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NOCTURNAL BIRD MIGRATION IN MEXICO: FIRST RECORDS FROM MARINE RADAR

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Resumen. – Migración nocturna de aves en México: primeros registros con un radar marino. – Millones de aves migratorias Neárticas-Neotropicales vuelan sobre México durante sus viajes a sus territorios de invierno, generando grandes concentraciones de aves migratorias en diferentes regiones del país. El lado del Atlántico del Istmo de Tehuantepec es conocido como una importante zona de descanso y como corredor para las aves que migran hacia Sudamérica, pero pocos estudios se han realizado en el lado del Pacífico hasta que recientemente se ha despertado el interés debido al potencial que esa zona presenta para el desarrollo de proyectos de energía eólica. Nosotros estudiamos la migración nocturna de aves con un radar marino de banda X durante 21 noches, del 15 de octubre al 8 de noviembre de 2010 en el lado del Pacífico del Istmo de Tehuantepec. Estimamos una Tasa de Flujo Migratorio (TFM) de 79,9 targets/km/h (intervalo promedio por noche = 25,3–158 targets/km/h), con un patrón de actividad migratoria típico a lo largo de la noche, con un pico de actividad alrededor de la media noche, decreciendo en adelante. La dirección de vuelo promedio fue acorde a lo esperado por la temporada migratoria de otoño (i.e., hacia el sureste). La altura de vuelo promedio fue de 523,5 m sobre el nivel del suelo (intervalo promedio por noche = 402–755 m sns). La cantidad de proyectos de energía eólica se han incrementado rápidamente en los últimos años en el Istmo, generando la necesidad de información disponible sobre las características de la migración de aves en el área. Aquí presentamos los primeros resultados publicados sobre migración nocturna en la región, información valiosa para evaluaciones de riesgo para las aves.

Abstract. – Millions of Nearctic-Neotropical migrant birds fly over Mexico during their migratory journeys to their wintering grounds, creating high concentrations of migrating birds in different regions of the country. The Atlantic side of the Isthmus of Tehuantepec is known as an important stopover site and corridor for birds migrating to Central and South America, but few studies have been conducted on the Pacific side until recently, when interest has been awakened because of the potential of that area for wind-energy development. We studied bird migration with an X-band marine radar during 21 nights from 15 October–8 November 2010 on the Pacific side of the Isthmus of Tehuantepec in Oaxaca. We estimated a mean Migratory Traffic Rate (MTR) of 79.9 targets/km/h (mean nightly range = 25.3–158 targets/km/h), with a typical pattern of migratory activity through the night, peaking around midnight and decreasing thereafter. Mean flight direction was seasonally appropriate for fall migration (i.e., southeast). Mean flight altitude was 523.5 m above ground level (range of nightly means = 402–755 m a.g.l.). Wind-energy development has recently increased within the Isthmus, generating the need for information on the characteristics of bird migration in the area. Here we present the first published results about nocturnal bird migration in the region, information valuable for avian risk assessments. *Accepted 22 October 2013*.

Key words: Isthmus of Tehuantepec, Mexico, Nearctic–Neotropical migrants, passerines, radar ornithology, wind energy.

INTRODUCTION

Millions of Nearctic-Neotropical migrant birds move annually to their wintering grounds following routes directly over Mexico (Newton 2008, Faaborg *et al.* 2010), representing ~ 50% of the bird species inhabiting the US that winter in the Neotropics (Rappole *et al.* 1983). Consequently, radar studies have recorded flight directions of passerines along the United States–Mexico border heading into Mexico during fall migration (Felix *et al.* 2008). Although many passerines migrate across the Gulf of Mexico (Langin *et al.* 2009, Buler & Moore 2011), others follow a circum-gulf route, flying along the coast of Texas to the states of Tamaulipas and Ve-racruz in Mexico (Rappole & Ramos 1994, Winker 1995a, Shaw & Winker 2011).

