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INTERDISCIPLINARY PERSPECTIVE

Prospects for monitoring bird migration along the East Asian-Australasian Flyway using weather radar

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Abstract

Each year, billions of birds migrate across the globe, and interpretation of weather radar signals is increasingly being used to document the spatial and temporal migration patterns in Europe and America. Such approaches are yet to be applied in the East Asian-Australasian Flyway (EAAF), one of the most species-rich and threatened flyways in the world. Logistical challenges limit direct on-ground monitoring of migratory birds in many parts of the EAAF, resulting in knowledge gaps on population status and site use that limit evidence-based conservation planning. Weather radar data have great potential for achieving comprehensive migratory bird monitoring along the EAAF. In this study, we discuss the feasibility and challenges of using weather radar to complement on-ground bird migration surveys in the flyway. We summarize the location, capacity and data availability of weather radars across EAAF countries, as well as the spatial coverage of the radars with respect to migrants' geographic distribution and migration hotspots along the flyway, with an exemplar analysis of biological movement patterns extracted from Chinese weather radars. There are more than 430 weather radars in EAAF countries, covering on average half of bird species' passage and non-breeding distributions, as well as 70% of internationally important sites for migratory shorebirds. We conclude that the weather radar network could be a powerful resource for monitoring bird movements over the full annual cycle throughout much of the EAAF, providing estimates of migration traffic rates, site use, and long-term population trends, especially in remote and less-surveyed regions. Analyses of weather radar data would complement existing ornithological surveys and help understand the past and present status of the avian community in a highly threatened flyway.

Introduction

Each year, billions of migratory birds move around the planet, transporting nutrients and energy, and providing ecosystem services across large geographical scales (Bauer & Hoye, 2014; Dokter et al., 2018; Hahn et al., 2009; Horton et al., 2019; Şekercioğlu et al., 2004; Van Doren & Horton, 2018). Migratory birds require intact chains of habitat all along their migration routes and are threatened by habitat loss on the breeding and non-breeding grounds

(Robinson & Wilcove, 1994; Wauchope et al., 2017), loss of staging areas (Mehlman et al., 2005; Studds et al., 2017), climate change (Renner & Zohner, 2018; Vickery et al., 2014), and hunting (Gallo-Cajiao et al., 2020; Mcculloch et al., 1992). Continental-scale estimates indicate that neotropical and Afro-Palearctic migratory birds are declining at an alarming pace (Gregory et al., 2019; Møller et al., 2008; Robbins et al., 1989; Rosenberg et al., 2019; Vickery et al., 2014), with long-distance migrants often declining faster than resident and short-distance migrants (Heldbjerg & Fox, 2008; Sanderson et al., 2006; Thaxter et al., 2010). Measuring the status and trends of avian populations remains an urgent task for both local and global conservation (Bauer et al., 2019; Jetz, McPherson, & Guralnick, 2012).

Migration routes and the population trajectories of migratory birds are rather well understood in the American and African-Eurasian flyways, but substantially less so for other regions (Yong et al., 2021). Despite being one of the most species-rich and threatened flyways in the world, the East Asian-Australasian Flyway (EAAF) is still a relatively poorly understood migration system (Kirby et al., 2008; Somveille et al., 2013). The EAAF hosts more than 700 migratory bird species (Kirby et al., 2008) and spans from Russia's far east and Alaska to Australia and New Zealand, covering much of East and Southeast Asia (Fig. 1). Rapid forest conversion, land use change, coastal reclamation, and urbanization in EAAF countries pose significant challenges to biodiversity (Sodhi et al., 2004). While population declines of certain groups of migratory species are documented (e.g., buntings and shorebirds; Choi et al., 2020; Clemens et al., 2016; Edenius et al., 2017; Kamp et al., 2015; Studds et al., 2017), status and trends of migratory populations at regional or continental scales have scarcely been evaluated (but see Kim et al., 2021). Fundamental ecological questions such as the amount and timing of bird migration remain to be answered along most of the EAAF (Dingle, 2008; Yong et al., 2021). Year-round, long-term and large-scale monitoring of migration systems are urgently needed to reveal the regional- and continental-wide patterns and changes to safeguard ecosystem integrity, function and services (Bauer et al., 2019; Cardinale et al., 2012; Şekercioğlu et al., 2004).

