Toward integrating citizen science and radar data for migrant bird conservation

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Abstract
Migrating birds face an array of challenging conditions and hazards during their annual movements, including novel threats of mortality from anthropogenic structures, such as wind energy turbines and buildings. There is a need for new data sources that can be used to create risk assessments across a wide range of spatial and temporal scales, and weather radar data have shown promise in this regard. A primary limitation on the use of weather radar data in macroscale ecology has been the difficulty in data access and processing to make real-time assessments, and the lack of species-level information. We compared two weather radar products, Level II and UNQC-CREF that differ in several aspects. We found the 2D UNQC-CREF product provides similar information to Level II data regarding spatial and temporal patterns of bioscat-ter, although not without caveats. Due to its rapid availability and ease of use, we combined UNQC-CREF data with eBird daily species counts to quantify autumnal migration along one of North America’s major migratory routes. During their autumn migration southward, we predicted birds would use prevailing winds and favorable atmospheric conditions to time their migratory movements. Wind direction and ordinal date were strong predictors as were variables associated with inclement weather, including barometric pressure and ambient temperature. These patterns suggest that at a coarse scale, migratory birds avoid headwinds during their southerly movements during autumn, and more broadly indicate that local weather conditions can be used to predict pulses of migratory activity in the aerosphere. Our results suggest that similar methods could be used to measure the temporal and spatial components of avian migration at greater spatial scales – providing crucial information for conservation and management for migratory faunas. Specifically, future algorithms should focus on real-time implementation for bird strike mitigation, by altering wind energy facility operation on nights of peak migratory flow, in addition to timing “lights-out” events to minimize collisions with existing infrastructure such as buildings.

Introduction
Characterizing temporal and spatial patterns of animal migration is necessary for effective conservation (Moore et al. 1995; Loss et al. 2013). Over two thirds of all North American birds migrate each year by traveling long distances between breeding grounds in temperate northern areas to the tropics for the winter. These annual movements are costly and it is during these movements that tradeoffs between time and energy and their impact on the full annual cycle become evident. It is also common for the most severe risks to survival to occur during trans- ²it (Alerstam 1990). Recently, anthropogenic land-use changes, such as renewable energy development and light
pollution, present new sources of mortality to migratory faunas (Hayes 2013; Erickson et al. 2014), with potential population-level consequences (Kunz et al. 2007; Faaborg et al. 2010).

Data on the spatial and temporal distribution and abundance of migrating birds and bats are particularly relevant in considering placement of new energy infrastructure (Loss et al. 2013). Millions of birds and bats are killed each year from collisions with wind turbines and buildings, with the majority of collisions occurring during autumn migration (Kuvelsky et al. 2007; Arnett et al. 2008; Loss et al. 2015). Wind energy sources are expected to supply 20% of the total energy in the United States by 2030, requiring turbine installments to increase by approximately 15% per year over the next 13 years (NREL 2008).

Identifying cost-effective and efficient ways to determine spatial and temporal patterns of migratory activity near areas identified for wind and solar energy development as well as existing infrastructure (i.e. high-rise buildings) could aid conservation efforts to reduce impacts on wildlife. For example, because most collisions with wind turbines occur during migration (Klaassen et al. 2014), operational strategies to reduce mortality, such as changing cut-in speeds during periods of high migrant flow, could be used to significantly reduce mortality with little loss of energy production (Arnett et al. 2011). In addition, evidence suggests that nocturnal migrants are attracted to sources of light such as buildings at night – where “lights-out” events have reduced the incidence of collision during migration (Evans Ogden 1996, 2002). For these management approaches to be effective, they require near real-time assessment of migrant density through a region based on seasonal timing and atmospheric conditions.

