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OVERVIEW

RADAR ORNITHOLOGY AND BIOLOGICAL CONSERVATION

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In the approximately 60 years since the discovery that birds were responsible for some of the puzzling radar echoes dubbed "angels" by the British (Lack and Varley 1945, Buss 1946), radar has proven to be a useful tool for the detection, monitoring, and quantification of bird movements in the atmosphere (Eastwood 1967; Richardson 1979; Vaughn 1985; Bruderer 1997a, b). Radar has been a particularly valuable tool for descriptive studies of daily and seasonal patterns of bird migration, but the technique has also been used to answer important questions about how birds orient during migration and the role of atmospheric structure in shaping flight strategies of birds. Within the last two decades, radar ornithology has played an increasingly important role in conservation of species that are migratory, endangered, threatened, or of special concern.

Types of Radar

Several types of radar have been used in those studies, and each type has characteristics (tracking or surveillance mode of operation, doppler capability, range of detection, wavelength) that make it especially suitable for a particular application. Small, low-powered, doppler-traffic radars have been used to measure ground speeds of birds flying within a distance of 1 km (Schnell 1965, Schnell and Hellack 1978, Blake et al. 1990, Evans and Drickamer 1994, Brigham et al. 1998). Military tracking radars have been used to measure density and altitudinal distribution of targets in a nontracking mode of operation and they have been used to acquire a target (a single bird or a flock of birds), track it through the atmosphere, plot the trajectory in three dimensions, and measure wing-beat patterns from the modulation of the returned radar signals (Bruderer et al. 1995). A large number of bird migration studies have used that approach in Europe, Israel, Africa, and in the Arctic (Gehring 1967, Schaeffer 1968, Steidinger 1968, Bruderer 1969, Bruderer and Steidinger 1972, Bruderer 1994, Liechti and Bruderer 1995, Alerstam and Gudmundsson 1999, Alerstam et al. 2001) as well as in the United States (Griffin 1973, Able 1977, Larkin 1978). Several studies have examined modulations of reflectivity from bird targets being tracked (wing-beat signatures) in an attempt to identify the type of bird (Schaefer 1968, Bruderer 1969, Vaughn 1974, Williams and Williams 1980, Renevey 1981), but most of the results to date are not very promising. Large, satellite-tracking radars operated by the National Aeronautics and Space Administration (NASA), which are capable of tracking a single bee (*Bombus* spp.) at a distance of 10 km (Glover et al. 1966), have been used to track migrating birds (Williams et al. 1972) and single birds released aloft (Emlen and Demong 1978, Demong and Emlen 1978) at much greater ranges.

Low-powered surveillance radars can detect movements of birds within a range of a few kilometers of the radar (Fig. 1). Those units have been used to study bird migration since the 1960s (airborne, Graber and Hassler 1962; marine shipboard, Casement 1966, Flock 1972, Williams 1984), but more recently, they also have been used to assess the influence of transmission lines, wind turbines, and other man-made structures on bird movements (Gauthreaux 1985, Cooper et al. 1991, Cooper 1996, Harmata et al. 1999, Deng and Frederick 2001) and to monitor movements of endangered and threatened species between feeding and breeding areas (Day and Cooper 1995, Cooper and Day 1998, Bertram et al. 1999, Burger 2001). High-resolution marine surveillance radar can detect and quantify birds as they approach or depart from breeding colonies or roosting areas, and they can be used to quantify the number of birds coming from different types of habitat in migration stopover areas (Gauthreaux and Belser 2003; S. A. Gauthreaux unpubl. data).