Various methods exist to track and study bird movement, the most direct of which are attaching bands, radio tags, or satellite tags to individual birds. Yet tracking studies inevitably focus on tracking the movements and population trajectories at individual- and species-level, whereas broader approaches are needed to reveal the status and trends of bird populations as a whole at regional or continental scales (Kelly & Horton, 2016). Weather radar networks are an excellent tool to study the large-scale aerial movements of birds. Weather radars provide continuous near real-time estimates of aerial bird movements, and have been used in North America and Western Europe to describe the speed, timing, height, intensity, and direction of nocturnal bird migration (Dokter et al., 2011; Farnsworth et al., 2016; Nilsson et al., 2019), identify key migration routes and stopover habitats (Buler & Dawson, 2014; Desholm et al., 2014), estimate continental fluxes, and mitigate human-wildlife conflicts (Nussbaumer et al., 2021; Van Doren et al., 2021; Van Doren & Horton, 2018). Weather radar networks exist in many countries and cover large amounts of land area (Saltikoff et al., 2019), especially in North America, Europe, East Asia, and Oceania. For some radar systems, data are archived back to the 1990s, representing a valuable store of historical information in cases where other sources of monitoring information are scarce (Ansari et al., 2018; Saltikoff et al., 2019; Soderholm et al., 2019).

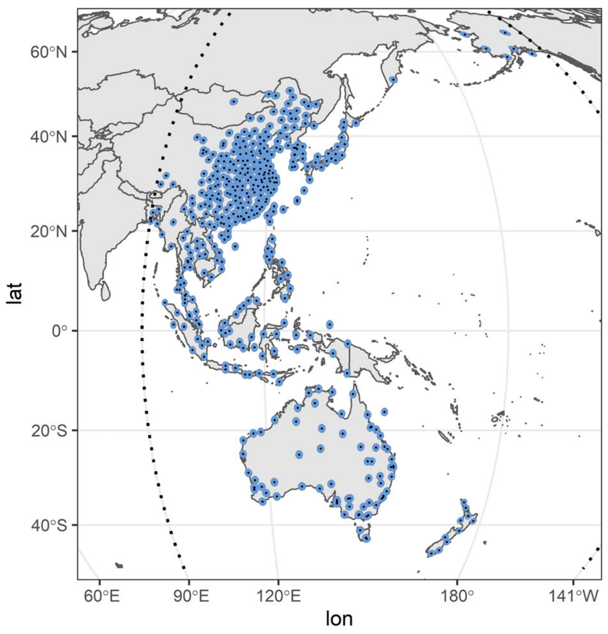

Figure 1. Weather radar locations and coverage in the EAAF countries. Black dots represent radar locations, with a 100 km buffer around the radar location shown in blue. Note that only radars within the EAAF range for each species (90° E-141° W, indicated by the dark dotted line, same for the following figures) are included, therefore some radars in Western China and Russia are not shown on the map.

Although radar ornithological studies in Asia and Oceania have a long history (e.g., Myres & Apps, 1973; Tulp et al., 1994; Williams, 1990), coordinated and continuous ornithological applications over wide geographical areas are still largely confined to Europe and North America, while the current extent and capacity of weather radars in EAAF countries are yet to be examined from an ecological point of view. Recently, Australian weather radar data have been made openly accessible online and studies have demonstrated great potential for ecological applications (Meade et al., 2019; Rogers et al., 2020). Cui et al. (2020) also showed that Chinese weather radars are able to detect large-scale aerial animal movements. Nonetheless, weather radar ornithological studies in the EAAF have been mainly experimental or opportunistic, with single radars and relatively limited spatial and temporal spans (e.g., Lane & Jessop, 1985; Minda et al., 2008; Myres & Apps, 1973; Sun et al., 2010; Ueta et al., 2009; Williams, 1990). The potential coverage of the migration routes of birds provided by weather radar networks have yet to be evaluated along the EAAF. Integrating data across these radar networks will be crucial for unveiling historical changes and predicting future trends of bird migration along the flyway.

In this study, we summarize the location and capacity of weather radar systems in the EAAF countries and consider the logistical and analytical challenges of using radars in the various countries along the flyway. To evaluate the potential of monitoring migration with weather radar in the EAAF, we calculate the spatial coverage of weather radar for different groups of migratory bird species during the different stages of the annual cycle, as well as the proportion of migratory species that are covered by weather radar in each country. To exemplify the potential for large-scale monitoring in the EAAF, we extracted and visualized nocturnal movement patterns from a set of weather surveillance radars in the China Next Generation Radar Network (CNRAD). We further discuss a number of potential new research topics in ecology and conservation that could be answered using weather radar data in this region.

Assessment of Spatial Coverage Provided by Weather Radars

Weather radar networks in EAAF countries

We determined the location, capacity, and availability of weather radars across the EAAF countries and regions from the World Meteorological Organization website (oscar.wmo.int) and complemented this using information from published papers, meteorological bureau websites and by personal communications with experts throughout the flyway. The exact sources for each country are given in the supplementary material. We used a 100 km radius around each radar location to illustrate a plausible detection range for migrating birds. This assumes no effect on terrain and elevation angle because it is impossible to assess beam blockage without prior knowledge of bird flight altitudes in the EAAF. Although many studies were conducted at a closer range (such as 37.5 km, i.e., Dokter et al., 2019; Nilsson et al., 2019; Van Doren & Horton, 2018), radar data can be analyzed up to 100 km when altitudinal/spatial resolution is not of primary interest (e.g., Buler & Dawson, 2014; Sivakumar et al., 2021). We thus decided to use this more generous range to estimate the broad potential of radar networks in the EAAF.

