RADAR MONITORING OF BIRD AND BAT MOVEMENT PATTERNS ON BLOCK ISLAND AND ITS COASTAL WATERS

FINAL REPORT

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EXECUTIVE SUMMARY

- This report presents results of a study conducted by New Jersey Audubon Society, for Rhode Island's Ocean Strategic Area Management Plan (Ocean SAMP) to assess flight dynamics and movement patterns of aerial vertebrates on Block Island and it nearshore waters. Specifically, our objectives were to (1) estimate daily, nightly and seasonal movement patterns of aerial vertebrates (i.e., birds, bats) traversing Block Island and its coastal waters, (2) estimate altitudinal distributions of bird/bat movements and determine what proportions occur at altitudes deemed a "risk" for collisions with wind turbines (3) determine flight directions and pathways of bird/bat "targets" in the study area and (4) investigate how meteorological conditions affect flight dynamics and behavior.

- The study was conducted from 19 March – 15 December 2009 using a dual marine radar system. Radar technology can provide information about movement patterns of aerial vertebrates that otherwise could not be acquired (e.g., monitoring of high flying and distant individuals, monitoring at night, accurate estimates of flight altitude). The radar system was located at the southern end of Block Island from 19 March – 30 April and then moved to the northern end of the island, where it remained until the study was completed. The radars sampled the air space out to one nautical mile in horizontal range and vertical range. During the last nine weeks of the study (8 October – 15 December) we used a parabolic dish antenna on the horizontally-oriented radar to reduce backscatter of electromagnetic energy from the ocean surface.

TARGET MOVEMENT AND MOVEMENT RATES

- Despite high variability within and among seasons, we found that Season, Period (i.e., day, night) and the interaction between these two factors had significant effects on targets recorded (i.e., birds, bats). Targets recorded in Fall (16 August – 15 December, mean = 408.89 ± SE 48.40) were significantly greater than Spring (19 March – 31 May, mean = 161.72 ± SE 17.75), but not Summer (1 June – 15 August, mean = 289.04 ± SE 45.13), while Spring and Summer were not statistically different from each other. Targets recorded at Night (mean = 439.86 ± SE 46.94) were significantly greater that during the Day (mean = 172.53 ± SE 17.19). *Post hoc* comparisons suggested that targets recorded during the Fall/Night period (mean = 634.90 ± SE 87.30) were significantly greater than all other Season/Period combinations except Summer/Night (408.10 ± SE 84.68). Summer/Night was also significantly greater than Fall/Day (184.82 ± SE 31.03), but not from any other Season/Period combinations. No Season/Period combinations were significantly different from each other.

- Although target movement rate (i.e., targets recorded/nautical mile/hour) was greater in Fall (37.37 ± SE 4.37) than in Spring (18.21 ± SE 1.92) and Summer (33.76 ± SE 5.88), these differences were not statistically significant. We did, however, find a significant differences between Night (mean = 46.36 ± SE 4.78) and Day movement rates (mean = 15.46 ± SE 1.43). We found a significant interaction between season and period (i.e., Night, Day) with Fall/Night (mean = 58.50 ± SE 7.98) and Summer/Night (mean = 53.89 ± SE 11.08) being significantly greater than all other SEASON/PERIOD combinations but not different from each other.

- Indices of movement magnitude also varied with time relative to sunrise and sunset. During the Day period, indices showed a distinct peak 6-8 hours after sunrise, except in fall when the pattern was bimodal. Peak magnitude in these indices during the Night period occurred 1-3 hours after sunset, regardless of season. We did not find significant differences in these patterns among seasons.

- These results indicate that seasonal bird/bat movements, especially during migration periods, were temporally episodic. Given that we were monitoring the entire spectrum of bird and bat fauna and that the phenology of movement varies widely within and among taxa (i.e., age, sex, species), this was not surprising. Indices of migration magnitude were markedly greater during the nocturnal compared to the diurnal period, regardless of season. The majority of waterfowl, wading birds, shorebirds and passerines are known to migrate at night. Additionally, indices of movement magnitude were highest during nocturnal periods in Summer and Fall. Southbound avian migration, which for some species begins in mid-July, typically includes large numbers of juveniles, which could explain the seasonal differences we observed.

- Our estimates for spring and fall were generally similar to those reported by GMI during their onshore and offshore radar studies along the New Jersey coast. In contrast, target movement rates we recorded during nocturnal periods on Block Island were lower than a study we conducted on the Cape May Peninsula. The Cape May Peninsula is a geographic feature that tends to concentrate migrating birds, especially in fall. Furthermore, birds from several migratory flyways (e.g., Atlantic, Delaware River Valley, Hudson River Valley) are often vectored to the Cape May Peninsula by prevailing winds in fall.

- Several terrestrial studies, including one we conducted in the mid-Atlantic Appalachian Mountain region, also had higher estimates of movement rates. This might suggest that overland migration is greater in magnitude than that occurring across Long Island Sound and the Block Island vicinity. However, these studies conducted radar observations for shorter periods during a given season and shorter hours during the night compared to our Block Island study. This could significantly bias movement rate estimates.

TARGET ALTITUDE

- The proportional distributions of targets recorded in each 100 m strata (i.e., 19, 100 m strata, 1900 m = ~one nautical mile) were not significantly different among seasons for the Day or Night periods. Regardless of season or period, altitudinal distributions of recorded targets generally increased with altitude to peak between 200 and 400 m across all hours, except during the Spring/Day period when the greatest proportion of recorded targets occurred in the 0-100 m stratum. Fifty percent of all targets we recorded occurred between 300 and 400 m during diurnal periods and at approximately 400 m during nocturnal sampling periods. Above 500 m, the proportion of targets recorded decreased asymptotically.

- Our data also suggest extensive within-season variation in the proportion and number of targets recorded ≤ 100 m in altitude. Cumulative frequency distributions characterizing daily changes in these indices were significantly different between Day and Night data collection periods in Spring and Summer, but not Fall. Additionally, statistical tests suggested a significant difference in the cumulative frequency distributions among seasons for the Day and Night data collection periods.

- Although the proportion of targets recorded ≤ 100 m in altitude (i.e., relative to all targets recorded) was highest in Spring (mean = 0.13 ± SE 0.01) compared to Summer (mean = 0.11 ± SE 0.01) and Fall (mean = 0.11 ± SE 0.01), these differences were not statistically significant. The proportion of targets recorded ≤ 100 m was significantly greater during the Day (mean = 0.15 ± SE 0.01) than at Night (mean = 0.08 ± SE 0.005). We also found a significant interaction between Season and Period. *Post hoc* comparisons indicated that Fall/Night and Summer/Night had a significantly smaller proportions of targets recorded in this stratum (mean = 0.07 ± SE 0.004, mean = 0.08 ± SE 0.01, respectively) than all other Season/Period combinations. Other Season/Period combinations were not significantly different from each other.

- The number of targets recorded ≤ 100 m in altitude was not significantly different among seasons or periods. However, the interaction between Season and Period was statistically significant. *Post hoc* comparisons indicated that the number of targets recorded ≤ 100 m during Fall/Night (mean = 33.71 ± SE 4.67) was significantly greater than Fall/Day (mean = 14.79 ± SE 2.32) and Spring/Night (mean = 11.68 ± SE 1.63). Furthermore, targets recorded in this strata during Fall/Day were significantly less than Summer/Day (mean = 21.18 ± SE 2.86). Other Season/Period combinations were not statistically different from each other.

- The proportion and number of targets recorded ≤ 100 m in altitude showed considerable hour-to-hour variation during Day and Night data collection periods, regardless of season However, cumulative frequency distributions that characterized hourly changes in the proportion of target recorded in this stratum were not significantly different between Day and Night data collection periods in any season. Additionally, we found no statistical differences among seasons for the Day or Night data collection periods.

- Similar to findings for the 0 – 100 m stratum, our data also suggest extensive within-season variation in the proportion of and number of targets recorded in the 101-200 m stratum. Cumulative frequency distributions that characterized daily changes in the proportion of targets recorded in the 101 – 200 m stratum were significantly different between Day and Night data collection periods in Spring and Summer, but not in Fall.

- The proportion of targets recorded in the 101 – 200 m stratum was greater in Summer (mean = 0.17 ± SE 0.01) than in Spring or Fall (mean = 0.15 ± SE 0.01, mean = 0.15 ± SE 0.01, respectively), however these differences were not statistically significant. Proportions in the in the 101 – 200 m stratum were significantly lower at Night (mean = 0.13 ± SE 0.01) than during the Day (mean = 0.13 ± SE 0.01). Although the proportion of targets recorded between 101 and 200 m in altitude differed among Season/Period combinations, these differences were not significant.

- We found a significant Season effect on the number of targets recorded in the 101 – 200 m stratum. Fall (mean = 45.39 ± SE 5.16) and Summer (mean = 37.42 ± SE 4.40) had significantly greater numbers recorded than Spring (mean = 18.12 ± SE 1.47), but Fall and

Summer were not statistically different from each other. This index also was significantly greater at Night (mean = 47.39 ± SE 4.84) than during the Day (mean = 23.54 ± SE 1.98). A significant interaction between Season and Period affected the number of targets recorded between in the 101 – 200 m stratum. Targets recorded in this stratum were significantly greater during Fall/Night (mean = 68.46 ± SE 9.27) than all other Season/Period combinations except for Summer/Day (mean = 32.21 ± SE 3.87) and Summer/Night (mean = 42.54 ± SE 7.85). Summer/Night was also significantly greater Spring/Day and Night and Fall/Day. None of the other Season/Period combinations were significantly different from each other.

- The proportion of targets recorded in the 101 – 200 m stratum showed hour-to-hour variation during Day and Night data collection periods, regardless of season. Cumulative frequency distributions characterizing hourly changes were significantly different between Day and Night data collection periods in Spring and Summer but not Fall. We found no statistical differences in the cumulative frequency distributions that characterize hourly variation among seasons for the Day and Night data collection per periods.

- We found a negative relationship between the proportion of targets recorded ≤ 100 and all targets recorded (i.e., targets recorded, all altitudinal strata) across all Season/Period combinations. That is, as total targets increased, the proportion of targets recorded ≤ 100 decreased, regardless of season or period. However, these relationships were only statistically significant for the Night data collection periods and the Fall/Day period. Only Spring/Day, Fall/Day and Fall/Night data collection periods exhibited negative relationships between proportion of targets recorded in the 101 – 200 m stratum and total targets recorded, and all of these were statistically significant. For Spring/Night, Summer/Day and Summer/Night periods, relationships between targets recorded in the 101 – 200 m stratum and all targets recorded were positive, however, none of these were relationships were significant.

- In general, our data suggest that proportionally more birds flew at lower altitudes, especially with respect to the altitudinal strata below 200 m, compared with altitudes reported in radar studies of avian movements over land. Our results, however, were similar to those reported in two radar studies of bird movement in the North Sea and to some extent, the altitudes of birds recorded in coastal and offshore New Jersey.

- On average, we recorded more targets ≤ 200 m during the day than at night. Diurnally migrating waterbirds (e.g., waterfowl, gulls, herons) are often recorded flying at low altitudes. Differences in flight altitude between diurnal and nocturnal migrants were reported from the North Sea and time of day is often cited as an important influence on flight altitude. Similarly, low altitude wind fields are generally more predictable and consistent at night than during the day, which might explain differences in the flight altitudes of diurnally and nocturnally migrating birds.
- Although our results suggest that birds flying during the day were at greater risk from interacting with a tall structure than birds and bats moving at night, this could be misleading with respect to potential overall effects. The number of birds we recorded during the nocturnal period was more than 2.5 times greater than during the diurnal period, meaning that

nearly 24,000 individuals were recorded at or below 200 m at night compared to approximately 14,000 during the day.

- At night and during the Fall/Day period proportions of targets ≤ 200 m were generally low during the first hour after sunset, declined throughout the night, rose as sunrise approached and peaked during the two hours preceding sunrise. This temporal pattern was effectively opposite to the one we observed for target movement magnitude in the same altitudinal stratum. That is, the highest numbers of targets we recorded at or below 200 m was greatest during the first 2-3 hours after sunset, declined gradually over the course of the night and were lowest at sunrise. These two data sets and our analysis on the correlation between movement magnitude and altitude suggest several important relationships. As nocturnal activity commences, and during the first 2-3 hours after sunset, the proportion of birds and bats flying at low altitudes is relatively small, but this is also the time when the greatest number of individuals are aloft. Conversely, during periods when the proportions of birds and bats flying at low altitudes are greatest (i.e., around sunrise) the number of birds and bats are low.

TARGET FLIGHT DIRECTION

- Second-order mean vectors of target flight directions recorded during Spring/Day and Spring/Night data collection periods were significantly oriented to the northeast and mean vectors for each were not statistically different from each other. In Summer, flight directions of targets recorded during Day and Night periods were significantly oriented toward the north-northeast and mean vectors were not statistically different from each other. Second-order mean vectors of target flight directions recorded during Fall/Day and Fall/Night periods were oriented to the west and southwest, respectively, but only Night vector was significantly different from random. Fall/Day and Fall/Night vectors were significantly different from each other. Overall, mean vectors of movement conform to seasonal appropriate directions reported in other studies from the NE region (i.e., NE in spring, SW in fall).

