ACOUSTIC SURVEY OF NOCTURNAL BIRD MIGRATION AT RICE UNIVERSITY IN HOUSTON, TX DURING FALL 2020

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ABSTRACT.—Urban centers are hazardous for migrating birds because of the lack of appropriate stopover habitat and the disorienting effects of light pollution on nocturnal migrants. Low background noise due to the 2020 COVID pandemic allowed for an acoustic survey of fall migration in Houston, Texas (USA), a major metropolitan area located on a critical part of the mid-continent flyway. Nocturnal flight call surveys were conducted each night at a microphone station at Rice University from 7 Jul to 30 Nov. A total of 3799 independent flight calls were detected with sparrows and warblers dominating. For many species, the migration windows established by this study matched those determined from sight surveys over many years, indicating the great potential of nocturnal acoustic monitoring as an accurate and efficient method of studying temporal patterns of bird migration. Nocturnal acoustic surveys may work particularly well for birds that are seldom seen during the day owing to their secretive habits. For example, 67 Grasshopper, 71 LeConte's, and 5 Nelson's Sparrows, which are rarely if ever seen in transit in the study area, were detected. Also noteworthy were numerous detections of thrushes, which are rarely seen in the fall along the upper Texas coast. Broad migratory patterns were also revealed in this study. The highest migrant fluxes as detected by nocturnal flight calls were associated with major cold fronts. During these nights, nocturnal flight calls were detected within an hour after sundown and descended two hours before sunrise. Nocturnal flight call surveys were compared to Doppler radar reflectivity. High flight call fluxes broadly correlated with high radar reflectivity in late fall. On any given night, the decline in flight call detections before dawn was coupled to a decline in radar reflectivity. However, radar reflectivity typically increased an hour before the first detection of flight calls each evening. In late fall (Nov), resurgences in flight call detections were observed at sunrise, invariably accompanied by a resurgence in radar reflectivity as well. This study shows that nocturnal acoustic surveys may provide useful information for reducing the number of nocturnal building collisions of migrating birds and possibly documenting the effects of climate and land-use change on migratory patterns from year-to-year.

Twice a year, with the changing of the seasons, birds across the planet take to the skies to migrate. In the northern spring, birds migrate north to take advantage of the plethora of sunlight and food in the northern latitudes to breed and rear their young. As fall approaches and the length of daylight shortens in the northern latitudes, these birds migrate south to their wintering grounds near the equator or southern hemisphere, only to repeat this cycle the next spring.

Migration can be perilous as the journey is long and the hazards are many (Able 1999, Robbins et al. 1989). Understanding the timing, magnitude and species composition of migrating birds is critical for bird conservation, particularly when it comes to assessing populations or potential human-made hazards during migration. For example, knowing exactly when and where birds migrate can help assess where wind turbines, a demonstrated hazard for birds, are placed and when they are operated (Howe et al. 2002). Similarly, it is well known that many birds, from shorebirds to songbirds, migrate at night so that they can use daylight hours to find food (Farnsworth et al. 2004, Horton et al. 2015, Larkin et al. 2002, Mabee and Cooper 2004). As such, nocturnal migrants face a unique hazard

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today—light pollution. In urban centers where lights and tall buildings coexist, the disorienting effects of lights can cause birds to collide into buildings or drive them to exhaustion, forcing them to the ground where they become victims to other hazards, such as cats, moving cars, etc. (Cabrera-Cruz et al. 2018, La Sorte et al. 2017, Longcore et al. 2013, Van Doren et al. 2017). Knowing when birds move through in the night would help inform when lights should be turned off or wind turbines shut down.

Most of our understanding of migration patterns comes from visual or audio surveys during daylight hours by field ornithologists or amateur birders. Diurnal surveys, however, produce variable results due to differences in observer skill and the inherent patchiness of how birds move through at a local level, which is strongly influenced by microhabitat variability and local weather. Establishing a generalized picture of migration patterns through diurnal surveys thus requires a big data approach in which surveys over large lengthscales and by many observers are pooled to average out observer bias and local variability. Community science projects, such as eBird, have harnessed the power of big data, revolutionizing our understanding of the geographic distribution and migratory patterns of birds (Sullivan et al. 2009, Walker and Taylor 2017). Many birds, however, migrate in the night (e.g., the "dark migration") and may go undetected during the day if they have secretive habits or if they do not stop in a particular study area. Thus, an open question is how much information regarding bird migration is not observed through diurnal surveys.

Doppler radar provides an essential complement to diurnal surveys because it allows for continuous continental and local scale monitoring and provides a window into "dark migration". There are, of course, challenges in converting bulk radar reflectivity into the numbers and species make-up of birds flying overhead (Farnsworth et al. 2004, Farnsworth et al. 2016, Gasteren et al. 2008, Gauthreaux Jr and Belser 2003). Over the last two decades, nocturnal acoustic surveys focused on detecting nocturnal flight calls (NFCs) have grown as an essential complement to radar studies. NFC surveys have helped to validate radar surveys and remain the only method for identifying nocturnal migrants to species. In particular, the pioneering work of Evans and co-workers (Evans and O'Brien 2002, Evans and Rosenberg 2000), along with community archives of bird calls (macaulay.org, ebird.org, xeno-canto.org), has led to significant advances in our understanding of NFC identification.

In early 2020, the COVID-19 pandemic caused the world to lock down, restricting travel and thereby forcing us to conduct surveys locally. Motivated by the desire to continue observing birds, we decided to monitor NFCs. We took advantage of the reduction in background noise associated with vehicular and aviation traffic. This paper presents the results of NFC surveys conducted by the first author between Aug 1-Nov 30 in urban Houston, TX (USA). Houston is the fourth largest city in the United States and is projected to become the third largest in the next few years. It is centered on one of the major flyways of North America, the mid-continent flyway, and being located on the Gulf of Mexico, it serves as a critical transit point along this flyway (Able 1999, Eubanks et al. 2006, Gauthreaux et al. 2006). In spring and fall, a large proportion of the world's neotropical migrants pass through the Houston area. To date, most NFC surveys have focused on eastern North America (Evans and O'Brien 2002, Evans and Rosenberg 2000, Farnsworth 2005, Farnsworth et al. 2004, Farnsworth and Lovette 2005). Fewer studies have been conducted in the western United States (Mabee and Cooper 2004) and along the Gulf Coast (Evans and Mellinger 1999, Larkin et al. 2002). Almost no NFC or radar studies have been published for fall migration on the Gulf Coast. Here, we present the first continuous NFC survey of fall migration along the Texas coast.

METHODS

Nightly NFC surveys from 7 Jul to 30 Nov, 2020 were conducted. Surveys began at sundown and continued until 2 hours before sunrise. An Olympus ME-31 compact shotgun microphone was attached to an Olympus LS-P4 digital recorder for audio recordings. The recording apparatus was placed inconspicuously at the top of a small lemon tree in the middle of an athletic field (O'Connor Field) on the Rice University campus in Houston, TX (29.718773, -95.404975). This site was chosen because it was the furthest from roads and thus had the lowest traffic noise in this urban area. In addition, the first author has conducted diurnal surveys of this site for the last 20 years.

The shotgun microphone was oriented vertically and unobstructed to the sky. The ME-31 microphone has a frequency response between 70-15,000 Hz and a sensitivity of −36.5 dB. No wind guard was applied to the microphone so as not to suppress high frequencies. Based on diurnal recordings of calling Yellow-rumped Warblers, whose exact distances from the microphone was known, we estimate that the microphone was able to detect overhead warbler flight calls from a distance of 70-100 m. However, because we used a shotgun microphone, we estimated that our cone of detection was approximately <35°, corresponding to a lateral detection radius of 22-32 m at a height of 70100 m above the microphone.

We recognize that our recording set up is less advanced than some existing protocols. Our use of off-the-shelf recording equipment was motivated by convenience. Given the urban nature of our site, its use for athletic activities during the day and evening, and the lack of a plug-in power supply, it was necessary to have a microphone that was of low cost, inconspicuous (to minimize theft or vandalism) and easy to remove every morning so that data could be downloaded and batteries replaed.

Occasionally, we were not able to record. No usable recordings were obtained during nights of heavy rains. On a few occasions, our recording apparatus malfunctioned due to being knocked down by wind or animal, so no data are provided for these nights. There were four nights in early September, where we were unable to record because the authors were not present to install the microphone. These hiatuses are few and should not influence the overall results of this study. The hiatuses are denoted in the data files as well as any figures depicting time series.

Weather data were taken from the University Place KTXHOUST3188 station. We report total daily precipitation and average daily temperatures, dew point, humidity, wind speed, and barometric pressure. We used the base reflectivity data from Houston's Nexrad radar system (KHGX) located in Dickinson, just south of Houston. The base reflectivity data correspond to a base azimuth angle of 0.5°. Historical data were retrieved from the National Centers for Environmental Information from the National Oceanic and Atmospheric Administration (ncdc.noaa.gov).

Recordings were manually processed through Audacity, an open-source signal processing software. Each night's recording was first visually scanned in spectral mode to pick NFCs. Identification or classification of calls was based on listening to and visually analyzing spectrograms. We used our own experience as well as comparisons to existing NFC databases (Macaulay.org, xeno-canto.org) and the oldbird.org archives (Evans and O'Brien 2002) to identify the spectrograms. When in doubt, the identification of an NFC was discussed among the authors as well as with NFC experts in the community. Many NFCs are not identifiable, so we have taken a conservative approach here in reporting our data. For example, we grouped all warblers as "warbler sp." because the great majority of the warbler NFCs were not identifiable. Many of the sparrow NFCs were identifiable, but those that were not identifiable to species have been categorized as "sparrow sp."

Select spectrograms were deposited in the Macaulay bird sound archives and linked to eBird reports. Recordings are all archived under the Rice University, Houston, Texas eBird hotspot under user "Cintylee". Numeric data on the numbers of each species per night are also stored on the eBird archives. More detailed data with exact time stamps within a given night survey can be requested from the first author.

