

# Monitoring seasonal bat activity on a coastal barrier island in Maryland, USA

Joshua B. Johnson · J. Edward Gates ·  
Nicolas P. Zegre

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**Abstract** Research on effects of wind turbines on bats has increased dramatically in recent years because of significant numbers of bats killed by rotating wind turbine blades. Whereas most research has focused on the Midwest and inland portions of eastern North America, bat activity and migration on the Atlantic Coast has largely been unexamined. We used three long-term acoustic monitoring stations to determine seasonal bat activity patterns on the Assateague Island National Seashore, a barrier island off the coast of Maryland, from 2005 to 2006. We recorded five species, including eastern red bats (*Lasiurus bore-*

*alis*), big brown bats (*Eptesicus fuscus*), hoary bats (*Lasiurus cinereus*), tri-colored bats (*Perimyotis subflavus*), and silver-haired bats (*Lasionycteris noctivagans*). Seasonal bat activity (number of bat passes recorded) followed a cosine function and gradually increased beginning in April, peaked in August, and declined gradually until cessation in December. Based on autoregressive models, inter-night bat activity was autocorrelated for lags of seven nights or fewer but varied among acoustic monitoring stations. Higher nightly temperatures and lower wind speeds positively affected bat activity. When autoregressive model predictions were fitted to the observed nightly bat pass totals, model residuals >2 standard deviations from the mean existed only during migration periods, indicating that periodic increases in bat activity could not be accounted for by seasonal trends and weather variables alone. Rather, the additional bat passes were attributable to migrating bats. We conclude that bats, specifically eastern red, hoary, and silver-haired bats, use this barrier island during migration and that this phenomenon may have implications for the development of near and offshore wind energy.

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J. B. Johnson · J. E. Gates  
Appalachian Laboratory, University of Maryland  
Center for Environmental Science, 301 Braddock  
Road, Frostburg, MD 21532, USA

N. P. Zegre  
Division of Forestry and Natural Resources,  
West Virginia University, P.O. Box 6125,  
Morgantown, WV 26506, USA

*Present Address:*  
J. B. Johnson (✉)  
Division of Forestry and Natural Resources,  
West Virginia University, P.O. Box 6125,  
Morgantown, WV 26506, USA  
e-mail: j-johnson3@juno.com

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Wind energy

## Introduction

Wind energy development in the United States and Europe has increased remarkably in recent years (AWEA 2009; GWEC 2008). Although there are no greenhouse gas emissions from this form of energy, the benefits have not come without consequences, particularly in terms of effects on wildlife and wildlife habitat (Kuvlesky et al. 2007). For example, it has been estimated that tens of thousands of bat mortalities can be attributed to close encounters with rotating wind turbine blades in the Mid-Atlantic region of the United States alone (Kunz et al. 2007). Consequently, there has been much recent research examining the causes of bat mortalities at wind energy facilities (e.g., Arnett et al. 2008; Horn et al. 2008; Baerwald et al. 2009). These studies documented bat behavior at wind turbines, temporal mortality patterns, and correlations between bat activity, mortality patterns, and weather variables, all in an attempt to determine the causal mechanisms of bat mortalities at wind energy facilities (Reynolds 2006; Arnett et al. 2008; Horn et al. 2008). To date, many hypotheses on the cause of bat mortality at wind energy facilities were suggested, and several were partially substantiated. Bats may be attracted to wind turbines because they are analogous to large trees used as visual cues during migration or mating (Kunz et al. 2007; Cryan 2008). Variation in weather characteristics, such as wind speed and temperature, may affect bat activity patterns and possibly mortality patterns (Reynolds 2006; Cryan and Brown 2007). Despite these insights, factors affecting bat mortality at wind energy facilities remain largely unclear.

Investigations have documented several fairly consistent aspects of bat mortality at wind energy facilities, mostly in the eastern United States (Kerns and Kerlinger 2004; Jain et al. 2007; Arnett et al. 2008). The majority of bat mortalities are migratory tree bats, including eastern red bats (*Lasiurus borealis*), hoary bats (*Lasiurus cinereus*), and silver-haired bats (*Lasionycteris noctivagans*), and it is unknown why these species are more susceptible than other bat species, such as the myotome species (Johnson et al. 2003; Kunz et al. 2007; Arnett et al. 2008). Mortality at wind energy facilities most commonly occurs during late

summer–early autumn when bats are migrating (Kunz et al. 2007; Arnett et al. 2008). Also, bat mortality commonly is higher during nights with low wind speeds (Arnett 2005; Baerwald et al. 2009). It is unknown if bats congregate and follow migratory pathways or linear landscape elements such as ridgelines where wind turbines commonly are situated, such as along the Appalachian Mountains, or if their distributions during migration are more widespread across the landscape, including coastal areas (Cryan 2003; Kunz et al. 2007).

Anecdotal accounts exist of bats, particularly eastern red bats, migrating off the Atlantic Coast (Norton 1930; Carter 1950; Mackiewicz and Backus 1956). These migrations may have implications for near and offshore wind energy facilities if bats commonly migrate along coastal areas (Kuvlesky et al. 2007). Furthermore, barrier islands along the Atlantic Coast may serve as stopover sites for migrating bats (Cooley 1954; Tenaza 1966; Cryan and Brown 2007). Bats migrating near the coastline could potentially encounter near and offshore wind energy facilities, which are currently proposed for Rhode Island, New York, New Jersey, Delaware, and Maryland, USA (Kuvlesky et al. 2007; Soper 2007; Bluewater Wind 2008). However, the extent of bat migration along coastlines and use of barrier islands by bats during migration remains unknown. Substantial research on causes of bat mortality and potential mitigation strategies at wind energy facilities in the eastern United States has focused on areas along the Appalachian Mountains (e.g., Arnett 2005). However, information on bat mortality at proposed wind energy facilities along the Atlantic Coast is needed. It is unknown if bat migration along this coastline is similar to migration in the Appalachian Mountains in magnitude and timing. An assessment of bat activity throughout the year along the Atlantic Coast is warranted to determine if coastal wind energy facilities could adversely impact bats. Therefore, our objectives were to (1) establish seasonal bat activity patterns on an Atlantic Ocean barrier island, (2) determine if bats use the barrier island during migration, and (3) determine if bat activity patterns were correlated with weather conditions. Based on anecdotal accounts and published literature (e.g., Norton 1930; Mackiewicz and Backus 1956; Cryan

2003), we hypothesized that (1) bats use barrier islands while migrating along the Atlantic Coast; (2) temporal patterns of migration are similar to those established at similar latitudes in North America, i.e., March to May and August to November (Cryan 2003; Kunz et al. 2007); and (3) that bat activity is positively associated with particular weather conditions, including higher temperatures, lower wind speeds, less precipitation, lower barometric pressure, and higher relative humidity (Lacki 1984; Paige 1995; Erickson and West 2002; Parsons et al. 2003; Reynolds 2006; Turbill 2008).