EFFECTS OF METEOROLOGICAL CONDITIONS ON MOVEMENT PATTERNS

- Results of our multiple model comparisons suggest that Julian day was the most consistent and significant modifier of movement magnitude. In Spring, movement magnitude increased with Julian day and in Fall, it decreased. "Global" models that included Julian day along with weather variables were usually among the best performing in Spring and Fall, regardless of period (i.e., Day, Night). For Summer, Julian day models alone had the strongest support during the nocturnal period.

- Among the various meteorological factors evaluated for their affect on the timing and magnitude in migrating birds, wind conditions have been repeatedly identified as a principal driver. Our data from Spring diurnal and nocturnal periods support this thesis. Wind vectors that facilitated movement toward the breeding grounds were significant parameters in the best performing models. Additionally, barometric pressure (negative parameter estimate) was a significant element in Spring/Day models. Changing wind fields are often associated with changes in barometric pressure. Decreasing barometric pressure can signal the infiltration of air masses from the south, bringing southerly winds favorable for northward migration. Although, wind conditions did not figure prominently as a predictor in Fall models, barometric pressure (positive parameter estimate) during the diurnal period did. Increasing barometric pressure is typically associated with colder, denser air masses from the north, which are accompanied by northerly winds.

- Differences between spring and fall results with respect to the importance of wind conditions may be related to the need for individuals to arrive on the breeding grounds in good physiological condition to improve reproductive output. This would put a premium on selecting wind conditions that vector an individual towards its goal using the least amount of energy (i.e., tailwinds blowing from the appropriate direction). In fall, the constraints posed by the breeding season are not apparent and birds may be less sensitive to weather conditions as modifiers of movement patterns.

- Our results suggested that synoptic weather patterns in spring that produced wind conditions appropriate for vectoring individuals northward toward the breeding grounds were important predictors of movement events. At temperate latitudes, this generally means southerly winds prevalent after the movement of a warm front and on the western side of a high pressure system, or in the light and variable winds near the center of high pressure areas.

- Similar to our analyses of local weather conditions and their effect on movement magnitude, synoptic weather conditions were not good predictors of movement magnitude during the Summer/Day period. However, in contrast, synoptic conditions producing southerly airflow featured prominently in explaining differences in migration magnitude during the Summer/Night period.

- Julian day was an important predictor of the proportion of targets we recorded ≤ 200 m. Parameter estimates suggest that in Spring and Fall the proportion of low flying ≤ 200 m birds and bats increased as the season progressed. In Spring, increasing atmospheric pressure, usually accompanied by northwesterly winds, caused increases in the proportion of low flying targets (i.e., ≤ 200 m) we recorded, as did conditions producing winds with a strong westerly component. These conditions would tend to oppose the general direction of migration in spring (i.e., north) or push individuals in an easterly direction out over the ocean.

- In Fall, but only for the nocturnal period, low altitude flight increased as temperature and air pressure decreased and cloud cover increased, conditions that generally portend the approach of a low pressure system and with it, southerly winds and precipitation. Flying low in the opposing winds, and under conditions that produce adverse weather, may save energy and allow an individual to respond more quickly in the event that it must land. However, low altitude flight likely increases the probability that an individual will encounter a tall structure in its flight path and the risk of encounter may increase further still if visibility is impaired because of adverse weather conditions.

- In spring, the approach of high pressure ridges (i.e., cold fronts) or low pressure cells, rather than synoptic conditions that produce winds opposed to the direction of migration, resulted in the greatest proportion of targets we recorded ≤ 200 m. Increasing clouds, low ceiling and precipitation are typical elements of these meso-scale pressure systems. These synoptic conditions also produce southerly winds that would facilitate movement north to the breeding grounds. Greater numbers of birds that typically fly at low altitudes coupled with the potential for adverse weather conditions could explain the relationships we found.

- Interestingly, the greatest proportion of targets we recorded at low altitudes during the Summer/Night period occurred under the same conditions as in spring. This is not surprising given that during this Season/Period had a significant northward mean vector of movement. Relationships between synoptic conditions and movement patterns during diurnal periods in summer were less clear. No single or combination of similar synoptic conditions appeared to explain the occurrence of low altitude flight. Movements during this period are likely unrelated to migration and thus, we would not expect close associations with particular weather patterns.

- Fall presented a different picture about the influences of meso-scale weather systems on flight at low altitudes. The proportion of targets we recorded ≤ 200 m was greatest when high pressure cells produced northwesterly winds, Given the prevailing direction of migration to the southwest (this study), northwesterly winds generally would be perpendicular to the preferred axis of movement and this can cause birds to fly at lower altitudes. Proportions of targets detected at low altitudes were lowest when pressure cells produced northeasterly winds, which would be considered tailwinds for birds migrating to the southwest. In Cape May, New Jersey, flight altitudes are usually greatest in birds of prey when these conditions prevail in autumn.

- Our results suggest that the targets we observed responded to wind conditions, both direction alone and direction and speed together (i.e., tailwind/headwind vectors). The mean vector of flight we observed were similar to nocturnal flight directions reported on the Cape May Peninsula and during radar and thermal imaging studies in coastal and offshore waters of New Jersey.

- We found that mean vectors of prevailing winds at sunrise and sunset during the Spring, Summer and Fall were significantly different than mean vectors for flight directions recorded during all Season/Periods (e.g., Spring/Night, Fall/day), except Summer/Day. Given what appears to be a consistent pattern of flight direction in aerial vertebrates in the mid-Atlantic coastal region, our results suggests that birds and bats were either selective about the wind conditions under which they flew, or that they were able to compensate for differences between wind directions and their directional goals. Clearly, these hypotheses are not mutually exclusive and could be operating in tandem to produce the behaviors we observed.

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1.0 INTRODUCTION

Over the last two decades, construction of tall structures (e.g., digital television towers, wind turbines, cellular phone towers) that penetrate the lower strata of the atmosphere (i.e., up to 1000 feet) has increased at a rapid rate (Shire et al. 2000, National Research Council 2007). Demands for improved communications capabilities and alternative energy have spurred this growth, in not only the number of tall structures, but also their overall height.

Several studies have documented that significant bird mortality at tall communication towers (Crawford, 1981, Kemper 1996) and the USFWS estimates that between four and five million birds may be killed each year from colliding with tall structures (Manville 2000). Studies conducted at wind power projects in different regions, sited in different habitat types and with varying configurations, indicate that the potential for collision incidents between aerial vertebrate biota (i.e., birds, bats) and wind turbines exists (e.g., Orloff and Flannery 1992, Johnson et al. 2002, Kerns and Kerlinger 2004, Fiedler et al. 2007, *cf* citations in Arnett et al. 2008) to varying degrees, but most frequently involves nocturnally migrating passerines and bats (Kunz et al. 2008). Other structures that penetrate the air space used by aerial vertebrates, such as buildings and power lines also are known to cause mortality during episodic migration events (*cf* citations in Erickson et al. 2005 regarding bird mortality).

Indices of bird and bat flight dynamics (e.g., movement magnitude, altitude of flight, direction) are critical for evaluating the potential risk that tall structures (e.g., wind turbines, communication towers, buildings, bridges) pose to aerial vertebrate biota. Regulatory agencies, natural resource managers and developers require this information to compare relative risk of tall structures, especially when they are proposed for areas known to have high bird or bat movement and activity rates. Additionally, stakeholders require information about other locations so that comparisons among sites can be made and characteristics of the specific site slated for development can be evaluated in a relevant context.

In 2009, New Jersey Audubon Society, in collaboration with the University of Rhode Island's Department of Natural Resource Science, undertook a project for the Rhode Island Ocean Strategic Area Management Plan (Ocean SAMP) to assess flight dynamics and movement patterns of aerial vertebrates in the vicinity of Block Island. Radar technology provides information about movement patterns in aerial vertebrates that otherwise could not be acquired. The intent of this work was to provide information that could be used to support decisions regarding possible development of natural resources in Rhode Island state waters, such as wind power. The scientific information presented in this report provides essential biological data that will inform development of Ocean SAMP policy, and support review processes by federal agencies such as the U.S. Fish and Wildlife Service and the U.S. Army Corps of Engineers, and state agencies including the R.I. Department of Environmental Management.

1.1 SCOPE OF REPORT

The following report describes the radar study conducted by New Jersey Audubon Society (NJAS) on Block Island in 2009. Radar technology can provide information about movement patterns of aerial vertebrates that otherwise could not be acquired (e.g., monitoring of high flying and distant individuals, monitoring at night, accurate estimates of flight altitude). We also present results of data analyses and discussion of these results in the context of collision risk and the findings of other relevant studies.

However, several caveats should be considered when evaluating results of this or other similar studies. Because our sampling was limited to single spring, summer and fall seasons, caution should be exercised when extending our results to longer time frames. Interannual variability in temporal patterns of avian migration is well documented (*cf* citations in Alerstam 1990, Berthold 1996). Similarly, we advise caution before applying inferences from this study to other areas or physiographic regions. Our radars were configured to sample relatively small volumes of space compared to the extent that migration and other types of bird and bat movement (e.g., post-breeding dispersal, post-fledging dispersal) that likely occurs in Long Island Sound and the Atlantic coastal region.

Our inability to distinguish between birds and bats during radar monitoring, or distinguish among species in each of these taxa, also is important to note. Flight behavior (e.g., migration phenology, altitude) of several avian taxa (e.g., passerines) overlap with those reported for bats (Larkin 1991, Bruderer and Boldt 2001, Kunz and Fenton 2003). Consequently, we could not determine the relative contribution of birds or bats in spatial or temporal patterns we observed. Future studies focused on flight dynamics and behavior of migrating birds and bats in the region must include tasks that provide this type of information. To reflect our uncertainty about the identity of aerial vertebrates in our radar data, we refer to entities detected by the radars as "targets," throughout this report. This is a widely used term in radar parlance for any object detected by radar.

Additionally, we use the term "target" rather than "individual" or "flock" because the number of birds or bats represented as single entities by the radar was unknown. Some studies report the ability to distinguish small, medium, large and flock-like targets by evaluating the relative strength or amount of radar return energy. This approach is problematic because inherent physical properties of radar affect the amount of energy reflected by a detected object, the basis by which target size would be evaluated. Distance between target and radar, a target's orientation relative to the radar and the location of a target in the radar beam (i.e., central versus peripheral) are among several characteristics that affect the amount of energy a target reflects. These characteristics influence target detection simultaneously, so can seriously confound target size classifications. Given these difficulties, we classified all aerial vertebrate detections as single targets. Thus, indices of movement magnitude we report are likely underestimates of the total number of birds and bats passing through the study site and the number that we recorded in any altitudinal strata.

1.2 GOALS AND OBJECTIVES

The goal of this study was to provide an improved understanding of bird and possibly bat movement patterns on Block Island, Rhode Island and its nearshore waters. Specifically, our objectives were to (1) estimate diel and seasonal movement patterns of aerial vertebrates (i.e., birds, bats) traversing Block Island and its coastal waters, (2) estimate altitudinal distributions of bird/bat movements and determine what proportions occur at altitudes deemed a "risk" for collisions with wind turbines (3) determine flight directions of bird/bat "targets" in the study area and (4) investigate how meteorological conditions, both local and meso-scale, affect flight dynamics and behavior.

2.0 METHODS

2.1 RADAR EQUIPMENT AND CONFIGURATION

We used a dual mobile marine radar system to collect data on bird and bat flight dynamics and behavior. This system consists of two 25 kW Furuno X-band marine radars (frequency = 9410 GHz, wavelength = 3 cm, model # FAR2127BB, Furuno Electric Company, Nishinomiya, Japan) mounted on a trailer 12' long x 6' wide x 8' high (Fig. 1). The radars and all computer equipment connected to them were powered with a single Honda EU6500i fitted with a 15 gallon external gas tank to extend uninterrupted operating time.

The radars were fitted with standard 6.5' open array antennas (Fig. 1), which produce a fan-shaped electromagnetic beam 1.23° wide x 20° high. The antennas rotate simultaneously to monitor various bird/bat flight dynamics and behavior patterns. In our system, one radar unit operates with the antenna rotating in the vertical plane (i.e., "vertically-oriented radar"). This is accomplished by mounting radar to the side of the trailer so that the antenna turning unit rotates perpendicular to the ground (Fig. 1). The antenna sweeps from horizon to horizon, describing a 180° arc above radar level (arl), 20^{o} wide (Fig. 2). Data collected with the radar in this orientation were used to generate target (i.e., birds, bats) movement estimates and to quantify altitudinal distributions of targets (see Fig. 3 for data image example). During data collection at the southern end of the island (i.e., 19 March – 30 April), the vertical radar was positioned so that the antenna swept an arc from South to North. This was done to maximize the number of targets detected as waterbirds moved east to west along the southern coast of the island. The second radar unit operated with the antenna rotating in the horizontal plane (i.e., "horizontally-oriented radar"), describing a 360° arc every 2.5 seconds (Fig. 4). Data collected with the radar in this orientation provided information on flight direction (see Fig. 5 for data image example).

Our radars can be set for detection ranges of 0.125 - 96 nautical miles (nm); however, ranges of ≤ 3 nautical miles are generally the upper limit for detecting bird and bats, depending on their size. For monitoring the diurnal period (i.e., sunrise – sunset the same day) we set the horizontal radar's range to 2 nm as we expected to monitor the movements of larger waterbirds (e.g., loons, sea ducks, gulls) during the day. During the nocturnal period (i.e., sunset – sunrise the following morning), we set the radars' range to 1 nm to increase the detection of small passerines and shorebirds that typically migrate at night. The range for the vertical radar was always set to 1.0 nm detection range regardless of the time of day.