RESULTS

Identification of Nocturnal Flight Calls

The frequency band of most songbirds lie above 5 kHz (warblers between 5-8 kHz and sparrows between 7-10 kHz) while ambient background noise was typically below 2 kHz. No noise corrections were applied to detect and identify calls. However, for archived recordings, a high pass filter was applied to remove low frequency background noise for ease of hearing. We chose a cutoff frequency that would not attenuate calls of interest but removed as much low frequency background noise as possible (typically <2 kHz). In some cases, signals were amplified, but otherwise no other processing was performed. Identification of spectrograms to species was based on the pioneering work of (Evans and O'Brien 2002). Representative spectrograms of NFCs recorded during our surveys are shown in Figure 1a-e (although we did not record any Grey-cheeked Thrushes (*Catharus minimus*) in the fall, we have added a recording from spring 2020 for completeness).

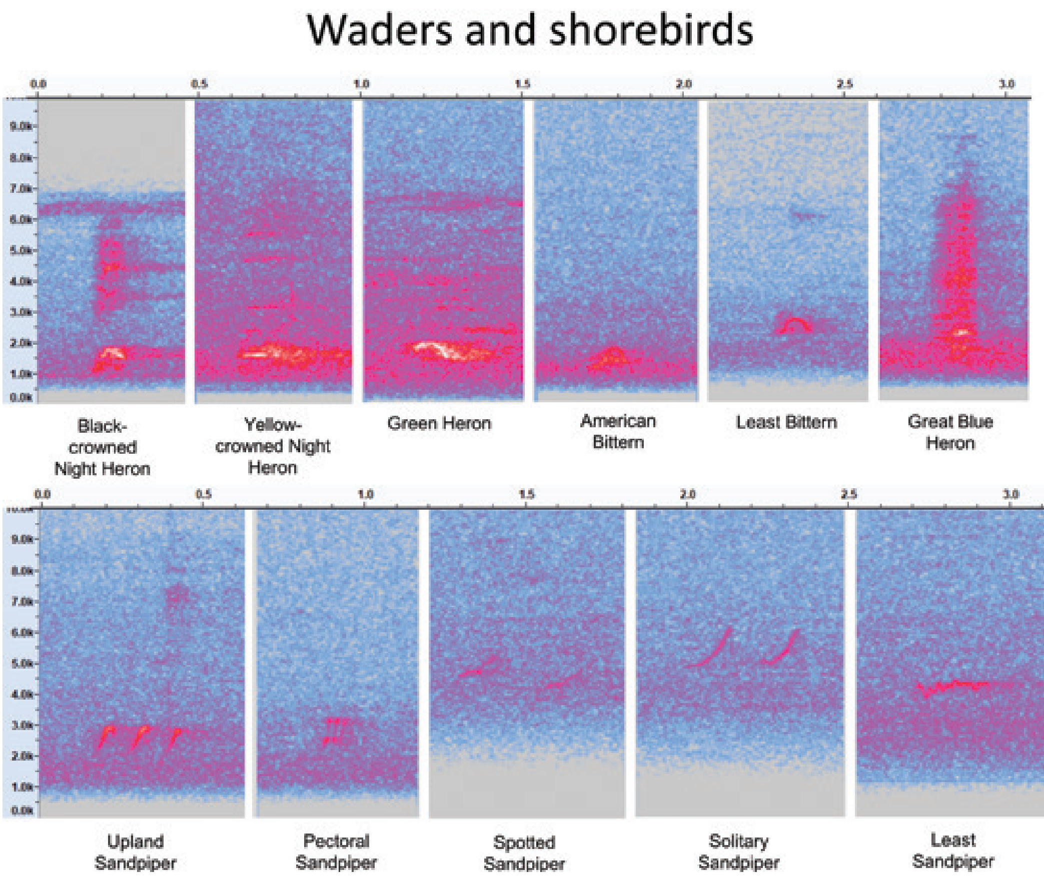

Figure 1A. Representative spectrograms of waders and shorebirds used for classification.

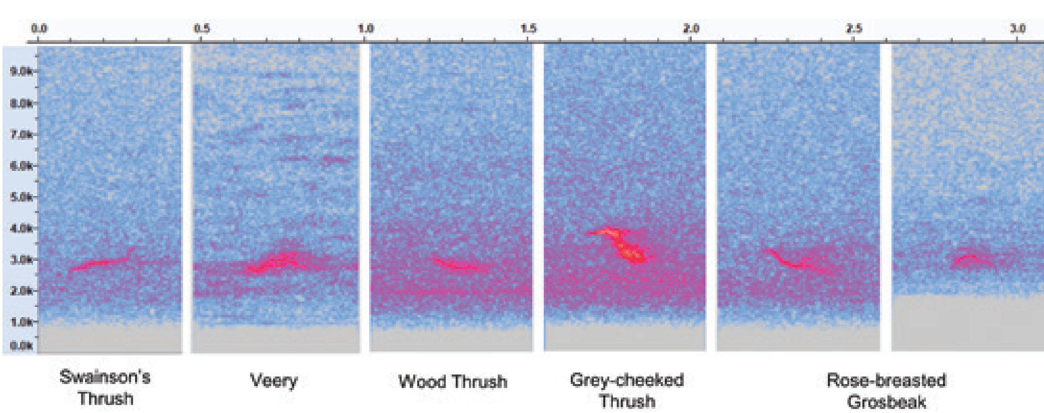

Figure 1B. Representative spectrograms of thrushes and grosbeaks. A Grey-cheeked Thrush from spring has been provided for comparison.

Estimating Numbers of Nocturnal Flight Calls

Although the goal was to estimate the number of birds flying overhead, audio surveys obviously only detect calling birds. Some species never call, but even for those species that give nocturnal flight calls, they must call when they are passing over the

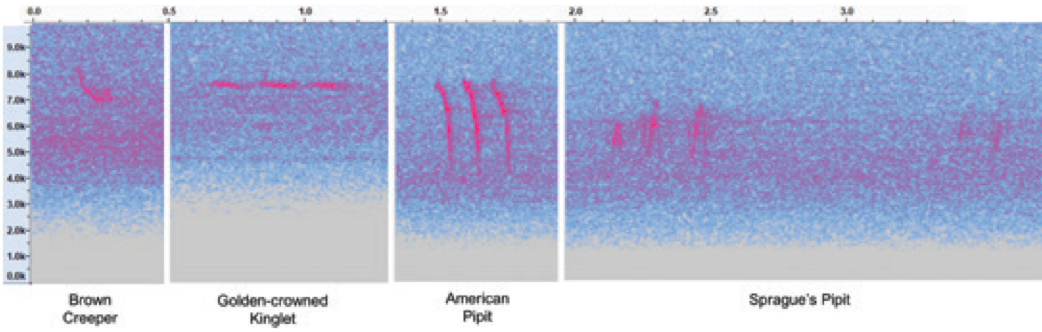

Figure 1C. Representative spectrograms of Brown Creeper, Golden-crowned Kinglet and American and Sprague's Pipits. Pipit spectrograms were recorded at dawn.

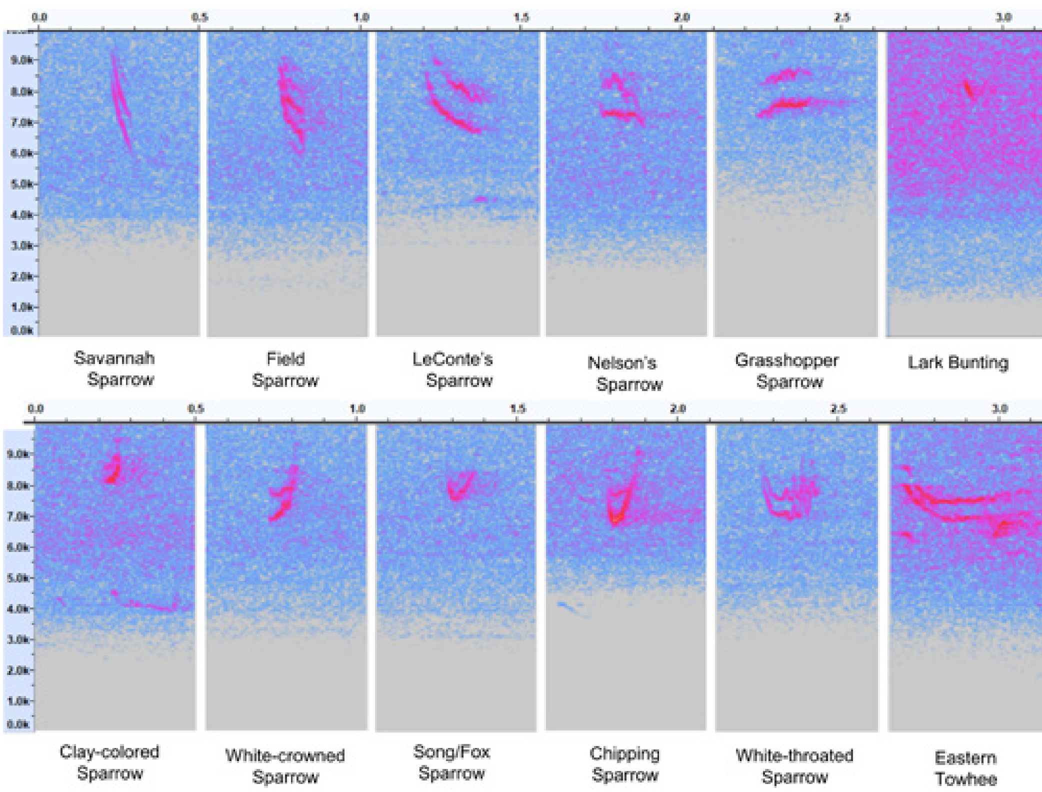

Figure 1D. Representative spectrograms of nocturnal flight calls of sparrows and related species.

microphone to be detected. The ability to detect calls also depends on how high a bird is flying above the microphone. Flying level, however, may differ between species or vary depending on weather conditions or time during the night. Numbers of NFC picks no doubt severely under-estimate the total numbers of birds flying over. Regardless of these uncertainties, numbers of NFCs should still provide valuable data on spatial and temporal patterns of migration for a given species. Assessing relative abundances between different species is made challenging by the species-specific behaviors described above.