Topography, ecosystem diversity, and the confluence of these inland migratory routes create a concentration of Nearctic-Neotropical passerines in western Mexico (Hutto 1987, Villaseñor-Gómez 2008), and a high flow of migrating passerines over the Gulf of Mexico (Winker *et al.* 1999, Martínez-Leyva *et al.* 2009) and the Yucatán Peninsula (Deppe & Rotenberry 2005). However, the Pacific side of the Isthmus has received little attention for bird migration studies, that is until the recent potential for wind-energy development awakened regional interest (e.g., Jaramillo & Borja 2004, AMDEE 2012).

The Isthmus of Tehuantepec is the narrowest part of Mexico between the Atlantic and Pacific oceans. It is bisected by mountain ranges running parallel to the Pacific slope that separate the Atlantic from Pacific side, creating a biogeographical barrier (Peterson *et al.* 2004) where the Neotropic and Nearctic realms overlap (Pérez-García *et al.* 2001). Gaps like Chivela Pass exist along the ridgelines, which generate gap winds from the Atlantic to the Pacific side (Steenburgh *et al.* 1998, Chelton *et al.* 1999). The most intense winds occur from November to February (Romero-Centeno *et al.* 2003), creating tailwind conditions that might be used to assist migratory flights (Richardson 1978, Åkesson & Hedenstrom 2000, but see Karlsson *et al.* 2011). Wind conditions combined with vegetative differences (rainforest in the Atlantic and dry forests in the Pacific; Rodríguez-Contreras 2007) may influence both the use and concentration of migratory passerines along the slopes of the Isthmus.

Although the Atlantic side of the Isthmus is recognized as an important stopover site for passerines during both spring and fall migration (Winker 1995a, Shaw & Winker 2011), we know little about the importance of the Pacific side. Recent work by McAndrews & Montejo (2010) has helped contribute knowledge of the avifauna composition, and in 2011, Ledec *et al.* (2011) identified the Wind Resource Area of southern Tehuantepec as a "world-class bird migration corridor." Yet to date, there are no published studies characterizing nocturnal migration in the area.

Our overall objective was to characterize avian migration during peak fall migration at a site proposed for wind-energy development on the Pacific side of the Isthmus of Tehuantepec. We measured the migration traffic rates, flight altitudes, and flight directions of nocturnal migrants to describe the key migration metrics and provide a starting point for our knowledge of nocturnal bird migration in this region.

METHODS

Study area. We operated a single radar monitoring station in an area being considered for wind-energy development on the Pacific side of the Isthmus of Tehuantepec, Oaxaca state, Mexico. Our monitoring station was ~ 5 km west of Juchitan City,