Pulse lengths (i.e., rate that electromagnetic energy is transmitted) for our radars can be set from 0.07 - 1.2 μsec. For both radars, we used a 0.15 μsec pulse length. Short pulse lengths provide better target resolution and more accurate location and distance estimates. Similarly, short detection ranges result in improved resolution of small passerine or bat-sized targets. The radars we use feature color-coded target representation that indicates return signal strength. This allows for discrimination and removal of weak reflectors that could be insects. The radar units also are equipped with an integrated global positioning system (GPS) and target tracking feature that allowed us to determine each target's coordinates and quantify target flight directions.

Each radar's processor unit was connected directly to a computer equipped with a PCI frame grabber circuit board. Using proprietary scheduling software developed by NJAS, we can automatically capture radar image data as bitmap files for any interval and for any duration. During this study we collected data images for five consecutive radar antenna sweeps (i.e., every 2.5 seconds), every 10 minutes, or a maximum of 720 images/24 hr/radar). We chose 10-minute intervals because we believe this minimized the possibility of double counting targets in consecutive samples. With the radar's range set to two nautical miles, a target moving 20 miles/hr would cross the widest part of our sample space (i.e., two nautical miles) in approximately six minutes.

During the study, we experienced persistent and often extensive backscatter of electromagnetic energy from ocean wave action, which dramatically affected the quality of data collected with the horizontally-oriented radar (Fig. 6 upper). On some days, this backscatter was extreme and it occluded the radar's entire view of the sample area over the ocean (Fig. 6 lower), especially at our southern study site (see Section 2.2, STUDY SITES AND DATA COLLECTION TIMEFRAME). This problem was exacerbated at this site because it was approximately 50 m above sea level. Typically, marine radars are equipped with the ability to suppress "sea clutter." However, sea clutter suppression also attenuates signal strength for all radar reflectors and this is particularly problematic when attempting to detect small targets like birds or bats that reflect relatively small amount of energy.

In an attempt to address this problem, we experimented with a parabolic dish antenna (Fig. 7). This antenna produces a 4°, conical-shaped electromagnetic beam and our mounting allowed it to be elevated in 2.5° increments above the scanning horizon. With the antenna elevated at 5° above the scanning horizon, we were able to eliminate detection of most ocean-generated, backscattered energy. Raising the antenna this far above the scanning horizon reduced our ability to sample low to the ocean surface, so we opted not to use the parabolic dish antenna at the southern site. However, we did use this antenna at the northern radar site for the last nine weeks of the study (8 October – 15 December) to reduce backscatter problems. We were able to do this by elevating the antenna only 2.5° above the scanning horizon, thereby maintaining the radar's view of areas close to the ocean surface.

2.2 STUDY SITES AND DATA COLLECTION TIME FRAME

From 19 March – April 30 2009, our radar system collected data on Audubon Society of Rhode Island property near the Lewis Farm, at the southern end of Block Island (i.e., "southern" site, 41°08.98' N, 71° 36.18' W, Fig. 8). The site was approximately 50 m above sea level and selected because of its wide, unobstructed view to the south. This location allowed us to monitor waterbirds (e.g., scoters, loons) that typically winter along the SE coast of Block Island. This location provided a view of the ocean from approximately 170-300° (i.e., S – NW or 130° of arc, Fig. 9) for the horizontally-oriented radar. The radar’s view of the ocean between 90-170° (i.e., E – S, or 80° of arc) was occluded by a rise along the edge of the landform. Areas from approximately 300-90° (NW – E, or 150° of arc, Fig. 9) were over land.

From 1 May – 15 December 2009, the NJAS radar system was located on Town of New Shoreham property, at the north end of the island, along the SW shore of Sachem Pond (i.e., "northern" site, 41°13.11' N, 71° 34.30' W, Fig. 8). We selected this site primarily to monitor northward and southward migration movements of passerines and other landbirds as well as waterbird (e.g., herons, egrets, terns) movements during the summer breeding season. The radar's view of the ocean was clear to the north, east and west. However, backscatter of electromagnetic energy from trees and low-rising dunes occluded some of the radar's view of the surrounding landscape (Fig. 10). Unlike the southeastern study site, we experienced only minor problems in a limited area with backscatter of electromagnetic energy from wave action (i.e., from 15-40° or 25° of arc).

Although we anticipated moving the radar, system back to the southern site on 1 Nov, (i.e., New Jersey Audubon Society, University of Rhode Island bird/bat monitoring principals) decided to leave the radar at the northern location through the end of the study period (i.e., 15 December). This was primarily because of issues related to extreme backscatter of radar energy from wave action experienced at the southern site (see Section 2.1, RADAR EQUIPMENT AND CONFIGURATION for description of problem).

To the extent possible, data were collected 24 hours/day, during the entire 272-day study period. We shut the radar system down approximately 30 min every two days to fill the generator's gas tank. From 9 – 14 July, the radar was offline for routine maintenance..

2.3 DATA PROCESSING AND ANALYSIS

In 2009, we collected approximately 3318 hours of data/radar during the diurnal data collection period (257 days, mean = 12.91 ± SE 0.12 hr/day, Table 1) and 2856 hours/radar during the nocturnal period (258 nights, mean = 11.07 ± SE 0.12 hr/night, Table 1). In total, we reviewed approximately 185,500 images/radar for each data collection period (i.e., 30 images/hr, 24 hrs/day, 258 days). For details of data collection during each season and data collection period (i.e., diurnal, nocturnal), see Appendices 2-7.

We conducted image reviews to determine occurrences of bird/bat movement episodes and identify precipitation events, insect contamination or any other unwanted radar energy propagation. Precipitation and insects typically have distinct characteristics that allow trained observers to distinguish them from bird and bat targets. Data images with precipitation, insect contamination or any other unwanted propagation were removed from subsequent data analyses either using data processing software developed by NJAS or by manually removing images from data sets before analyses. In extreme cases (e.g., continuous rain), we removed entire days or nights of data from analysis.

2.3.1 *Vertically-oriented radar*

Using image-processing software developed by NJAS, we extracted target information from data images collected with the vertically-oriented radar. The integrated image processing software performs the following tasks:

- Identifies the sample area and creates a template (Fig. 11) to remove stationary radar reflectors (i.e., ground clutter, sea clutter, main bang).
- Removes targets with low signal strength likely to be insects (i.e., based on color value).
- Smooths the data and locates and marks the centroid of each discrete target that remains
- Exports a text file that includes information on every target's signal strength and its position (i.e., the distance of its centroid) in the *X*- and *Y*-planes relative to the radar's position
- Outputs a bitmap image showing the transformed data with marked targets (Fig.12). This last feature allows us to review the data processing output to identify possible spurious targets and remove them from subsequent data analysis steps.

Using an analysis software program developed by NJAS staff, we summarized target counts, movement rates and altitudinal distribution (i.e., target position in the *Y*-plane relative to radar's position) for 10 min and hourly intervals. The software's output includes the total number of targets recorded in each image and the mean number of targets recorded in each five-image sample. Our analysis software also quantifies the number of targets recorded in discrete altitudinal bins (e.g., 100 m). We configured the software to assign targets to one of 19, 100 m (i.e., 1900 m or approximately 1 nm) altitudinal bins. The software also has a threshold feature that allowed us to filter out data with unusually high target counts, typically an indication of precipitation or insect contamination.

The results of analyses in this report are based on the average for each five-image sampling bout, which occurred at 10-minute intervals. These values are summed for the entire night's data collection (sum of the sample averages) to generate hourly, daily and nightly movement estimates. We believe using the sum of the sample averages is a more accurate assessment for the number of targets crossing through the study area because it minimizes the effect of enumerating the same targets multiple times during a single sampling bout. Analyses to quantify variation in target counts in successive images in a sampling bout indicated that coefficients of variation (CV) were very low (< 2%).

We used General Linear Model procedures (GLM, Zar 2009) to investigate the affects of SEASON (i.e., Spring: 19 Mar – 31 May, Summer: 1 June – 15 August, Fall: 16 August – 15 December), PERIOD (Day: sunrise to sunset the same day, Night: sunset to sunrise the following morning) and the interaction between the two factors on number of targets recorded (TR, sum of 10-minute sample means) and movement rates (i.e., targets recorded/nautical mile/hour, TR/hr). The same statistical approach was used to investigate the effect of these factors on the proportion and number of targets recorded in two altitudinal strata, ≤ 100 m (PROP100, TR100) and 100 < ≤ 200 m (PROP200, TR200). WE chose these two strata because they are likely the most relevant to the heights of wind turbines birds and bats would encounter in the nearshore waters of Block Island. When GLM procedures suggested significant affects of predictor variables (i.e., SEASON, PERIOD, SEASON*PERIOD interaction) on response variables, we used Bonferonni procedures to make *post hoc* pairwise comparisons. We used Kolmogorov-Smirnoff two-sample tests (Corder and Foreman 2009) to compare altitudinal distributions among seasons and between Day and Night periods.

2.3.2 *Horizontally-oriented radar*

We used NJAS-developed software to calculate target directions from images collected with the horizontally radar. To calculate a target's direction of movement, the program uses the end point of a target's trail and the target position (Fig. 13). For Day and Night periods, we analyzed one image/hour of data collected. Targets for each hour were compiled and we used circular statistical analysis to generate mean vectors (directional tendency, Mardia and Jupp 2000), vector lengths (*r*, strength of directional tendency, Mardia and Jupp 2000) and test statistical significance (i.e., Rayleigh's *Z* test, Zar 2009). We calculated second-order mean vectors (i.e., mean of mean vectors) for each season (i.e., Day and Night separately) and tested for statistical significance using Hotelling T^2 test (Mardia and Jupp 2000).

2.4 WEATHER PATTERNS AND BIRD/BAT FLIGHT DYNAMICS

2.4.1 *Local weather conditions*

For all analyses, we used local climatological data collected at the Westerly, RI State Airport (41.350° N, 71.799° W) and purchased from the National Weather Service's National Climatic Data Center web site (http://www.ncdc.noaa.gov/oa/ncdc.html). We selected this station because of its proximity to our study site (approximately14.5 miles) and the consistency and completeness of the data available during the study period. Although the station at Block Island State Airport (41.166° N, 71.580° W) was closer to our study sites, data prior to July 2009 were not available. Also, data from the Montauk, NY State Airport (41.073° N, 71.923° W) were available for the full term of the study, however, several weather variables (e.g., cloud cover, ceiling, visibility, precipitation) were not as this is an unmanned automated station. Additionally, the station was approximately 21.0 miles from our study site. For Day period analyses, we used weather data recorded at or as close to sunrise as data were available. We used weather data recorded at or as close to sunset as data were available for Night period analyses.

We used GLM procedures to investigate relationships between several weather variables (Table 2) and the four bird/bat flight dynamics response variables used in previously described analyses: TR, TR/hr, PROP100 and PROP200. *A priori*, we identified three weather variable groups that migrating birds and bats likely respond to: (1) sky conditions, which included cloud cover, ceiling, visibility and precipitation, (2) atmospheric conditions, such as dry bulb temperature [in degrees Celsius], dry bulb dew point [in degrees Celsius] and barometric pressure [in millibars] and (3) wind conditions (i.e., velocity and direction) (see Table 2 for descriptions of each variable).

Given the difficulty using circular data (i.e., wind directions) in linear statistical analyses (Mardia and Jupp 2000), we calculated headwind/tailwind vectors (THV, vectors parallel to the assumed direction of migration) and sidewind vectors (SWV, vectors perpendicular to the assumed direction of migration) using an equation proposed by Piersma and Jukema (1990):

$$THV = W\cos\alpha + \sqrt{\{A^2 - (W\sin\alpha)^2\}} - A,$$

where W is the wind velocity, A is the bird's air velocity, and α is the difference between wind direction and the assumed directional goal of movement ± 180° (see Appendix 1 for diagram and derivation of equation). Using wind vectors effectively resolves the circular variable, wind azimuth, into its rectangular components (i.e., cosine and sine), and incorporates wind speed. Thus, this conversion provides a way to examine the entire affect of wind on movement patterns. This particular wind vector equation assesses wind conditions relative to the assumed axis of movement.

We used actual mean vectors of movement derived from data collected with the horizontally-oriented radar for each season and period as the assumed directional goal of movement in the calculations of THV and SWV). The strength or weakness of tailwinds, headwinds and crosswinds (i.e., SWV) is known to affect migration behavior in birds (Liechti 2006).

In our analyses, we also considered assumed migration directions of "north" (i.e., 360°) in Spring and "south" (i.e., 180°) in Fall. For Summer, we considered both north and south as possible directional goals as post-breeding dispersal can often be northerly for some species. We modeled THV and SWV for each assumed migration direction separately to see which performed better at capturing variance in response variables.

Prior to GLM procedures, we conducted Pearson's product moment correlation analyses (Zar 2009) to identify weather variables in each grouping that might be correlated. When variables exhibited correlation coefficients ≥ 0.5 (i.e., positive or negative) they were not included together in the same model. Results of Pearson's product moment correlation analyses for each Season/Period combination are presented in Tables 3-8. *Post hoc*, we took an information-theoretic approach (Burnham and Anderson 2002) to evaluate model performance among the multiple models we tested.

