Modelling the flow of nocturnal bird migration with year-round European weather radar network.

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Abstract

The movements of migratory birds constitute huge biomass flows that influence ecosystems and human economy, agriculture and health through the transport of energy, nutrients, seeds, and parasites. To better understand the influence on ecosystems and the corresponding services and disservices, we need to characterize and quantify the movements of migratory birds at various spatial and temporal scales.

Representing the flow of birds in the air as a fluid, we applied a flow model to interpolated maps of bird density and velocity retrieved from the European weather radar network, covering almost a full year. Using this model, we quantify how many birds take-off, flight and land each night across Europe. Cumulating these daily fluxes of take-off and landing over time, we can summarize the change in the number of birds on the ground over the seasons and the entire year, track waves of bird migration between nights across Europe, and identify regions that see major biomass movements.

The resulting numbers are impressive: We estimate that during the breeding season, 187 million (M) more birds (623M arriving and 436M leaving) reside in Western Europe (than during winter), while 452 M more birds departed in autumn (934M leaving and 482M arriving).

Our study show-cases the enormous potential of combining interdisciplinary data and methods to elucidate the dynamics of avian migration at various spatial and temporal scales, and once more emphasizes the importance of weather radar data being made available from all European countries.

Keywords

biomass flow, weather radar, migration ecology, ornithology, fluid dynamics, interactive visualisation, ecological modelling.

Background

Myriads of birds embark on migratory journeys in spring and autumn (Alerstam, 1993). Their sheer numbers create huge biomass flows (Dokter et al., 2018; Hahn, Bauer, & Liechti, 2009) that impact ecosystem functions and human economy, agriculture and health through the transport of energy, nutrients, seeds, and parasites (Bauer & Hoye, 2014). To understand these influences on ecosystems and make use of, or avoid, the resulting services and disservices, we need year-round and continental-wide monitoring of migratory fluxes and their quantification at various spatial and temporal scales. Continental networks of weather radars are becoming an essential tool for monitoring large-scale migratory movements (Bauer et al., 2019). However, most studies so far have focused on migratory flights (Dokter et al., 2018; Nilsson et al., 2019; Nussbaumer et al., 2019; Van Doren & Horton, 2018), and a few modelled the stop-over distribution of birds on the ground (Buler et al., 2017; McLaren et al., 2018). Yet, none have linked these two stages and we therefore lack a comprehensive model of the entire migratory journey including the explicit consideration of the successive stages of take-off, flight and landing. To integrate migratory take-off, flight and landing into a single framework, we use a methodology from fluid mechanics. While novel in aeroecology, fluid mechanics methods have earlier been applied in ecology, for instance the concept of permeability from Darcy's Law to calculate species movement rates (Jones, Watts, & Whytock, 2018) or a hydrological residence time model to estimate the stop-over duration of migratory birds (Drever & Hrachowitz, 2017). Here, we represent nocturnal migratory movements of birds as a fluid because the averaged density and flight speed of birds have a smooth spatio-temporal variation. More specifically, we combine interpolated maps of both bird density and velocity field (i.e. the vector field of bird's flight speed and direction) inferred from weather radar (Nussbaumer et al., 2019) into a discretized flow model (Figure 1). Since we assume that the mass of birds moving from one grid cell to another is conserved, any change of bird density (in the air) is explained by movements to and from the ground. Thus, we can quantify how many birds take-off or land at a given time and location. In subsequent steps, we use the resulting maps of take-off and landing to (1) visualize the dynamics of daily stop-overs, (2) estimate the accumulation (i.e. changes in numbers) of birds on the ground throughout the year and (3) compare the migration flows across regions.