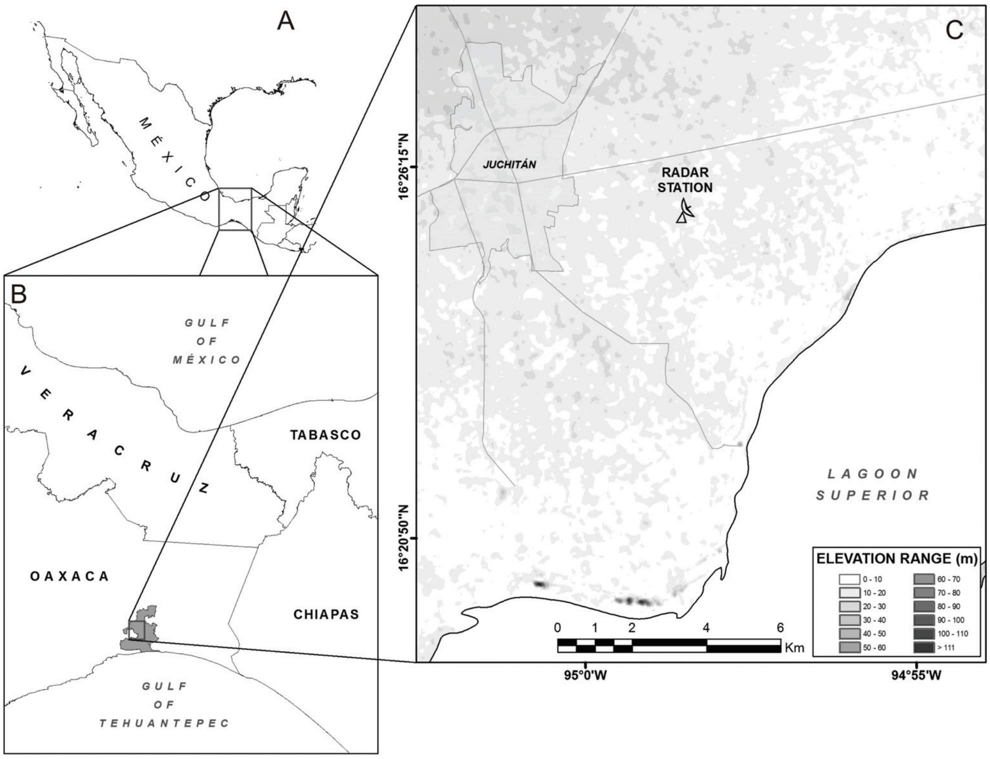

FIG. 1. Location of the Isthmus of Tehuantepec within Mexico (A), Juchitan Municipality within the Isthmus (B) and the monitoring site east of the town of Juchitan (C).

south of the Juchitan – Unión Hidalgo state road and northwest of the Laguna Interior (16°35'29"N, 94°48'40"W, 15 m a.s.l.; Fig. 1).

Radar equipment. We studied nocturnal bird migration with an X-band marine radar (Model FR-1525 Mark 3, Furuno, Nishinomiya, Japan) mounted on a truck adapted as a mobile unit. A description of a similar radar laboratory can be found in Cooper *et al.* (1991) and Harmata *et al.* (1999). The radar transmitted at a frequency of 9140 MHz through a 2-m-long slotted waveguide (antenna) with a maximum output of 25 kW and was operated with a pulse length of 0.07 microseconds. The display unit had a range resolution of 35 m, and the antenna emitted a beam with a width of 1.23° (horizontal) x 20° (vertical) with side lobes ± 10° (Furuno 2002). The unit was powered with a low-noise electric generator.

Study design. Winker (1995b) reported a bimodal distribution in the abundance of migrant passerines in the Atlantic coast of the Isthmus, with the first peak occurring between ~ 22 September and ~ 12 October, and the second between ~ 17 and 30 October. We used a horizontal and vertical mode of radar operation to observe nocturnal bird migration during 21 nights between 15 October and 8 November 2010, overlapping the second peak period. We sampled in 6-day intervals, with observations starting ~ 45 min after sunset and consisting of six 1-h sampling sessions/

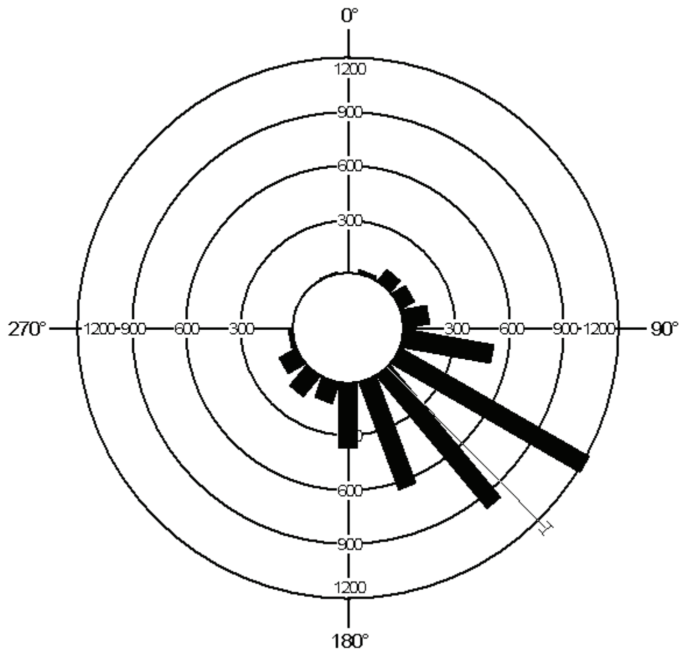

FIG. 2. Flight direction of radar targets ($N = 4478$) recorded in our study site in the Isthmus of Tehuantepec, Mexico, during the 2010 fall migratory season. The thin black line shows the mean flight direction, and the arcs extending to either side represent the 95% confidence interval.

