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Monitoring continent-wide aerial patterns of bird movements using weather radars

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Billions of insects, birds and bats use the aerosphere for migration, dispersive movements or foraging. This enormous movement of biomass plays a key role in ecological connectivity, yet monitoring aerial movements is technically very challenging. Individual tracking devices have been increasingly used over the last decade but these are currently only suitable for relatively large organisms, and the associated costs limits monitoring to a very small sample of the aerial animal community. Radars provide a tool for investigating and quantifying movement patterns for a wide range of flying organisms (birds, bats and insects), across communities and populations. However, research efforts in this field have often been local and uncoordinated. As a network of operational weather radars is continuously recording atmospheric conditions all over Europe, ENRAM (The European Network for the Radar surveillance of Animal Movement) has been recently established to explore the potential for coordinated, large-scale studies of the aerial movements of animals (Shamoun-Baranes *et al.* 2014). Here, we present the first outcomes of this collaborative research, and provide details on the visualization of a case study of mass migration of birds tracked using several national weather radars in the Netherlands and Belgium simultaneously. Finally we will also discuss the opportunities that a large sensor network can provide for movement ecology research at the continental scale.

Why track avian movements at the continental scale?

Bird migration is the natural phenomenon that routinely tackles the largest ecological barriers on the planet. Seed dispersal has been recorded for distances of 650–1540 km over unsuitable habitats (Sorensen 1986), but several bird species migrate between continents, often travelling several thousands of kilometres, over oceans, deserts and mountain ranges (e.g. the Himalayas). Due to these movements, birds also function as long-distance dispersal agents for other species (plant propagules, parasites; see Bauer & Hoye 2014 for a review). Furthermore, migrant birds move energy and nutrients across the planet, influencing trophic interactions and linking ecological communities across the globe (Bauer & Hoye 2014). These translocations of biomass are not trivial as for the Afro-Palaearctic system alone 2.1 billion (song and near-passerine) birds are estimated to move between Europe and Africa each year (Hahn *et al*. 2009). The ability to track and quantify avian migration at the continental scale therefore provides a unique opportunity to monitor a major flux of biomass between regions of the globe with cascading implications for biodiversity conservation, ecosystem connectivity and potentially human health.

Combining and processing bird movement data from multiple weather radars

Weather radars across Europe are operated by national governmental institutions. However, geo-political borders are of little relevance to meteorological (and animal movement) events, and more accurate forecasts can be achieved if information from neighbouring countries is available, and hence international networks based upon data sharing agreements are already in operation across Europe (e.g. BALTRAD, OPERA; Huuskonen *et al.* 2014). Despite capitalizing on previous agreements, one of the major challenges faced by ENRAM is to be able to access unprocessed data from the 149 weather radars from the 24 countries currently participating in the OPERA network and exchanging data (for area covered see Fig. 1). Attaining bird (or animal) movement data requires such information to be extracted before the data are converted to two-dimensional precipitation maps, as these maps generally contain information from the atmospheric layer above that which includes birds and insects. This implies accessing data that some countries might consider sensitive and therefore new data sharing agreements need to be forged between ENRAM parties and close collaboration is needed between ecologists and meteorologists.

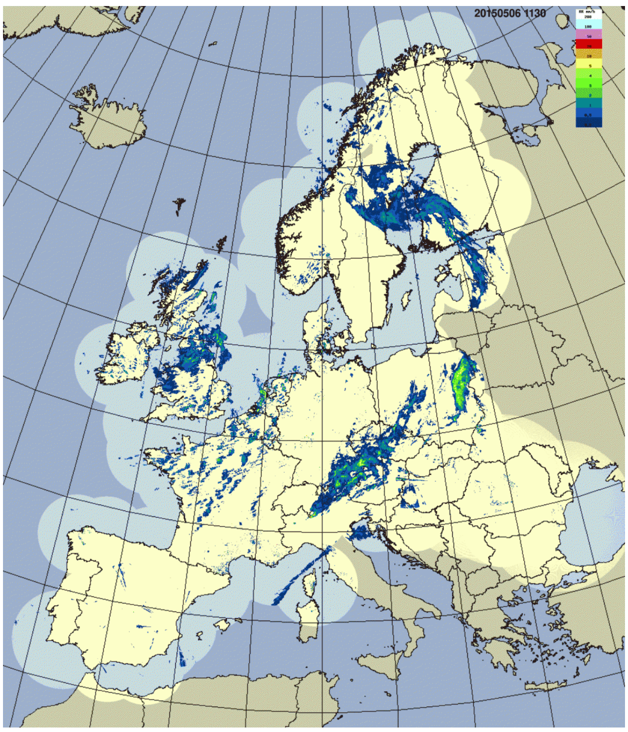

Figure 1. Example of an OPERA rainfall rate composite, showing the area of Europe currently monitored by weather radars in the OPERA network http://www.eumetnet.eu/opera

Nevertheless, access to weather radar data from several countries is already possible and recent advances in bird data extraction have enabled the merging of data from multiple radars (Dokter *et al.* 2011). Based on bird movement data collected simultaneously at five weather radars in Belgium (Jabbeke, Zaventem, Wideumont) and the Netherlands (Den Helder and De Bilt), it has been possible to interpolate and visualize large-scale patterns of migration flux for the first time in Europe (Fig. 2). The dataset reflects a mass migration period in these countries that occurred between 7 and 8 April 2013, when weather conditions became favourable for northeasterly migration after a relatively long period of unfavourable northerly winds.