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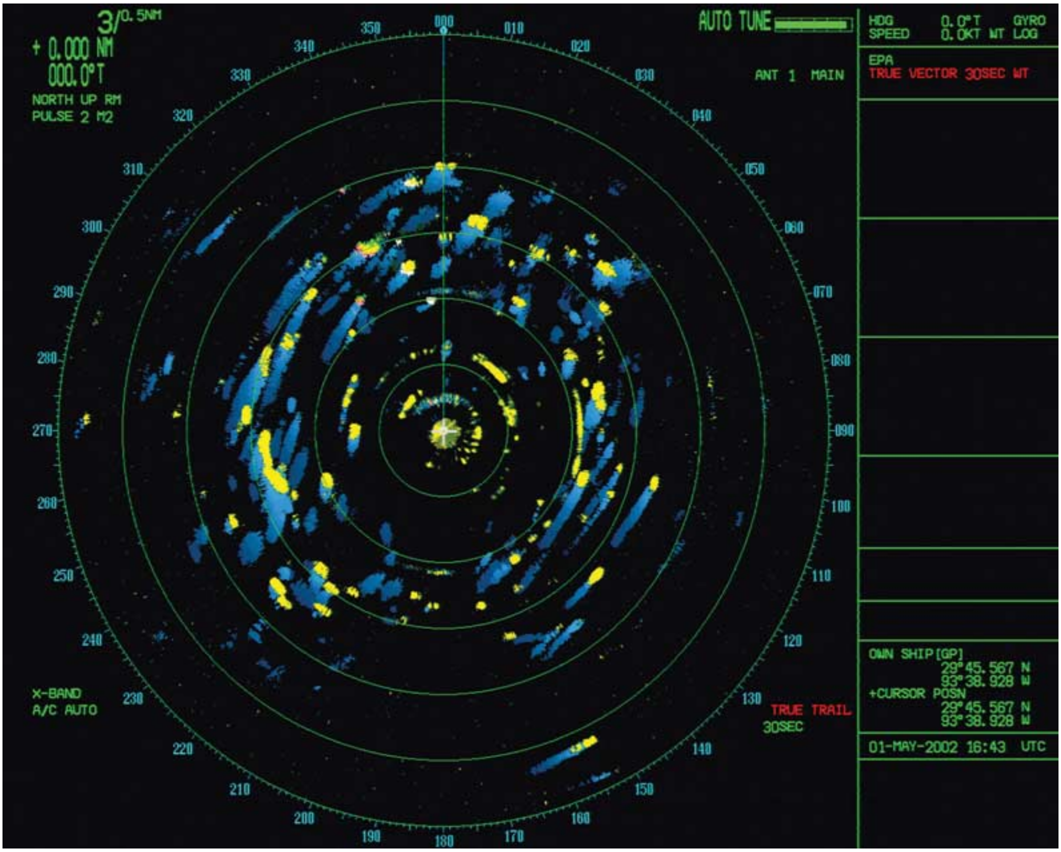

Fig. 1. Radar image of the arrival of trans-Gulf migrants on the coast of southwestern Louisiana on 1 May 2002 at 1643 UTC. The radar is a 50 kW marine surveillance radar fitted with a 1 m parabolic antenna tilted 30° above horizontal. The range is 3 nautical miles and range marks are 0.5 nautical miles. Altitude of birds is 0.5× range. Position of a target when the image was captured is colored yellow and the echo trail is colored shades of blue. We observed with 10× binoculars flocks of songbirds and shorebirds and single migrants flying overhead at the limit of visibility when this image was captured.

Long-range, powerful surveillance radars can detect birds at ranges of 100–240 km, and researchers have used them to study bird movements within 120 km of airports (airport surveillance radars [ASR], Sutter 1957a, b; Gauthreaux 1974; Gudmundsson 1993; Alfiya 1995), within 240 km of weather stations (weather surveillance radars [WSR], Gauthreaux 1970; Williams et al. 1977; Gauthreaux and Belser 1998, 1999a; Koistinen 2000; Larkin et al. 2002; Diehl et al. 2003), and within 240 km of air route surveillance radars [ARSR] and high powered military surveillance radars (Nisbet 1963, Richardson and Gunn 1971, Beason 1978, Williams et al. 1986, Buurma 1995). In some cases, that work has been used to address important conservation concerns such as the decline of Neotropical migrants (Gauthreaux 1992) and radar mapping of important migration stopover areas (see below).

Conservation Applicatons

The application of radar ornithology to conservation issues began when mobile, low-powered, high-resolution marine surveillance radar was first used in 1979 to monitor collision risks of birds near power lines (Gauthreaux 1985). Although that study found that radar provided valuable information on bird movements at night and during the day, observations with video camera, or binoculars during the day and image intensifier at night, complemented the radar record. Visual techniques provided detailed information on types and numbers of birds and their flight behavior near lines. Radar, on the other hand, detected approaching birds and provided accurate information on the distance of the crossing. The marine radar (10 kW) detected only the supporting towers and not the lines themselves, and it detected birds at greater distances than could be done with binoculars or video camera. When short pulse lengths were selected, small birds were detected out to a distance of 0.5 km, and birds the size of geese could be detected out to a distance of 2.4 km. With long pulse lengths, those distances were increased by a factor of 2, but resolution was poorer.