## Materials and methods

### Study site

We conducted our research at the Assateague Island National Seashore (ASIS), located on Assateague Island, Worcester County, Maryland (38°10' N, 75°10' W). Assateague Island is a 0.4- to 4.0-km-wide × 59.6-km-long barrier island that extends from Ocean City, Maryland, to Chincoteague, Virginia. ASIS lies wholly in Maryland and comprises the northern 35.4 linear kilometer of the island. Sinepuxent Bay and Chincoteague Bay are situated between ASIS and the mainland. These saltwater bays range in width from 1 km on the northern terminus of ASIS to about 8 km near the southern terminus (Maryland–Virginia state line).

The Assateague Island National Seashore included approximately 3,600 ha of beaches, dunes, shrublands, forests, marshes, and freshwater pools. The northern 8 km of ASIS is sparsely vegetated, consisting mostly of cordgrass (*Spartina* sp.) and shrubs (*Myrica* sp.). Bayside marsh vegetation consists largely of cordgrass. Forests are distributed patchily on the southern two thirds of the island's western side and are comprised mostly of mature loblolly pine (*Pinus taeda*). Red maple (*Acer rubrum*), sweetgum (*Liquidambar styraciflua*), and wild black cherry (*Prunus serotina*) occur sporadically as canopy intermediates. The shrub layer beneath the forest canopy exists as dense, discontinuous patches of waxmyrtle (*Myrica cerifera*), bayberry (*Myrica*

*pensylvanica*), and groundsel tree (*Baccharis halimifolia*). In many areas, forest tracts are juxtaposed to bayside marshes with vegetative transition, when present, consisting mostly of shrubs (e.g., waxmyrtle). Shrubland transitions between forest and beach were a mosaic of stunted loblolly pine, rushes (*Juncus* sp.), woolly beachheather (*Hudsonia tomentosa*), and shrubs (e.g., waxmyrtle) scattered among the dunes (Higgins et al. 1971). Freshwater pools (<6 ha) occur throughout the island but are mostly concentrated in shrublands and forests. Approximately 75 pools exist at ASIS, and many are ephemeral. The mean annual precipitation at ASIS was 112.6 cm, the mean summer (June to August) temperature was 23.2°C, and the mean winter (December to February) temperature was 3.6°C (NOAA 2004).

Ten bat species occur in Maryland, including big brown bats (*Eptesicus fuscus*), silver-haired bats, eastern red bats, hoary bats, eastern small-footed myotis (*Myotis leibii*), little brown myotis (*M. lucifugus*), northern myotis (*M. septentrionalis*), Indiana myotis (*M. sodalis*), evening bats (*Nycticeius humeralis*), and tri-colored bats (*Perimyotis subflavus*; Paradiso 1969). However, only big brown bats, eastern red bats, hoary bats, silver-haired bats, and tri-colored bats have been documented at ASIS (Johnson and Gates 2008).

### Acoustic monitoring

We used Anabat II (Titley Scientific, Ballina, Australia) broadband, frequency division bat detectors linked to compact flash storage zero crossing analysis interface modules (ZCAIM), to monitor bat echolocation passes. We defined bat passes as a series of echolocation pulses or calls emitted by bats as they navigated and searched for food (Thomas 1988; Broders 2003). We passively monitored bat passes by establishing three autonomous bat monitoring stations (BMS), 1 on the northern (5.8 km south of Ocean City Inlet and 0.5 km from the coastline), middle (11.8 km south of the northern BMS and 1.0 km from the coastline), and southern portions (15.2 km south of the middle BMS and 0.5 km from the coastline) of ASIS. Each BMS consisted of an Anabat II bat detector and ZCAIM contained in a weatherproof enclosure, which was attached to a guyed

10-m pole. A downward-facing microphone and 45° deflector were attached to the top of each pole and connected to the Anabat II via a 10-m audio cable. The microphones of all three BMS were above the surrounding vegetation and located near freshwater pools. Vegetation near the northernmost BMS was situated in a low-lying sand wash largely devoid of vegetation except for an adjacent small (<0.5 ha) patch of shrubs. The middle BMS was located in a canopy gap within a loblolly pine forest. The southern BMS was located in a stunted loblolly pine forest. Power was provided by an external 12-V, 12-A·h battery recharged by a 10-W photovoltaic panel. Each BMS monitored bat activity from 1700–0700 hours nightly from July 2005 to December 2006.

We used the Analoop computer software to determine which bat species produced each recorded bat pass (Corben 2001). We identified bat passes by comparing structure (e.g., frequency modulated and quasi-constant frequency), frequency, and change in octaves per second of unknown bat passes to a library. Our library consisted of 273 bat passes collected from hand-released bats marked with chemiluminescent tags collected throughout the southeastern and Mid-Atlantic United States and known to occur at ASIS (Fenton and Bell 1981; O'Farrell et al. 1999; Murray et al. 2001; Menzel et al. 2002; Johnson and Gates 2008). We attempted identification of bat passes containing three or more pulses (Johnson et al. 2002). Bat passes containing 1 or more echolocation pulses, identified or not, counted toward the total number of bat passes in a sample. The senior author identified all bat passes to reduce bias and increase identification precision (O'Farrell et al. 1999; Johnson et al. 2002). The total number of bat passes (Passes) was summed for each BMS nightly, which we used as an index of bat activity.