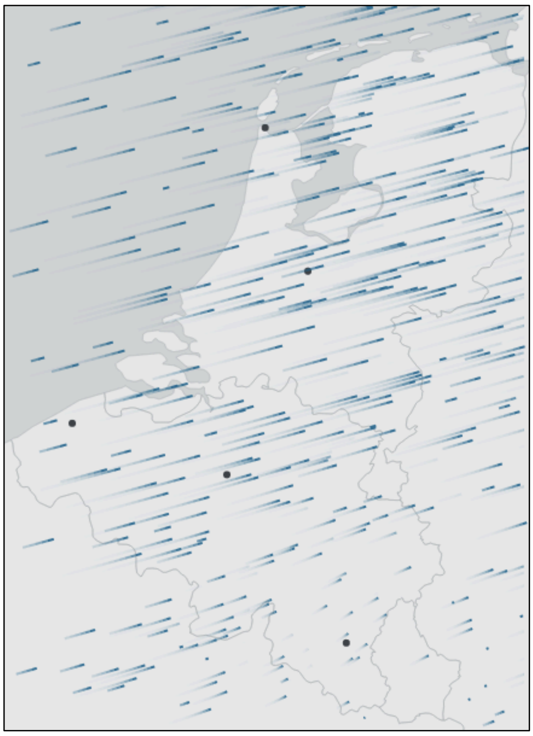

Figure 2. Bird Migration Flow Visualization. Bird migration over Belgium and the Netherlands recorded by five weather radars (blue dots) on 7 April 2013 at 00:40 h. Line angle indicates direction and line length increases with speed. http://enram.github.io/bird-migration-flow-visualization/viz/2/nl-be/index.html

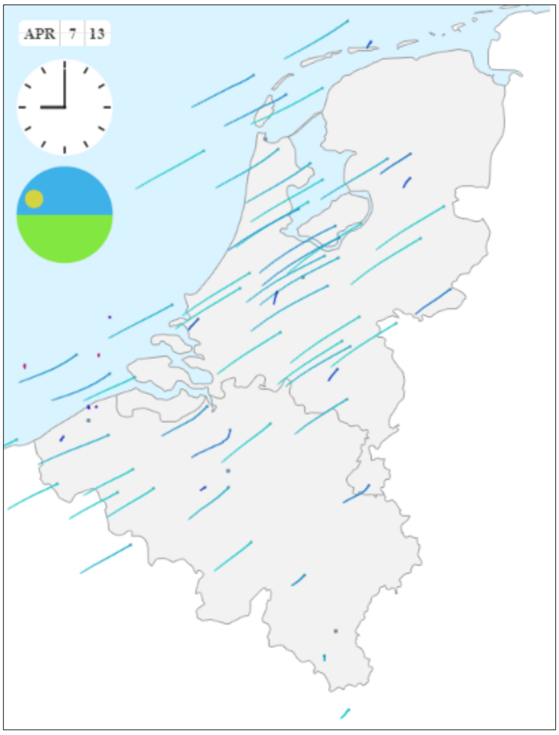

Figure 3. TIMAMP – Time Integrated Multi-Altitude Migration Patterns (Animated Migration Flowlines version). Length of the lines indicates projected travel distance during a 2-h window and line colour indicates altitude. http://timamp.github.io/

The Bird Migration Flow Visualization (Fig. 2) uses flying direction detected by each radar (decomposed in u and v speed) of migration (not individual birds or flocks) to construct an interpolated grid upon which particles are randomly released acquiring the speed and direction of each point in the grid they encounter (follow the link for animated version). Recently this same dataset was re-analysed, resulting in both static and animated visualizations with migration represented at several altitudes (Fig. 3).

These early analyses of bird migration data recorded simultaneously at multiple weather radars demonstrates the potential for expanding this approach to the continental scale. By quantifying the direction, speed and density of migrants across large spatial and temporal scales we will be able to tackle previously unanswered questions of bird migration.

Research opportunities

A major limitation in avian radar-ecology is the inability to determine the species being detected. Some radar types, specifically those designed to study animal movement, are able to detect species groups (e.g. waders, passerines; Zaugg *et al.* 2008) or species that are unique in their flight patterns, e.g. swifts (*Apus* sp.) that have an identifiable wing beat pattern (e.g. Bäckman & Alerstam 2002; Dokter *et al.* 2013). Weather radars do not have identification capabilities, and despite promising advances using dual polarization beams which enable cross-section measurements and other parameters of targets (e.g. Zrnic & Ryzhkov, 1998), species-level identification is currently not achievable in operational meteorological scanning. However, this is also an opportunity to go beyond individual species and investigate bird movement at the community level.

The community of avian migrants moves along paths in three-dimensional space which might vary seasonally, and mapping these paths in space and time is likely to be crucial for the planning of large human structures, e.g. airports and aviation paths, and on- and off-shore windfarms. By quantifying the relative density of migrants at concentration points during spring or autumn passage, annual changes in their populations may be investigated (e.g. Gauthreaux 1992). Radar studies can potentially inform on both breeding success and winter mortality of migrants as they move from their breeding and wintering areas, respectively. By using radars and data collected across a continental network, entire flyways can potentially be surveyed, thus facilitating the monitoring of seasonal and annual demographic changes in migration patterns. Furthermore, comparisons between different migratory routes might allow identification of locations of relatively high mortality (or breeding success) and by tracking migrants along the same flyway, location and periods of mortality can potentially be discriminated. This information is extremely valuable for the conservation of migrants and can be used to establish conservation areas for these species, on land, at sea and in the air.

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