As of 2021, a total of 439 radars are installed in the EAAF region (Fig. 1, see also supplementary material). China has the most radars (n = 206), concentrated on its eastern and southern coasts. Australia has the second largest number of radars (76, although only 54 of them are currently operating as of 2022), mostly located in the coastal regions, followed by Indonesia (n = 42) and Japan (n = 21). For those we can find information, 90% are Doppler (single or dual polarized) radars.

Migratory birds in the EAAF

We made a list of East Asian migratory bird species from Yong et al. (2021), complementing this with migratory non-pelagic species from the Anseriformes, Charadriiformes, Pelecaniformes, and Podicipediformes, with their migratory status determined from Brazil (2009) and MacKinnon et al. (2000). We further added to the list the Australian species with strong or suggestive evidence for large-scale movement from Griffioen and Clarke (2002) and categorized each species as “raptors,” “waterbirds” (including “shorebirds”), “passerines” and “others” based on their taxonomic affinities. This resulted in a total of 616 bird species being included in this study. The complete list of birds can be found in the supplementary material. We acknowledge that many Australian species are likely not regularly fully migratory in the way that typical northern hemisphere birds migrate, and that many species included in this study are likely to be partial migrants (Chan, 2001). This does not diminish the need to understand the migratory movements of such species. Species distribution data were acquired from the Birdlife International species distribution dataset (BirdLife International, 2019). We selected only the extant and native components of species’ distributions as defined in the Birdlife dataset. We cropped and calculated the area of each species distribution to the east of 90° E following Yong et al. (2021) and west of 141° W (the approximate boundary of Alaska, USA), and calculated the amount of migratory bird species in each EAAF country. The EAAF area was further cropped by the radar coverage to calculate the EEAF area covered by radars, from which we also calculated the amount of species distribution intersected by each radar, as well as its relative proportion to each country’s total number of migratory species.

Radar coverage of internationally important sites for shorebirds (a subset of the waterbird category) was also analyzed, since shorebirds adopt different migration strategies than other broad-front migrants, with big numbers occurring from a relatively constrained set of stopover and non-breeding sites. We compiled a list of important shorebird sites in the EAAF countries from Conklin et al. (2014) and identified the sites within 100 km of radars.

The highest number of migrants were covered by weather radars in Laos (214 species, one radar, 75% of country total), followed by Vietnam (210.2 ± 29.3, on average 66% of country total) and China (205.7 ± 42.9, 33%, Fig. 2 and Table 1). The Oceania radars cover lower numbers of migrants (Australia: 86.3 ± 23.1, 47%; New Zealand: 30.1 ± 3.3, 67%) compared to the Asian ones. On average, a single radar provides coverage of 45% of the migrants in its country.

Non-breeding and passage ranges are best covered by radar (45% [interquartile range: 31%–66%] for all non-breeding ranges, 40% [7%–64%] for all passage ranges, Fig. 3), except for waterbirds' passage ranges (21% [0%–50%]). Breeding ranges are least covered by radar, especially for raptors (6% [2%–20%]) and waterbirds (7% [1%–32%]). Resident ranges of all bird categories are similarly covered within radar range (38% [22%–57%]). For more than half of the passerine species, weather radars provide at a maximum of 50% coverage during one phase of their life history (55% [38%–79%], Fig. 4), which is similar for waterbirds (53% [39%–77%]) and other species (54% [37%–69%]), although the maximum coverage radar can provide is slightly lower for raptors (52% [30%–73%]).

Of a total of 354 internationally important shorebird sites across the EAAF, 248 (70%) are within 100 km of a weather radar (Fig. 5), 93 (38%) of these 248 sites are close enough for the radars to detect birds down to 500 m above the ground, and 175 (71%) can be detected down to 1000 m. In the high-latitude breeding grounds (Alaska, Russia), 2 of the 31 sites are covered by radar. For the mid-latitude countries with important stopover sites, China has 75 (90%) sites within 100 km of a radar, while Japan and South Korea each has 64 (78%) and 26 (93%) sites within 100 km of a radar. Australia and New Zealand have 40 (62%) and 8 (42%) sites within 100 km of a radar, respectively.