To examine the effects of weather on bat activity, we obtained data from a remote automated weather station located at the approximate center of Assateague Island. Data included hourly rain accumulations (centimeters;  $Rain_{acc}$ ), hourly air temperature (degrees Celsius;  $Temp_{hr}$ ), daily maximum air temperature (degrees Celsius;  $Temp_{max}$ ), daily minimum air temperature (degrees Celsius;  $Temp_{min}$ ), hourly mean wind speed (meters per second;  $Wind_{mean}$ ), hourly maximum

wind gust (meters per second;  $Wind_{max}$ ), hourly relative humidity (percent;  $RelHum$ ), and hourly barometric pressure (kilopascal;  $Baro$ ). Hourly data were averaged for each night. To achieve statistical normality, we log transformed the number of hours that rainfall accumulated within a night ( $Rain_{hr}$ ),  $Passes$ , and  $Wind_{mean}$ . We arcsine transformed relative humidity data (Zar 1984).

Prior to analyzing the effects of weather on bat activity, we tested explanatory variables for collinearity to reduce model over-fitting. We computed the Pearson's product moment correlation coefficients for all pairs of variables and censored one member of any pair having a correlation >0.60 (Grewal et al. 2004). Collinearity was significant for five variable pairs, including  $Rain_{hr}$  and  $Rain_{acc}$  ( $r = 0.83$ ),  $Temp_{hr}$  and  $Temp_{max}$  ( $r = 0.95$ ),  $Temp_{hr}$  and  $Temp_{min}$  ( $r = 0.96$ ),  $Temp_{max}$  and  $Temp_{min}$  ( $r = 0.93$ ), and  $Wind_{mean}$  and  $Wind_{max}$  ( $r = 0.95$ ). We retained  $Rain_{hr}$  because the periodicity of rain may have more of an effect on bat activity than precipitation totals. We retained  $Temp_{hr}$  because it represented mean temperatures recorded throughout the night when bats are active rather than the maximum and minimum temperatures recorded throughout the day. We retained  $Wind_{mean}$ , which reported nightly sustained mean wind velocities rather than brief gusts.

## Model structure

To investigate potential bat migration activity at ASIS, we used a time series analysis to account for weather and to model nightly and seasonal bat passes. Seasonal trends in bat passes and weather in the Mid-Atlantic region generally follow a pattern, bat activity increases in summer in concert with increases in temperature, humidity, and precipitation and gradually decreases to a minimum in winter (Whitaker et al. 1997; Cryan 2003). Simple correlation analyses (e.g., Pearson's product moment correlation) between bat passes and weather variables are unlikely to produce meaningful results from a long-term monitoring dataset. Seasonal trends may follow a sine or cosine function (Montgomery et al. 2008). Therefore, we incorporated a sinusoidal trigonometric function into our time series analysis to account

for the seasonal trend in bat passes and weather patterns.

The number of bat passes may be serially autocorrelated; i.e., bat passes are not independent on successive nights (Hayes 1997; Milne et al. 2005). As with seasonal trends, autocorrelation also must be accounted for in the time series analysis. We used an autoregressive (AR) modeling approach to estimate the autocorrelation structure of bat passes (RDCT 2008). We iteratively incorporated AR ( $p$ ) structures, where  $p = \text{lag}$ , to estimate the appropriate AR order. We used Akaike’s information criterion ( $AIC_c$ ) for small sample sizes to determine parsimonious models. Candidate models separated by  $\leq 3 AIC_c$  were considered competing models. We used Akaike weights,  $w_{AIC_c}$ , to indicate the probability that a particular model was the best approximating model in the candidate set. After selecting the best approximating model, we incorporated the estimated correlation coefficient ( $\Phi$ ) in the final models to account for nightly serial autocorrelation of bat passes.

We used generalized least squares to develop a predictive model of bat activity and account for seasonal and climatic influences. Models followed the general form of

$$\begin{aligned} \log(\text{Passes}_j) = & \beta_0 + \beta_1 \log(\text{Rain}_{\text{hr}}) \\ & + \beta_2(\text{Temp}_{\text{hr}}) + \beta_3 \log(\text{Wind}_{\text{mean}}) \\ & + \beta_4 \sin(\text{RelHum}) + \beta_5(\text{Baro}) \\ & + \beta_6 \sin\left(\frac{2\pi j}{T}\right) + \beta_7 \cos\left(\frac{2\pi j}{T}\right) + \varepsilon_j, \end{aligned}$$

where  $\text{Passes}_j$  was the number of bat passes recorded on night  $j$ ;  $\text{Rain}_{\text{hr}}$  was the number of hours of precipitation on night  $j$ ;  $\text{Wind}_{\text{mean}}$  was the average nightly wind speed on night  $j$ ;  $\text{RelHum}$  was the average nightly relative humidity on day  $j$ ;  $\text{Baro}$  was the average nightly barometric pressure on day  $j$ ;  $\beta_s$  were coefficients estimated by regression,  $\sin$  and  $\cos$  terms described seasonality, where  $j$  was day and  $T$  was the total number of nights per year; and  $\varepsilon_j$  was an error term.

We examined model residuals (predicted–observed data) that exceeded 2 standard deviations from the mean. Nightly bat pass totals that exceed the predicted value by  $>2$  standard deviations may be evidence of migration events,

particularly if these events occur during spring or autumn and occur on the same nights among the three BMS. Determining migration events is complicated by simultaneous autumn migration and onset of juvenile bat volancy. Currently, it is not possible to distinguish females from males or adult bats from those of juvenile bats based on echolocation call characteristics. Therefore, we used the ancillary capture data from mist netting that occurred July to August 2005 at ASIS to determine the timing of juvenile volancy (Johnson and Gates 2008). We qualitatively considered the percentage of nightly total captures comprised of juveniles when examining the overall bat activity trends at ASIS for migrants. In addition, we parsed our dataset for evidence of migration events using the multiplicative probability rule to determine the chances of each bat species being detected at the three BMS on the same night (when all the three BMS were operating). A bat species that does not occur at ASIS throughout the active season will have a low probability of being detected at two or three BMS on the same night. Conversely, a bat species that occurs at ASIS throughout the active season will have a relatively high probability of being detected.