In addition to models consisting of weather variables in each specific grouping (see description above), we assessed the performance of date (i.e., Julian day, quadratic form of Julian day) and three "Global" models. Global-1 models included all uncorrelated weather variables (i.e., Season/Period specific, based on Pearson's product moment correlation analyses). Global-2 models included Julian day (JD) and all uncorrelated weather variables, except any that were correlated with Julian day (see Tables 3-8 for Season/Period specific correlations). Global-3 models included the quadratic form of Julian day (JD-Q) and any weather variables included in Global-2 models. We present the variables included in "Global" models used for each Season/Period combination (e.g., Fall/Night) in Table 9.

Model performance was evaluated using Akaike Information Criteria corrected for small sample sizes (AIC_c). We considered models with the lowest AIC_c scores and with ΔAIC_c values > 2 compared to the model with the next lowest AIC_c values to be the "best performing model" or the model with the "strongest support" (Burnham and Anderson 2002). Models with ΔAIC_c values ≤ 2 of the model with the lowest score was considered equal.

2.4.2 *Synoptic weather conditions*

We used NWS surface weather maps (Fig. 14) generated at 0000 Greewich Mean Time (GMT, 2000 Eastern Standard Time) and 1200 GMT to determine the position of synoptic weather systems (i.e., meso scale atmospheric condition) relative to Block Island. The position of the reference location, in this case, Block Island, was then plotted on a generalized synoptic weather map (Fig. 15, after Richardson 1976, Lank 1983). For statistical purposes, we defined five regions on the synoptic map based on geostrophic wind patterns (Table 10). For each Season/Period combination we used one-way Likelihood Ratio χ^2 tests (Zar 2009) to test the null hypothesis that the proportion of TR across the five synoptic weather conditions was not significantly different (i.e., equal proportions). We used the same statistical approach to test null hypotheses for TR/hr, TR100 and TR200.

Additionally, we used two-way Likelihood Ratio χ^2 tests (Zar 2009) to test the null hypothesis that the distribution of TR across the five synoptic weather conditions was not significantly different from the proportional occurrence of the five synoptic conditions. If we failed to reject the null hypothesis, then we might infer that bird and bats preferentially "used" particular synoptic conditions disproportionate to their occurrence. Again, we used the same statistical approach to test null hypotheses for TR/hr, TR100 and TR200 for each SEASON/PERIOD combination.

2.4.3 *Effect of wind condition of flight direction*

We investigated relationships between vectors of bird/bat movement for each Season/Period combination and wind directions using circular-circular correlation coefficients (Fisher 1993, Mardia and Jupp, 2000). This method is analogous to the Pearson product-moment correlation commonly used for linear data. As with Pearson's correlation, this coefficient ranges from -1 to +1, with the former indicating a perfect negative correlation, the latter a perfect positive correlation, and 0 indicating no correlation. The significance of the correlation is tested using the jackknife method described in Zar (2009). We used circular-linear correlation coefficients (Fisher 1993, Mardia and Jupp 2000) to examine relationships between vectors of bird/bat movement and tailwind/headwind vectors (THV). The circular-linear correlation coefficient ranges from 0 – 1, so there is no index for negative correlations. The calculation of significance for correlations followed Mardia and Jupp (2000), using their approximation of the *F* distribution. Finally, we used Watson-Williams *F*-tests (Fisher 1993, Mardia and Jupp 2000) to compare SEASON/PERIOD specific mean wind vectors with corresponding mean vectors of corresponding bird/bat movement. This test determines if mean angles of two or more samples differ significantly by comparing the lengths of the mean vectors for each sample with that for the pooled data of the samples. The resulting *F* statistic is the same as Fisher's variance ratio statistic, which is commonly used in linear statistics

2.5 STATISTICAL ANALYSIS

Prior to statistical analyses, we evaluated response and predictor variables to determine if they met assumptions of parametric tests we proposed to use. If assumptions were not met, we transformed data or used non-parametric tests. Based on these assessments, we used the log transformation to normalize the response variable representing number of targets recorded (TR), hourly rates of targets recorded (TR/hr) and targets recorded within two altitudinal strata (TR100, TR200). We used arcsine transformations to normalize variables represented as proportions (e.g., proportion of targets recorded in various altitudinal strata). Although we present results of statistical analyses that used transformed variables, we present summary statistics (e.g., means, standard errors) for response variables in their untransformed state in textual, tabular and graphical accounts, unless otherwise indicated.

All standard statistical analyses were performed using SAS® 9.2 (SAS Institute, Inc. 2004) and SYSTAT® 11.0 (SYSTAT Software, Inc. 2004). Statistical tests involving directional data (i.e., flight direction, circular-circular comparisons, circular-circular and circular-linear correlations) were performed using Orianna 3.0© (Kovach Computing Services 2007). We considered results of statistical tests significant at $\alpha \leq 0.05$.

3.0 RESULTS

3.1 TARGET MOVEMENT AND MOVEMENT RATES

Targets recorded (i.e., TR, sums of the 10-minute sample averages) varied widely within and among seasons and between Day and Night data collection periods (Tables 11-16, Figs. 16, 17, 18, see Appendix 8 for summary statistics from each Season/Period, Appendices 9-20 for tabular and graphical presentations of data). Kolmogorov Smirnov (K-S) two-sample tests suggested that Day and Night cumulative frequency distributions, which characterize daily changes in target movements, were significantly different in Spring (maximum difference = 0.402, $P < 0.001$, Fig. 19 upper) and Summer (maximum difference = 0.28, $P < 0.009$, Fig. 17 center), but not in Fall (maximum difference = 0.12, $P < 0.37$, Fig. 19 lower).

Despite high variability in TR, we found statistically significant SEASON ($F_{2,\,513} = 2.99$, $P = 0.05$) and PERIOD (i.e., Day, Night; $F_{1,\,514} = 23.22$, $P < 0.0001$) effects. TR was significantly greater during the Fall (mean = 408.89 ± SE 48.40) than in Spring (mean = 161.72 ± SE 17.75), however, Fall and Spring TR were not significantly different (both *P*s > 0.22) from Summer (mean = 289.04 ± SE 45.13). TR at Night (mean = 439.86 ± SE 46.94) was significantly greater ($P < 0.0001$) than during the Day (mean = 172.53 ± SE 17.19). We also found a significant SEASON*PERIOD interaction ($F_{2,\,513} = 13.05$, $P < 0.0001$). *Post hoc* comparisons suggested that TR during Fall/Night (mean = 634.90 ± SE 87.30) was significantly greater than all other SEASON/PERIOD combinations (all *P*s < 0.0001, Fig. 20 upper) except Summer/Night (mean = 408.10 ± SE 84.68, $P = 0.22$). TR for Summer/Night was also statistically different from Fall/Day (mean = 184.82 ± SE 31.03, $P = 0.0006$) but not from any other SEASON/PERIOD combinations (Fig. 20 upper). No other SEASON/PERIOD combinations were significantly different from each other (Fig. 20 upper).

Although TR/hr was greater in Fall (mean = 37.37 ± SE 4.37) than in Spring (mean = 18.21 ± SE 1.92) and Summer (mean = 33.76 ± SE 5.88), we did not find a significant SEASON effect ($F_{2,\,513} = 2.46$, $P = 0.09$). We did, however, find a significant PERIOD effect ($F_{1,\,514} = 43.18$, $P < 0.0001$), with rates at Night being significantly greater than Day (means = 46.36 ± SE 4.78 and 15.46 ± SE 1.43, respectively). We found a significant SEASON*PERIOD interaction ($F_{2,\,513} = 6.54$, $P < 0.002$). *Post hoc* comparisons indicated that TR/hr during Fall/Night (mean = 58.50 ± SE 7.98) and Summer/Night (mean = 53.89 ± SE 11.08) were significantly greater than all other SEASON/PERIOD combinations (all *P*s < 0.002 and all Ps < 0.03, respectively, Fig. 20 lower) while none of the other combinations were statistically different from each other (Fig. 20 lower).

TR also varied with time relative to sunrise and sunset. During the Day period, TR showed a distinct peak 6-8 hours after sunrise (Fig. 21), except in fall when the pattern was bimodal, with peaks at sunrise and again eight hours later (Fig. 21, lower). Peak TR during the Night period occurred 1-3 hours after sunset, regardless of season (Fig. 22). K-S two-sample tests suggested that cumulative frequency distributions, which characterized hourly changes in target detections, were not significantly different among seasons for Day (Fig. 23 upper, all Ps > 0.90) or Night (Fig. 23 lower, all Ps > 0.70) data collection periods.

3.2 TARGET ALTITUDE

The altitudinal distribution of targets recorded across all altitudinal strata (i.e., 19, 100 m strata, one nautical mile) did not appear to vary significantly within and among seasons or between Day and Night data collection periods (Tables 11-16, Figs. 16, 17, 18, see Appendix 8 for summary statistics from each Season/Period, Appendices 9-20 for tabular and graphical presentations of data). Results from Kolmogorov-Smirvov two-sample tests suggest that proportional distribution of targets recorded in each 100 m strata (i.e., up to one nautical mile or approximately 1900 m) were not significantly different among seasons for Day (all Ps > 0.48, Fig. 24, upper) or Night periods (all Ps > 0.48, Fig. 24, lower). Regardless of season or period, altitudinal distributions of recorded targets generally increased with altitude to peak between 200 and 400 m (Figs. 25, 26, 27) across all hours, except during the Spring/Day period when the greatest proportion of recorded targets occurred in the 0-100 m stratum. Fifty percent of all targets we recorded occurred between 300 and 400 m during diurnal periods (Fig. 24, upper) and at approximately 400 m during nocturnal sampling periods (Fig. 24, lower). Generally, targets recorded decreased asymptotically at altitudes greater than 500 m.

3.2.1 *0-100 meter stratum*

Our data also suggest extensive within-season variation in PROP100 (i.e., the proportion of targets recorded $\leq$ 100 m relative to all targets recorded) and TR100 (i.e., number of targets recorded $\leq$ 100 m) (Tables 11-16, Figs. 28, 29, 30). KS two-sample tests suggested that cumulative frequency distributions characterizing daily changes in PROP100 were significantly different between Day and Night data collection periods in Spring (maximum difference = 0.40, $P < 0.001$, Fig. 31 upper) and Summer (maximum difference = 0.32, $P < 0.002$, Fig. 31, center), but not in Fall (maximum difference = 0.16, $P < 0.13$, Fig. 31, lower). Additionally, K-S two-sample tests suggested a significant difference in the cumulative frequency distributions among seasons for the Day (*cf* Fig. 31, all Ps < 0.005,) and Night (*cf* Fig. 31, all Ps < 0.0009) data collection periods.

Although PROP100 was highest in Spring (mean = 0.13 ± SE 0.01) compared to Summer (mean = 0.11 ± SE 0.01) and Fall (mean = 0.11 ± SE 0.01), these differences were not significant (i.e., no SEASON effect, $F_{2, 513} = 2.04$, $P = 0.13$). PROP100 during the Day (mean = 0.15 ± SE 0.01) was significantly greater (PERIOD effect, $F_{1, 514} = 41.83$, $P < 0.0001$) than the proportion recorded at Night (mean = 0.08 ± SE 0.005).

We also found a significant a SEASON*PERIOD interaction effect on PROP100 ($F_{2, 513} = 4.06$, $P < 0.02$). *Post hoc* comparisons indicated that Fall/Night and Summer/Night had a significantly smaller proportions of targets recorded in this stratum (mean = 0.07 ± SE 0.004, mean = 0.08 ± SE 0.01, respectively) than all other SEASON/PERIOD combinations (all Ps < 0.05, Fig. 32, upper). Other SEASON/PERIOD combinations were not significantly different from each other (Fig. 32, upper).

We did not find significant SEASON ($F_{2, 513} = 1.99$, $P = 0.14$) or PERIOD ($F_{1, 514} = 0.59$, $P = 0.44$) effects on TR100. However, the SEASON*PERIOD interaction was significant ($F_{2, 513} = 9.80$, $P < 0.0001$). *Post hoc* comparisons indicated TR100 during Fall/Night (mean = 33.71 ± SE 4.67) was significantly greater (all Ps < 0.004, Fig. 32, lower) than Fall/Day (mean = 14.79 ± SE 2.32) and Spring/Night (mean = 11.68 ± SE 1.63). Furthermore, TR100 during Fall/Day was significantly less ($P = 0.05$) than during Summer/Day (mean = 21.18 ± SE 2.86). Other SEASON/PERIOD combinations were not statistically different from each other (Fig. 32, lower).

PROP100 and TR100 showed considerable hourly variation during Day and Night data collection periods, regardless of season (Spring: Figs. 33, Summer: Fig. 34, Fall: Fig. 35). However, K-S two-sample tests suggested that cumulative frequency distributions, which characterized hourly changes in the proportion of target recorded in the 0-100 m stratum were not significantly different between Day and Night data collection periods during any season (all Ps > 0.51, Fig. 36). Additionally, results of K-S two-sample tests showed that there were no statistical differences in hourly variation among seasons for the Day (all Ps > 0.99, *cf* Fig. 36) and Night (all Ps > 0.89, *cf* Fig. 36) data collection periods.