A similar setup (Cooper et al. 1991) to the mobile radar laboratory of Gauthreaux (1985) was used in a study designed to monitor the crossing distances and flight behavior of two threatened seabirds—the Hawaiian Petrel (*Pterodroma sandwichensis*) and Townsend's Shearwater (*Puffinus auricularis*)—as they flew to and from breeding colonies in Kauai, Hawaii (Day and Cooper 1995, Cooper and Day 1998). They found that Hawaiian Petrels moved during dawn and dusk, but Townsend's Shearwaters were nocturnal with single birds moving in greatest numbers ~2 h after sunset and before sunrise. Inland movements occurred in the first part of the night whereas seaward movements occurred late at night. Movements were in both directions during the middle of the night. Outbound flights were at lower altitudes than inbound flights, and most of the Townsend's Shearwater mortality was during late night seaward flights. Deng and Frederick (2001) used a combination of marine surveillance radar and night vision optical equipment to observe nocturnal flight behavior of flocks of herons and Wood Storks (*Mycteria americana*) crossing a 550 V transmission power line in the Florida Everglades. They found that birds were less likely to react to the power line at night—suggesting that risks of collisions were greater, but they also noted that water birds flew higher at night than during the day and were less likely to enter the collision zone at night than during the day.

Radar studies have also examined the nocturnal flight behavior of migrating birds and the daytime movements of raptors in relation to the development of wind energy. As part of a national research program on bird interactions with wind turbines, a radar study of nocturnal flight activities and flight altitudes in tidal and semioffshore areas of Oosterschelde estuary, in southwestern Netherlands found that nocturnal movements of tidal waders to and from inland high-tide roosting areas were predominantly below 100 m (Spaans 1998). Flights of Greater Scaup (*Aythya marila*) to and from feeding grounds occurred predominantly during dusk and dawn, but Tufted Ducks (*Aythya fuligula*) and Common Pochards (*Aythya ferina*) flew mainly during darkness and seldom >100 m above ground level. Radar observations near a line of four middle-sized wind turbines showed that during moonlit nights Tufted Ducks and pochards crossed perpendicular to the line by passing between the turbines, but on moonless nights more birds flew parallel to the line. The findings suggest that on moonless nights a line of turbines can act as a flight path barrier, but by interrupting long lines of turbines the effect can be reduced (Spaans 1998).

Radar ornithology is also being used in studies of wind farm development in the United States (Cooper 1996). Harmata et al. (1999) used marine surveillance radar scanning 360° of azimuth to monitor rates and timing of bird passage in a horizontal plane and a vertical marine radar configuration to measure the altitude of the flights at a proposed Norris Hill Wind Resource Area (NHWRA) in southwestern Montana. The average altitude of birds flying within 2 km east and west of the project area was 209 m in autumn and 388 m in spring with more birds passing over valleys and swales than high points. Rates of movement decreased with falling barometric pressure in autumn (headwind conditions), but the reverse was true in spring (tailwind conditions). In a study of the effect of wind turbines on nocturnal bird movements in southwestern Minnesota, radar data indicated that ~3.5 million birds migrate over the wind farm each year, but the proportion of birds flying at altitudes where they are at risk is unknown (Johnson et al. 2002). According to Johnson et al. (2002) the development of wind power will likely contribute to cumulative collision mortality of birds in the United States. There is also great concern about migrating birds colliding with communication and broadcast towers as the number of those structures proliferate across the landscape, but to date only one study has used radar (tracking) to examine flight paths of migrating birds near a 308-m-tall broadcast tower (Larkin and Frase 1988). This study found that when low clouds surrounded the tower, birds flew in arcs and circles (in excess of 100 m) centered on the tower; but when the sky was clear or the cloud layer higher, this behavior was not observed.