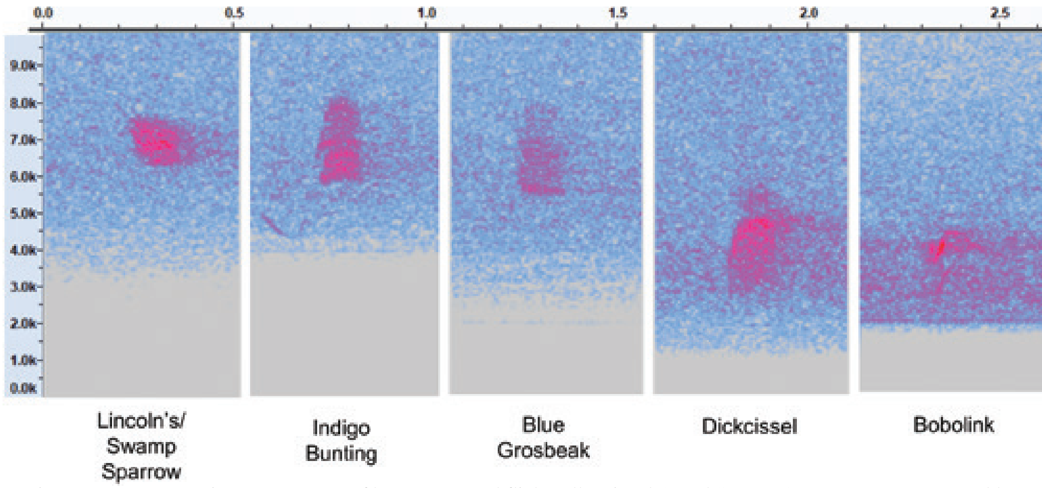

Figure 1E. Representative spectrograms of buzzy nocturnal flight calls. Lincoln's and Swamp Sparrows were not separable.

Our aim was to determine the number of unique NFCs. In general, we counted calls outside of a 15 second window to be independent. Individual birds flying overhead passed over within this time window based on our analysis of call series that show increasing and then decreasing amplitude with time, which we interpret to represent the approach to and the retreat of the bird from our microphone. Most NFCs recorded during our fall survey, however, were single calls separated by much longer timescales than 15 seconds, so the problem of over-counting was generally not an issue. Nevertheless, we attempted to count multiple birds within 15 second windows when possible. Series showing increasing followed by decreasing amplitudes of calls were designated as one bird. Calls with different amplitudes within a 3 second window were designated as different birds. For most bird species, we never had to apply these protocols because the number of migrants per unit time was low. However, these protocols had to be adopted for Yellow-rumped Warblers, which often displayed high flight call fluxes at dawn, making it difficult to distinguish between unique individuals. There is thus considerable uncertainty in our reported Yellow-rumped Warbler numbers. We do not report numbers of species that have both a migratory and resident population (e.g., American Robin, American Crow, Blue Jay) as we were unable to distinguish between migrants and residents from flight calls alone.

Migratory Patterns

A total of 3799 presumed independent NFCs were recorded between 1 Aug-30 Nov, 2020. Most NFCs were recorded between 15 Oct-15 Nov, with sparrows (*Passerellidae*), warblers (*Parulidae*) and buntings (*Passerina*) making up >90% of all calls. Although we lumped all warbler calls into one generalized warbler sp., most of the warbler calls represent morning flight Yellow-rumped Warblers (*Setophaga coronata*). Sparrows and buntings were primarily nocturnal. Total number of birds without warblers was 1773. Figure 2 shows the species breakdown of the dominant nocturnal migrants.

Where data were available, we compared our NFC results to 20 years of diurnal surveys conducted at Rice University. These data were primarily collected by the first author and are archived and publicly available in eBird under the Rice University eBird Hotspot. We chose not to compare to eBird data for larger regions, such as Harris county or the upper Texas coast because regional eBird data do not always distinguish between birds that both migrate and winter in the region. For example, regional eBird data for all sparrows on the upper Texas coast blend migrants with wintering birds so that only first arrivals in the fall and last departures in the early spring can be determined. The lack of habitat at Rice University makes the campus unfavorable for wintering or summering birds. Rice University is thus strictly a migratory stopover, making it

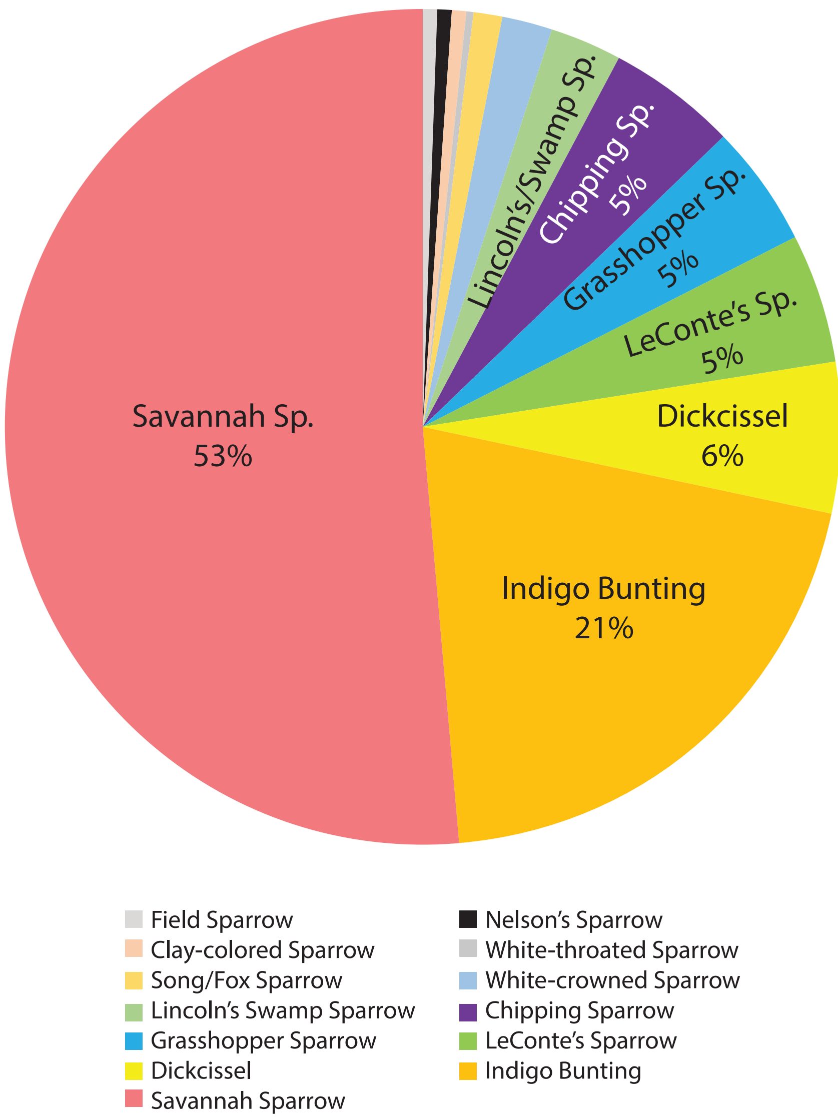

Figure 2. Pie chart showing the species breakdown of sparrows, Dickcissels and Indigo Buntings over the course of the fall survey.

an ideal location to compare diurnal surveys of migration with NFC data.

As discussed below in more detail, the NFC-based temporal patterns match those established from 20 years of diurnal surveys at Rice for most species (Figs. 3 and 4). In Figures 3 and 4, we show migration windows inferred from combining 20 years of diurnal surveys at Rice University. For a number of species, many years of diurnal surveys are needed to establish the migration window. This is particularly so for secretive birds or those that may primarily fly over the study site rather than stop. Diurnal surveys are also heavily dependent on observer skill as well as the presence of appropriate microhabitats for certain species. The distribution of microhabitats may change from year to year or even disappear due to changes in land use and development. The consistency of our NFC results with our two decades of diurnal surveys shows that continuous NFC monitoring over just one season is likely sufficient to define the migration window for many species. For very secretive birds, such as