3.2.2 *101-200 meter stratum*

Similar to findings for the 0-100 m stratum, our data also suggest extensive within-season variation in the proportion of and number of targets recorded in the 101-200 m stratum (PROP200, TR200, respectively, Tables 11-16, Figs. 28, 29, 30). K-S two-sample tests suggested that cumulative frequency distributions characterizing daily changes in the proportion of targets recorded in this stratum were significantly different between Day and Night in Spring (maximum difference = 0.24, $P = 0.03$, Fig. 37 upper) and Summer (maximum difference = 0.25, $P < 0.03$, Fig. 37, center), but not in Fall (maximum difference = 0.13, $P < 0.19$, Fig. 37, lower). Additionally, K-S two-sample tests suggested the cumulative frequency distribution for the diurnal data collection period in Fall was significantly different than in Spring and Summer (all Ps ≤ 0.0001 *cf* Fig. 37), but that Spring and Summer were not statistically different from each other ($P = 0.54$). For the nocturnal data collection period, cumulative frequency distributions for all seasons were statistically different (K-S tests, all Ps < 0.0001).

PROP200 was greater in Summer (mean = 0.17 ± SE 0.01) than in Spring or Fall (mean = 0.15 ± SE 0.01, mean = 0.15 ± SE 0.01, respectively), although we did not find a significant SEASON effect ($F_{2, 513} = 2.54$, $P = 0.08$). However, PROP200 at Night (mean = 0.13 ± SE 0.01) was significantly lower (PERIOD effect: $F_{1, 514} = 33.17$, $P < 0.0001$) than during the Day (mean = 0.13 ± SE 0.01). Although PROP200 differed among SEASON/PERIOD combinations, these differences were not significant (SEASON/PERIOD interaction, $F_{2, 513} = 1.95$, $P = 0.14$, Fig. 38, upper).

In contrast to our analysis of PROP200, we found a significant SEASON effect on TR200 ($F_{2, 513}$ = 7.00, $P = 0.001$). Fall (mean = 45.39 ± SE 5.16) and Summer (mean = 37.42 ± SE 4.40) had significantly greater TR200 (all *P*s < 0.004) than Spring (mean = 18.12 ± SE 1.47), but Fall and Summer were not statistically different from each other ($P = 1.00$). TR200 at Night (mean = 47.39 ± SE 4.84) was significantly greater (PERIOD effect: $F_{1, 513}$ = 4.34, $P = 0.04$) than during the Day (mean = 23.54 ± SE 1.98).

We also found a significant SEASON*PERIOD effect ($F_{2, 513}$ = 13.18, $P < 0.0001$) on TR200. Fall/Night was significantly greater (mean = 68.46 ± SE 9.27, (Fig. 38, lower) than all other SEASON/PERIOD combinations (all *P*s ≤ 0.0008) except for Summer/Day ($P = 0.21$, mean = 32.21 ± SE 3.87, Fig. 38, lower) and Summer/Night ($P = 0.48$, mean = 42.54 ± SE 7.85, Fig. 38, lower). TR200 for Summer/Night was also significantly greater Spring/Day and Night and Fall/Day (Fig. 38 lower). No other SEASON/PERIOD combinations were significantly different from each other (Fig. 38, lower).

Similar to the 0-100 m altitudinal stratum, the PROP200 and TR200 showed hour-to-hour variation during Day and Night data collection periods, regardless of season (Spring: Figs. 33, Summer: Fig. 34, Fall: Fig. 35). K-S two-sample tests suggested that cumulative frequency distributions characterizing hourly changes in PROP200 were significantly different between Day and Night data collection periods in Spring and Summer (all *P*s < 0.04) but not Fall ($P = 0.13$, Fig. 39). Additionally, K-S tests suggested there were no statistical differences in the cumulative frequency distributions that characterize hourly variation among seasons for the Day (all *P*s > 0.60, *cf* Fig. 39) and Night (all *P*s > 0.90, *cf* Fig. 39) data collection periods.

3.3 RELATIONSHIPS BETWEEN TARGET ALTITUDE AND MOVEMENT MAGNITUDE

3.3.1 *0-100 meter stratum*

Generally, we found a negative relationship between PROP100 and TR (targets recorded, all altitudinal strata) across all SEASON/PERIOD combinations. That is, as TR increased, PROP100 decreased regardless of season or period (Figs. 40, 41, 42). However, these relationships were only statistically significant for the Night data collection periods (all *P*s < 0.003, Table 17) and the Fall/Day period (all *P*s < 0.0001, Table 17).

3.3.2 *101-200 meter stratum*

Only Spring/Day, Fall/Day and Fall/Night exhibited negative relationships between the PROP200 m and TR (Figs. 40, 42) and all of these were statistically significant (all *P*s < 0.04, Table 17). For Spring/Night, Summer/Day and Summer/Night periods, relationships between tPROP200 and TR were positive (Figs. 40, 41), however, none of these were significant.

3.4 TARGET FLIGHT DIRECTION

Second-order mean vectors of target flight directions recorded during Spring/Day and Spring/Night were oriented toward 51° and 64°, respectively, and each vector was significantly different from random (Day: Rayleigh's $Z_{73} = 27.13$, $P < 0.0001$, Night: Rayleigh's $Z_{72} = 21.20$, $P < 0.0001$, Fig. 43). Spring/Day and Spring/Night mean vectors were not statistically different from each other ($F_{1,\,144} = 1.55$, $P = 0.22$). In Summer, flight directions of targets recorded during Day and Night periods were oriented toward 13° and 19°, respectively. Each second-order vector was significantly different from random (Day: Rayleigh's $Z_{71} = 13.96$, $P < 0.0001$, Night: Rayleigh's $Z_{67} = 10.79$, $P < 0.0001$, Fig. 44). Again, Summer Day and Night vectors were not statistically different from each other ($F_{1,\,137} = 0.70$, $P = 0.40$). Second-order mean vectors for Fall/Day and Fall/Night periods were oriented to 285° and 224°, respectively, but only the latter vector was significantly different from random (Day: Rayleigh's $Z_{114} = 1.80$, $P = 0.17$, Night: Rayleigh's $Z_{117} = 4.71$, $P < 0.009$, Fig. 45). Finally, Fall/Day and Fall/Night vectors were significantly different from each other ($F_{1,\,230} = 8.86$, $P = 0.003$). Detailed summary statistics on daily and nightly mean vectors for all seasons are presented in Appendices 21-26.

3.5 EFFECTS OF METEOROLOGICAL CONDITIONS ON BIRD/BAT MOVEMENT PATTERNS

3.5.1 *Local conditions*

Season/period results of multi-model comparisons for each response variable (i.e., TR, log-transformed, TR/hr, log-transformed, PROP100, arcsine transformed, PROP200, arcsine transformed) are presented in Tables 18, 20, 22, 24, 26 and 28. Parameter estimates for best performing models are presented in Tables 19, 21, 23, 25, 27 and 29.

3.5.1.1 Spring/Day (Model comparisons: Table 18; Model parameter estimates: Table 19)

Model comparison procedures suggest that several models performed equally well in explaining variability in TR. Julian day-quadratic (JD-Q) had the lowest AIC_c and the highest model weight ($w_i = 0.25$), however, Julian day (JD), Temperature/Barometric Pressure and the Global-3 (i.e., JD-Q + uncorrelated weather variables, see Table 9) models all had ΔAIC_c values within 2.0. Among these models, Global-3 explained more variability in TR ($R^2 = 0.19$) compared with JD-Q, which had the next highest R^2 (0.10). Parameter estimates for the linear or quadratic terms in the JD-Q model were not significant, however, in the Global-3 model JD-Q and several variables, such as Barometric Pressure (BP) and Tailwind-Headwind Vector (THV) were significant or nearly so. The parameter estimates for JD-Q (+) and BP (-) suggested that TR increased as the season progressed and increased as barometric pressure decreased. The THV (+) parameter estimate indicated that as winds became more southwesterly, TR increased.

For TR/hr, the Global-3 model had the lowest AIC_c value and model weight ($w_i = 0.34$), but JD-Q and Global-2 models (i.e., JD plus uncorrelated weather variables, see Table 9) had ΔAIC_c values within 2.0, suggesting that they were similarly effective determinants of variability in the response. Global-3 and Global-2 models explained similar amounts of variation in TR/hr (R^2s = 0.30 and 0.29, respectively) and variables with significant parameter estimates were the same in each (i.e., BP [-], SWV[-]). Only the quadratic term was significant in the JD-Q model. Parameter estimates for JD-Q were positive for the linear term and negative for the quadratic term, indicating that TR/hr first increased as JD increased, then decreased as the season progressed. Negative estimates for BP and SWV suggested that TR/hr increased as barometric pressure decreased and when winds were westerly.

The Precipitation model had the lowest AIC_c value, but four other models, JD, Dew Point, Cloud Cover/Visibility and Ceiling all had AIC_c values within 1.0, suggesting that they performed similarly. For all of these models, R^2 values were < 0.03 and none of the parameter estimates were significant, indicating that they were not effective at explaining daily variation in PROP100.

For PROP200, the Global-2 had the lowest AIC_c, but ΔAIC_c for the Global-3 model was 0.85, suggesting that each model performed similarly in determining variation in the response. R^2 values for each model was 0.40, also indicating similar model performance. Parameter estimates in each model were similar. In each, JD (+) and SWV (+) were significant and BP nearly so (P = 0.07). These estimates suggested that PROP200 increased as the season progressed and as winds became more SE.

3.5.1.2 Spring/Night (Model comparisons: Table 20; Model parameter estimates: Table 21)

For the TR response variable, the Global-1 model (Table 9) had the lowest AIC_c value and model weight ($w_i = 0.69$) among all models considered. The next best performing model, Global-2, had a ΔAIC_c of 3.0 and a model weight of 0.15, providing strong support for Global-1. Additionally, the Global-1 model explained 39% of the variation in TR. Among the five weather variables included in the Global-1 model, Temperature (+), THV (+) and SWV (-) had significant parameter estimates suggesting that TR increased with temperature and as winds became SW–W.

Model selection results for TR/hr were similar to TR. The Global-1 model was the best performing based on AIC_c values. However, the Global-2 model had a ΔAIC_c of 0.09, suggesting that this model performed similarly to Global-1. Although Global-1 had a higher model weight than Global-2 ($w_i = 0.52$ versus 0.33), both models had similar abilities to explain variation in TR/hr (R^2 values = 0.48 and 0.47, Global-1 and Global-2, respectively). In the Globa1-1 model, Temperature (+), THV (+) and SWV (-) parameter estimates were significant, while in the Global-2 model, JD (+), THV (+) and SWV(-) parameter estimates were significant. These results suggest that TR/hr increased as the season progressed and temperatures increased (i.e., both variables are significantly correlated) and when winds were from the SW–W.

For PROP100, JD had the lowest AIC_c, but several models had ΔAIC_c values within 2.0. This included JD-Q, both THV-SWV models, the Temperature/BP model, and the Dew Point, Visibility and Precipitation models. All models had weights ≤ 0.16 and explained relatively little of the variation in PROP100 (all R^2 values ≤ 0.06). Additionally, only parameter estimates for THV (-), SWV (+) and Temperature (-) were significant or nearly so. These results indicate the PROP100 increased as temperature decreased and when winds were NE–E.

Although the Global-2 model had the lowest AIC_c value and highest model weight ($w_i = 0.61$) for the PROP200 response variable, the Global-3 model performed similarly well (ΔAIC_c = 1.44). Both models also had similar R^2 values (0.31 and 0.30, respectively) suggesting that each model was similarly effective at explaining daily variation in PROP200. In each model, JD (+) Cloud Cover (-) and SWV (+) parameter estimates were significant, suggesting that PROP200 increased as the season progressed, when cloud cover decreased and when winds were easterly.

3.5.1.3 Summer/Day (Model comparisons: Table 22; Model parameter estimates: Table 23)

Among the models assessed for TR, JD-Q had the lowest AIC_c value and highest model weight ($w_i = 0.52$). However, the model that included Cloud Cover, Ceiling and Visibility had a ΔAIC_c value of 1.04, suggesting that it performed similarly to JD-Q. This model also explained more of the daily variation in TR ($R^2 = 0.22$) compared to the JD-Q model ($R^2 = 0.14$). Parameter estimates for the linear (-) and quadratic (+) terms in the JD-Q model were significant, while only Ceiling (+) and Visibility (+) parameter estimates were significant. JD-Q parameter estimates suggested that TR was high early, declined toward mid-season and increased markedly as the season ended. TR also appeared to increase as cloud ceiling and visibility increased.

For TR/hr, JD-Q had the lowest AIC_c value and highest model weight ($w_i = 0.70$). The next best performing model, Cloud Cover/Ceiling/Visibility had a ΔAIC_c value of 3.98 and model weight of 0.10, suggesting strong support for the JD-Q model. Although the Cloud Cover/Ceiling/Visibility model explained more variation in TR/hr ($R^2 = 0.19$) than JD-Q ($R^2 = 0.15$), as did all of the Global models (all R^2s > 0.25), these models did not perform as well as JD-Q. This was likely because of the greater number of variables in these models and the general lack of significance in parameters estimates for the variables included. Parameter estimates for both the linear (-) and quadratic (+) variables in the JD-Q model were significant, suggesting a temporal pattern similar to TR (see preceding paragraph).