Several studies have used marine surveillance radar to study the movements of the threatened Marbled Murrelet (*Brachyramphus marmoratus*) between the Pacific Ocean and inland sites in Vancouver, British Columbia and in Washington and Oregon (Hamer et al. 1995; Burger 1997, 2001; Cooper et al. 2001; Raphael et al. 2002; and Cooper and Blaha 2002), and others have used marine radar to monitor the movements of alcids between feeding areas and breeding colonies near the ocean (Bertram et al. 1999, Lilliendahl et al. 2003). Studies of Marbled Murrelet movements to and from watersheds on Vancouver Island, showed that radar detected 5–10× more murrelets than the audiovisual Pacific Seabird Group (PSG) protocol, and radar recorded a concentrated influx of murrelets 35–60 min before sunrise when audio-visual surveys did not (Burger 1997). Radar also revealed considerable activity at dusk—a period not normally sampled in the PSG protocol. Radar counts of murrelets at 18 watersheds were most strongly correlated with areas of mature forest below 600 m and significantly correlated with total watershed area and areas of mature forest (>140 year old; Burger 2001).

Cooper et al. (2001) used radar to measure daily, monthly, and annual patterns of Marbled Murrelet abundance and movements at 12 major river valleys in the Olympic Peninsula of Washington. Landward movements peaked from ~75 min to ~20 min before sunrise, followed by a seaward departure from 20 min before sunrise to ~65 min after sunrise. They found that landward radar targets averaged twice the numbers of seaward targets, and morning numbers were ~5× those recorded in the evening. The seaward departure was later from May to July as radar counts increased. Counts dropped in August. Like Burger (1997), Cooper and Blaha (2002) working in Washington and Oregon also found that audiovisual observers detected an average of only 10–23% of the murrelets detected by radar during official survey periods and that the difference in counts between the techniques was highly variable from day to day. In a marine surveillance radar study, Raphael et al. (2002) found that the maximum number of murrelet radar targets was positively correlated with amount of late-seral forest within 10 river drainages on the Olympic Peninsula, Washington, and not correlated with the combined amounts of harvested, developed, and agricultural lands. Their results suggest that changes in amount or distribution of nesting habitat should result in detectable changes in murrelet numbers for individual drainages. They surmise that Marbled Murrelet populations may be regulated by amount and distribution of nesting habitat and providing nesting habitat may be an effective conservation and restoration technique for that species.

Marine surveillance radar has also been used to census nocturnal burrow-nesting Cassin's Auklets (*Ptychoramphus aleuticus*) on the world's largest colony at Triangle Island, British Columbia (Bertram et al. 1999). They compared use of radar and traditional methods based on burrow counts and identified several major advantages for radar in long-term population monitoring and seabird research programs. Colony activity began ~1.5 h after sunset, peaked around 2300 hours, and ended at least 15 min before sunrise. Activity levels showed considerable nightly variation and increased from 30 April to 10 May when the maximum estimate of individual birds detected was 156,327. Radar can provide an overall picture of alcid distribution near colonies and compliment studies on foraging flights of individual birds. Lilliendahl et al. (2003) used marine surveillance radar (25 kW) to track flocks of colonially breeding alcids at Latrabjarg, northwest Iceland, as they returned from feeding grounds during the chick-rearing period. By comparing flight directions of incoming flocks with alcid densities at sea during both the incubation and chick-rearing periods they found that direction of incoming flocks was significantly related to alcid distribution at sea, suggesting that marine surveillance radar can be used for monitoring preferred foraging areas of alcids within seasons and between years.

Studies using high-powered weather surveillance radar (WSR) operated by the National Weather Service are also contributing to conservation of migratory birds. By comparing WSR-57 archived radar records of the arrival of trans-

Gulf migration in southwestern Louisiana from three years in the 1960s (1965–1967) with three years in the late 1980s (1987–1989), Gauthreaux (1992) noted a significant decline in the number of flights arriving on the upper Texas and southwestern Louisiana coasts—locations where trans-Gulf flights arrive with greater frequency than elsewhere on the northern coast of the Gulf of Mexico (Gauthreaux and Belser 1999b). Not surprisingly, the decline has also affected the number and frequency of trans-Gulf migrants observed in coastal woodlands in spring (V. Emanuel pers. comm., R. Bacon pers. comm.).