night to sample peak nocturnal migratory activity (Gauthreaux 1971, Mabee & Cooper 2004, Mabee *et al.* 2006), during the ~ 11 h of nocturnal conditions during this study. Each 1-h session was subdivided into: 1) a 10-min period to adjust radar to the horizontal mode, 2) 10 min in horizontal mode to count targets with a manual counter, 3) 15 min in horizontal mode to record flight speeds and directions, 4) 10 min to switch radar to vertical mode, and 5) 15 min in vertical mode to record flight altitudes. This subdivision was necessary because data collection was done by hand in real time, and the operator could not perform all the actions at the same time. Following Mabee *et al.* (2006), we used a 1.5 km radius of observation for both horizontal and vertical modes of operation. When the radar was operating in vertical mode, the antenna was rotated vertically 90º with respect to the leveled radar (Harmata *et al.* 1999). We moved the radar unit daily to the same location, a clearing within a patch of deciduous forest on flat terrain where the surrounding vegetation (4–5 m tall) worked as a partial radar fence (Larkin & Diehl 2012), allowing a clear view of the surroundings (ground clutter < 10% of radar display concentrated near the radar unit).

Data collection. We estimated the Migratory Traffic Rate (MTR, targets/km/h) from the count data, measured flight speeds and directions using a hand-held scale and inner compass from the radar monitor, and measured flight altitudes with an index line from the monitor. Before starting the horizontal mode of operation, we adjusted the radar screen to north so as to allow accurate determination of flight directions.

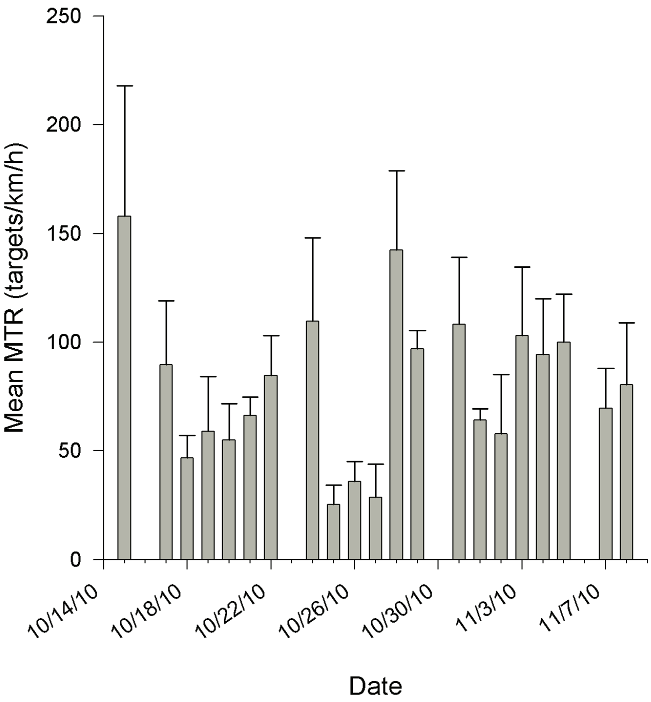

FIG. 3. Mean traffic rates (targets/km/h ± 1 SE) by date at our study site in the Isthmus of Tehuantepec, Mexico, during the 2010 fall migratory season.

We used the term "target" to designate objects detected because radar does not allow unequivocal identification of vertebrates and direct observations were not made to confirm the identity of migrants. To minimize counting of non-bird targets (such as insects), we omitted small targets appearing at the center of the screen (within a 600-m radius of the radar station) flying at slow speeds (< 6.7 m/s, slower speeds could not be accurately measured with our hand-held scale). These small, slow flying targets mainly moved in a non-linear direction, a pattern atypical of most migratory birds.