JD-Q was also the best performing model ($w_i = 0.84$) with respect to PROP100. The next best performing model was JD, but with a ΔAIC_c value of 5.69 and a model weight of 0.05, it was not supported. JD-Q explained 14% of the daily variation in PROP100 and the parameter estimates for the linear (+) and quadratic (-) variables in the model were both significant. The signs for the term estimates suggest that PROP100 was low early in the season, increased to peak midway through the summer and decreased to low levels toward the end of the season.

Although the Temperature/BP model had the lowest AIC_c value and highest model weight ($w_i = 0.40$), the Dew Point model performed equally well ($\Delta AIC_c = 0.06$, $w_i = 0.39$) with respect to PROP200. The two models explained 15% and 12% of the daily variation in PROP200, respectively. The parameter estimate for Dew Point (-) was significant as was Temperature (-), suggesting that PROP200 increased as temperature and dew points (i.e., two significantly correlated variables) decreased.

3.5.1.4 Summer/Night (Model comparisons: Table 24; Model parameter estimates: Table 25)

For TR and TR/hr, JD-Q had strong support as the best performing model. Model weights were 1.0, for both response variables and JD-Q explained 42% and 51% of the daily variation in TR and TR/hr, respectively. The linear (-) and quadratic (+) terms were significant for both response variables, suggesting that targets recorded and movement rate were high early in the season, declined to lows mid-season and increased to peak toward the end of summer.

The Global-1 model had the greatest support (i.e., lowest AIC_c, $w_i = 0.52$) with respect to PROP100. The next best models, Global-2 and Global-3 each had ΔAIC_c values of 2.66 and models weights of 0.14. All three models explained similar amounts of daily variation in PROP100 (all R^2 values 0.31 – 0.34). Only Temperature (-) and SWV (+) had significant parameter estimates in the Global-1 model, suggesting that PROP100 increased as temperature declined and when winds had an easterly component.

Although the THV-SWV(360°) had the lowest AIC_c the other two THV-SWV models (i.e., 19°, 180°) performed equally well ($\Delta AIC_c = 0.14 – 0.34$) as determinants of PROP200. All had similar model weights ($w_i = 0.28 – 0.33$) and R^2 values (0.15 – 0.16). In each model only the THV terms were significant and the parameter estimates suggest that southerly winds had a positive effect on PROP200, regardless of which model was considered.

3.5.1.5 Fall/Day (Model comparisons: Table 26; Model parameter estimates: Table 27)

Global-2 and Global-3 models had equal support regarding the TR response variable. They were nearly indistinguishable, with AIC_c values within = 0.1 of each other, model weights of 0.47 and 0.51, respectively and R^2 values of 0.48 each. In the Global-2 model, JD (-), Cloud Clover (-) and Barometric Pressure (+) were significant parameters. JD-Q and the same weather variables were significant in the Global-3. The date terms suggest that TR decreased as the season progressed. In addition, TR increased with diminishing cloud cover and increasing barometric pressure.

For TR/hr, the JD-Q model had the lowest AIC_c value and the highest model weight ($w_i = 0.57$). However, JD had a ΔAIC_c value of 1.01 and a model weight of 0.34, supporting this model as similarly effective determinant of TR/hr. Both models explained a similar amount of daily variation in TR/hr (R^2s = 0.37 – 0.38). Parameter estimates for JD and JD-Q were negative, suggesting that movement rate declined as the Fall season progressed.

The THV(285°) model had the lowest AIC_c value, highest model weight ($w_i = 0.99$) and explained 21% of the variation in PROP100. Based on a positive parameter estimate for THV, it appears that PROP100 increased was winds had a greater tailwind component (i.e., easterly).

JD-Q was clearly the best performing model ($w_i = 1.0$) and explained 29% of variation in the response variable PROP200. The linear (-) and quadratic (+) terms were both significant and suggest that PROP200 decreased initially at the beginning of the season and increased exponentially as the season progressed.

3.5.1.6 Fall/Night (Model comparisons: Table 28; Model parameter estimates: Table 29)

With respect to TR, JD-Q and Global-3 models performed similarly ($\Delta AIC_c = 0.78$, $w_i = 0.54$ and 0.36 respectively). The two models also explained similar amounts of variation in the response variable (R^2s = 0.57 and 0.53 for Global-3 and JD-Q, respectively). Linear (+) and quadratic (-) terms were both significant and suggest that TR was high early in the Fall and declined exponentially as the season progressed. JD-Q and Ceiling (+) were significant variables in the Global-3 model. The parameter estimate for Ceiling suggests that TR increased as cloud ceiling became higher.

JD-Q was clearly the model with the strongest support ($w_i = 0.88$), explaining 61% of variation in TR/hr. Although the next best model, Global-3 explained 62% of TR/hr variation, its ΔAIC_c value was 5.37 and its model weight was 0.06. Similar to TR, the linear (-) and quadratic (+) terms were both significant, suggesting that TR/hr was high early in the Fall and declined exponentially as the season progressed.

Although the Precipitation model had the greatest support (model weight = 0.35) as a determinant of PROP100, JD, JD-Q and Cloud cover/Ceiling all had ΔAIC_c values within 2.0. All four models were similarly poor at explaining variation in the response variable (all (R^2s < 0.05). The parameter estimate for Precipitation (-) was significant, suggesting that PROP100 increased when rain was present. JD (+) and Ceiling (+) estimates were nearly significant ($P <$ 0.10), possibly suggesting that PROP100 increased as the season progressed and as cloud ceiling became higher. Neither parameter in the JD-Q model was significant.

For PROP200, the model containing Temperature and BP had the greatest support (model weight = 0.63), but the Global-1 model had a ΔAIC_c value of 1.48 and a model weight of 0.30, suggesting support for this model as well. The Temperature/BP model explained 12% of the variation in PROP200, while the Global-1 model explained 19%. In the Temperature/BP model, both parameters were significant and negative. For the Global-1 model, Cloud Cover (+), Ceiling (+) Temperature (-) and BP (-) were all significant or nearly so (all Ps < 0.06). Together, these results suggest that PROP200 increased under clearing skies and falling temperatures or pressure.

3.5.2 *Synoptic weather conditions*

3.5.2.1 Spring/Day (Figure 46)

Results of the one-way Likelihood Ratio χ^2 tests suggested that the proportion of TR across the five synoptic conditions were not equal (all Ps < 0.0001). We found similar results for the response variables TR/hr, TR100 and TR200. Except for TR200, proportions under condition "1" (41-44%), which typically produce southerly winds, were greater than under all other conditions. The smallest proportions were apparent under condition "5", which is typically associated with calm winds produced by high pressure (Table 10, Fig. 15).

Differences between the proportions of TR/hr and TR100 across synoptic conditions and the proportional occurrence of those conditions during the Spring/Day data collection period were significantly different (two-way Likelihood Ratio χ^2 tests, TR/hr: $\chi^2 = 10.94$, df = 4, $P = 0.03$, TR100: $\chi^2 = 16.61$ df = 4, $P = 0.002$) For TR/hr, synoptic conditions "2" and "3", that typically produce NW and NE winds, respectively (Table 10, Fig. 15), occurred on 57% of the days but accounted for only 38% of the response. Furthermore, synoptic conditions "1" and "4", which typically produce southerly winds (Table 10, Fig. 15) occurred on 42% of the days but accounted for 57% of the response. Finally, differences between the proportions of TR and TR200 across synoptic conditions and the proportional occurrence of those conditions were not significant (TR: $\chi^2 = 8.47$, df = 4, $P = 0.08$, TR200: $\chi^2 = 4.87$, df = 4, $P = 0.30$).

3.5.2.2 Spring/Night (Figure 47)

One-way Likelihood Ratio χ^2 tests for each response variable suggested that proportions were not equal across synoptic conditions (all *P*s < 0.006). For all response variables, proportions under condition "4" (33-44%) were greater than under all other conditions. For TR and TR/hr, the smallest proportions were apparent under condition "2", while the smallest proportions for TR100 and TR200 were found under condition "5" (7% and 9%, respectively).

The proportions of each response variable were significantly different from the proportional occurrence of the five synoptic conditions during the Spring/Night data collection period (all *P*s < 0.0001). Condition "4" occurred on 10% but 35% of TR and 33% of TR/hr, respectively, occurred under this condition. Conversely, conditions "2" and "3" occurred on 49% of the nights during the Spring/Night period but accounted for only 28% of TR and TR/hr. Results for TR100 and TR200 were similar. Forty-four percent and 37%, respectively, occurred during condition"4", while only 34% occurred under conditions "2" and "3".

3.5.2.3 Summer/Day (Figure 48)

Of the four response variables considered, only proportions of TR100 were not equal across the five synoptic conditions ($\chi^2 = 15.39$, df = 4, $P = 0.004$). Two-way Likelihood Ratio χ^2 tests suggest that the proportions of TR100 and TR200 were significantly different across the five synoptic conditions from the proportional occurrence of those conditions (TR100: $\chi^2 = 10.57$, df = 4, $P = 0.03$, $\chi^2 = 13.83$, df = 4, $P = 0.008$). Condition "5" occurred on 10% of the days in Summer, but accounted for 26% of all TR100. In contrast, condition "3" occurred 28% of the time but only accounted for 17% of all TR100. Together, conditions "4" and "5" occurred on 20% of the days but 45% of all TR200 occurred during these conditions. We classified 57% of the Summer/Day period as experiencing "2" and "3" conditions, but only 40% of TR200 occurred under these conditions.

3.5.2.4 Summer/Night (Figure 49)

One-way Likelihood Ratio χ^2 tests for each response variable suggested that proportions were not equal across synoptic conditions (all *P*s < 0.0001). In all cases, proportions were greatest under condition "1" (37-41%) and smallest under condition "5" (4-7%).

Proportions across the five synoptic conditions for each response variables were significantly different from the proportional occurrence of those conditions (two-way Likelihood Ratio χ^2 tests, all *P*s < 0.007). This appeared to be related primarily to conditions "3" and "4". We classified 33% of all nights during the Summer/Night period as condition "3". Nine percent, 12%, 9%, 8% of TR, TR/hr, TR100 and TR200, respectively, occurred under this same condition. In contrast, we classified 14% of nights as condition "4" but 24-29%, depending on the response variable, occurred under this condition.

3.5.2.5 Fall/Day (Figure 50)

One-way Likelihood Ratio χ^2 tests suggested that proportions of TR, TR100 and TR200 were not equal across synoptic conditions (all *P*s < 0.04). For TR and TR200, proportions under condition "2" were greater (32%) than under other conditions, while for TR100, condition "5" had the greatest proportion (37%) among synoptic conditions.

Two-way Likelihood Ratio χ^2 tests suggested that proportions across the five synoptic conditions for each response variables were significantly different from the proportional occurrence of those conditions (all *P*s < 0.0001). Conditions "1", "3" and "5" appeared to be most responsible for these differences. They occurred 26%, 34% and 4%, respectively, during the Fall/Day data collection period. For conditions "1" and "3", response variable proportions were always smaller (12-16%, 15-16%, respectively) than the occurrence of these conditions, while under condition "5", they were always greater than the condition occurred (17-37%).

3.5.2.6 Fall/Night (Figure 51)

For all response variables, proportions under each synoptic condition were significantly different (one-way Likelihood Ratio tests, all *P*s ≤ 0.0008). For all response variables, condition "2" had the greatest proportion (34% - 41%), while condition "4" had the smallest proportion (7%-11%).

Proportions across the five synoptic conditions for each response variables were significantly different from the proportional occurrence of those conditions (two-way Likelihood Ratio χ^2 tests, all *P*s < 0.0004). Significance differences appeared related primarily to differences in proportions for condition "3" and to some extent, condition "4". We classified 31% of all nights as condition"3", but proportions for response variable only ranged from 14-16%. Condition "4" occurred only 1% of the time during the Fall/Night data collection period, but 7-10%, depending on response variable, occurred under this condition.

3.5.3 *Effects of wind on flight direction*

For all Season/Period combinations we found significant and positive correlations (all *P*s < 0.05, Table 31) between wind and target directions (i.e., for a given Season/Period combination). Similarly, we found significant correlations between THVs and all target directions for all Season/Period combinations (all Ps < 0.05, Table 32). Interestingly, however, we found significant differences for Season/Period-specific wind vectors (Fig. 52) and corresponding target vectors (all *P*s ≤ 0.01, Table 32), except for Summer/Day (*P* = 0.90).

4.0 DISCUSSION

In the following "Discussion" sections, we compare our results to those reported in other marine radar studies conducted primarily to assess potential impacts of wind power development. However, caution should be used when interpreting differences between this and some other studies because of inherent differences in equipment, data collection procedures and analytical approaches. Several of the studies cited in this section used a single 12 kW X-band radar with the antenna rotating parallel to the ground (i.e., what we refer to in this report as "horizontally-oriented"). Data collected with the radar in this orientation are used to estimate target movement rates and flight direction. Many practitioners then periodically rotate this unit 90^{o} so that the antenna spins perpendicular to the ground (i.e., what we refer to in this report as "vertically-oriented"). Data collected with the radar in this orientation are used to estimate target altitudes. In this study, we used two 25 kW X-band radars operating simultaneously as described in the "Methods" section.