Extraction of Nocturnal Biological Movement Patterns from Weather Radars in China

We accessed data from 55 Chinese weather radars for the month of October 2017, a time of the year when ground observations suggest migration activity is high in the region. Radar polar volumes from 20:00 to 02:00 the next day at 30 min interval were selected using the 5–35 km radius and elevation angles from 0.5° to 4.3°, up to 3000 m above ground level at 20 m altitudinal intervals

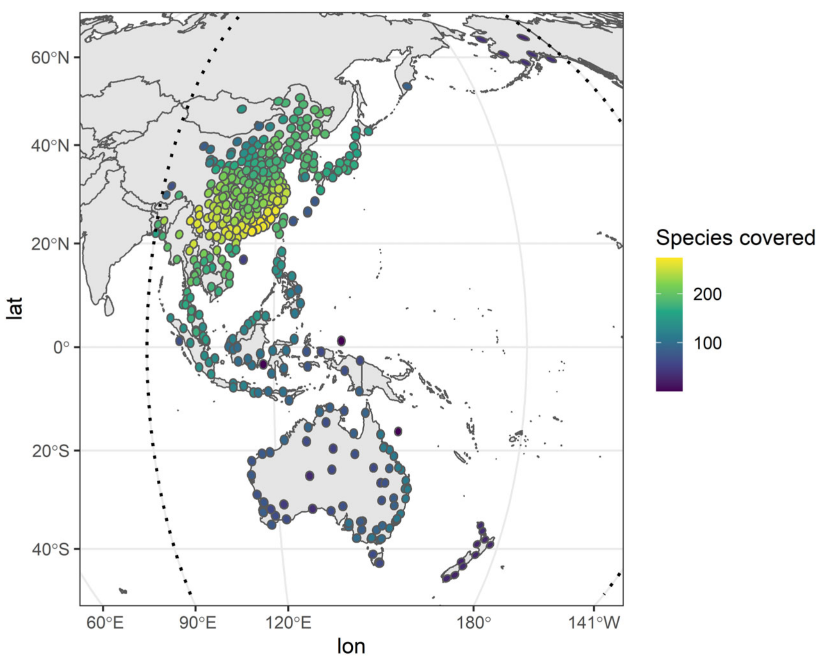

Figure 2. Number of migratory bird species potentially covered by each radar. The dots represent radar locations and the color ramp represents the number of bird species with at least one of their seasonal distributions covered within 100 km of each radar.

Table 1. Coverage of migratory species by weather radars in the EAAF. Standard deviation is not shown for countries with one radar, and the proportion of a country's species covered is limited to 100% if radar range extends beyond the country's boundary and covers more species than the country total.

Country	Species covered per radar	Standard deviation	Total number of migratory species	Proportion covered
Australia	86.3	23.1	184	47%
Bangladesh	187.8	33.7	258	73%
Brunei	146.0	–	133	100%
Cambodia	176.0	–	214	82%
China	205.7	42.9	629	33%
Indonesia	101.5	32.6	228	45%
Japan	148.1	35.8	249	59%
Laos	214.0	–	286	75%
Malaysia	148.6	18.5	203	73%
Mongolia	146.0	–	231	63%
Myanmar	205.3	16.2	367	56%
New Zealand	30.1	3.3	45	67%
Philippines	127.4	17.3	158	81%
Russia	139.0	73.5	336	41%
Singapore	152.0	–	106	100%
South Korea	175.2	21.8	202	87%
Thailand	186.4	26.3	317	59%
United States	37.3	4.1	92	41%
Vietnam	210.2	29.3	317	66%

(Dokter et al., 2011). Biological information in the weather radar data was identified by image segmentation with a deep-learning-based convolutional neural network (CNN, see also Lin et al., 2019). We first developed an image segmentation tool trained with manually labeled radar images containing meteorological or biological signals, then converted polar-gridded reflectivity factor radar data to greyscale images and segmented this to extract biological information. For each radar, the resulting biological reflectivity is integrated vertically (VIR, see Dokter et al., 2019) and averaged for each time interval and day. A more detailed step-by-step documentation of the methodology can be found in Cui et al. (2020). We also converted the biological reflectivity to bird density (birds km^{-3}) following Dokter et al. (2011) assuming all signals are birds and same average radar cross section with European studies (11 cm^2) for nocturnally migrating birds. Assuming all signals are birds would most definitely overestimate the numbers, therefore the bird density given in this study is for experimental reference only.

In October 2017, the pattern of nocturnal animal movement was strikingly coherent across the entire region, predominantly toward the southwest (mean direction: 214°; Fig. 6) and highly consistent within sites, with 75% of the sites had a mean vector length >0.7. Movement intensity was highest in the central area of our study region, that is, Central China, with the highest VIR values from Shaoyang, Hunan Province (VIR: 37.8; bird density: 79.3 birds km^{-3}), Jingzhou, Hubei Province (37.2; 74.0 birds km^{-3}) and Buyang, Anhui Province (37.0; 66.0 birds km^{-3}), while being relatively lower at coastal, southern, and southeastern sites.