Flight speeds of bats partially overlap those of birds, mainly at the lower speeds (Hedenström *et al.* 2009), so it was not possible to distinguish bats based solely on flight speed. We did not record targets with erratic flight patterns because they may have been foraging bats; migrating birds tend to have linear paths (Bruderer & Popa-Lisseanu 2005). We acknowledge, however, that there could be some bats displaying a linear flight and similar speed to birds, considering that migratory bat species like hoary (*Lasiurus cinereus*) and western red (*L. blossevillii*) bats have been recorded near our study area in October and November (Cryan 2003). Although passerines seem to migrate together (Moore 1990), the distances between them (Millikin 2002, Larkin & Szafoni 2008) and the range resolution of our radar unit (Furuno 2002) allowed us to assume that most of the targets were individual birds. All data were recorded manually into a laptop computer.

Data analysis. Radar data were not corrected for differences in detectability with distance from the radar unit, hence all estimates are

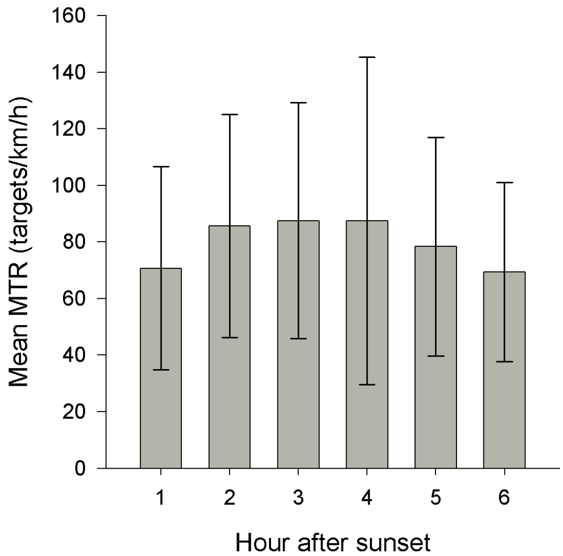

FIG. 4. Mean migratory traffic rates (targets/km/h ± 1 SE) by working hour (starting ~ 45 min after sunset) at our study site in the Isthmus of Tehuantepec, Mexico, during the 2010 fall migratory season.

indices. To reduce data contamination by insects, we corrected ground speeds for airspeeds of every target recorded (Mabee *et al.* 2006), and removed targets with corrected airspeeds ≤ 7 m/s because they were likely insects (Larkin 1991, Cabrera-Cruz *et al.* 2013). Wind data used to correct groundspeeds were collected at ground level because higher-elevation measurements were not available, hence, for vertical radar, we estimated minimum airspeeds.

We analyzed flight directions with the software of circular statistics Oriana ver. 4.01 (Kovach 2012), reporting mean flight direction (μ) and the length of the mean vector (*r*). We report Migratory Traffic Rate (MTR) as the mean (± 1 SE) number of targets passing through a 1-km migratory front in 1 h (targets/km/h), and flight altitudes in meters above ground level (m a.g.l.). We calculated MTRs, flight altitudes and their standard errors in the statistical software R (R Development Core Team 2012). We compared MTRs and flight altitudes among hours of the night with repeated measures ANOVA tests using STATISTICA (StatSoft 2011), specifying MTR and flight altitudes as dependent variables and hourly working sessions as categorical predictors.

RESULTS

Flight direction and Migratory Traffic Rate (MTR). Most recorded targets were flying to the southeast (Fig. 2), with a high concentration around the mean direction (μ = 135.3°, r = 0.77, N = 4478). The mean MTR during our study was 79.9 ± 3.7 targets/km/h (median = 78 targets/km/h; N = 21 nights), and mean rates varied among nights (range = 25–158 targets/km/h; Fig. 3). Hourly traffic rates were typically lower at the beginning and end of the night, with a peak 3–4 h after sunset (Fig. 4), and did not differ among sessions ($F_{5\text{-}119}$ = 0.8, P = 0.53).