Understanding how atmospheric conditions influence migratory behavior and movements provides unique challenges – in part due to the difficulty of acquiring accurate information on how animals distribute themselves within the airspace (Kunz et al. 2008; Berthold et al. 2013; Diehl 2013). Most North American birds migrate at night and are of small body size, further hindering the study of migratory behavior on the wing (Gauthreaux and Belser 2003). At daily or short-term scales, birds use sources of information to make informed migratory decisions that reflect present and future conditions (Winkler et al. 2014). For example, low atmospheric pressure is typically associated with precipitation and birds may use this information and other environmental cues such as headwinds, precipitation, and turbulence to avoid unfavorable conditions during migration (Åkesson and Hedenström 2000; Liechti 2006; Chapman et al. 2015 Åkesson 2016). Thus, determining how migration patterns correspond to changing atmospheric conditions at large spatial scales could prove useful for predicting how and when birds or bats migrate and the relative risk of mortality from energy and other infrastructure (Richardson 1978).

Indirect methods of observation have the potential to increase our understanding of migratory behavior at scales ranging from local to regional to continental. For example, remote sensing technologies, such as weather radars, provide tools to understand the spatial and temporal flux of aerial biomass (Buler et al. 2012; Kelly et al. 2012; Kelly and Horton 2016). Radar provides information on reflectivity, a measurement of the power returned from objects in the aerosphere, a unit that can be converted into measurements of biomass aloft (Chilson et al. 2012b). An increasing number of studies support the utility of using weather radars for ecological questions relating how meteorological drivers influence movement and density, at varying spatial and temporal scales (Frick et al. 2012; La Sorte et al. 2014, 2015; Horton et al. 2016; Kelly et al. 2016). In addition, citizen science databases such as eBird provide count data containing both spatial and temporal information at the species level. eBird can be used to recreate summer and winter resident communities, and estimate their time of departure or arrival. By combining the information from these two datasets, we can begin to address one of the limitations of radar (species-level identification) with eBird’s species-/community-level data to produce an estimate of whether the observed bioscatter is simply flying organisms aloft or are likely to be migrants on the move.

In this research, our goal was to determine whether species-level occurrence data such as eBird can complement the broad spatial information from radar to document avian migration, and if these periodic movements were correlated with local weather conditions. Avian migration is typically viewed to be costly, both in terms of energetics and mortality risk – thus, information regarding the drivers of migratory movement could be invaluable to understand mortality risks associated with anthropogenic structures. First, we compared two types of data from the NEXRAD weather surveillance network (Level II and UNQC-CREF). We asked whether these data could be used to measure seasonal and nightly patterns of migratory activity and would provide comparable results. Due to its rapid availability and ease of use, we proceeded with further analyses using the UNQC-CREF data. Second, we used the occurrence of a list of summer or winter resident species from eBird to determine when migration is likely to occur in autumn, (i.e. when eBird records show summer resident bird species were departing or winter residents arriving locally); and we compared the aerial biomass measure via radar before, during, and after the migratory period. Thirdly, we determined if
weather variables were associated with nightly migratory intensity near wind energy production facilities in central California. We hypothesized that aerial biomass would be greatest during migration, the time coinciding with the highest rate of fatalities at wind energy facilities (Klaassen et al. 2014). Finally, we predicted that nightly variation in migratory intensity is associated with local weather conditions, and that migratory intensity is likely to be less intense during periods of unfavorable conditions such as headwinds, low temperatures, or incoming weather fronts (i.e. low atmospheric pressure).

**Materials and Methods**

**Weather surveillance radar data**

We obtained NEXRAD reflectivity data across a 21,000 km² domain centered near Sacramento, California (geographic extent: −122.7358 W, 39.2833 N, −120.9322 E, 37.8818 S; Fig. 1) from before, during, and after the autumn migratory period (September 1st through November 30th) for 2009, 2010, and 2011 at 5-minute intervals. We downloaded level II data for the KDAX weather surveillance radar (WSR) from the National Centers for Environmental Information and were provided un-quality controlled composite reflectivity (UNQC CREF) data by the National Severe Storms Laboratory (NSSL).

We compared level II data from KDAX to the un-quality controlled composite reflectivity (UNQC-CREF, see supplemental material) to validate use of the UNQC-CREF product for interpretation of bioscatter signatures (for detailed description of comparison see supplemental material). Level II reflectivity data have been used routinely in aerocological studies (Gauthreaux and Belser 1998; Horn and Kunz 2008; Buler and Diehl 2009), but the UNQC-CREF is a relatively recent product and its utility for use in aerocological applications has been suggested (Chilson et al. 2012a) but not widely implemented (although see Kelly et al. 2012 and Bridge et al. 2016).