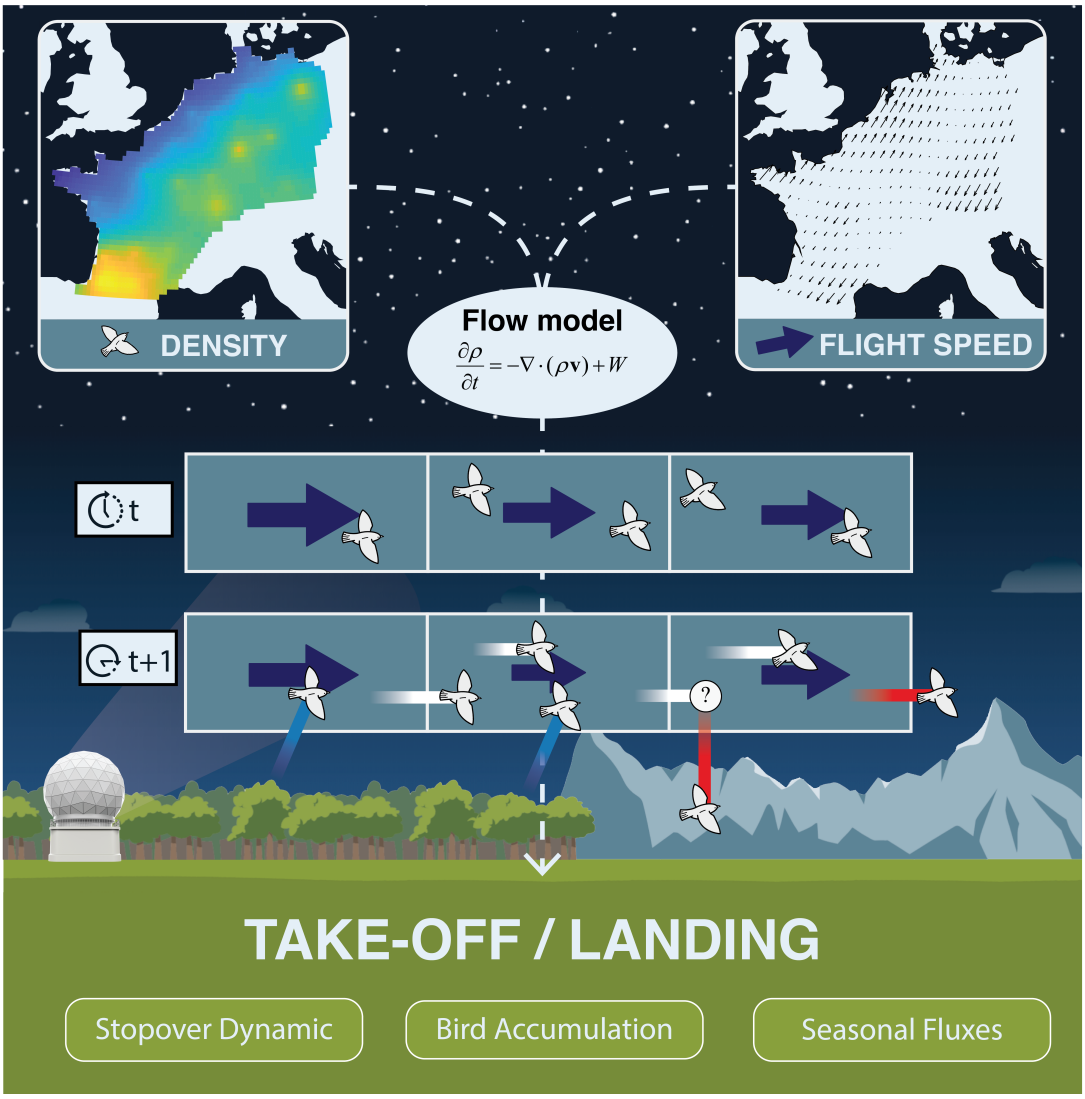

Figure 1. Overview of the methodology presented. Nocturnal bird migration is modelled as a fluid flow at the continental scale. Continuous maps of bird density and velocity field are combined in a flow model to estimate fluxes of birds moving in and out of the migration media (i.e. sky). The method relies on comparing the number of birds in each cell of the maps (illustrated in 1D with only three white frames) between two consecutive time steps (t and t+1). Combining the initial position of birds at time t with their respective flight speed (blue arrow; size of arrow is proportional to the locally varying flight speed), the model predicts the position of birds at the next time step t+1 (movement represented as white line at t+1). The difference between the predicted and the observed number of birds corresponds to birds appearing (illustrated as blue line) or disappearing (red line/question mark). The appearance and disappearance can respectively be due to either birds taking off and landing over the area or leaving and entering the area at the boundary. The resulting maps of take-off and landing birds allow us to investigate the spatio-temporal variation of stop-over dynamics, accumulation of birds on the ground, and geographic variation in the seasonal fluxes of birds.

Methodology

Data

We use the data from 37 weather radars in France, Germany, the Netherlands and Belgium operating between 13 February 2018 and 1 January 2019. This dataset is currently the longest available time series over a large part of Western Europe. It consists of vertical profiles of bird density [bird/km^3], their flight speed [m/s] and direction [°] which were generated with the vol2bird software (Dokter et al., 2011) and are available on the ENRAM repository (ENRAM, 2020) at a 5 min x 200 m (0-5000m a.s.l.) resolution (supplementary material 1.1). Similar to previous studies (Nilsson et al., 2019; Nussbaumer et al., 2019), the vertical profiles were manually cleaned with a dedicated graphical user interface to eliminate rain and ground scatter, as well as to fill gaps in bird density, flight speed and direction (supplementary material 1.2). In addition, insect contamination was identified and removed from radar signal based on their low airspeed (computed from (Copernicus Climate Change Service (C3S), 2017)) and their low standard deviation of ground speed (supplementary material 1.3). Furthermore, we improved the method to integrate vertically (i.e. volumetric to