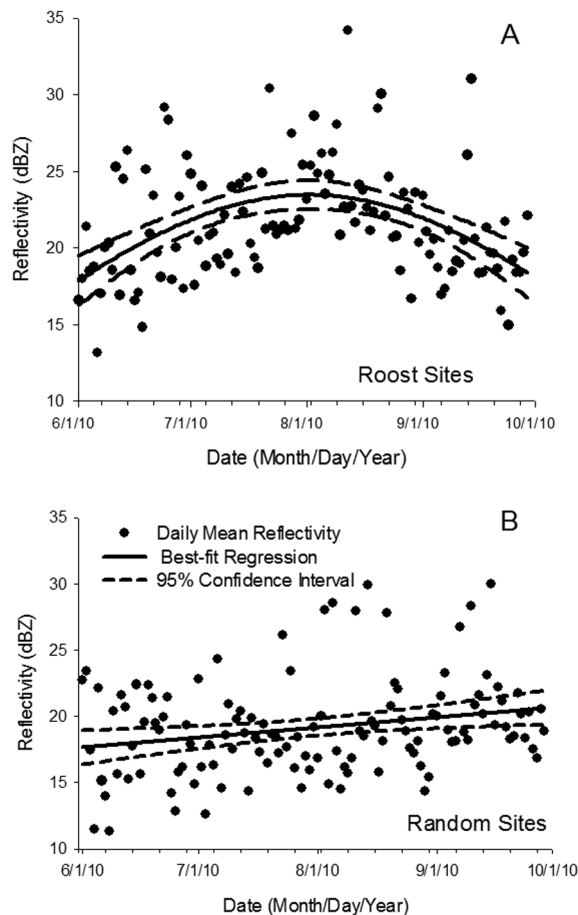

Fig. 1. Maximum radar reflectivity in the hour before sunrise averaged over 358 purple martin roost sites and a quadratic best-fit line with 95% confidence limits (A) and maximum radar reflectivity in the hour before sunrise for 100 random points with a linear best-fit and 95% confidence limits (B).

Table 1. Regression coefficients and goodness-of-fit statistics for linear (dBZ = intercept + a × date) and quadratic (dBZ = intercept + a × date + b × date^2) models of the relationship between maximum radar reflectivity (dBZ) and day of the year (date). Both linear and quadratic models are presented for analyses of all 358 roosts and 100 random sites. Only quadratic models are shown for the subsets of roosts within 100, 50 and 25 km of a NEXRAD. Equations in bold are plotted in figures. Those not bolded are considered inferior models based on comparison of model fit and number of parameters included in the model. For all models, date was coded sequentially starting at June 1st = 1. Standard errors of the coefficients are in parentheses.

Data used	Best-fit equation	R^2	P
All roosts	dBZ = 21.31(0.67) + 0.04(0.010) × date	0.01	<0.67
	dBZ = 17.59(0.92) + 0.19(0.040) × date − 0.001(0.0003) × date^2	**0.18**	**<0.0001**
Random	**dBZ = 17.63(0.65) + 0.03(0.009) × date**	**0.05**	**<0.008**
	dBZ = 17.69(1.00) + 0.02(0.003) × date − 0.00002(0.0003) × date^2	0.04	<0.03
100 km	**dBZ = 17.75(0.90) + 0.19(0.03) × date − 0.0015(0.0003) × date^2**	**0.20**	**<0.0001**
50 km	**dBZ = 18.35(0.95) + 0.23(0.04) × date − 0.00002(0.0003) × date^2**	**0.27**	**<0.0001**
25 km	**dBZ = 19.15(0.62) + 0.29(0.02) × date − 0.0022(0.0002) × date^2**	**0.56**	**<0.0001**

ing phenological signals and inference from between site comparisons. We also need to employ more sophisticated analytical techniques to be able to make quantitative comparisons among WSR-derived phenology curves across years (e.g., dates of maximum and minimum slope), as has been done for MODIS data (e.g., White et al. 2005). For spatial and temporal comparisons it would be useful to have robust measures of starting and ending dates of roosts

occupancy as well as the peak abundance of these aggregations. It is clear from our analysis that the citizen scientists who are engaged in monitoring purple martin roosts are providing critical ground-truthing data that enables more advanced interpretation of radar reflectivity data. Expanding the connections among radars, as a biological observation platform, and citizen science for a multitude of biological phenomena in the aerosphere (e.g., insect emergences, bird migrations) will be a key step for increasing our
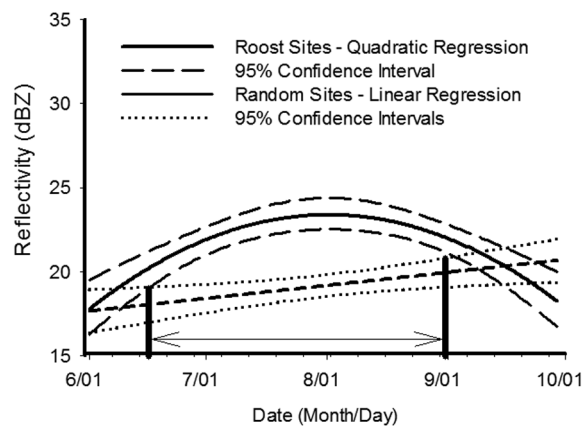