We used a combination of visual screening and volume coverage pattern (VCP) information from Level II data to exclude nights from the UNQC-CREF data when KDAX was not operating in clear air mode (VCP 31 or 32), obvious precipitation was within 100 km of the radar, or abnormal refraction of the radar beam. Over the 3-year study period, 38% (106 of 272) of sampled days were excluded from further analysis due to missing data, precipitation, or anomalous propagation. Regions of the sampling domain impacted by ground clutter contamination were masked from UNQC-CREF data (Fig. 1, Fig. S2).

**Migration intensity**

UNQC-CREF data are natively in logarithmic units of the radar reflectivity factor (dBZ), which is a convenient measure for covering a wide range of values, but depends on some assumptions that are inappropriate for investigations of bioscatter (Chilson et al. 2012b). We converted dBZ into radar reflectivity ($\sigma_0$) using the methods described by Chilson et al. (2012b). This results in a more meaningful interpretation of volume reflectivity in units of ($\eta$[cm²/km³]) (Dokter et al. 2011), appropriate for research on bioscatter (Shamoun-Baranes et al. 2011; Chilson et al. 2012b; Dokter et al. 2013a,b). Eta values can be converted to an estimate of bird density, for example, an value of 500 ($\eta$[cm²/km³]) could be from approximately 250 wood thrushes (RCS = 2 cm²), where the radar cross-section value is known (Alerstam 1990). To create a daily measure of bioscatter intensity in the region between 30 and 100 km from the radar, we calculated 4-h running averages of radar reflectivity ($\eta$) starting 30 min before sunset and ending 30 min after sunrise and took

![Figure 1. NEXRAD weather surveillance network coverage of region of analysis – The study region is a key migratory area for millions of birds along the Pacific Flyway in California’s Central Valley. We analyzed UNQC-CREF data between 30 and 100 km distance from the nearest NEXRAD station (KDAX), located near Sacramento, CA. Mountains, urban areas, and wind farms that created persistent clutter or partial radar beam blockage were excluded from analysis.](image-url)
the maximum average value for each day for each 1 x 1 km pixel. We calculated and analyzed means of this nightly average radar reflectivity (\( \eta \)) across 3 years (2009–2011).

We created spatial heat maps of radar reflectivity by averaging five nights from each year with the greatest reflectivity (Fig. 3), in each of the three migratory time periods (pre-, during, and postmigration) as defined by eBird.

**Citizen science observational data (eBird)**

eBird is an online database maintained by the Cornell Lab of Ornithology and the National Audubon Society that contains bird observational data documenting the presence or absence of species based on citizen scientist submissions (Sullivan et al. 2014). Data are open access and have been quality controlled for species identification and accuracy (Sullivan et al. 2009). We downloaded complete count data from completed lists of daily bird sightings (2009: 23,291; 2010: 20,948; 2011: 37,384) for the Sacramento, CA area within 50 km of the KDAX WSR and compiled a list of 13 bird species representative of birds occurring during the summer and 14 species during the winter (Table S1). We quantified the change in the number of summer and winter birds species observed per day to define the autumn migratory period in each study year (La Sorte et al. 2013). We defined the beginning of migration as the date when the occurrences of summer birds fell below a 95% confidence limit based on daily average occurrences and the end of migration as the date when winter bird occurrences exceeded the 95% confidence interval for each season (Fig. 2).