In the early 1990s, the National Weather Service began upgrading weather surveillance radar in the United States by replacing the network of WSR-57 radars with 151 new doppler weather surveillance radars (WSR-88D). The WSR-88D (referred to as "NEXRAD" [next generation radar] during the developmental and early operational years) has a peak transmitter power of 750 kW and a frequency range of 2.7 GHz to 3.0 GHz (10.3–11.1 cm or S band). The parabolic antenna diameter is 9 m and the beam width is 0.96–1.0° with pulse widths of 1.57 µs to 4.5–5.0 µs. Larkin (1991) was first to examine bird detection with the WSR-88D and Gauthreaux and Belser (1998) characterized the patterns of bird echoes on the WSR-88D and used moon-watching to quantify the reflectivity displays of bird targets. Black and Donaldson (1999) and Gauthreaux and Belser (1999a) further developed the quantification procedure. The doppler units have proven to be very useful for studies of bird migration (Gauthreaux and Belser 1999b, Larkin et al 2002, Diehl et al. 2003, Gauthreaux et al. 2003) and Russell et al. (1998) and Russell and Gauthreaux (1998, 1999) have used those radars for studies of premigratory roosting behavior of Purple Martins (*Progne subis*) (Fig. 2A, B).

Two current projects that use the WSR-88D have important consequences for conservation of migratory birds. One emphasizes the mapping of migration stopover areas throughout the United States and monitoring input to and output from those areas (Gauthreaux and Belser 2003, S. A. Gauthreaux unpubl. data). The other concerns mapping the distribution and abundance patterns of bird migration over the entire United States on the basis of data from the national network of WSR-88D stations (Gauthreaux et al. 2003).

For delimiting migration stopover areas during spring and fall two WSR-88D products are used: base reflectivity and base velocity images (see fig. 6 in Diehl et al. 2003). The base velocity image shows the radial velocity of radar echoes and is used with winds aloft data to distinguish birds from other reflectors in the atmosphere. The two to five reflectivity images that show the beginning of bird migration on a given night and are free of obscuring precipitation or other radar interference within 120 km of the radar are compiled for further processing. Generally from 8 to 17 nights per site per year meet the above criteria. The reflectivity images are then processed to emphasize areas of high relative bird density (birds per cubic kilometer) and the resulting imagery is converted to rectangular raster and imported into ARCINFO. The map showing relative density of birds departing from migration stopover areas can then be compared with land cover maps based on classified Landsat data (Figs. 3A, B). Preliminary findings suggest that most stopover areas along the coastal plain of the northern coast of the Gulf of Mexico and the Atlantic Ocean are associated with riverine floodplain topography and upland areas are used less. With respect to forested landscapes, bottomlands are used almost exclusively and extensive pine flatlands are rarely used as important stopover areas (Fig. 3A, B; S. A. Gauthreaux unpubl. data). Similar studies have been conducted around the Great Lakes (D. Bonter unpubl. data; R. H. Diehl unpubl. data), in New Jersey (D. Mizrahi unpubl. data), and in Iowa (K. Jungbluth unpubl. data). Delineation and protection of important, traditional migration stopover areas for songbirds and water birds should be a high conservation priority.

The network of 151 WSR-88D radars in the contiguous United States presents a unique opportunity to monitor bird migration over the whole country. It is now possible to monitor the quantity of bird migration nation-wide by making a mosaic of unfiltered reflectivity products (lowest antenna elevation) from all the individual stations (Fig. 4A). The direction and mean ground speeds of targets can be mapped similarly by using the associated radial velocity products, but fewer stations are used because when inbound (moving toward the radar) and outbound (moving away from the radar) velocities overlap, data from one station may obscure