Several of the studies we cite for comparison use manual methods to estimate the number, altitude and flight direction of targets detected by their radar. These methods may be subject to observer biases, especially because most of these studies are conducted at night and for many consecutive hours. Additionally, these studies do not archive the image data produced by their radars. In these cases, investigators are unable to conduct quality control assessments of their data analyses. In contrast, we used automated image data collection and algorithm-based data processing and target quantification, which allows for standardized assessment of target movement indices (i.e., magnitude, altitude and direction), data quality control and improved precision of estimates.

Our radars were more powerful (i.e., 25 kW versus 12 kW) than used in some studies. Greater peak power output typically results in improved ability to resolve small targets at greater distances (Desholm et al. 2006). Importantly, we used the data collected with the "vertically-oriented" radar to estimate target movement indices as well as flight altitude. Given the inherent properties of the radar systems used in several of these studies, we believe that data collected with the vertically-oriented radar provide the best estimates of target movement.

Our radar system, data collection approach and data processing are more similar to those employed by Geo-Marine, Incorporated (GMI). GMI (2004) conducted marine radar studies for the Nantucket Sound environmental impact assessment and recently completed a radar study in New Jersey nearshore and offshore waters (GMI 2010) conducted during spring and fall 2008 and 2009. We will most often reference the latter study and a study we conducted in 2005 in coastal Cape May County, NJ when comparing our results from Block Island. We limit our GMI's recent study (2010) because they appear to address issues related to false target detections caused by ocean waves, which was not done in their Nantucket Sound study.

4.1 MOVEMENT MAGNITUDE

In this section, we discuss our findings regarding movement magnitude (number of targets recorded or TR) and rate of movement (TR/hr). Although using target movement rates as an index of migration magnitude allows for comparisons among studies, they can be misleading. This is especially true when differences in data collection methods (e.g., hours of radar operation) are not fully explored. Furthermore, target movement rates as a measure of migration magnitude can obfuscate what is likely the more important metric for assessing collision risk, that is, the total number of birds and bats exposed to the tall structure in question.

4.1.1 *Effects of season and period on movement magnitude*

Generally, TR and TR/hr ranged 2-3 orders of magnitude within a single Season/Period and coefficients of variation were > 95%. These results indicate that seasonal bird/bat movements, especially during migration periods (i.e., both diurnal and nocturnal), were temporally episodic. Given that we were monitoring the entire spectrum of bird and bat fauna in the air space occurring above and around Block Island and that the phenology of movement varies widely within and among taxa (i.e., age, sex, species), this was not surprising. TR and TR/hr were markedly greater during the nocturnal compared to the diurnal period, regardless of season. The majority of waterfowl, long-legged wading birds (e.g., herons, egrets), shorebirds and passerines are known to migrate at night (Alerstam 1990). This result is important, as bird appear to be better able to avoid wind turbines during the day than at night (Desholm and Kahlert 2005). Furthermore, indices of movement magnitude were highest during nocturnal periods in Summer and Fall. Southbound bird and bat migration, which for some species begins in mid-July, typically includes large numbers of juveniles, which could explain the seasonal differences we observed.

Seasonal differences also may have been related post-breeding dispersal in birds, which for some species can occur in late July at temperate and northern latitudes (Alerstam 1990), or in part to greater bat activity during the post breeding season (i.e., August and September) compared to other times of year (Arnett et al. 2008, Horn et al. 2008). Seasonal differences in movement indices generated from marine radar data have been reported widely (*cf* studies listed in Kerns et al. 2007, Table 7, p. 31) and whether spring or fall exhibits greater numbers of migrants depends primarily on the location under consideration and how it corresponds spatially to migration flyways and breeding areas.

Our TR and TR/hr estimates for spring and fall were generally similar to those reported by GMI (2010) during their onshore and offshore radar studies along the New Jersey coast. Although GMI did not specifically report mean movement magnitude or movement rates (i.e., referred to as adjusted migration traffic rate, AMTR) by season or period, and results of statistical tests to explore differences between seasons and periods (i.e., diurnal, nocturnal) were not available in the printed report, Season/Period peak values of movement rates appeared to be similar. Additionally, graphical representations of their data suggest that the range movement rates they observed were similar to ones we report for Block Island.

In contrast, the number of targets (TR) and target movement rates (TR/hr) we recorded during nocturnal periods on Block Island were lower than in a spring and fall nocturnal migration study conducted along the coast of Cape May, New Jersey (Mizrahi et al. 2009). The Cape May Peninsula is a geographic feature that tends to concentrate migrating birds, especially in fall. Furthermore, birds from several migration flyways (e.g., Atlantic, Delaware River Valley, Hudson River Valley) are often vectored to the Cape May Peninsula by prevailing winds in fall.

TR and TR/hr from our Block Island study were also lower than those we recorded during a study in the mid-Atlantic Appalachian Mountain region (Mizrahi et al. 2008) and from several terrestrial studies conducted in the northeast (e.g., Plissner et al. 2006, Mabee et al. 2005, Cooper et al. 2004a, 2004b) and the northwest U.S. (Mabee and Cooper 2004). This might suggest that overland migration is greater in magnitude than that occurring across Long Island Sound and the Block Island vicinity. However, except for Mizrahi et al. (2008), the terrestrial studies we cite for comparison conducted radar observations for shorter periods during a given season compared to our Block Island study. Our review of relevant literature suggested that most impact-assessment studies using marine radar focus on what is the assumed peak of movement for a given season. For example, two different studies conducted in northern New York during fall migration covered only two month periods in September and October (Mabee et al. 2005) or from mid August through mid October (Kerns et al. 2007), while a study from western New York was conducted for only 30 days in September and October (Cooper et al. 2004b).

Additionally, many of the studies we reviewed began their radar observations approximately one hour after sunset and continued for approximately six hours (Cooper et al. 2004a, 2004b, Mabee et al. 2005, 2006, Plissner et al. 2006), far less than the average number of hours/night we made. Nightly data collection in these studies appeared to focus on what is the assumed nightly peak of movement. Although some studies did conduct radar observations from sunset to sunrise the next morning (e.g., Kerns et al. 2007) we are unaware of any studies that made radar observations during both diurnal and nocturnal periods except those conducted by GMI (2004, 2010).

Differences in diel and seasonal radar observation periods are noteworthy and must be accounted for when comparing target movement and movement rate estimates among studies. Estimates that include significant sampling during non-peak periods of movement, as in our study, likely are lower than reported in studies with markedly fewer hours of observation focused on peak migration periods. Additionally, extending sampling periods provides insight into times of day and during a season when bird and bats are most vulnerable (i.e., migration periods, take off and landing, Richardson 2000). We believe that broader temporal coverage is essential to a comprehensive understanding of how tall structures might affect bird and bat flight dynamics and behavior.

4.1.2 *Diel patterns of movement magnitude*

Temporal patterns in nightly movements we observed were distinct, predictable and generally consistent with those reported for nocturnal landbird migration (Gauthreaux 1971, Åkesson et al. 1996). That is, migrants ascend rapidly within the first hour after sunset; numbers increased markedly and peaked approximately 2-4 hours after sunset, and then declined gradually until the following morning. Åkesson et al. (1996) suggest that various bird species make nocturnal migration ascents at different times relative to sunset and civil twilight, which could result in the 2-3 hour interval to reach peak numbers that we observed. Horn et al. (2008) and Reynolds (2006) suggest that bats in West Virginia and New York, respectively, exhibit similar within-night activity patterns as reported for birds, but whether this behavior is widespread is unclear because data are lacking.

Our monitoring during the diurnal period suggests that sizable numbers of targets were airborne just before sunset. Movements during this period were likely birds flying to roosting areas or possibly bats beginning nightly foraging bouts. We also detected a rapid increase in movement just after sunrise in fall. This could have been related to birds moving from roosting areas to begin foraging or the morning flight of nocturnally migrating passerines reorienting after a night of migration (Wiedner et al. 1992). Unfortunately, we found little information about temporal patterns of movement in diurnal migrants from other radar studies.

4.1.3 *Environmental factors affecting variation in movement magnitude*

4.1.3.1 Date and local weather conditions

Inherent circannual time programs entrained by photoperiod are well-known instigators of migratory behavior in birds (Gwinner and Helm 2003). Although, seasonally appropriate migration behavior is often predictable, daily variation is less so, and likely affected to a great extent by interactions between the physiological condition of individuals (Berthold 1996) and the environment (e.g., weather conditions, Richardson 1978, 1990a). Furthermore, date within season and local and regional weather conditions are intrinsically linked. For example, in the northern hemisphere, air temperatures increase with the onset of spring, continue this trend through the summer and decline as day length decreases with the onset of autumn. At temperate latitudes, the onset of spring and progress toward summer is accompanied by increasing penetration of tropical air masses.

Results of our multiple model comparisons suggest that Julian day was the most consistent and significant modifier of movement magnitude (i.e., TR, TR/hr). In Spring, movement magnitude increased with Julian day and in Fall, it decreased. "Global" models that included Julian day along with weather variables were usually among the best performing with respect to TR and TR/hr in Spring and Fall, regardless of period (i.e., Day, Night). For Summer, Julian day models alone had the strongest support during the nocturnal period.

Among the various meteorological factors evaluated for their affect on the timing and magnitude in migrating birds, wind conditions have been repeatedly identified as a principal driver (Nisbet and Drury 1968, Alerstam 1978, 1979, Richardson 1978, 1990a, 1990b, Pyle et al. 1993, Butler et al. 1997, Liechti and Bruderer 1998, Weber et al. 1998, Åkesson and Hedenström 2000, Williams et al. 2001, Erni et al. 2002). Our data from Spring diurnal and nocturnal periods support this thesis. Wind vectors that facilitated movement toward the breeding grounds were significant elements in the best performing models.

Additionally, lower barometric pressure tendencies (i.e., negative parameter estimate) were a significant element in Spring/Day models. Changing wind fields are often associated with changes in barometric pressure. Dropping barometric pressure can signal the infiltration of air masses from the south, bringing southerly winds favorable for northward migration. Although, wind conditions did not figure prominently as a predictor in Fall models, higher barometric pressure tendencies (i.e., positive parameter estimate) during the diurnal period did. Increasing barometric pressure is typically associated with colder, heavier air masses accompanied by northerly winds, especially in fall.

The differences between spring and fall results with respect to the importance of wind conditions may be related to the need for individuals to arrive on the breeding grounds in with sufficient energy reserves to improve reproductive output (Sandberg 1996, Sandberg and Moore 1996).

Carryover effects from one part of the annual cycle to another can have profound influence on fitness (Baker et al. 2004, Norris and Marra 2007). This would put a premium on selecting wind conditions that would vector an individual towards its goal using the least amount of energy (i.e., tailwinds blowing from the appropriate direction). In fall, the constraints posed by the breeding season are not apparent and birds may be less sensitive to weather conditions as behavioral modifiers. Additionally, the fall migration period includes a large proportion of naive migrants making their first trip south. Naive migrants may respond less effectively to weather conditions conducive to migration. As much as 85-95% of individuals found along the Atlantic Coast during fall migration are young of the year (i.e., hatched during that summer's breeding season, *cf* citations in Ralph 1981, Mizrahi unpublished data).

The lack of relationships between weather conditions and movement magnitude during the Summer period is not surprising. Movement patterns during this season are likely shaped primarily by nesting behavior, which is not generally influenced by daily changes in local weather conditions. For example, birds will move between nesting and foraging areas regardless of prevailing weather conditions, as long as they are relatively benign.

Although climatological conditions in part appear to underlie the evolution of migration in bats (Fleming and Ebby 2003), their proximate affect on variability in migration patterns is not well described. Given that migrating bats face similar ecological and physiological constraints (e.g., energy conservation) of prolonged flight, it is likely they respond in similar ways to weather conditions that favor transport between migration goals. More work in this area is needed to improve our understanding of which weather conditions put migrating bats are at greatest risk from colliding with tall structures that penetrate the atmosphere.

4.1.3.2 Synoptic weather conditions

Our results suggested that synoptic weather patterns that produced wind conditions appropriate for vectoring individuals northward toward the breeding grounds were important predictors of movement events in Spring. At temperate latitudes, this generally means southerly winds prevalent after the passage of a warm front and on the western side of a high pressure system, or in the light and variable winds near the center of high pressure areas (*cf* citations in Richardson 1978, 1990a, Alerstam 1990).

Nearly 60% of targets we detected during the day and more than 50% of those at night were when weather patterns produced prevailing southerly winds, or when winds were generally calm. These conditions were important predictors of spring bird migration in coastal Massachusetts (Drury and Keith 1962). We detected a disproportionately greater number of targets when pressure systems produced southerly winds or calm conditions relative to the occurrence of these conditions. This suggests that birds, and possibly bats, were selective about the conditions under which they were actively migrating. Birds can reduce energetic costs significantly by migrating under favorable winds (i.e., tailwinds, Gauthreaux 1991, Piersma and van de Sant 1992, Liechti et al. 2000), thus large migration events are often coincidental with these conditions (Richardson 1972, 1974, Able 1973 Blokpoel and Gauthier 1974, Pyle et al. 1993, Williams et al. 1977, 2001). This may be especially important for species that rely on nutrient reserves acquired prior to or during migration to initiate nesting and egg laying (i.e., capital breeders). The energy they save by flying under conditions that facilitate movement during migration may improve success during the breeding season.