We compared the number of bat passes among the three BMS with a one-way analysis of variance (ANOVA) and Duncan’s new multiple range test (Proc GLM; SAS Institute, Inc. 2004). To compare bat activity among the BMS, we used data only from nights when all three were operating. Moreover, to avoid temporal pseudoreplication, we eliminated data from autocorrelated nights; the number of nights eliminated was indicated by the maximum AR process value among the three BMS (Hayes 1997; Montgomery et al. 2008). Autoregressive analyses indicated significant lags up to seven nights for all three BMS. Therefore, we used data from every seventh night in our analysis. However, because including only data from nights 1, 8, 15, ... from each BMS is arbitrary, we also analyzed data starting on nights 2, 9, 16, ..., and so on through nights 7, 14, 21, ... so that data from all independent nights were used. Therefore, we conducted ANOVA seven times to account for all independent datasets. Statistical significance for all the analyses was set at  $P \leq 0.05$ .

## Results and discussion

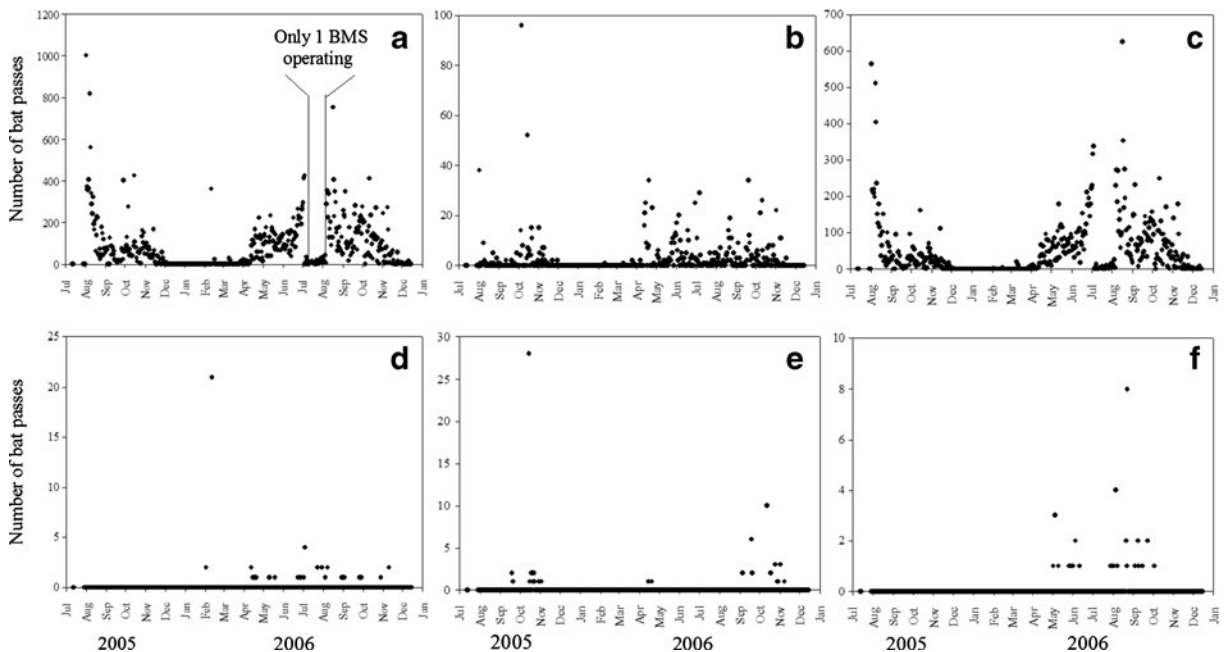
### Acoustic monitoring

We recorded 39,384 bat passes from five species, including eastern red bats (59.33% of total bat passes), big brown bats (3.05%), hoary bats (0.13%), eastern pipistrelles (0.10%), and silver-haired bats (0.07%). The remaining 36.66% of the recorded bat passes were not identified to species because they consisted of fewer than three echolocation pulses. All the BMS experienced malfunctions at some period during monitoring, possibly due to thunderstorms, which caused them to cease recording until maintenance was performed. The northern, middle, and southern BMS functioned for 94.9%, 91.3%, and 84.2% of the study period, respectively. All the BMS operated simultaneously for 400 of 499 (80.2%) potential sampling nights. Bat passes gradually increased beginning in April, peaked in August, and declined gradually until December when relatively few passes

were recorded (Fig. 1a). Big brown bats were recorded during all of the active season (April to December) and on 11 February and in March (Fig. 1b). Eastern red bats were recorded by all the BMS during all of the active season and in February and early March (Fig. 1c). Hoary bats were recorded by all the BMS during all of the active season and in February (Fig. 1d). Silver-haired bats were recorded mostly in autumn and on two nights in April (Fig. 1e). Tri-colored bats were recorded from early May to early October and almost exclusively at the northern BMS (Fig. 1f). Only one tri-colored bat pass was recorded by the middle BMS, and none were recorded by the southern BMS.

### Model structure

The best candidate AR function for the time series models differed among the BMS according to  $w_{AICc}$  values. There were two or more competing models for each BMS (Table 1). Of



**Fig. 1** Nightly activity of **a** all bat species combined, **b** big brown bats (*E. fuscus*), **c** eastern red bats (*Lasiurus borealis*), **d** hoary bats (*Lasiurus cinereus*), **e** silver-haired bats (*Lasionycteris noctivagans*), and **f** tri-colored bats (*P. subflavus*) recorded by BMS at Assateague Island Na-

tional Seashore, Maryland, 2005–2006. Only one BMS was operating from 6 July to 7 August 2006. Data for silver-haired bats include undetermined big brown or silver-haired bat echolocation passes. Note the different scales on *ordinate axes*

**Table 1** AR model selection using Akaike Information Criteria (AIC<sub>c</sub>) difference with correction for small sample sizes (ΔAIC<sub>c</sub>) and model weight (*w*<sub>AIC<sub>c</sub></sub>) for determining temporal independence of bat echolocation passes recorded at three BMS at Assateague Island National Seashore, 2005–2006