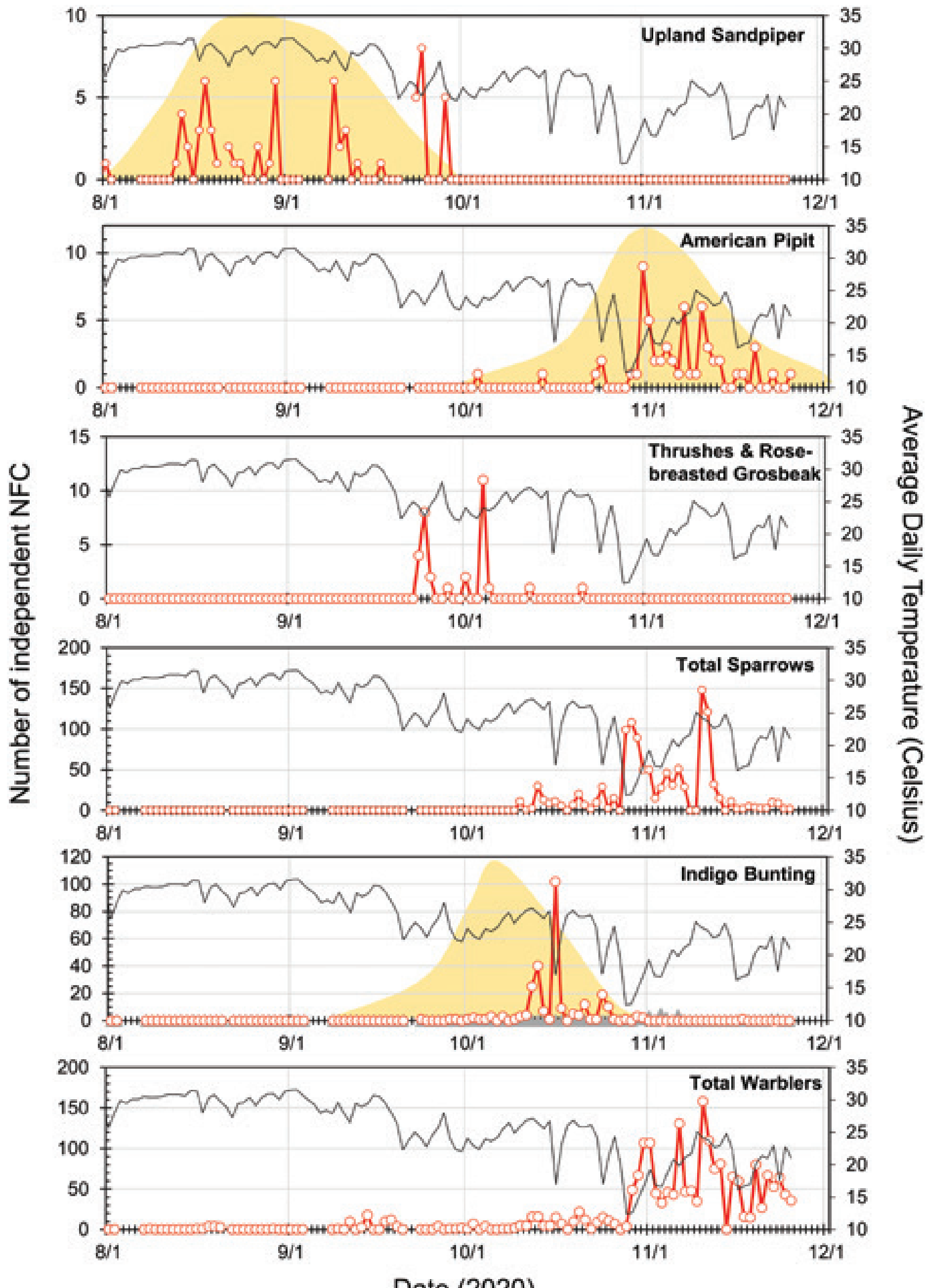

Figure 3. NFC detections as a function of calendar date (red lines). From top to bottom: Upland Sandpiper, American Pipit, thrushes and Rose-breasted Grosbeak, total sparrows, Indigo Bunting, and total warblers. Most of the warbler detections pertain to morning flight Yellow-rumped Warblers. Thin black line corresponds to 24-hr average temperature. Yellow shaded regimes correspond to the diurnal record, which was approximated from 20 years of diurnal observations conducted in the same location. Yellow-shaded regime is not drawn to scale and is only meant to represent relative variations, not absolute numbers. Diurnal observations not shown for thrushes and grosbeaks because none have been recorded in the fall. Diurnal observations not shown for total sparrows and total warblers.

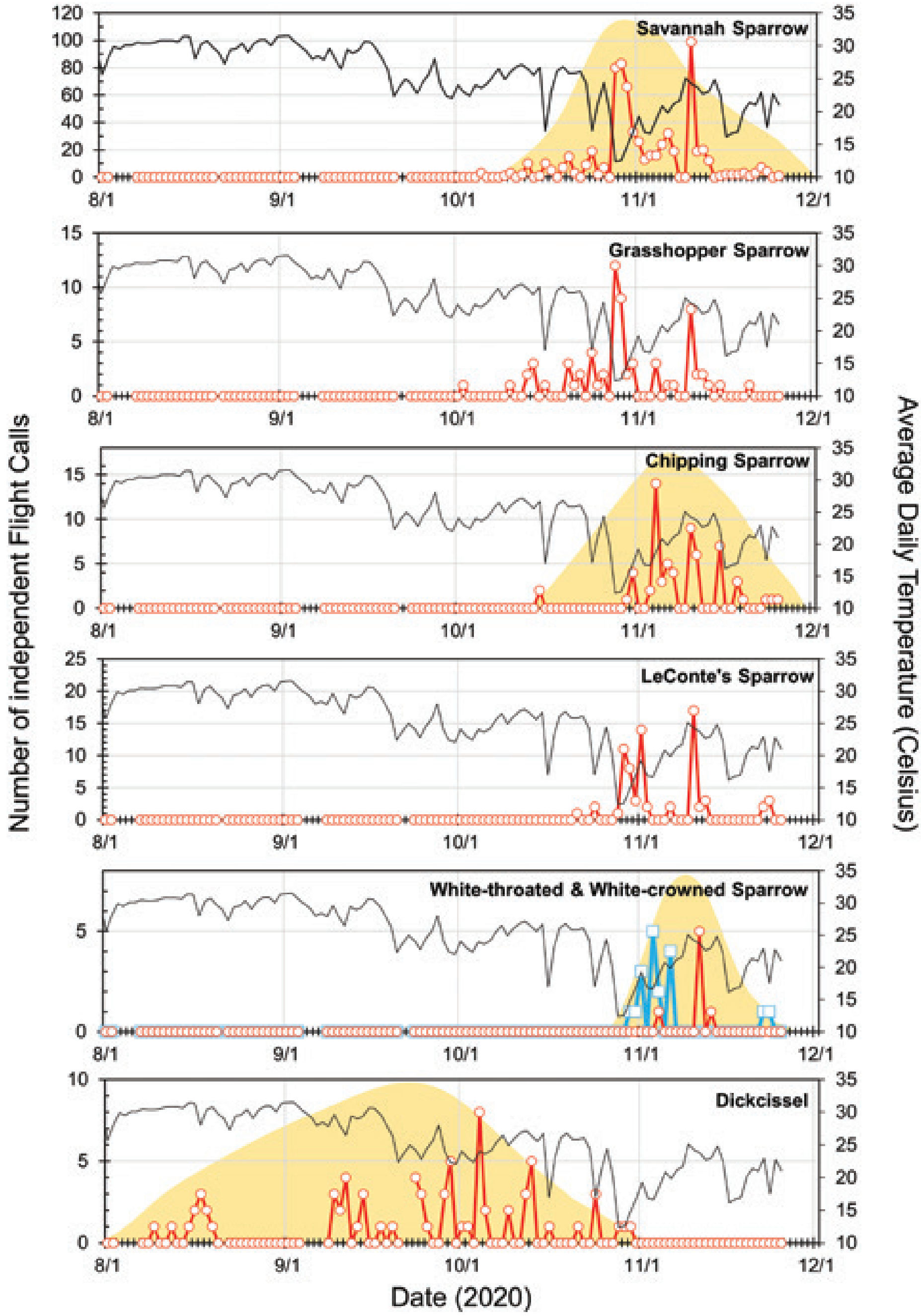

Figure 4. Number of independent NFC detections as a function of calendar date (red lines). From top to bottom: Savannah, Grasshopper, Chipping, LeConte's, White-throated, and White-crowned Sparrows (blue) and Dickcissel. Thin black line corresponds to 24-hr average temperature. Yellow shaded regimes correspond to trends inferred from 20 years of diurnal observations conducted in the same location. Yellow-shaded regime is not drawn to scale and is only meant to represent relative variations, not absolute numbers.

some grassland sparrows, the number of diurnal sightings over two decades was too low to even establish a migration window.

Shorebirds

Shorebirds (primarily *Scolopacidae*) were recorded from 1 Aug to 15 Oct. Upland Sandpipers (*Bartramia longicauda*) dominated with 65 recorded between 1 Aug-28 Sep (Fig. 3). Upland Sandpipers were the most frequently detected shorebird although this is likely because they are highly vocal during migration and their calls are loud. Numbers of Uplands increased abruptly in mid-August and continued until the end of September, after which there was a rapid drop off in detections.

Spotted (*Actitis macularius*) and Solitary Sandpipers (*Tringa solitaria*) were the only other regularly recorded nocturnal shorebird migrants with 9 (15 Aug-14 Sep) and 8 recorded (17 Aug-20 Oct), respectively. We detected surprisingly few other shorebirds. Additional shorebirds included 1 Greater Yellowlegs (*Tringa melanoleuca*; 15 Oct), 1 Whimbrel (*Numenius hudsonicus*; 22 Aug), 4 Least Sandpipers (*Calidris minutilla*; 2 on 17 Aug; one on 12, 13 and 15 Sep), and 2 Pectoral Sandpipers (*Calidris melanotos*; 24 and 28 Sep), all between mid-Aug and mid-Sep.

Except for Upland, Spotted and Solitary Sandpipers, the general paucity of other species is curious given that large numbers of shorebirds undoubtedly pass through our region in the fall. One explanation is that most shorebirds do not call when migrating. Another possibility is that most shorebirds fly too high to be detected.

Waders

A few waders were detected. Green Heron (*Butorides virescens*) was detected 14 times between 1 Aug-4 Oct with most in the last half of September and early October. We also detected 2 Great Blue Herons (*Ardea herodia*s; 13 and 28 Oct), 2 Least Bitterns (*Ixobrychus exilis*; 15 Aug and 11 Sep), 2 American Bitterns (*Botaurus lentiginosus*; 28 Sep and 16 Nov), and 11 Black-crowned Night-Herons (*Nycticorax nycticorax*; 9 Jul-2 Oct). No Yellow-crowned Night Herons (*Nyctanassa violacea*) were detected nocturnally in the fall.

Waterfowl

The only waterfowl detected during our nocturnal surveys were Black-bellied Whistling Ducks (*Dendrocygna autumnalis*) and a small flock of Snow Geese (*Anser caerulescens*) on 13 Nov.

Thrushes

Thrushes are generally thought to be rare fall migrants in Texas based on diurnal observations. We were thus surprised to detect numerous thrushes in the night (Fig. 3): 13 Swainson's Thrushes (*Catharus ustulatus*) were detected between 24 Sep-4 Oct with a total of 6 detected during the night of 24-25 Sep; 13 Veeries (*Catharus fuscescens*) were detected between 23 Sep-4 Oct with 7 recorded on 4 Oct, and 6 Wood Thrushes (*Hylocichla mustelina*) were detected between 4-20 Oct with 4 on 4 Oct.

We detected more Veeries and Swainson's and Wood Thrushes during our nocturnal fall surveys than the total recorded with visual surveys over the last 20 fall seasons at Rice. Although these species are abundant spring migrants in central and east Texas, they are considered rare during fall migration as their fall migration paths are thought to lie further east of their spring migration paths (Eubanks et al. 2006). Only one or two thrushes are detected in any given night during fall migration compared to hundreds per night during spring migration. While our results are consistent with the general understanding that fall migrants are rare, our results suggest that thrushes may be more regular migrants through east Texas than currently recognized.