**Meteorological data**

We estimated atmospheric conditions for each evening using data from the NCDC Global Historical Climatology Network (GHCN) for Sacramento, CA (http://www.ncdc.noaa.gov/cdo-web/datasets), North American Regional Reanalysis (NARR, http://rda.ucar.edu/datasets/ds608.0/, dataset ds608.0), and the day of year (DOY), resulting in a total of 11 variables for analysis (dataset ds608.0). NARR variables included (1) mean surface temperature and (2) barometric pressure from the GHCN, (3) wind direction 925 mbar, (4) wind direction 825 mbar, (5) wind direction 725 mbar, (6) wind direction at 30 m above ground level, (7) wind speed 925 mbar, (8) wind speed 825 mbar, (9) wind speed 725 mbar, (10) wind speed at 30 m above ground level, and (11) day of year. Isobaric pressure levels 925, 825, and 725 mbar correspond to ~750, 1700, and 2750 m above sea level, respectively. NARR data are produced at 3 h intervals and are spatially organized into a grid at ca. 32-km resolution (minimal resolution due to projection). The 10 variables from the NARR dataset were summarized for each evening by averaging the data that occurred between sunset and sunrise for the cell closest to the NEXRAD station KDAX. Wind speed was log10 transformed before averaging and nightly wind direction was estimated using the circular mean.

**Statistical analyses**

**Seasonal patterns of bioscatter intensity**

We tested whether nightly peaks of averaged radar reflectivity (\( \eta \)) from KDAX were greater during the autumn migratory period compared to winter with a generalized linear model (GLM, gaussian family with identity link function) with nightly peaks of averaged radar reflectivity (\( \eta \)) as the response variable and season (pre-, during, and postmigration defined from eBird data, Fig. 2) as a categorical predictor and year as a categorical fixed effect.
Predicting nightly migratory intensity from meteorological conditions

We examined whether meteorological conditions were associated with nightly variation in migratory activity during the autumn migratory period by fitting generalized additive mixed models (GAMMs) using maximum likelihood (ML) estimation with nightly average radar reflectivity as the response variable, and ordinal date, temperature, barometric pressure, wind speed, and wind direction as predictor variables. Year was included as a random effect in all models. We fit 64 a priori models and used AIC (Burnham and Anderson 2003) for model selection including single-term models. We did not include any models with highly correlated terms (Pearson’s $r > 0.75$). The wind direction variables calculated at three different pressure levels were correlated with each other, and were not included in the same model.

We conducted analyses in R, version 3.2.2 (R Development Core Team 2015). The library “corrplot” was used to calculate pairwise correlation between predictor variables (Wei 2013) and the “gamm4” library was used to fit GAMMs (Wood 2006). The default optimization procedure was used to estimate the degree of smoothing for all generalized additive mixed models.

Results

Level II data were positively correlated with UNQC-CREF data ($R^2 = 0.56$, RMSE = 8.76, MAE = 5.73) across the entire domain when calculated on a cell-by-cell basis. The strongest correlation was between distances of 40–80 km from the KDAX radar (Fig. S1), therefore we restricted further analyses to data from within this range (Chilson et al. 2012b). The results from our comparison of the two datasets suggest UNQC-CREF data (used hereforth in all analyses) were valid for describing seasonal and spatial migratory patterns.

Nightly bioscatter intensity was significantly higher during peak migratory period as defined by eBird observations compared to both before (GLM; $t_{4,149} = -2.723$, $P = 0.007$) and after (GLM; $t_{4,149} = 15.207$, $P < 0.001$). In addition, reflectivity varied by year with significantly higher values in 2011 than in 2009 or 2010 (GLM; $t_{4,149} = 3.552$, $P < 0.001$). Bioscatter intensity varied from night to night, but 71.8% of the nights in the upper quartile of bioscatter intensity (>1551 g) fell within the predominant migratory period as opposed to 5.1 and 23.1% during the pre- and post-migration period, respectively (Fig. 2). The timing of the migratory period was similar in all 3 years (September 6th to October 11th in 2009, September 5th to October 3rd in 2010, and September 11th to October 10th in 2011) (Figs. 2 and 3).

Atmospheric conditions such as temperature, pressure, and wind direction (725 mbar), as well as ordinal date were included in the best-fit model for describing nightly variation in bioscatter intensity (Fig. 4, Table 1). In the two best models, migratory intensity was greatest on nights with winds originating from the north, when temperature was greater than 10° C and barometric pressure was above 1015 mbar. There was a temporal aspect of migratory intensity as well, with most high-intensity nights occurring before day 285 for each year (~October 12th, depending on year).