Discussion

Radar coverage and research prospects in the EAAF

We have shown that an extensive weather radar network exists in the EAAF flyway with broad coverage of migratory birds, from breeding grounds in North Asia to the non-breeding regions in Southeast Asia and Australia, covering all life stages of avian migrants. The extensive coverage across a range of taxonomic groups throughout

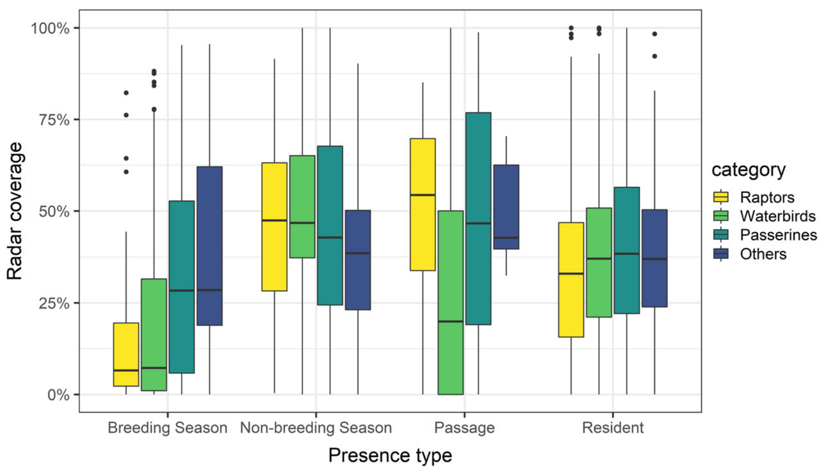

Figure 3. Spatial coverage by weather radar across the full annual cycle of migratory birds in the EAAF

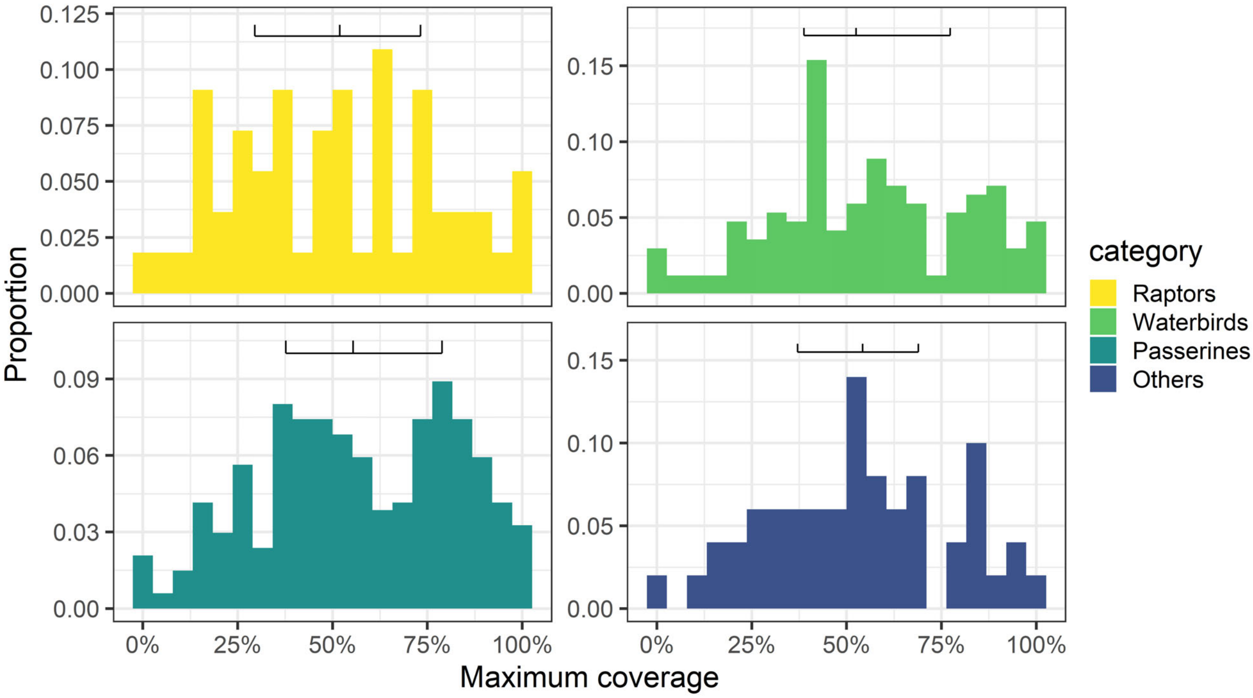

Figure 4. Weather radar's maximum coverage among the four presence types in each species' life history. Horizontal bar above each histogram represents the interquartile range.