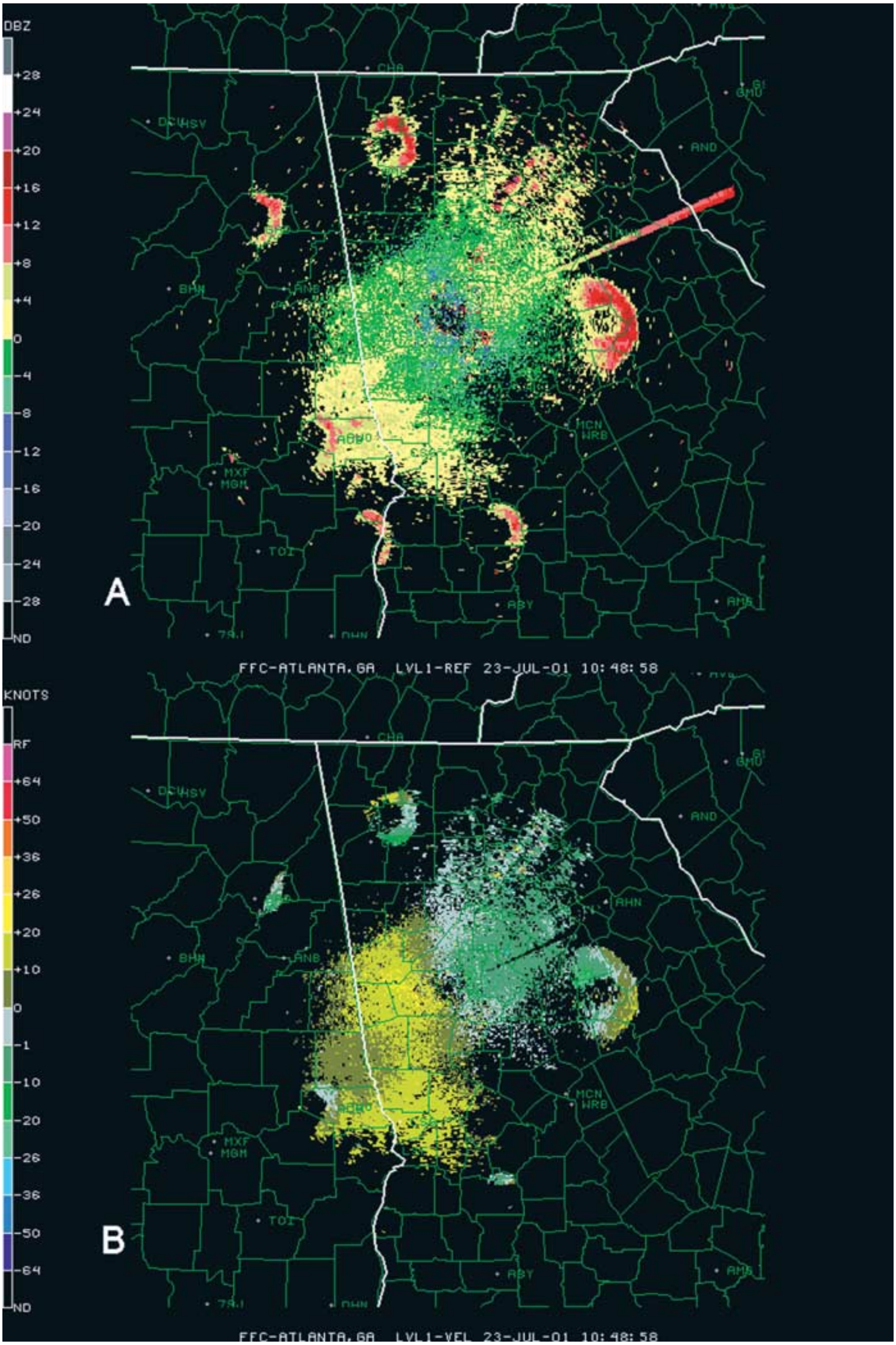

FIG. 2. WSR-88D radar images showing the exodus of Purple Martins from roost sites around Atlanta, Georgia on 23 July 2001 at 1048 UTC. (A) base reflectivity image (clear air mode) showing the strobe from the rising sun and ring echoes from six roost sites, (B) base velocity image showing component of velocity moving toward the radar (green colors) and away from the radar (yellow colors). Targets moving perpendicular to the radar beam have no radial velocity and are colored gray.