Bat monitoring station	AIC <sub>c</sub>	ΔAIC <sub>c</sub>	<i>w</i> <sub>AIC<sub>c</sub></sub>	AR( <i>p</i> ) model <sup>a</sup>
Northern BMS	363.26	0.00	0.690	7
	364.86	1.60	0.310	8
	366.16	2.90	0.162	9
Middle BMS	429.46	0.00	0.693	4
	431.11	1.65	0.304	5
Southern BMS	349.41	0.00	0.680	4
	350.92	1.50	0.320	5
	351.31	1.90	0.263	6

Only candidate models <3 ΔAIC<sub>c</sub> are included  
<sup>a</sup>*p* = order of AR model

the competing models for each BMS, we chose the model with the highest *w*<sub>AIC<sub>c</sub></sub>: AR(7) for the northern BMS and AR(4) for both the middle and southern BMS. Seasonal trends in bat passes followed cosine functions. After accounting for seasonal trends and autocorrelation, all weather variables explained some residual variation in bat activity but varied among the BMS in terms of significance. Some weather variables did not have a consistent significant effect on bat activity among

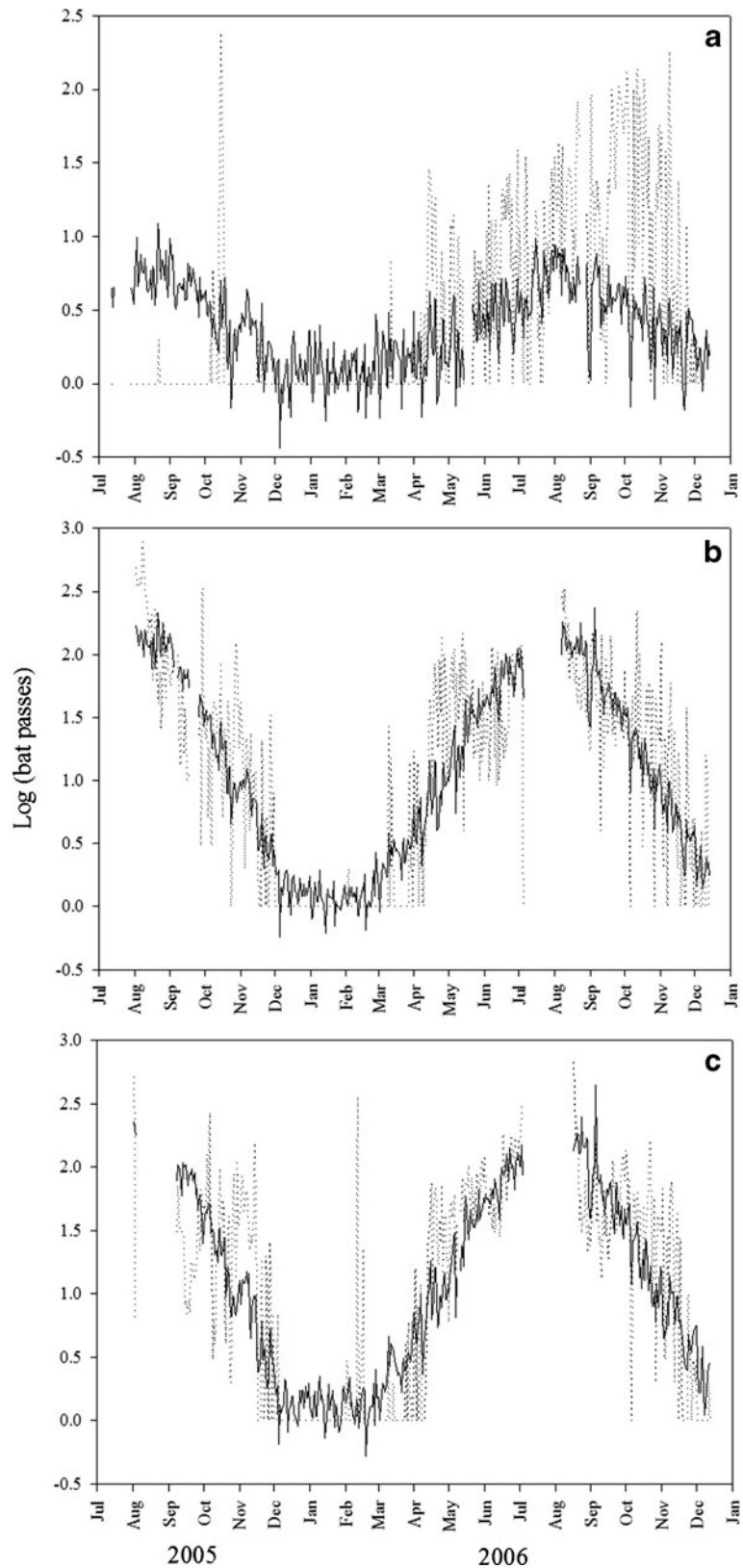
the BMS (Table 2). However, mean nightly temperatures (Temp<sub>hr</sub>) consistently had a significant positive effect on bat activity, and mean nightly wind speeds (Wind<sub>mean</sub>) consistently had a negative effect on bat activity (Table 2).

Final models were used to predict seasonal trends in bat activity, which varied by night and location (Fig. 2a–c). Residual standard errors of final models for the northern, middle, and southern BMS were 0.555, 0.417, and 0.447, respectively (Fig. 3a–c). Residuals that exceeded 2 standard deviations (*n* = 57) only occurred during migration periods, i.e., spring (*n* = 12) and autumn (*n* = 45). During the months of June, July, or August, no residuals exceeding 2 standard deviations occurred, indicating that seasonal trends and weather co-variables adequately explained variation in bat activity during summer (Fig. 4). Only juvenile eastern red bats were captured at ASIS (the first on 20 July) and gradually comprised a larger percentage of total captures through August (Fig. 5). On 25 April and 12 and 22 October 2006, at least two BMS had residuals that exceeded 2 standard deviations. On 2 November 2006, all the three BMS had residuals that exceeded 2 standard deviations. On 15 October 2005 and 2 November 2006, silver-haired bat passes and/or indiscernible silver-haired bat/big brown bat passes were recorded by all the three BMS.