Thrushes may be too secretive, especially in the fall, to detect with visual surveys. Fall migrants may also fly over the region without stopping and thus go undetected during the day. Recent work on Veery and Wood Thrush flight paths using GPS tracking confirms that small numbers of these thrushes indeed go through east Texas and Louisiana in the fall (Hobson and Kardynal 2015, Kardynal and Hobson 2017, Stanley et al. 2015).

Creepers and kinglets

We recorded one Brown Creeper (*Certhia americana*) (20 Nov) and one Golden-crowned Kinglet (*Regulus satrapa*) (10 Nov) several hours before sunrise. Golden-crowned Kinglets are known to occasionally call in the night, but Brown Creepers are generally not thought to call in the night, making our creeper nocturnal flight call noteworthy.

Pipits

We detected 59 American Pipits (*Anthus rubescens*). Most American pipits were detected from late October (23 Oct) to the end of November, with a high of 9 on 31 Oct (Fig. 3). Single birds on 4 and 14 Oct were early arrivals. Pipits were detected only after sunrise. Three Sprague's Pipits (*Anthus spragueii*) were detected (19 and 30 Oct, 24 Nov), all just before sunrise.

Grosbeaks, Dickcissels, Buntings and Bobolinks

We detected 266 Indigo Buntings (*Passerina cyanea*) with >95% occurring within a narrow window of time between 11-25 Oct (Figs. 3, 5). Most Indigo Buntings passed through between 11-17 Oct with a peak of 102 (38% of the total) on

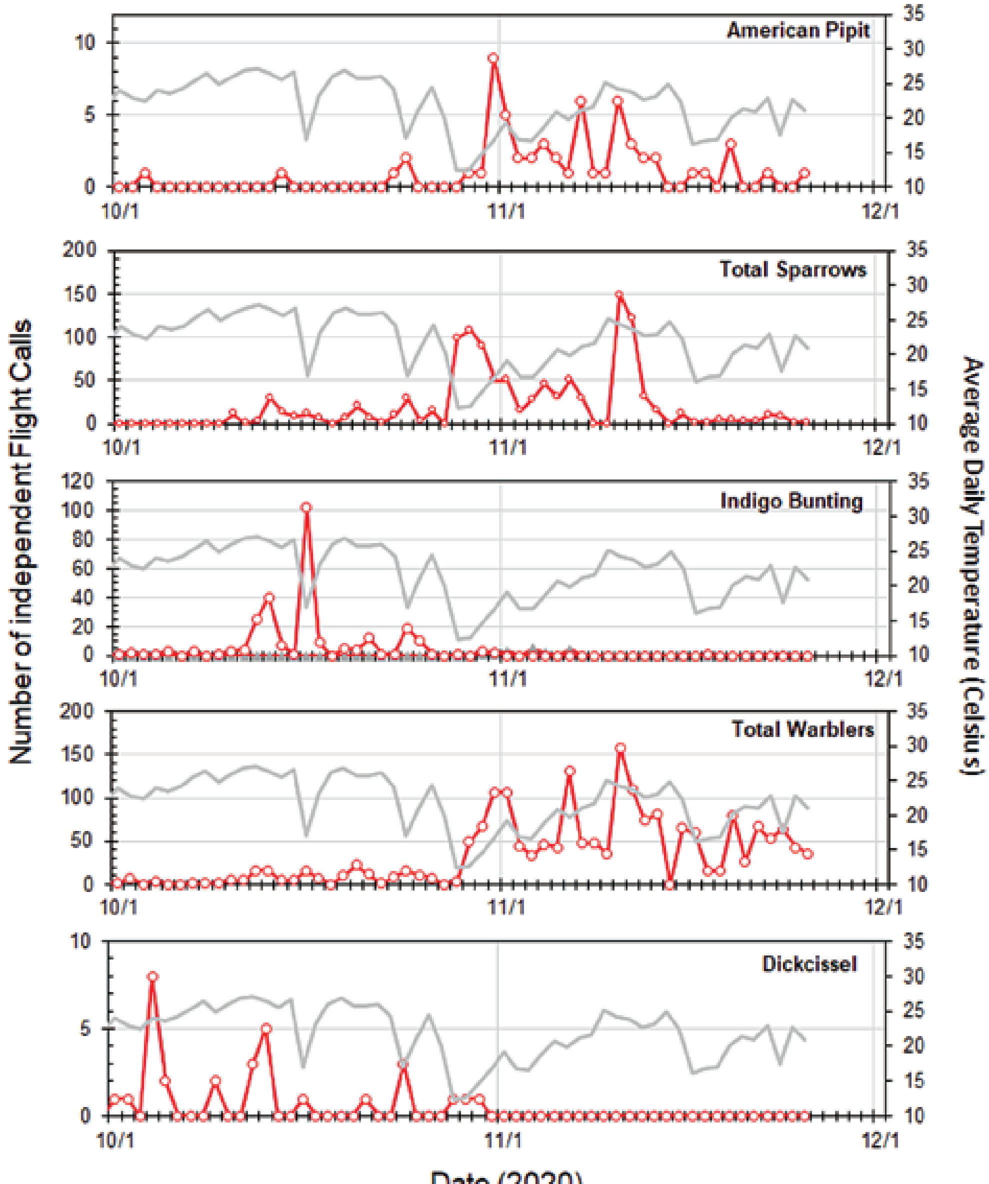

Figure 5. Number of independent NFC detections as a function of calendar date (red lines) zoomed in to include only Oct and Nov. From top to bottom: American Pipit, total sparrows, Indigo Bunting, total warblers, and Dickcissel. Thin black line corresponds to 24-hr average temperature.

Table 1. Season totals (Aug-Nov, 2020)

Species		total	Noc/ Dawn*	First	Peak	Last
Black-bellied Whistling Duck	*Dendrocygna autumnalis*	16	Noc	thru		thru
Snow Goose	*Anser caerulescens*	1	Noc		11/13	
Upland Sandpiper	*Bartramia longicauda*	65	Noc	8/1		9/28
Whimbrel	*Numenius hudsonicus*	1	Noc		8/22	
Least Sandpiper	*Calidris minutilla*	5	Noc	8/17		9/15
Pectoral Sandpiper	*Calidris melanatos*	2	Noc		9/24, 9/28	
Spotted Sandpiper	*Actitis macularius*	9	Noc	7/31		9/14
Solitary Sandpiper	*Tringa solitaria*	7	Noc	8/17		10/20
Greater Yellowlegs	*Tringa melanoleuca*	1	Noc		10/15	
American Bittern	*Botaurus lentiginosus*	2	Noc		9/28, 11/16	
Least Bittern	*lxobrychus exilis*	2	Noc		8/15, 9/11	
Great Blue Heron	*Ardea herodias*	2	Noc		10/01, 10/28	
Green Heron	*Butorides virescens*	14	Noc	7/29	9/15	10/21
Black-crowned Night Heron	*Nycticorac nycticorax*	12	Noc	7/9	9/28	10/2
Barn Owl	*Tyto alba*	19	Noc	10/13	11/17	11/19
Golden-crowned Kinglet	*Regulus satrapa*	1	Noc		11/10	
Brown Creeper	*Certhia americana*	1	Noc		11/20	
Veery	*Catharus fuscescens*	13	Noc	9/23		9/25
Swainson's Thrush	*Catharus ustulatus*	13	Noc	9/24		10/4
Wood Thrush	*Hylocichla mustelina*	6	Noc	10/4		10/10
Cedar Waxwing	*Bombycilla cedrorum*	30	Dawn	10/29		thru
American Pipit	*Anthus rubescens*	59	Dawn	10/1		12/7
Sprague's Pipit	*Anthus spragueii*	3	Dawn	10/19		12/24
Pine Siskin	*Spinus pinus*	93	Dawn	10/19		thru
American Goldfinch	*Spinus tristis*	40	Dawn	11/3		thru
Grasshopper Sparrow	*Ammodramus savannarum*	67	Noc	10/2	10/28	11/20
Chipping Sparrow	*Spizella passerina*	64	Noc	10/10	11/4	11/24
Clay-colored Sparrow	*Spizella pallida*	6	Noc	9/26		10/29
Field Sparrow	*Spizella pusilla*	3	Noc	10/28		10/31
Lark Bunting	*Calamospiza melanocorys*	1	Noc		10/28	
White-crowned Sparrow	*Zonotrichia leucophrys*	18	Noc	10/31	11/6	11/22
White-throated Sparrow	*Zonotrichia albicollis*	7	Noc	11/1	11/11	11/13
LeConte's Sparrow	*Ammospiza leconteii*	71	Noc	10/21	11/10	11/23
Nelson's Sparrow	*Ammospiza nelsoni*	5	Noc	10/7		10/29
Savannah Sparrow	*Passerculus sandwichensis*	681	Noc	10/5	11/10	11/30
Song/Fox Sparrow	*Melospiza melodia/Passerella iliaca*	7	Noc			
Lincoln's/Swamp Sparrow	*Melospiza lincolnii/Melospiza georgiana*	26	Noc	10/26	10/29	11/24
Sparrow Sp.	*Passerellidae*	99	Noc			
Total sparrow	*Passerellidae*	1055	Noc	10/10	11/10	11/25
Eastern Towhee	*Pipilo erythrophthalmus*	2	Dawn		11/22, 11/24	
Yellow-breasted Chat	*lcteria virens*		Noc		10/19	
Bobolink	*Dolichonyx oryzivorus*		Noc		10/20	
Eastern Meadowlark	*Sturnella magna*		Noc		10/28	
Total warblers	*Parulidae*	1970	Noc	9/11	11/10	11/25
Rose-breasted Grosbeak	*Pheucticus ludovicianus*	14	Noc	9/23	10/4	10/21
Indigo Bunting	*Passerina cyanea*	266	Noc	9/23	10/16	11/17
Dickcissel	*Spiza americana*	72	Noc	8/16	10/4	11/22
Total individuals		3799				

*Noc = detected nocturnally, Dawn = detected at sunrise

Dates of passage bracketed by first and last arrival as detected by NFCs. Peak passage in NFC surveys are noted. If numbers of detections are low, no peak passage or first/last arrivals shown. Where only one or two NFCs were detected, exact dates of detection are shown under peak passage column.

the night of 16 Oct after a major cold front. A total of 72 Dickcissels (*Spiza americana*) were detected between 9 Aug-30 Oct. Dickcissel passage appears to occur in two stages: a brief pulse in mid-Aug and a protracted passage between mid-Sep and late Oct (Fig. 4, 5). Peak Dickcissel passage appears to be in early October. A Bobolink (*Dolichonyx oryzivorus*), rarely ever detected in the fall during diurnal surveys, was detected on 20 Oct just before dawn. Five Rose-breasted Grosbeaks (*Pheucticus ludovicianus*) were detected between 23 Sep-21 Oct. We note that no Rose-breasted Grosbeaks were ever reported from diurnal surveys at Rice University in the last twenty years. Rose-breasted Grosbeak is also considered to be an uncommon fall migrant on the Texas coast, so our results suggest that fall migrants may be more regular in east Texas than currently appreciated.