Flight altitudes. Mean flight altitude was 523.5 ± 3.3 m a.g.l. (median = 492.5 m a.g.l.; N =

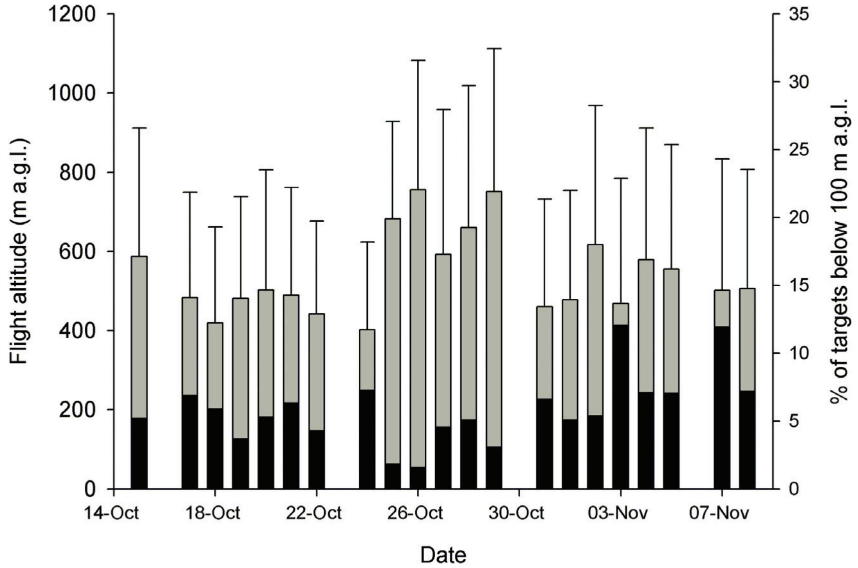

FIG. 5. Mean flight altitudes in meters above ground level (m a.g.l. ± 1 SE; gray bars, left axis) and percent of targets flying below 100 m above ground level by date (black bars, right axis) at our study site in the Isthmus of Tehuantepec, Mexico, during the 2010 fall migratory season.

8482 targets); mean altitudes of nights ranged from 402 to 755 m a.g.l. (Fig. 5) with 6.2% targets detected below 100 m a.g.l. (Table 1). Mean flight altitudes increased during the night from 490 m a.g.l. in the first session to 552 m a.g.l. in the last one (Fig. 6), and differed among working sessions ($F_{5\text{-}8476}$ = 8.2, $P < 0.001$). At the end of some working sessions with high migratory intensity, we increased the vertical range of detection to 3 km to observe the proportion of targets flying above 1.5 km, revealing that most of the targets (> 95%) were concentrated within the established monitoring range of 1.5 km.

DISCUSSION

Mexico is encouraging the use of renewable energies, giving priority to solar and wind-energy developments (SENER 2012). The Isthmus of Tehuantepec is the region with the fastest pace of wind-energy development (Pierrot 2012, Wood *et al.* 2012) and is known for its importance to migratory passerines (Winker 1995a). Unfortunately, information collected from the Isthmus currently remain unavailable in unpublished reports, hence our goal of providing the first documented accounts of nocturnal bird migration from this region.

Flight direction. Countries in Central America, particularly Mexico, are the center of winter distribution for Nearctic migrants (Rappole *et al.* 1983) consequently a southwards flight direction is expected during the fall migratory season. Faaborg *et al.* (2010) stated that the geographical position of South America to the east of North America results in many long-distance migrants heading southeast in the fall and northwest in spring. Consistent with this idea, the mean flight direction in this study during fall was toward the southeast.

Migratory Traffic Rate (MTR). Given the Isthmus has been considered an avenue for

TABLE 1. Percent of radar targets (*N* = 8482) detected per flight altitude categories (meters above ground level – m a.g.l.) at our study site in the Isthmus of Tehuantepec, Mexico, during the 2010 fall migratory season.