**Table 2** Effects of weather conditions on bat activity recorded at Assateague Island National Seashore, 2005–2006

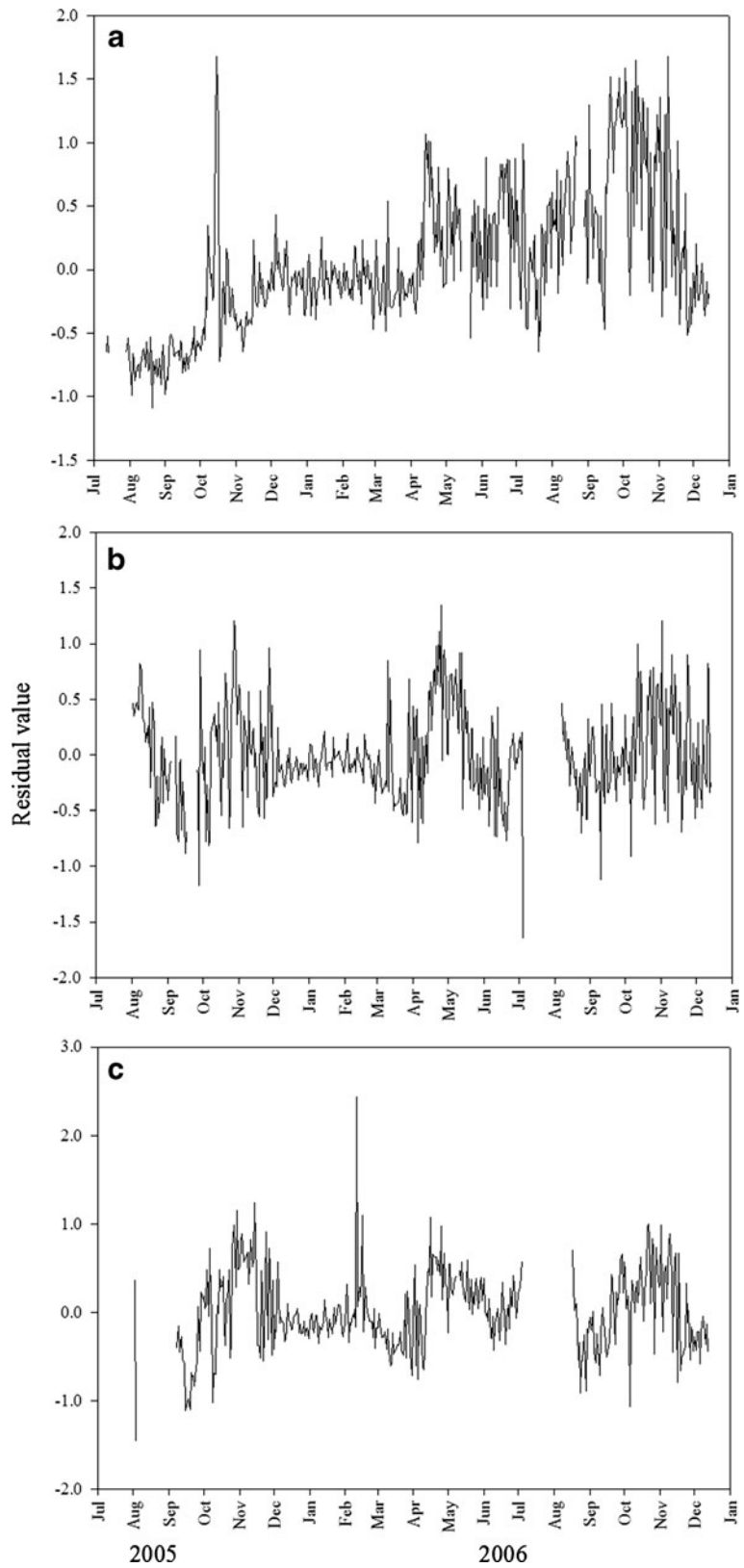
Bat monitoring station	Variable	Coefficient	SE	<i>P</i>
Northern BMS	Intercept	0.859	0.985	0.383
	Rain <sub>hr</sub>	−0.068	0.063	0.281
	Temp <sub>hr</sub>	0.022	0.003	<0.001
	Wind <sub>mean</sub>	−0.755	0.085	<0.001
	RelHum	−0.536	0.099	<0.001
	Baro	−0.021	0.031	0.497
Middle BMS	Intercept	2.542	1.077	0.019
	Rain <sub>hr</sub>	−0.222	0.079	0.005
	Temp <sub>hr</sub>	0.020	0.004	<0.001
	Wind <sub>mean</sub>	−0.424	0.120	<0.001
	RelHum	−0.364	0.113	0.001
	Baro	−0.066	0.034	0.055
Southern BMS	Intercept	3.072	1.025	0.003
	Rain <sub>hr</sub>	−0.255	0.075	<0.001
	Temp <sub>hr</sub>	0.025	0.004	<0.001
	Wind <sub>mean</sub>	−0.286	0.117	0.015
	RelHum	−0.167	0.111	0.133
	Baro	−0.100	0.033	0.003

**Fig. 2** Model predictions (*solid line*) of bat passes (log transformed) based on seasonal trends and weather variables and observed (*dotted line*) values of bat passes (log transformed) recorded at three BMS on the northern (**a**), middle (**b**), and southern (**c**) portions of Assateague Island National Seashore, Maryland, 2005–2006. *Line gaps* are due to malfunctioning BMS. Note the different scales on the *ordinate axes*