New World Sparrows

Sparrows represented the largest number of migrants detected by nocturnal flight calls (Fig. 2). A total of 1065 sparrows was detected, with most in late fall from 9 Oct-15 Nov (Figs. 4, 5). Sparrow numbers begin building in the 2nd week of October and increase substantially in late October to mid-November. The largest fluxes appear to occur immediately after the passage of cold fronts and then decline rapidly in the days afterward. Warm, humid days just before the arrival of a cold front show highly reduced numbers.

Savannah Sparrows (*Passerculus sandwichensis*) were by far the most abundant species with a total of 681 detected between 5 Oct-30 Nov. The next most abundant sparrow species detected were LeConte's Sparrows (*Ammospiza leconteii*) with 71 between 21 Oct-23 Nov, Grasshopper Sparrows (*Ammodramus savannarum*) with 67 between 2 Oct-20 Nov, and Chipping Sparrows (*Spizella passerina*) with 64 between 10 Oct-24 Nov. We were not able to confidently distinguish between the flight calls of Lincoln's (*Melospiza lincolnii*) and Swamp Sparrows (*Melospiza georgiana*); 26 Lincoln's/Swamp Sparrows were detected between 26 Oct-24 Nov. We also recorded 14 White-crowned Sparrows (*Zonotrichia leucophrys*) between 31 Oct-22 Nov), 7 White-throated Sparrows (*Zonotrichia albicollis*) between 1-13 Nov, 3 Field Sparrows (*Spizella pusilla*) between 28-31 Oct, 6 Clay-colored Sparrows (*Spizella pallida*) between 26 Sep-29 Oct, 5 Nelson's Sparrows (*Ammospiza nelsoni*) between 7-29 Oct and 7 Song/Fox Sparrows (*Melospiza melodia/Passerella iliaca*) between 30 Oct-11 Nov (Song and Fox calls were indistinguishable). One Lark Bunting (*Calamospiza melanocorys*) was detected on 28 Oct.

The NFC surveys revealed new migratory information about sparrows, which are either secretive or require highly specific habitat to be found during the day. For example, over 20 years of surveying at Rice University, no more than a total of 10 Grasshopper and LeConte's Sparrows each were observed, too few to establish an accurate migratory window. The fact that we recorded more than 60 independent NFCs of these two species in one season underscores the power and efficiency of using NFCs to study the migration of certain sparrow species. Nelson's Sparrows are almost never seen during the day along the Gulf coast except in coastal salt marsh habitats, so our NFC surveys provide a rare glimpse of their migration window. We also note that Clay-colored Sparrows, which are generally considered rare along the upper Texas coast, have shown up in diurnal surveys at Rice University, making our study site somewhat of an anomaly. The multiple Clay-colored Sparrow NFC detections suggest that this species is a regular fall migrant in our region, but rarely detected during diurnal surveys.

Finally, the number of NFC detections of Zonotrichia sparrows, such as White-crowned and White-throated, seemed to be far lower than their abundances in visual surveys. White-throated Sparrows are common fall migrants at Rice University, but the fact that only 7 NFCs were detected during this study suggests that White-throated Sparrows may not call as frequently as many of the grassland sparrows. White-crowned Sparrows are common along the Texas coast, but only a handful of sight records exist for our study site, so it is unclear if the lack of NFC detections of White-crowned Sparrows represents rarity or under-detection.

Warblers

We were unable or hesitant to identify most warbler flight calls to species. Only a few species were confidently identified: American Redstart (*Setophaga ruticilla*), Black-and-white Warbler (*Mniotilta varia*), Ovenbird (*Seiurus aurocapilla*), Mourning Warbler (*Geothlypis Philadelphia*), and Northern Waterthrush (*Parkesia noveboracensis*).

Because of the difficulty in identifying warbler flight calls, we lumped all warblers together for the purposes of this paper. In late fall, most of the warblers detected were most likely Yellow-rumped (*Setophaga coronate*) and Orange-crowned Warblers (*Leiothlypis celata*), but we did not attempt to separate them.

Warbler NFCs were detected in early fall (before late Oct), but typically only a few per night. This contrasts with spring migration, when hundreds of calls are detected on some nights. We do not know if this reflects just a lower intensity of warbler migrants in the fall due to a more protracted fall migration window. A more likely possibility is that warblers typically fly at elevations too high for their low amplitude calls to be detected. In the spring, low hanging clouds associated with cold fronts may force warblers down to lower elevations, allowing their flight calls to be detected. With the exception of Yellow-rumped and Orange-crowned Warblers, the bulk of fall warbler migration may pass through in late Aug to late Sep, before the arrival of strong cold fronts.

Interestingly, Yellow-rumped and Orange-crowned Warblers were often not detected in the night, but instead during a large pulse from sunrise to 1-2 hours after sunrise, almost all between late Oct and late Nov (Figs. 4, 5). The numbers of independent flight calls reported for these two species is highly uncertain and the uncertainty itself is difficult to quantify due to the challenge of separating multiple calls when there are numerous birds. Our approach, however, should be a lower bound on the number of independent flight calls. We interpret these early morning pulses of flight call activity to be related to highly active morning flights. As we discuss below, these morning flights detected through flight calls appear to coincide with a morning resurgence in base radar reflectivity, suggesting that large numbers of migrating birds, after settling down in pre-dawn hours, take to the skies again in the early morning hours.

Relationship With Cold Fronts

The first major cold fronts appeared in mid-October. From mid-October through the end of November, 7 cold fronts passed through: 16, 24, and 28 Oct; 3, 6, 10 and 14 Nov (Figs. 3-5). These early cold fronts resulted in an influx of Indigo Buntings, but only moderate influxes of sparrows. Sparrow passage did not escalate until the passage of a major cold front in late October (28 Oct), which saw the drop to the lowest temperature over the entire fall survey. Sparrow flux increased only modestly after the passage of a moderate cold front on 6 Nov. However, another moderate cold front immediately afterwards (10 Nov) resulted in a major flux of sparrows. Sparrow numbers decreased rapidly after this front. A major front on 14 Nov produced almost no sparrows, indicating that the passage of sparrows was largely complete by 11 Nov. After the initial pulse of sparrows immediately following a cold front, numbers declined within the following 2-3 days as temperatures warmed back up. In some cases, numbers decline to zero the night before the arrival of a cold front.

Dickcissels, thrushes, shorebirds and waders mostly pass through before mid-Oct and hence before the arrival of major cold fronts, so these birds do not appear to be influenced by cold fronts. Most warblers, with the exception of Yellow-rumped Warblers, also pass through before mid-Oct and are also not influenced by cold fronts. Yellow-rumped Warblers, however, arrive late in the fall and appear to follow the patterns of sparrows in responding to cold fronts.

To more objectively evaluate the link between cold fronts and the passage of birds, it was necessary to develop a quantitative way to identify "cold" days. To do this, we reasoned that the baseline climate in Houston was subtropical with "cold" days defined as deviations away from this warm, subtropical baseline. We regressed a polynomial function through the temperature maxima in our time series. The deviation of temperatures from this warm baseline represents cold fronts or the aftermath of a cold front. The polynomial function adopted is given by T_{base} (°C) $= -2.557\times10^{-7}d^4 + 8.461\times10^{-5}d^3 - 9.837\times10^{-3}d^2 + 3.717\times10^{-1}d + 27.310$, where d represents the number of days after an arbitrary start date, which in this case was 7/25/2020.

Using the above approach in defining cold temperature swings we find that 54% of Upland Sandpiper, 88% of American Pipit, 71% of sparrow and 78% of Indigo Bunting abundance peaks coincided with low temperatures. To make these calculations, we only considered the days within the migration window of the relevant species. These results indicate that late fall migrants, that is, those that pass through primarily in Oct and Nov are strongly influenced by cold fronts. We note that the percentage of cold temperatures, which also coincided with high NFC counts tend to be lower (Table 2). Only 30%, 27% and 45% of temperature lows were associated with high counts of Upland Sandpipers, American Pipits, and Indigo Buntings, indicating that although high counts of NFCs may correlate with low temperatures, low temperatures alone do not always yield high NFCs. Only in the case of sparrows is the percentage of temperature drops associated with high sparrow counts similar to the percentage of high sparrow counts associated with low temperatures. This indicates that the influx of sparrows is linked to low temperatures. These effects can be seen in Figure 6. These results confirm that the flux of migrants is highest immediately after a cold front, but numbers decrease rapidly in the days after the cold front.

Night Schedule

From 16 Oct-25 Nov, we noted the times of every nocturnal flight call detected. For surveys conducted before 16 Oct, total numbers of flight calls were noted, but we unfortunately did not record the times of every call at that time. Fortunately, our records for 16 Oct-25 Nov coincide with peak intensity of fall migrants. With the exception of warblers, nocturnal migrants begin to be detected between 2-4 hours after sunset (Figs. 7 and 8). Detections continue until 3 to 0 hours before sunrise although, in most cases, nocturnal flight calls declined significantly by 2 hours before sunrise.

Warbler flight calls between 16 Oct-25 Nov were mostly unidentified, but undoubtedly dominated by Yellow-rumped Warblers and to a lesser extent Orange-crowned Warblers, both of which are terminal migrants. In almost all cases, most of the warbler flight calls occurred within the hour before and after sunrise, with peak detection occurring within 30 minutes before sunrise. We consider the bulk of these flight calls to be associated with morning flights of Yellow-rumped and Orange-crowned Warblers on the "ground", that is, flying from tree to tree or just above the canopy (<50 m). Only small numbers of warbler flight calls were detected during the night, perhaps because they fly too high for their faint calls to be detected.