Fig. 2. Best-fit regression lines for maximum reflectivity at 358 purple martin roosts (solid curve) and at 100 random points (dashed line) each with 95% confidence limits. Vertical lines separated by an arrow indicate the time period during which the 95% confidence limits of the lines do not overlap (17 June to 3 September 2010), indicating a significant phenological signal associated with known martin roost locations from random locations.
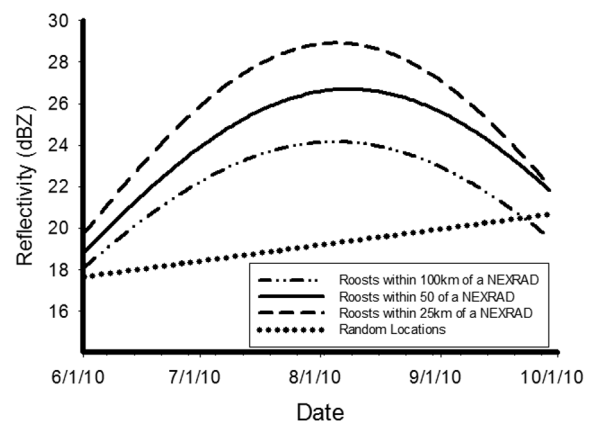

Fig. 3. Best-fit quadratic curves fitted to patterns in maximum radar reflectivity in the hour before sunrise at purple martin roosts (dBZ) across the summer of 2010 for roosts categorized by their distance from nearest NEXRAD (100, 50, and 25 km). The best-fit line for 100 random points is provided for reference and equation coefficients and fit parameters are provided in Table1.

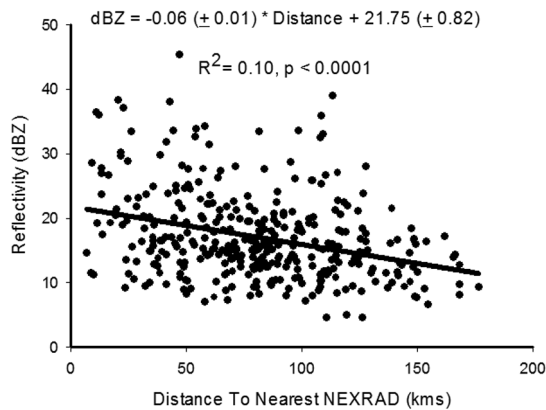dBZ = -0.06 (± 0.01) * Distance + 21.75 (± 0.82)

$R^2 = 0.10$, $p < 0.0001$

Fig. 4. Ordinary least squares regression between mean maximum radar reflectivity measured in the hour before sunrise at each martin roost (averaged over 31 days from 15 July and 15 August) and distance between each roost and the nearest NEXRAD. The equation describes the line with standard errors of the coefficients provided in parentheses; $n = 358$ roosts.

understanding of aeroecology (Kunz et al. 2008).

Concern over the ecological impacts of climate change provides considerable incentive for ecologists to find new and better ways to assess the impacts of climate on phenologies at higher tropic levels. Pettorelli et al. (2011) showed that MODIS derived NDVI was useful in predicting the distribution of herbivores and their responses to climate variation, which compels further research on possibilities for using NDVI to understand changes in animal biology over the 30-year archive of NDVI data. The method we present here provides a direct estimate of animal distribution and abundance in the aerosphere using an existing network of remote sensors. As far as we are aware, WSR data are the only source of remotely sensed data available for directly assessing the presence, abundance and distributions of airborne animals.

The general method we have employed should translate directly to seasonal aggregations of other birds (blackbirds, robins, tree swallows, waterbird colonies), as well as to colonial bats, and masses or swarms of airborne arthropods. Our results encourage next steps to extend our phenological analyses to the 20-year archive of radar data to explore questions about how phenologies of volant animals change in response to climate variation and for assessing

the impacts of land use changes on phenology. For example, there appear to be strong regional differences between southern and northern roosting phenologies of purple martins as well as roosts in urban versus more natural settings. These differences likely contain information that will be valuable for understanding phenological shifts of purple martins and other colonially roosting species within and among regions. Our results are the first to demonstrate that new mosaicked radar products can be used to assess continental-scale patterns of animal phenologies. These results also demonstrate that radar products produce meaningful biological signals at a continental scale that can be used for answering important questions regarding ecological responses to environmental change.

Acknowledgments

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