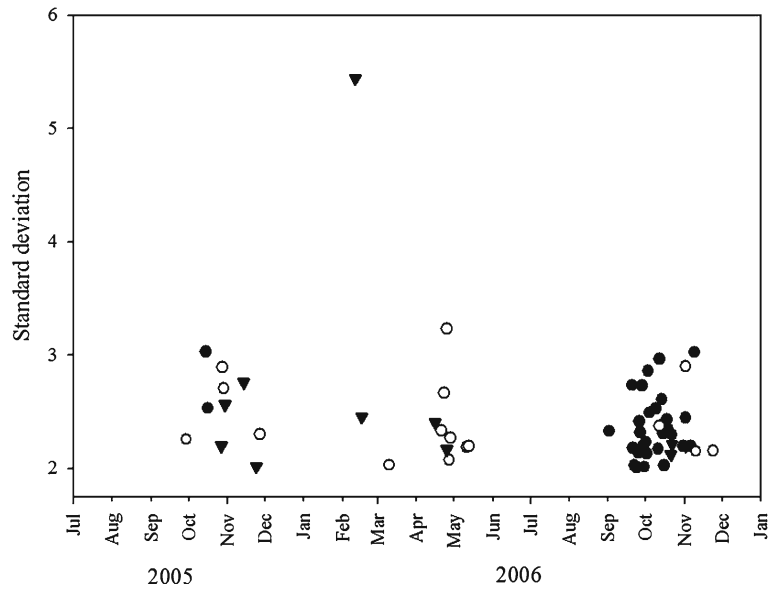




**Fig. 3** Model residuals calculated as the differences between predicted and observed values of bat passes recorded at three bat monitoring stations on the northern (a), middle (b), and southern (c) portions of Assateague Island National Seashore, Maryland, 2005–2006. Note the different scales on the *ordinate axes*



**Fig. 4** Model residuals that exceeded means by  $\geq 2$  standard deviations, calculated as the differences between predicted and observed values of bat passes recorded at three bat monitoring stations on the northern (*filled circle*), middle (*empty circle*), and southern (*inverted triangle*) portions of Assateague Island National Seashore, Maryland, 2005–2006

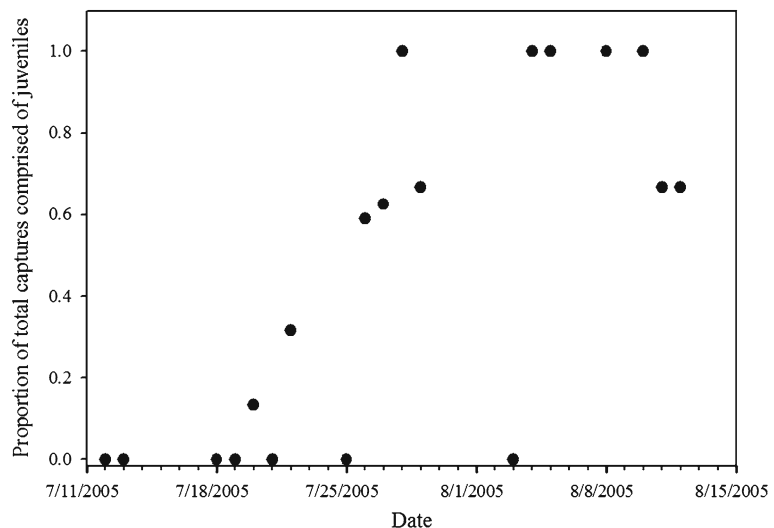


According to the multiplicative probability rule, the chances of recording silver-haired bat passes and/or indiscernible silver-haired bat/big brown bat passes on all BMS on any single night was 1 in 96,970. In contrast, there was about 1 in 7 chance of recording eastern red bat passes and a 1 in 130 chance of recording big brown bat passes on any single night at all the three BMS.

The final models indicated that after accounting for seasonal trends (sine and cosine functions),

bat activity was autocorrelated (not independent) for a seven-night period at the northern BMS and for a four-night period at both the middle and southern BMS. Therefore, to compare bat activity among the BMS, we used data from seven-night intervals. The middle and southern BMS recorded similar levels of nightly bat passes (regardless of night analyzed) but recorded more bat passes than the northern BMS (night 1,  $F_{182,2} = 13.5$ ,  $P < 0.001$ ; night 2,  $F_{182,2} = 11.9$ ,  $P < 0.001$ ; night

**Fig. 5** Percent of nightly total mist netting captures comprised of juveniles at Assateague Island National Seashore, Maryland, 2005–2006



3,  $F_{173,2} = 8.36$ ,  $P < 0.001$ ; night 4,  $F_{165,2} = 11.0$ ,  $P < 0.001$ ; night 5,  $F_{168,2} = 9.5$ ,  $P < 0.001$ ; night 6,  $F_{165,2} = 6.7$ ,  $P = 0.002$ ; night 7,  $F_{165,2} = 7.3$ ,  $P = 0.001$ ).

Bat species composition documented with continuous long-term acoustic monitoring at ASIS was similar to that on the lower Coastal Plain of the southeastern United States where the majority of activity throughout the year was comprised of lasiurine bats and myotine bats were absent (Menzel et al. 2000, 2003; Limpert et al. 2007; Johnson and Gates 2008). On the Coastal Plain of the southeastern United States, including Maryland, myotine bats were documented less frequently than in the western Piedmont (Menzel et al. 2000, 2003; Johnson and Gates 2008; Johnson et al. 2008). Although it is unclear why myotine bats are not common on the Coastal Plain, it is possible that at long distances from hibernacula and particularly at ASIS, a low diversity of roosting structures discourage their presence (Humphrey 1975; Furlonger et al. 1987; Johnson and Gates 2008).

Our data indicate that migrant bats use ASIS, including silver-haired bats, hoary bats, and eastern red bats, but the extent of use during migration is uncertain. Silver-haired bats were only recorded during migration periods, indicating that they may use ASIS as a stopover during migration but likely do not use the area during the summer maternity period. A study using radio-telemetry on migrant bats would be necessary to determine the extent of bat use of ASIS during migration. Our acoustic recordings of silver-haired bats were not the first documentation of this species at ASIS during autumn migration. Silver-haired bats were captured in mist nets at ASIS during northern saw-whet owl (*Aegolius acadicus*) surveys in late-October 1992, 1995, and 2001 (D. Brinker, Maryland Department of Natural Resources, personal communication). Two nights of mist netting for bats in October 2006 recorded only eastern red bats (Johnson and Gates 2008). Hoary bats and eastern red bats were recorded by the BMS during all seasons, making it more difficult to determine if echolocation passes were recorded from migrants or residents. Moreover, the majority of bat passes were those of eastern red bats. Many of the nights that we determined were migration events

were probably attributable to migrant eastern red bats.