Comparisons to Radar

We also compared our results to the base radar reflectivity each night. We considered two quantities. We first determined the average base reflectivity for each night by taking the average reflectivity over the city of Houston at midnight. We also determined base reflectivity over our monitoring station at Rice University each night as a function of time (Fig. 9).

Nights with high counts of Upland Sandpipers, sparrows, Indigo Buntings and Dickcissels appear to be accompanied by high radar reflectivity as shown in Table 2 and Fig. 6, confirming that high radar reflectivity in the night most likely represents birds. However, we note that high radar reflectivity itself is not always accompanied by high NFC detections, suggesting that birds flying overhead might not always be detected from recording stations either because they fly too high or are not calling.

Comparisons of radar and NFC time series through a given night was particularly interesting (Figs. 7 and 8). Radar intensity picks up rapidly after sundown (within a half hour after sundown), but NFC intensity appears to be delayed, picking up 2 hours after sunset. By contrast, the decline in radar and NFC intensity in the 1-2 hours before sunrise are coupled. Assuming that radar indeed represents flying birds, these results indicate that fall migrating birds, represented in this study mostly

Table 2. Associations between migratory pulses with radar and temperature

		# bird peaks associated with a radar peak	# radar peaks associated with a bird peak	# bird peaks associated with a temperature lows	# temperature lows associated with bird peaks
		%	%	%	%
Upland Sandpiper	*Bartramia longicauda*	80	53	54	30
American Pipit	*Anthus rubescens*	55	38	88	27
Sparrows	*Passerellidae*	71	62	71	72
Indigo Bunting	*Passerina cyanea*	83	75	78	45

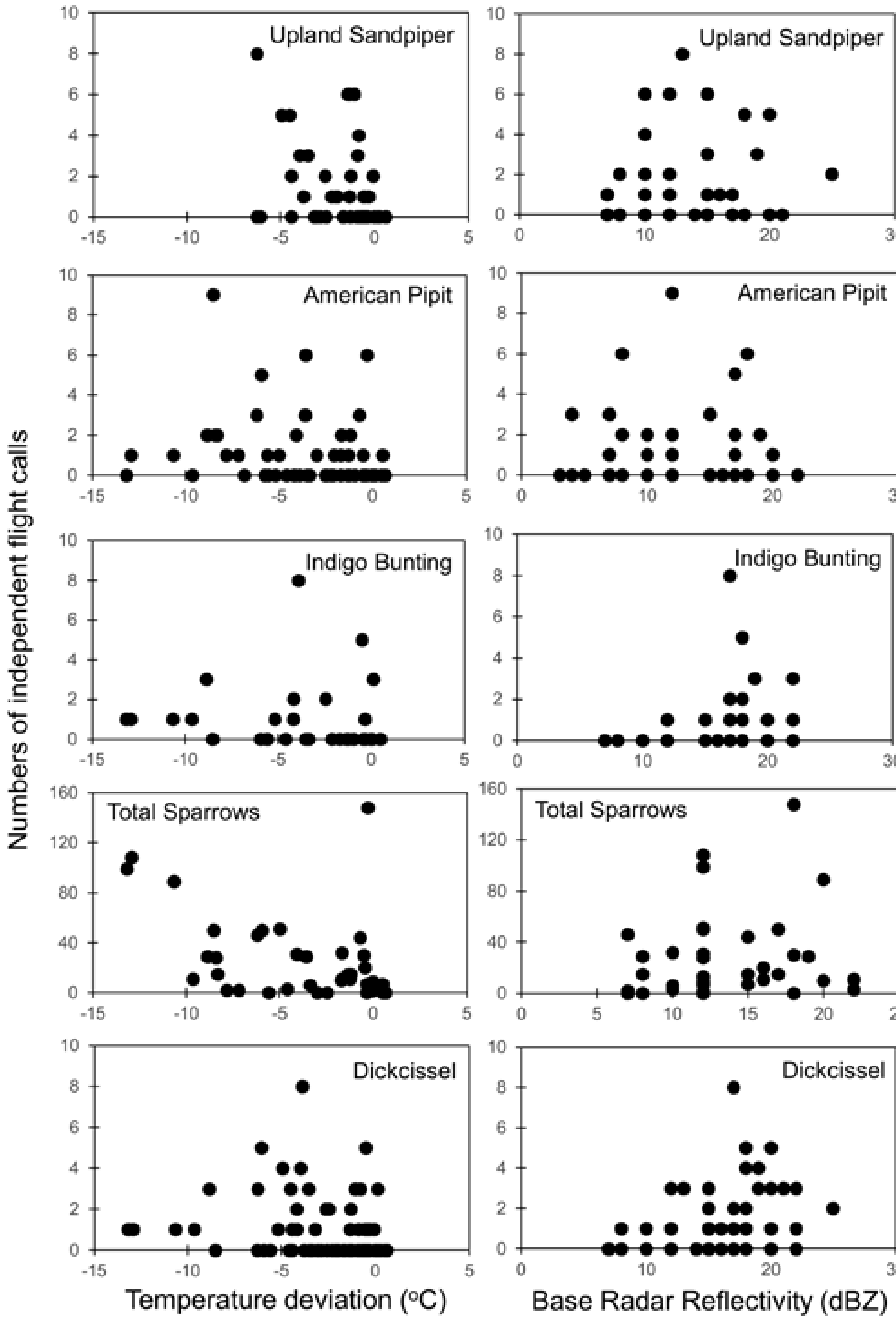

Figure 6. Numbers of NFCs for various species as a function of negative temperature deviations (left column) and base radar reflectivity (right column). Temperature deviation is referenced to an upper envelope of average daily temperature from Aug to Nov, 2020.

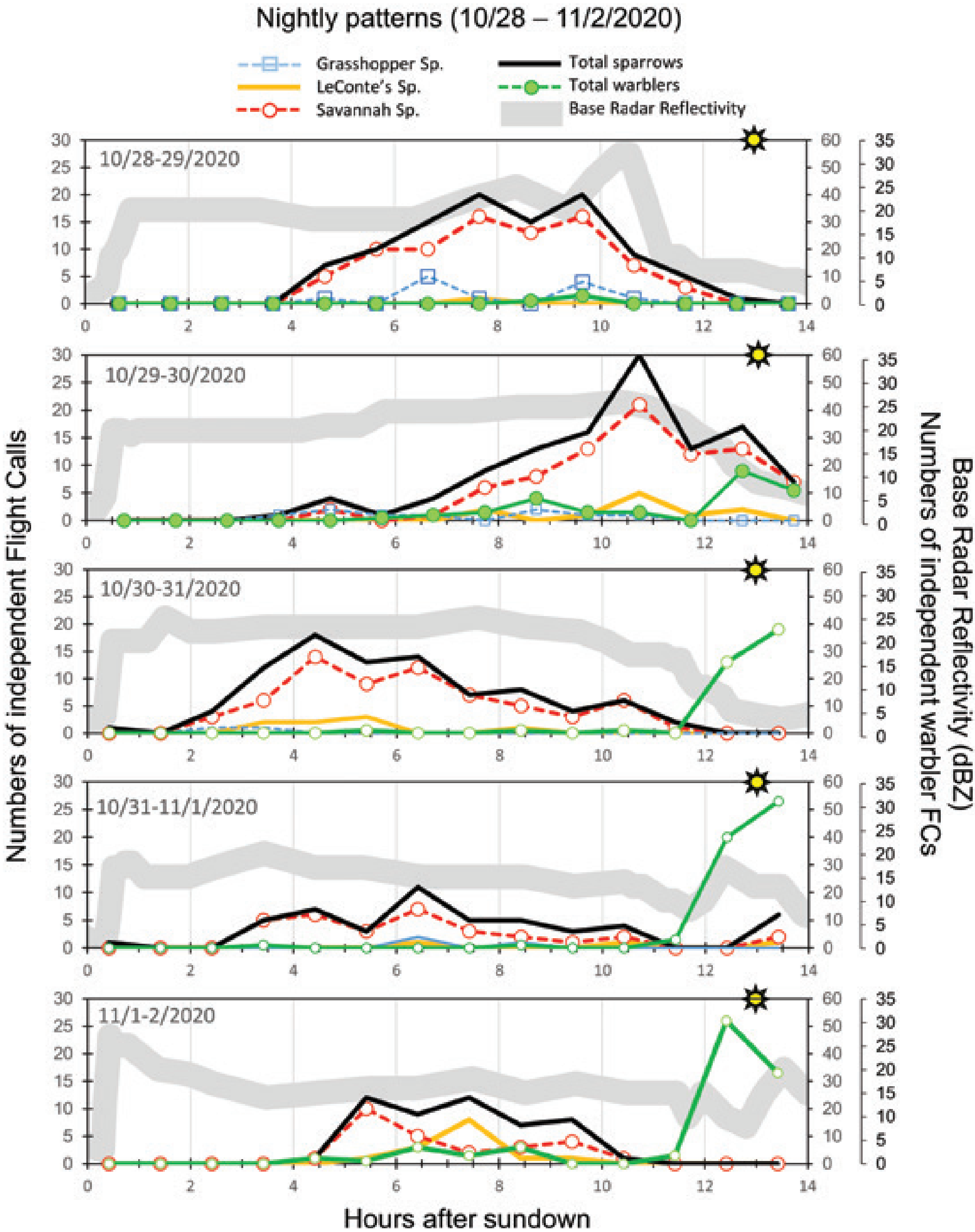

Figure 7. Numbers of independent NFC detections versus hours after sunset from 28 Oct-2 Nov. This range in dates corresponds to the aftermath of a major cold front that passed through on 28 Oct during the day. Sun symbol shows the time of sunrise. Data were binned in 1-hour intervals. Data are shown for Grasshopper, LeConte's and Savannah Sparrows, along with total sparrows and warblers. Warblers pertain to morning flights of Yellow-rumped and Orange-crowned Warblers, which may represent local movements of birds that arrived for the winter rather than transients.