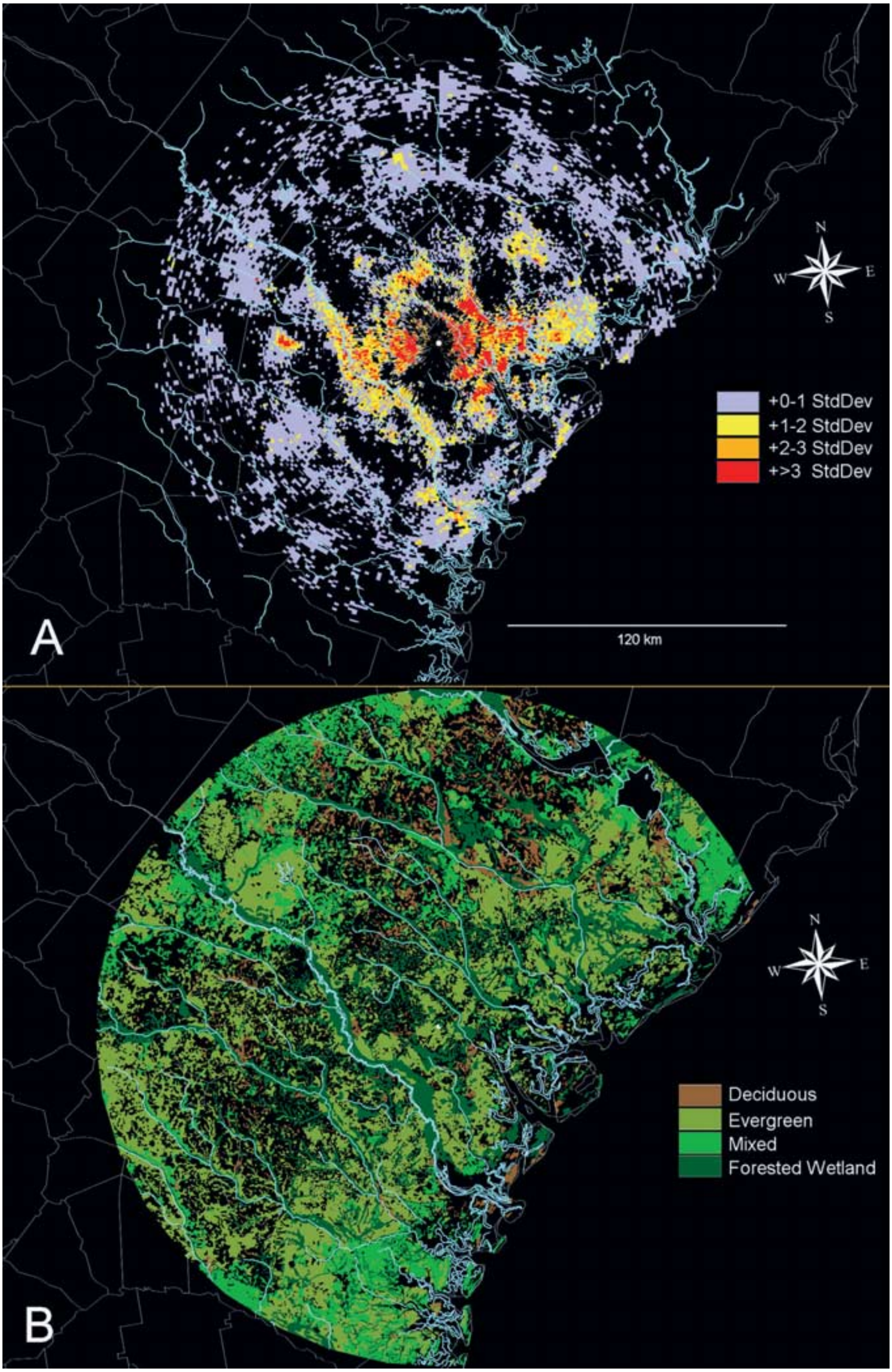

FIG. 3. Maps relating patterns of radar return from migrants departing stopover areas to topography and forested habitats within 120 km of the Charleston, South Carolina WSR-88D. (A) density of migrants (birds per cubic kilometer) departing from stopover areas displayed as standard deviations above the mean and (B) classified Landsat imagery showing forest types. The highest densities appear to be associated with bottomland forests and not the extensive pinelands characteristic of the area.