![Figure 3](image-url)
Discussion

The majority of North American bird species migrate at night, and often species depart the summer breeding grounds over a period of a several days to a few weeks. Our results show that periods of peak radar reflectivity measured at night corresponded to independent ground-based eBird observations of species counts during daytime, suggesting that peak reflectivity occurred during periods of bird community turnover (e.g. where summer residents were departing or winter residents were arriving). Many different flying organisms are found within the airspace, and at the present there are no methods to distinguish between them if they co-occur within a single radar volume (Dokter et al. 2011; Cabrera-Cruz, et al. 2013), however, volume measurements are often biased toward the characteristics of the largest scatterers (Stepanian et al. 2016). Although we cannot exclude all possible biological contaminants, the simplest and most likely explanation for the observed correlation is the predominant biological signal was birds arriving or departing at night during migration.

Migratory intensity measured via bioscatter was associated with a predictable seasonal pattern as peak migration intensity occurred during a 3- to 4-week period between September and early October. Despite a strong seasonal trend across the study area (Fig. 3), changes in reflectivity were highly episodic and varied considerably from night to night. The nightly variation in migratory intensity was strongly associated with atmospheric conditions such as temperature and atmospheric pressure (panels A and B) show a positive correlation with radar reflectivity values, whereas ordinal date (panel C) illustrates a non-linear seasonal decline between the pre, during, and post migration seasons. Panel (D) illustrates the wind direction (0 and 360 equals wind originating from the north) with a positive association with northerly winds and a negative association with southerly winds during the autumn period.

Table 1. Summary of model selection results for models with the most support based on Akaike Information Criteria (AIC).

| Coefficients | ΔAIC | Weight | $R^2$ | d.f. |
|--------------|------|--------|-------|------|
| $Y \sim \text{temp}^* + \text{baro}^* + \text{doy}^* + \text{dir} 725 \text{ m}^1$ | 0 | 0.92 | 0.54 | 13 |
| $Y \sim \text{temp}^* + \text{baro}^* + \text{doy}^* + \text{dir} 725 \text{ m}^1 + \text{spd} 725 \text{ m}$ | 2.76 | 0.03 | 0.497 | 11 |
| $Y \sim \text{temp}^* + \text{doy}^* + \text{dir} 725 \text{ m}^1$ | 8.77 | 0 | 0.49 | 16 |
| $Y \sim \text{temp}^* + \text{baro}^* + \text{doy}^* + \text{dir} 925 \text{ m}^1$ | 8.78 | 0 | 0.46 | 13 |
| $Y \sim \text{temp}^* + \text{baro}^* + \text{doy}^* + \text{dir} 30 \text{ m}^2$ | 10.73 | 0 | 0.47 | 13 |

We tested 64 candidate models using combinations of the variables temperature (temp), barometric pressure (baro), ordinal date (doy), and wind direction (dir) and speed (spd) at four different altitudes.

* $P < 0.001$.
† $P < 0.01$.
‡ $P < 0.05$. 

Figure 4. Non-parametric splines for all four predictors from the best-fit GAMM—temperature and atmospheric pressure (panels A and B) show a positive correlation with radar reflectivity values, whereas ordinal date (panel C) illustrates a non-linear seasonal decline between the pre, during, and post migration seasons. Panel (D) illustrates the wind direction (0 and 360 equals wind originating from the north) with a positive association with northerly winds and a negative association with southerly winds during the autumn period.
temperature, wind direction, and barometric pressure, suggesting that migratory movements are associated with local meteorological cues.

As birds face the rigorous demands of migration, they must use environmental information to determine the timing of individual movements as they travel to wintering grounds (Alerstam 1990). Birds may use favorable weather conditions, such as tailwinds, during migration to reduce the energetic costs of long distance movements (Chapman et al. 2015; Akesson 2016; Wainwright et al. 2016). Current evidence suggests birds tend to migrate at altitudes of 500–2500 m above sea level (mean 900 m), and select the lowest altitudes with favorable conditions (Dokter et al. 2011, 2013b; La Sorte et al. 2015). Our results suggest that meteorological conditions, such as wind direction at the 725 millibar isobaric level that corresponds to ~2750 m above sea level, were significantly associated with nightly pulses of migratory intensity. These relationships between migratory intensity and meteorological conditions provide support for hypotheses that birds utilize favorable weather conditions during migration (Akesson 2016; Chapman et al. 2016). In our study, migration intensity was greatest on autumn nights when there was a northerly wind, likely representing energetically favorable conditions as birds venture southward during autumn migration.