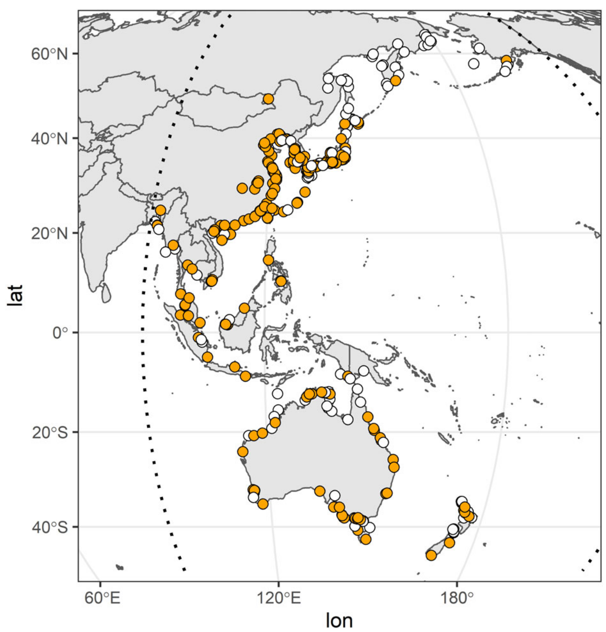

Figure 5. Important shorebirds sites within (orange) and outside (white) 100 km of a radar. Shorebird site information is extracted from Conklin et al. (2014).

the life cycle highlights a unique opportunity for full annual cycle monitoring with radar networks in the EAAF. Weather radars in other flyways are mostly concentrated in the northern hemisphere, while radars in the southern part of the flyway (i.e., Africa and South America) covering the non-breeding ranges of migrants are generally lacking. Radar studies are therefore biased toward breeding and migration seasons, hindering the evaluation of how migrants interact with biotic and abiotic conditions during the non-breeding season that may have profound impacts on the population dynamics of migratory birds (Marra et al., 2015; Rushing et al., 2016). In comparison, weather radars have high potential coverage of the non-breeding (wintering) ranges of EAAF migrants: radar networks in the southern part of the EAAF provide unique opportunities for monitoring the status of migrant passerines, waterbirds, and raptors migrating to South and Southeast Asia, as well as shorebirds that fly to Australia and New Zealand.

With only two radars in the Siberian part of Russia and one in Mongolia, radar coverage on the breeding grounds of most migratory birds is relatively low in the EAAF. Nonetheless, radars in Alaska, Northern China, South Korea, and Japan could monitor the timing and amount of arrival and departure on the southern parts of breeding grounds of many species. The dense radar network in the mid-latitudes, especially in Central and Eastern China, provides good coverage of migrants' passage ranges, as well as the resident populations of some partially migrating species. The relatively low coverage of

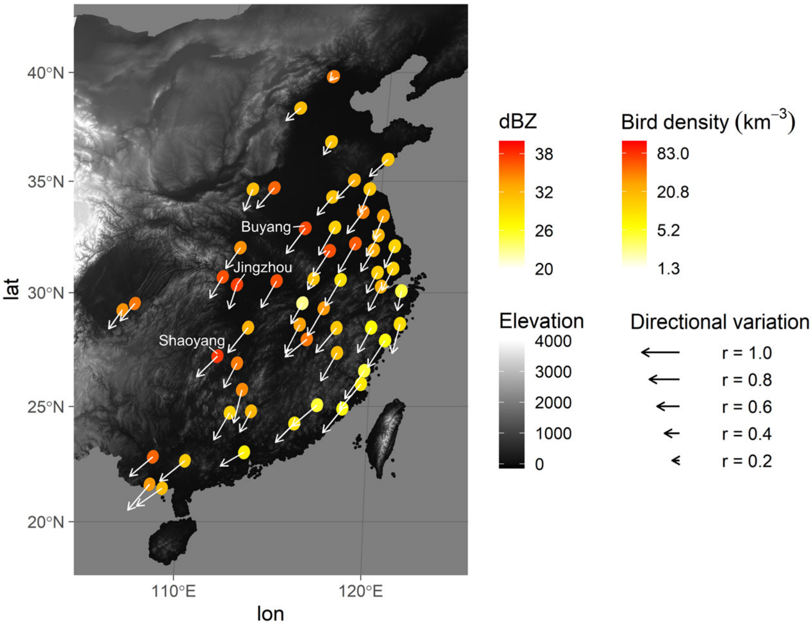

Figure 6. The pattern of animal migration extracted from a set of Chinese weather radars during October 2017. The Biological VIR is log-transformed and multiplied by 10, hence displayed in dBZ and also converted to bird density (birds km^{-3}), assuming all signals are birds. The arrows represent the associated mean movement direction at each location and the length of the arrows represents the mean vector length (r).