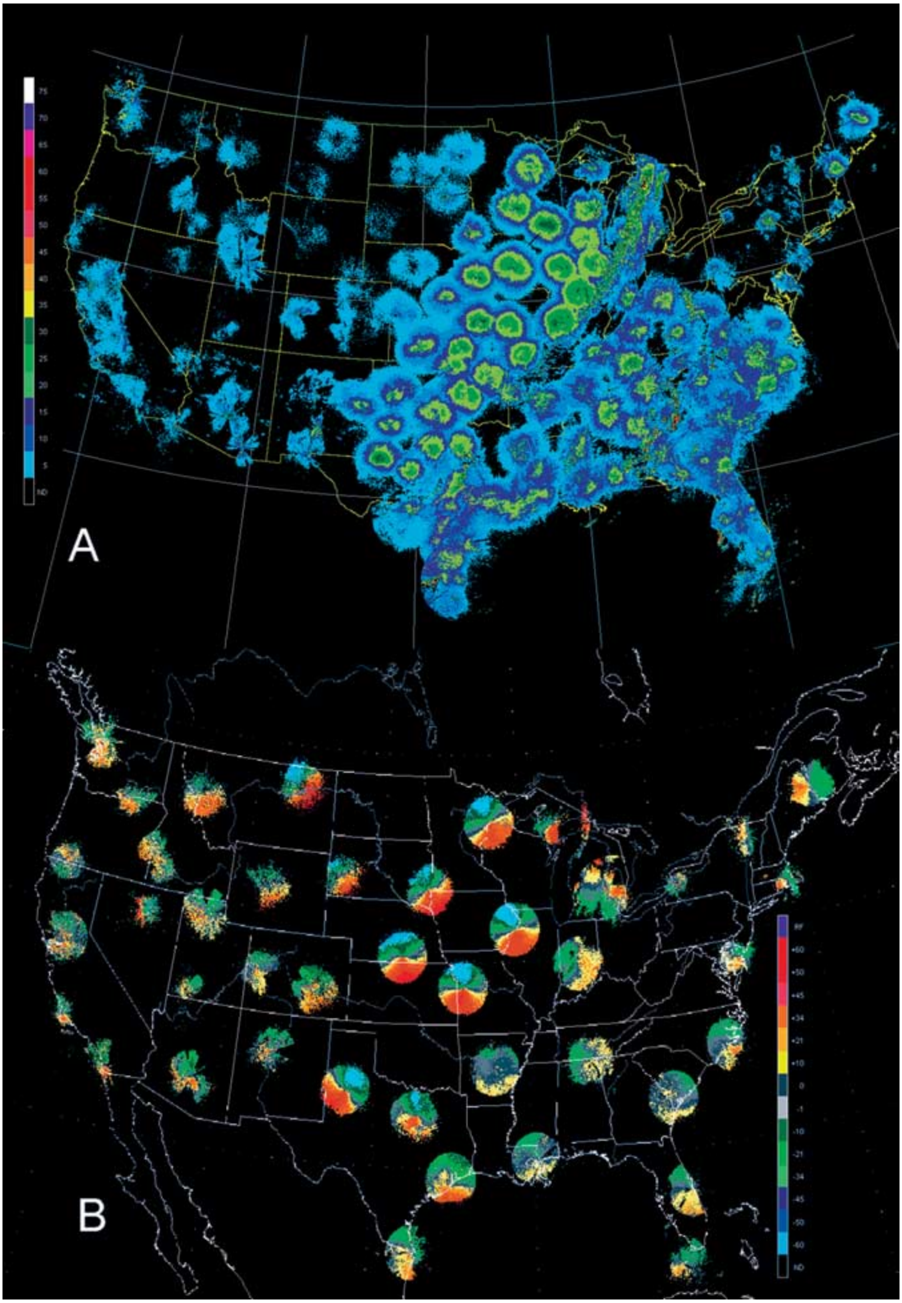

FIG. 4. National mosaics of WSR-88D radars. (A) National mosaic of unfiltered base reflectivity products from all operational WSR-88D stations in the United States on 13 October 2002 at 0415 UTC. Heavy migration is occurring behind a cold front moving through the Mississippi River Valley. Radar locations are surrounded by return from migrating birds and other reflectors in the atmosphere. The colors are related to the number of reflectors and the edge of the disc is defined when the base of the radar beam goes above the migration layer. (B) Mosaic of base velocity products from 42 WSR-88D stations (gathered 4 h after sunset) showing the direction of bird movements (from green-blue to yellow-red). The fastest birds are following the cold front in the central United States and moving southeast at more northern latitudes and south and southwest at more southern latitudes.

data from another (Figure 4B). Reflectivity and velocity data from the WSR-88D are also used to construct national migration maps of the relative density and direction of bird migration for each night during spring and fall (Gauthreaux et al. 2003). Images are collected each night between 2–3 h after sunset and near the peak of a night's migration from each of 70 WSR-88D stations near weather stations that measure winds aloft. Winds-aloft data are necessary for processing radar imagery to measure the level of insect contamination. Maps for four different altitudinal strata are produced. Arrows show the direction of migration for a radar station, and the color of the arrow indicates the average number of birds per cubic kilometer. The use of a standardized procedure to generate national migration maps based on radar data will not only document the temporal and spatial patterns of migration for four altitudinal zones nationwide but also permit quantitative season-to-season and year-to-year comparisons among different regions of the United States (Gauthreaux et al 2003). In the long term, the maps can be used to monitor the health of the North American bird migration system.

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