In fall, the greatest number of targets recorded and highest movement rates were recorded after a cold front, when the western portion of a low pressure system was positioned north and east of Block Island or during calm conditions associated with high pressure. Drury and Keith (1962) reported that these conditions were important predictors of fall bird migration in coastal Massachusetts. Similar to spring, the proportion of targets (i.e., of the total targets detected) we detected under these conditions were significantly different from their overall occurrence, suggesting that aerial vertebrates respond specifically to the occurrence of meso scale weather conditions that are favorable for fall migration.

Similar to our analyses of local weather conditions and their effect on movement magnitude, synoptic weather conditions were not good predictors of movement magnitude during the Summer/Day period. However, in contrast, synoptic conditions producing southerly airflow featured prominently in explaining differences in movement magnitude during the Summer/Night period. This result is interesting as it appears to support results from our analyses of flight direction (see Section 3.4), where we found that the mean vector of movement during this period was to the north.

Importantly, results from our modeling of relationships between local weather conditions and movement magnitude appear to support the results of analyses we conducted to assess the importance of synoptic weather conditions as determinants of movement.

4.2 MOVEMENT ALTITUDE IN THE LOWEST ALTITUDINAL STRATA

Determining flight altitudes of birds and bats is an essential element in assessing the potential effects of tall structures on aerial vertebrates. Most investigators working on environmental impact assessments of tall structures, such as wind turbines, limit their evaluation of potential risk to the altitudinal strata immediately associated with a wind turbine's rotor swept area. However, expanding the range considered as "risky" may provide improved insight into the broader extent of potential impacts.

4.2.1 *Effects of season and period*

In general, our data suggest that proportionally more birds flew at lower altitudes, especially with respect to the two altitudinal strata below 200 m, compared with altitudes reported in radar studies of avian movements over land (*cf* Table 7 in Kerns et al. 2007). Our results, however, were similar to those reported in a radar study of bird movement in the North Sea (Hüppop et al. 2006) and the altitudes of birds recorded in coastal and offshore New Jersey (Geo-Marine 2010).

Birds often fly at altitudes that minimize energy costs (Bellrose 1971, Bruderer et al. 1995). Which altitudinal stratum an individual chooses appears to be primarily a response to changing wind fields (Able 1970, Alerstam 1985, Gauthreaux 1991, Bruderer et al. 1995). Headwinds and atmospheric turbulence can increase energy expenditures during flight (Bruderer 1978, Williams et al. 2001). With respect to the latter, the atmosphere is often more turbulent and turbulence extends higher into the atmosphere over land and along coastlines than over water (Kerlinger and Moore 1989). This results primarily from an absence of thermal convection and topographic relief over water. Low altitude winds can often be faster and more persistent over water compared to land (Hüppop et al. 2006), which could explain low altitude flights by birds over water when tailwinds are present. Furthermore, when wind conditions are favorable across many strata, birds may select lower altitudes to avoid lower temperatures, relative humidity and partial pressure of oxygen typical of higher altitudes. These conditions could accelerate water loss and convective heat loss, which could reduce flight efficiency (Carmi et al. 1992, Klassen 1996, Liechti et al. 2000).

4.2.2 *Diel patterns in altitudinal distribution*

On average, we recorded more targets at or below 200 m during the day than at night. Diurnally migrating waterbirds (e.g., waterfowl, gulls, herons) are often recorded flying at low altitudes (Cooper and Ritchie 1995, Hüppop et al. 2004). Differences in flight altitude between diurnal and nocturnal migrants were reported in a radar study of bird movement in the North Sea (Hüppop et al. 2006) and time of day is often cited as an important influence on flight altitude (Lack 1960, Eastwood and Rider 1965, Able 1970 Hüppop et al. 2004). Similarly, wind fields are generally more predictable and consistent at night than during the day, which might explain differences in the flight altitudes of diurnally and nocturnally migrating birds (Kerlinger and Moore 1989).

Although our results suggest that birds and bats flying during the day were at greater risk of interacting with a tall structure than at night, this could be misleading with respect to potential overall effects. The numbers of birds we recorded during the nocturnal period were more than 2.5 times greater than during the diurnal period, meaning that nearly 24,000 individuals were recorded at or below 200 m at night compared to approximately 14,000 during the day.

Hourly variation in proportion of targets we recorded at or below 200 m appeared to follow different patterns during the day than at night, except during the Fall/Day period. During the Spring/Day and Summer/Day periods, the proportion of birds and bats recorded at the lowest altitudes were smallest during the first 5-6 hours after sunrise, gradually increased to peak in the early afternoon then declined as sunset approached. Numbers of birds and bats we recorded in the same altitudinal strata followed a similar pattern.

At night and during the Fall/Day period proportions of targets at the lowest altitudes were moderately low during the first hour after sunset, declined throughout the night, but rose as sunrise approached, peaking during the two hours preceding sunrise. This temporal pattern was effectively opposite to the one we observed for target movement magnitude in the same altitudinal stratum. That is, the greatest number of targets we recorded at or below 200 m was during the first 2-3 hours after sunset, declined gradually over the course of the night and were lowest at sunrise. These two data sets and our analysis of correlations between movement magnitude and altitude suggest several important relationships. As nocturnal activity commenced, and during the first 2-3 hours after sunset, the proportion of birds and bats flying at low altitudes is relatively small, but this is also the time when the greatest number of individuals are aloft. Conversely, during periods when the proportions of birds and bats flying at low altitudes are greatest (i.e., around sunrise) the number of birds and bats are low.

Similar relationships were alluded to in radar studies of bird migration in New England (Nisbet 1963), the Gulf of Mexico (Able 1970) and apparent in a study conducted in the mid Atlantic Appalachian Mountain region (Mizrahi et al. 2008). They are important to consider when evaluating the risk of collision with tall structures. Although the thesis that nocturnal migrants may be at greatest risk of collision during ascent and descent has been suggested (e.g., Richardson 2000), the greatest number of individuals may be exposed to risk during the peak periods of migration, as was the case in our study. Using proportions of targets detected in various altitudinal strata allows for comparison among studies, however, they can be misleading. In our study, numerically greater numbers of individuals were detected in those lowest strata during the nightly peak of movement. However, the proportions of individuals in these altitudinal strata, relative to the total, were not. Again, the total number of birds and bats exposed to the tall structure in question is likely the more important measure of risk.

4.2.3 *Environmental factors affecting variation in movement altitude*

4.2.3.1 Date and local weather conditions

Similar to indices of migration magnitude, our results indicate that Julian day was an important predictor for the proportion of targets we recorded below 200 m. Parameter estimates suggest that during migration periods (i.e., spring, fall), the proportion of low flying (i.e., ≤ 200 m) birds and bats increased. This could result if the conditions that produce lower altitude flights became increasingly more frequent as the spring and fall progressed, or that species with a tendency to fly at lower altitudes were more prevalent as Julian day increased. Differences in flight altitudes during migration among avian taxa have been widely reported (Alerstam 1978, 1990).

Weather conditions are known to affect the vertical distribution of birds in the atmosphere. Headwinds, strong crosswinds and indices of approaching adverse weather conditions (e.g., precipitation) often lead to reductions in flight altitude (Richardson 1978, 1990a, 1990b). Generally, our results appear to support this thesis, although relationships between local weather conditions were not as pronounced compared to other studies we conducted (Mizrahi et al. 2008, 2009) and their importance varied depending on season and period.

In Spring, increasing atmospheric pressure, usually accompanied by northwesterly winds, caused increases in the proportion of low flying targets we recorded, as did conditions producing winds with a strong westerly component. These conditions would tend to oppose the general direction of migration in spring (i.e., north) or push individuals in an easterly direction out over the ocean. In fall, but only for the nocturnal period, low altitude flight increased as temperature and air pressure decreased and cloud cover increased, conditions that generally portend the approach of a low pressure system and with it, southerly winds and precipitation. Flying low in the opposing winds and under conditions that produce adverse weather may save energy and allow an individual to respond quickly in the event that it must land. However, low altitude flight likely increases the probability that an individual will encounter a tall structure in its flight path and the risk of encounter may increase further still if visibility is impaired because of adverse weather conditions.

4.2.3.2 Synoptic weather conditions

Results from these synoptic weather analyses provided similar insight into weather conditions that affect the vertical distribution of birds and bats in the atmosphere as those described in the previous section. That is, synoptic conditions during the spring and fall migration periods appeared to affect the proportion of targets we recorded in the strata ≤ 200 m.

In spring, the approach of high pressure ridges (i.e., cold fronts) or low pressure cells, rather than synoptic conditions that produce winds opposed to the direction of migration, resulted in the greatest proportion of targets we recorded ≤ 200 m. Increasing clouds, low ceiling and precipitation are typical elements of these meso-scale pressure systems. These synoptic conditions also produce southerly winds that would facilitate movement north to the breeding grounds. Greater numbers of birds that typically fly at low altitudes coupled with the potential for adverse weather conditions could explain the relationships we found.

Interestingly, the greatest proportion of birds and bats we recorded at low altitudes during the Summer/Night period occurred under the same conditions as in spring. This is not surprising given that during this Season/Period had a significant northward mean vector of movement. Relationships between synoptic conditions and the propensity to fly at low altitudes were less clear during summer diurnal periods. No single or combination of similar synoptic conditions appeared to explain the occurrence of low altitude flight. Movements during this period are likely unrelated to migration and thus, we would not expect close associations with particular weather patterns.

Fall presented a different picture about the influences of meso-scale weather systems on flight at low altitudes. The proportion of targets we recorded ≤ 200 m was greatest when high pressure cells produced northwesterly winds. Given the prevailing direction of migration to the southwest (this study), northwesterly winds would be perpendicular to the preferred axis of movement and this can cause birds to fly at lower altitudes (Alerstam 1978, Richardson 1990). Kerlinger (1989) also reported this behavior in raptors migrating along the Cape May Peninsula in fall. Importantly, these conditions are also associated with proportionally greater movement magnitude (this study), supporting the thesis that the greatest risk to aerial vertebrates may be when the greatest number, not the greatest proportion, of individuals are flying at low altitude. Proportions of targets detected at low altitudes were lowest when pressure cells produced northeasterly winds, which would be considered tailwinds for birds migrating to the southwest. In Cape May, New Jersey, flight altitudes are usually greatest in birds of prey when these conditions prevail in autumn (Kerlinger 1989).

4.3 FLIGHT ORIENTATION

Mechanisms used by migrating birds to find their way between breeding and wintering grounds have been studied extensively (*cf* citations in Gauthreaux 1980, Alerstam 1990, Berthold 1991).

"Pilotage," the use of visible features in the landscape as a guide (e.g., coastlines, rivers, mountain ranges), is often associated with diurnal migrants (Kerlinger 1989, Alerstam 1990, Berthold 1991), although some nocturnal migrants also exhibit this behavior (Bingman et al. 1982). On the other hand, "orientation," the use of an environmental cue or cues that provide directional information (e.g., celestial rotation, Earth's magnetic inclination) appears to be more prevalent in nocturnal migrants (e.g., passerines, shorebirds)(Able and Bingman1987).

Wind conditions, however, can play an important role in modifying the directional behavior of flying vertebrates (Richardson 1990b). Our results suggest that the targets we observed responded to wind conditions, both direction alone and direction and speed together (i.e., tailwind/headwind vectors). In spring, birds and bats we recorded flew primarily in a northeasterly direction. In fall, the mean vector of flight during the day was westerly and at night it was southwesterly. The nocturnal flight directions are similar to ones reported in other radar studies conducted in New England and mid-Atlantic coastal regions (Drury and Nisbet 1964, Mizrahi et al. 2008, Geo-Marine 2010).

We found that mean vectors of prevailing winds at sunrise and sunset during the spring, summer and fall were significantly different than mean vectors for flight directions recorded during all Season/Periods (e.g., Spring/Night, Fall/day), except Summer/Day. Given what appears to be a consistent pattern of flight direction in aerial vertebrates in the mid-Atlantic, our results suggests that birds and bats were either selective about the wind conditions under which they flew, or that they were able to compensate for differences between wind directions and their directional goals. Clearly, these hypotheses are not mutually exclusive and could be operating in tandem to produce the behaviors we observed. (e.g., Citations).

5.0 CONCLUSIONS

Despite some limitations, we believe our project was successful in documenting key elements of bird and bat flight dynamics around Block Island during their north and southbound migrations through the region and during the breeding season Moreover, the results reported here will provide informational support for Rhode Island Ocean Strategic Area Management Plan to evaluate the potential impacts of development on natural resources, especially as it pertains to the development of wind resources.

Clearly, our results suggest that the movement of aerial vertebrates through the study area was substantial. The flight altitudes of many thousands of birds and bats could have resulted in their encountering structures 100-200 m in height. Whether those encounters would have resulted in collisions is an open question that is beyond the scope of this study. Our results also shed light on meteorological conditions that modify flight dynamics and behavior. Furthermore, they suggest weather patterns that might affect when birds and bats may have the greatest probability of encountering a tall structure during daily movements or along their migration routes if one was in its flight path.

However, an important caveat must be considered when drawing inferences about the movement behavior of birds and bats observed in this study. Although this study was conducted 24 hours per day for almost nine months, which is more than most studies like this, the data collected can only reveal patterns for single spring, summer and fall season. Interannual variability in marine environments and meteorological conditions are widely acknowledged. Without capturing this variability through extended observation, our understanding of movement patterns in aerial vertebrates in the Block Island region is clearly limited.

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