waterbirds' passage ranges is mainly due to the lack of information in the Birdlife dataset, and our results probably underestimate the coverage of passage ranges for these species. By quantifying the biomass flow of avian migration observed by radar in different parts of the flyway, it is possible to compare the survival of migrants in the breeding, passage, and non-breeding grounds (Dokter et al., 2018; Nussbaumer et al., 2021). With the stopover and wintering ranges in South and Southeast Asia undergoing rapid habitat loss (Murray et al., 2014; Sodhi et al., 2004), such understanding would be crucial for avian conservation across the entire flyway. Taken together, the relatively complete radar coverage of avian migrants in the EAAF would enable ecologists to evaluate the status of avian migrants throughout the year.

Due to relatively small landmass, the average national proportion of migratory species covered by each radar is usually higher in island countries/regions and peninsulas, such as South Korea (86% of all migrants), the Philippines (81%), Taiwan (73%), and Malaysia (73%). East Asian migrants often congregate at these narrow land corridors to minimize the lengths of sea crossings during migration, leading to large concentration of birds during the migration season (DeCandido et al., 2004, 2010; Nourani et al., 2018; Sugasawa & Higuchi, 2019). A prime example would be raptors that breed in North Asia and migrate *via* the island chains of Japan, Taiwan, and the Philippines (commonly referred to as the East-Asian Oceanic Flyway), often in tens of thousands of individuals that form large flocks visible on radar screens (Chen et al., 2022; Concepcion et al., 2017; Sun et al., 2010). Weather radars in these islands/peninsulas and narrow land corridors are therefore able to achieve nearly complete coverage of all migrant species with relatively few radars. Some selected radars at key migration corridors, such as Kenting radar (21.90° N, 120.85° E) in Taiwan, Chumphon radar (10.50° N, 99.19° E) in Thailand, and Aparri radar (18.36° N, 121.63° E) in the Philippines, would be able to record large amounts of migration that can be linked with species information by on-ground observation, sampling migration in a core part of the flyway. To date studies have used the Kenting radar to observe raptor migration (Sun et al., 2010), while we found no ornithological applications of the selected weather radars in Thailand and the Philippines, regional exchange of radar data exists (Kakihara, 2018) and might be possible for ornithologists to harness data from these key sites.

Weather radar has also proved to be a successful tool to detect and estimate large congregations of birds and other flying organisms (Bridge et al., 2016; Chilson et al., 2019; Meade et al., 2019; Russell & Gauthreaux, 1998); this could be very useful in evaluating shorebird numbers at established important sites along the coast, as well as detecting unknown locations of high shorebird concentration in un-surveyed habitats. Previous studies have shown that radars can detect shorebird movements (Lane & Jessop, 1985; Richardson, 1979; Tulp et al., 1994; Williams & Williams, 1988), especially in remote, un-surveyed regions, and during periods when ground-based monitoring is not feasible. High-resolution spatial radar studies of songbird migration (e.g., Buler & Dawson, 2014; Cohen et al., 2021) have been used to identify very discrete areas of high-quality stopover habitat based on mass nocturnal take-offs from limited geographical areas, and similar studies could be done to identify and evaluate important shorebird stopovers. With about 70% of currently known important shorebird sites within 100 km of weather radars, weather radar data could be a crucial tool to detect shorebird movement, providing low-cost, repeated, and year-long monitoring in highly threatened habitats such as the Yellow Sea coast of China and South Korea (Studds et al., 2017), as well as less-surveyed regions in Southeast Asia and Australia.

Autumn nocturnal movement pattern from weather radars in China

The algorithm we used distinguishes biological signals from meteorological ones but does not differentiate among insects, bats, and birds. Hence the pattern documented in this analysis relates to general autumn migration of all flying animals, and should be interpreted with care; it is mainly intended here as a demonstration of the monitoring capacity and ecological potential of large-scale weather radar networks in the EAAF. Nonetheless, the radar-observed patterns are in overall agreement with bird tracking and banding studies in this region (e.g., Heim et al., 2018; Jiao et al., 2016; Yong et al., 2015), with autumn movement aligned toward the southwest in East China. Although it is difficult to compare the amount of individuals without information on the bird-insect proportion and the average size of migrants, our results indicate that the inland, central part of our study region (e.g., Hubei, Hunan, and Anhui Provinces) may have higher amounts of migration than the coastal regions. Current studies of migration quantification and conservation interventions are concentrated along the east coast of China, while knowledge on the ecological and conservation status of avian migrants are largely incomplete from Central China where the highest number of migrants may occur in the whole country. A full year of data from a few selected radars in Central China could help quantify migration intensity in this under-studied region, and subsequently identify unknown migration hotspots and potential conservation needs. With the rapid growth of citizen science data such as the eBird (Sullivan et al., 2009), researchers would also be able to cross-reference migrant assemblage and phenology between citizen science observation and radar estimations to unveil more details of bird migration in this region.