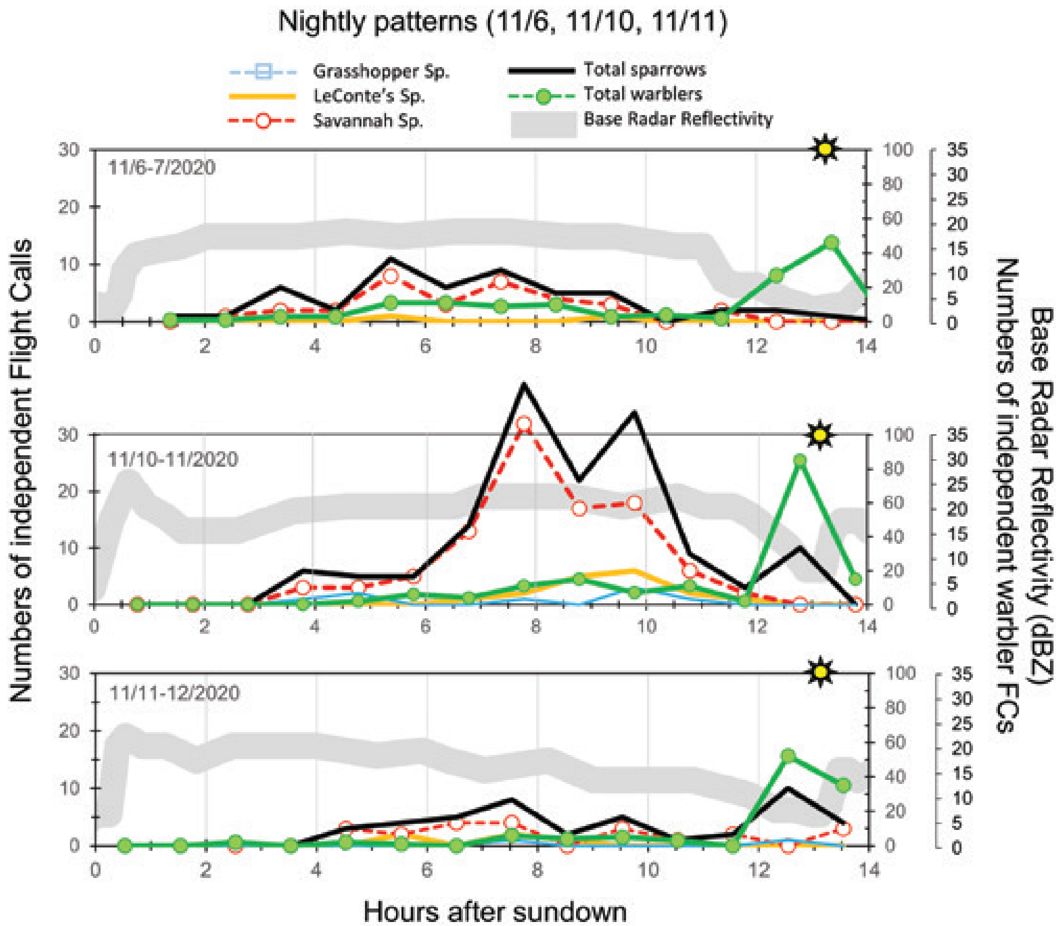

Figure 8. Numbers of independent NFC detections versus hours after sunset from three different nights in which birds were detected. These dates immediately follow the passage of moderate cold fronts. Sun symbol shows the time of sunrise. Data were binned in 1-hour intervals. Data are shown for Grasshopper, LeConte's and Savannah Sparrows, along with total sparrows and warblers. Warblers pertain to morning flights of Yellow-rumped and Orange-crowned Warblers, which may represent local movements of birds that arrived for the winter rather than transients.

by sparrows, do not call during take-off. Sparrows appear to primarily call after they have reached their migrating elevations. Sparrow NFCs decrease in the 1-2 hours before sunrise, but the synchronous decline in radar picks suggests that this decrease in overhead NFCs is simply due to sparrows landing 1-2 hours before sunrise.

In late fall (early Nov), we recorded large numbers of warbler flight calls at dawn. As noted above, these are dominated by Yellow-rumped Warblers. From flight calls alone, it was not clear if these represented local movements of terminal migrants. However, these dawn influxes of NFCs are often associated with a brief resurgence in radar intensity (Figs. 7 and 8), suggesting that these warblers are flying back up high into the sky, perhaps to explore immediate surroundings for better habitats to settle down in for the day.

DISCUSSION AND CONCLUSIONS

Our results have several implications. First, our study demonstrates that NFC surveys robustly define the timing of migration in one season unlike visual surveys, which may take years or decades,

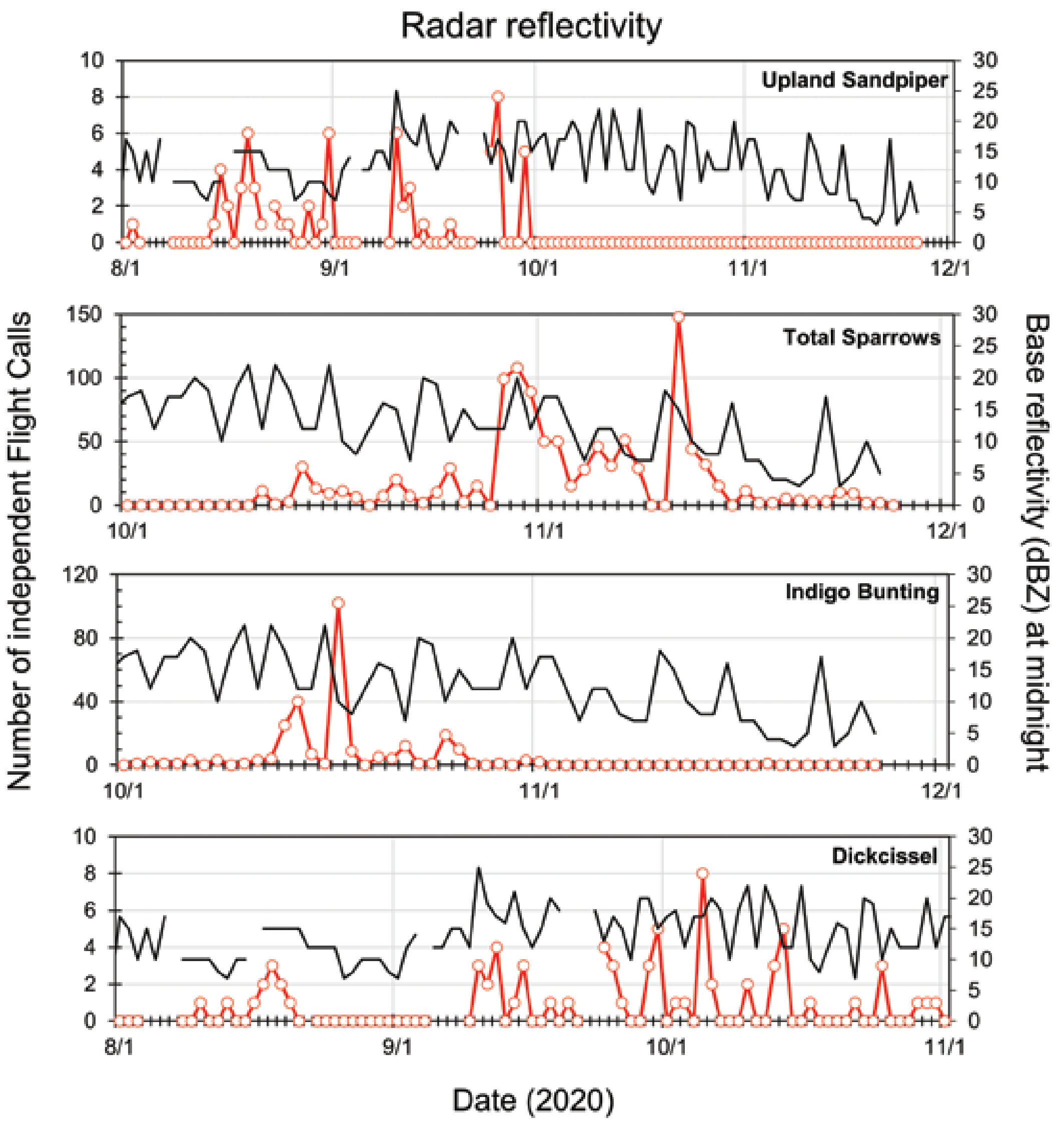

Figure 9. Nightly radar (base reflectivity) at midnight over the study site versus number of independent NFCs.

to establish migration windows especially for more secretive species. The advantage of NFC surveys is that they offer the ability for continuous monitoring over a large area, whereas the human-hours needed to conduct continuous visual surveys would be cost-prohibitive. NFC surveys may thus be the ideal method for objectively documenting annual or decadal changes in the timing of migration due to climate or other environmental change.

Our results also have implications for minimizing building strike mortality. Our NFC and radar observations indicate that the main movements of fall songbird migration in Houston, TX happens between mid-Sep and the end of Nov. This is the window of time that songbird migrants face the greatest threats from building collisions. The most vulnerable time for night-time strikes is between sunset and two hours before sunrise. The largest flights occur immediately after the passage of cold fronts. The associations between high NFC fluxes and high radar intensity further suggests that migration forecasts based on radar (e.g., Cornell Laboratory of Ornithology's Birdcast) should predict well whether a given night will have a high flux of migrants. These migration forecasts, however, do not have the resolution to predict the temporal pattern of migrants within a given night, so radar-based forecasts need to be complemented with empirical NFC data.

Similar studies like ours should be conducted in spring and fall for every major metropolitan area to establish peak migration windows. We also suspect that the timing of flights during the night may also be site-dependent owing to changes in land use. For example, because of lack of extensive sparrow habitat in the immediate area of our monitoring station, these sparrows presumably took to the skies from less developed areas to the north. With urban development projected to expand northward in the next decade (Hakkenberg et al. 2018), habitats for birds will be pushed farther away from urban Houston. The time it takes for southbound songbirds to arrive over Houston from these retreating habitats will thus increase, which would mean that by the time these birds encounter the light-polluted urban center of Houston and the Texas coast, they could be more exhausted and more likely to experience higher mortality. Annual NFC surveys are needed to track the effects of land use change to the arrival time of migrating birds over urban centers.

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