Flight altitude (m a.g.l.)	% Radar targets
0-100	6.2
101-200	11.2
201-300	11.0
301-400	11.1
401-500	11.3
501-600	11.3
601-700	9.7
701-800	8.5
801-900	6.5
901-1000	4.9
1001-1100	3.4
1101-1200	2.6
1201-1300	1.2
1301-1400	0.9
1401-1500	0.2

migrants (Binford 1989), we expected a potentially high MTR. No data exist for comparison in Mexico, however, our observed MTR (79.9 ± 3.7 targets/km/h) was higher than some fall migratory studies done in western North America, including northeastern Oregon and southeastern Washington (17–28 targets/km/h; Mabee & Cooper 2004), but lower than fall estimates collected in eastern North America, such as West Virginia (199–241 targets/km/h; Mabee *et al.* 2006), New York, and Pennsylvania (> 300–400 targets/km/h; Johnston *et al.* 2013 and references therein). Several reasons may explain why the MTR in this study was lower than expected. First, the initial peak of migratory activity on the Atlantic side of the Isthmus has been recorded to start almost one month before our study began (~ 22 September, Winker 1995b) and it showed a higher abundance of migratory passerines than in the second peak. Although we are not sure that those dates match with the migratory activity on the Pacific side of the Isthmus, our highest mean MTR was recorded on the first night, suggesting our observations started when migration was underway. Other radar studies in fall migratory seasons made with similar methods have found patterns of MTR within a night similar to ours where migration peaks several hours after sunset (Gauthreaux 1971, Harmata *et al.* 2000, Mabee *et al.* 2006).

Flight altitudes. The vertical distribution of targets was similar to that recorded in other areas of North America where most targets have been observed between 200 and 600 m above ground level including central Alaska (77% of targets below 500 m a.g.l.; Cooper & Ritchie 1995), northeastern Oregon (mean = 606 and 647 m a.g.l. for two study sites; Mabee & Cooper 2004), California (means ranged between 329 and 479 m a.g.l. across four sites; Johnston *et al.* 2013), and West Virginia (mean = 410 m a.g.l.; Mabee *et al.* 2006). Additionally, ~ 6% of targets flew at flight altitudes = 100 m a.g.l. that could put them at risk of collision if a wind farm is actually built in the area, considering that towers of the proposed wind turbines are 55 m high with a rotor of 44 m diameter (URS 2008).

Future considerations. Future radar-monitoring efforts would benefit from beginning studies earlier in the migration season (ideally matching or preceding Atlantic slope movement periods), obtaining wind speed and direction data above ground (closer to where most birds migrate), and having an independent method to corroborate the composition of nocturnal migrants (e.g., night vision optics and/or acoustic microphones).

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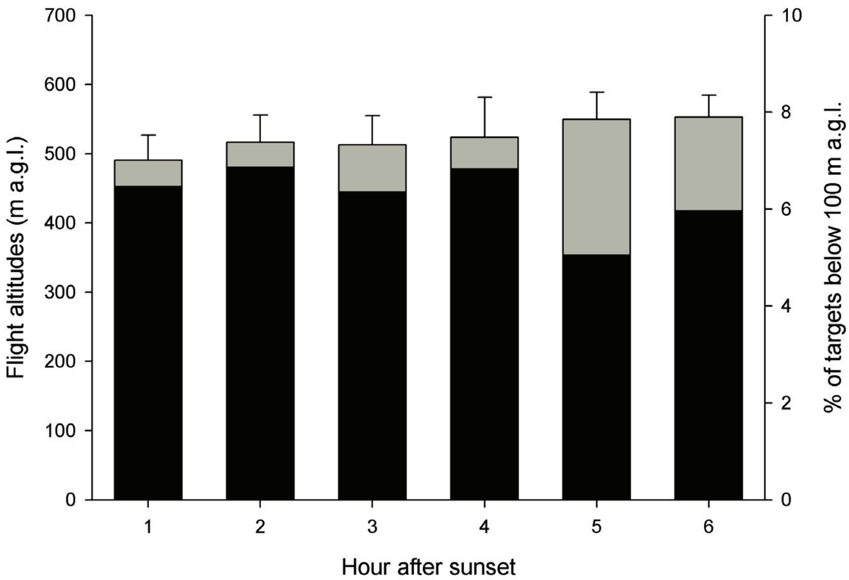

FIG. 6. Mean flight altitudes in meters above ground level (m a.g.l. ± 1 SE; gray bars, left axis) and percent of targets flying below 100 m above ground level by hour after sunset (black bars, right axis) at our study site in the Isthmus of Tehuantepec, Mexico, during the 2010 fall migratory season.

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