Because residuals exceeding 2 standard deviations in the final model occurred only during migration periods and not during the summer maternity period, our models performed well in predicting summer bat activity. However, we were unable to account for additional bat passes, probably contributed by migrant bats. Moreover, fitted models accounted for the addition of juvenile bat activity during late July and August. Our models indicated that autumn bat migration occurs at ASIS from early September through November, and spring migration occurs from as early as mid-February to mid-May. However, unusually high activity levels in February may have been due to arousal of overwintering bats on warm winter evenings as observed in the Mid-Atlantic region (Whitaker et al. 1997; Moorman et al. 1999; Cryan 2003; Dunbar and Tomasi 2006). Because they roost in trees or leaf litter, tree-roosting bats, i.e., hoary, eastern red, and silver-haired bats, may be more exposed to short-term changes than other bat species in the region and arouse during weather anomalies (Turbill 2008). The majority of residuals exceeding 2 standard deviations occurred during the autumn migration period, suggesting that bat migration in spring is more episodic or simply that more bats are migrating through ASIS in autumn than in spring. Higher activity levels during autumn may be attributable to the activity of mating bats (Turbill 2008), but the characteristics, i.e., timing and location, of bat mating activity in the local area remains unclear. The most compelling evidence that bats migrate through ASIS is the significant event that occurred on 2 November 2006 when silver-haired bats were recorded at all three BMS and large model residuals existed in the dataset. On this night, the average predicted bat activity among the three BMS was 6.2, whereas the actual bat activity was 91.3. No weather anomalies were associated with this date; the mean temperature was 7.7°C, and the mean wind speed was 3.0 m/s.

Seasonal trends in bat activity at ASIS were consistent with patterns in the Appalachian Mountain region (e.g., Fiedler 2004; Lott 2007). Also, bat activity levels at ASIS were similar to those documented at wind energy development

sites in North America (Reynolds 2006). However, the number of bat passes represents an index of bat activity rather than the number of bats traveling through an area, which makes it difficult to assess or predict the number of bats that potentially could be affected by near and offshore wind energy facilities (Broders 2003). Also, most bat passes were eastern red bats, suggesting that coastal areas may be as important, if not more important, than the Appalachian Mountains for this migratory species. Moreover, because most of the total bat activity was eastern red bats, our models may be most appropriately applied to this species.

Many studies have focused on the effects of weather on bat activity. These studies typically found that greater winds, precipitation, and barometric pressure, and lower temperatures and relative humidity were negatively associated with bat activity (Lacki 1984; Paige 1995; Erickson and West 2002; Parsons et al. 2003; Reynolds 2006). Our findings support these generalizations, although some weather variables did not significantly affect bat activity. While not consistently significant among the three BMS, barometric pressure, relative humidity, and precipitation generally had a negative association with bat activity. Greater nightly mean temperatures and lesser mean wind speeds were positively associated with bat activity at all areas sampled. Greater nightly and seasonal temperatures commonly are associated with greater bat activity, mostly due to greater insect availability during warmer temperatures and seasons (O'Farrell et al. 1967; Hayes 1997; Erickson and West 2002; Ciechanowski et al. 2007). Lesser wind speeds also are associated with greater bat activity, as well as greater mortality rates at wind energy facilities (Reynolds 2006; Baerwald et al. 2009). However, it is unclear if high winds reduced the effective sampling range of the bat detectors, resulting in an artificially low number of bat detections. Our results support the notion of possible bat mortality mitigation through increased wind turbine cut-in wind speeds, particularly during migration periods (Baerwald et al. 2009). In order for wind turbines to efficiently convert kinetic energy of wind to mechanical energy to turn a generator, a minimum wind speed (e.g., 3 m/s) is

required. Below this cut-in wind speed, turbines are inefficient and wind turbine blade speed can be reduced or even stopped to reduce the risk of bat-blade collision (Baerwald et al. 2009).

The BMS differed in the amount of bat passes they recorded, probably due to differences in habitat surrounding them. The northern BMS recorded far fewer bat echolocation passes, on average, than the middle and southern BMS presumably because it was located far from mature forest stands where bats were more likely to roost. Indeed, the nearest roosting habitat to the northern BMS was on the mainland ( $\geq 1$  km), Fenwick Island to the north, or farther south on ASIS. The final model for the northern BMS indicated that bats migrate through ASIS during autumn but not spring. Conversely, models for the middle and southern BMS indicated that bats migrate through ASIS in autumn and, to a lesser extent, in spring. Further research is needed to determine the extent of bat use of ASIS and other coastal barrier islands during migration and to determine potential impacts of near and offshore wind energy facilities on bats.

## Conclusions

Our research indicates that bats migrate along the Atlantic coastline and use barrier islands, possibly for navigation or as stopover sites (Fleming and Eby 2003). This may have implications for proposed offshore wind energy facilities in that bats migrating along the coast may collide with wind turbines. Our results corroborate anecdotal accounts of bats observed at sea and suggest that bats may migrate over the Atlantic Ocean and along the coastline. Wind turbines offshore may be attractive to bats as resting places or possible mating areas, increasing the risk of bat mortality (Cryan 2008; Horn et al. 2008). Although the BMS did not detect possible bat activity at the swept height of wind turbines and were not located offshore, our results support previous observations suggesting bats, particularly eastern red, hoary, and silver-haired bats, may be at risk for colliding with near and offshore wind turbines. Furthermore, these species may be affected more

by wind energy facilities near the coast than myotis bats, including the federally listed Indiana myotis, which is not known to occur on the lower Coastal Plain of the Mid-Atlantic States (USFWS 2007). Bat migration activity appears to be greater in autumn and is influenced by nightly temperatures and wind speeds. Bats were less active during periods of low temperatures and high wind speeds, possibly above thresholds for wind turbine cut-in speed. We conclude that bats, specifically eastern red, hoary, and silver-haired bats, use this barrier island during migration and that this phenomenon may have implications for the development of near and offshore wind energy.

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