Challenges of studying bird movement using weather radar data

Although there is a large amount of radars in the EAAF regions, not all radars in this region have the Doppler capacity that records objects' velocity components, which is often a core part of algorithms that separate birds from other airborne objects (Dokter et al., 2019). For example, less than half of the Australian radars are Doppler-capable (Rogers et al., 2020), mostly concentrated in the more populated coastal area, although updates to Doppler are planned for all Australian radars in the near future. Updates to dual-polarization have only recently begun in a few countries, compared to an already complete upgrade to dual-polarization in the United States and many European countries. Other technological limitations, including lack of species-level information and discrimination from meteorological and non-bird biological signals, are perennial challenges in radar ornithology that will also hamper the ecological applications of weather radar data in the EAAF.

Spatial gaps of radar coverage in the EAAF still remain in sparsely populated regions, including inland Australia, mountainous regions of Southeast Asia, Mongolia, and Siberia. Beam blockage by terrain will also limit radar coverage in mountainous regions, especially in Southwest China and inland Southeast Asia, biodiversity hotspots that host high amounts of bird species (Jetz et al., 2012). Temporal availability is also an issue for the weather radars in the EAAF. In some countries, installation of weather radars and upgrade to Doppler capacity has taken place only in recent years, storage of historical data is often patchy and the quality of data is inhomogeneous, so there remains significant uncertainty about the amount of historical data available (Saltikoff et al., 2019).

Another major issue limiting the ecological application of weather radar is data accessibility. So far only Australian and Alaskan (USA) radar data are made openly accessible under creative commons licenses, most countries have not made public whether and how their radar data is accessible. A few countries require payment (e.g., New Zealand) or authorized personnel (e.g., China) for access, which limits its application for ecologists that are not affiliated to meteorological agencies. Cross-border collaboration can also be challenging in the EAAF, as weather radars are in some cases considered sensitive defense infrastructure, and data are considered confidential (Min et al., 2019). Drawing on the European radar network (Huuskonen et al., 2014; Shamoun-Baranes et al., 2014), a multi-country strategy to build a platform that facilitates data exchange and shared use in the EAAF is probably key to fulfilling the potential of the radar network in this region for migratory bird research and constitutes a long-term objective of radar ecologists.

Conclusion

Unveiling trends in migratory bird populations require long-term, large-scale datasets that arise from decades of standardized monitoring. While biodiversity surveys and citizen science projects are quickly emerging in East and Southeast Asia, these are often conducted at a much smaller temporal and spatial scale than in Europe and North America (Chandler et al., 2017; Martin et al., 2012). Baseline avian status data are often lacking, biased toward more populated areas and accessible sites, limiting their potential to inform conservation decision-making (Callaghan et al., 2021). Infrequent and biased observations often result in an incomplete picture of the past situation that limits the accuracy of population change estimations. Radar data streams thus embody a potentially invaluable historical and contemporary record of biodiversity information in the EAAF regions, especially during a period of unprecedented natural habitat conversion in the last decades that would likely have led to drastic changes in the avian community. With recent analytical advances such as the MistNet (Lin et al., 2019), ornithologists are able to analyze decadal time series of radar data to infer avian population status using fully automated approaches. Biological information in the EAAF radars could be harvested in a similar manner to create historical trajectories of population changes.

Weather radar networks in the EAAF region provide a great opportunity for large-scale, full annual cycle monitoring of avian migrants, yet the prospect of such research is limited by the availability and accessibility of radar data and the difficulty for cross-border collaboration. Before a complete network is in place, aero-ecology studies from countries with wide spatial coverage and easy access to radar data are the most feasible option and will be representative of the whole region. For example, weather radars in Central and Southern China and the northern Indochinese Peninsula appear to offer good coverage of a relatively high number of species during their migration, while the Australian radars seem particularly useful for monitoring the movement of migratory shorebirds and the intracontinental movements of Australian landbirds. Thus, we suggest ecologists in the region start to make use of the opportunities afforded by weather radar systems around the EAAF. We recommend that as a first step ornithologists in the region should work with meteorological agencies from within each country/region in the EAAF to facilitate data access and overcome the availability issues. Subsequently, platforms can be organized that share results, build analytical capacity, and promote data exchange that transcends boundaries, and eventually establish a large-scale network that oversees the whole flyway. In combination with essential "ground-truthing" data from visual observations of migrant birds, the radar networks along the EAAF hold great promise for monitoring and understanding migration patterns and population trends in this region of critical conservation importance.

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Appendix S1 List of bird species included in this study.

Appendix S2 List of radars included in this study.