Inclement weather can adversely impact foraging success, body condition, and metabolic requirements during migration (Newton 2006). Meteorological variables, such as temperature and atmospheric pressure, provide birds information about environmental conditions during migration. Descending atmospheric pressure is associated with many behavioral changes in vertebrates (Metcalf et al. 2013) as it can serve as an informative environmental cue regarding imminent storms and thus provide time for altering behavior. We found a positive correlation between migratory intensity and atmospheric pressure, demonstrating that these cues likely play a role in determining migratory behavior. These results are consistent with other studies that found that birds perceive changes in atmospheric pressure and may alter movements and behavior to avoid unfavorable weather conditions during migration (Pyle et al. 1993; Shamoun-Baranes et al. 2006; Matthews and Rodewald 2010; Horton et al. 2016).

Autumn migration is the seasonal period when the greatest numbers of bird and bat strike incidents occur at wind farms in North America (Arnett et al. 2008, 2011; Kunz et al. 2008; Piorkowski et al. 2012). These methods also apply to “lights-out” events, where migratory intensity could inform the need to minimize the risk for collisions with buildings by lowering light emission levels at a finer temporal scale. Our study shows how the existing network of weather radars and meteorological monitoring programs can be used to aid conservation efforts aimed at minimizing impacts of renewable energy on wildlife.

Mitigating the risks that existing infrastructure poses to in-transit migrants requires a responsive workflow that allows for decisions to be made quickly, ideally in real time. Recent changes in the data delivery and processing timescale for Level II information via Amazon Web Services (https://aws.amazon.com/noaa-big-data/nexrad/) has greatly increased the potential of using the level II product for responsive, near real-time analyses. The change in level II availability may limit the utility of UNQC-CREF in conservation applications where accuracy supersedes tractability. For example, changing wind turbine operational schedules will incur a cost and with the known limitations (two-dimensional nature, lack of velocity information and other radar moments, and lower accuracy) it is unlikely that a data pipeline based on UNQC-CREF would be adopted by the energy industry. However, despite these disadvantages our analysis suggests that the UNQC-CREF data product still has heuristic value for certain scientific questions, exploratory analysis, and rapid data screening for quality control.

As we enter an era of dramatic environmental change resulting from global warming and the activities of a rapidly growing human population, there is an imperative to determine how natural systems will respond to these myriad anthropogenic changes. Data that match the temporal and spatial scales at which impacts from climate change might be evident has become a central challenge for ecologists (e.g. Jetz et al. 2012) as evinced by investment in new national observatories, such as the National Ecological Observatory Network (Schimel 2011). Even...
with these new investments, the ability to remotely sense the dynamics of aerial vertebrate populations and how they respond to climate change has remained largely hypotheti-
cal (Pettorelli et al. 2005). Our study here adds to a grow-
ing body of work that demonstrates that weather radar networks provide a useful broad-scale, remote sensing sys-
tem for answering basic and applied ecological questions (Buler and Dawson 2014; La Sorte et al. 2015, Horton et al. 2016), and that responsive and accurate data processing coupled with a rapid delivery framework is required to make effective management decisions.

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**Supporting Information**

Additional supporting information may be found online in the supporting information tab for this article.

**Appendix S1.** Quantitative comparisons between the UNQC-CREF and Level II radar data.

**Figure S1.** Correlation between reflectivity from a composite reflectivity product (CREF) and Level II radar reflectivity.

**Figure S2.** Comparison of Montezuma hills wind farm to random sites – To test if the wind farm is a consistent source of reflectivity contamination, we created masks of five different random sites (A–E) within 20 km and of the Montezuma Hills wind farm (WF).

**Table S1.** Summer and winter bird species occurrence in Sacramento area near KDAX – We compiled a selection of 27 total different bird species known to occur predominantly in either the summer (June–August) or winter (December–February) months in Central California.