areal) bird density and flight speed by (1) accounting for the impact of local topography on the surveyed volume, and (2) simulating bird density in the volume of air below the altitude surveyed (supplementary material 1.4). Since the radars provide point observations (averaged over a 5-25 km radius around the radar location), the bird density [bird/km^2] was interpolated into a spatio-temporal grid using the methodology developed in (Nussbaumer et al., 2019). Nights without data were excluded from the interpolation, resulting in a small gap in early April, and a larger gap during the month of July (Figure 3). Bird velocity field was interpolated for the two N-S and E-W components separately. Adjustments of the interpolation method to a year-round dataset and to velocity fields are detailed in supplementary material 2. The interpolation grid is defined between latitudes 43° and 55° and longitudes -5° and 16°, with a resolution of 0.25° and between 13 February 2018 and 1 January 2019 with a resolution of 15 min. Grid cells are excluded if (1) they are located over a water body or above 2000 m a.s.l, (2) they are more than 150 km away from a weather radar, (3) they span over day time (i.e., from sunrise to sunset), or (4) rain intensity exceeds 1mm/hr (ERA5 dataset from (Copernicus Climate Change Service (C3S), 2017) was used to estimate rain intensity).

The resulting interpolation maps can be visualized at `www.bmm.raphaelnussbaumer.com/2018`.

Flow Model

Based on the principle of mass conservation, the continuity equation describes the transport of a conserved quantity (Figure 2): for a given volume (or area in 2D), the rate of change of this quantity is equal to its flux into and out of the volume. The equation can also include a source/sink term, which accounts for the appearance (and disappearance) of the quantity, such as through chemical reaction, reproduction, or in our case, the take-off and landing of migratory birds. The differential form of the continuity equation for bird density ρ [bird/km^2] is

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{v}) + W, \tag{1}$$

where $\mathbf{v} = [v_{lat}, v_{lon}]$ is the bird's velocity field [km/hr] along latitude and longitude and W is the source/sink term [bird/hr/km^2]. The continuity equation is discretized with a Forward Time Centered Space (FTCS) scheme (Roache, 1972), as illustrated in Figure 2. The source/sink term can be computed for each cell (i, j, t) with

$$W_{i,j}^{t\to t+1} = \frac{\rho_{i,j}^{t+1} - \rho_{i,j}^{t}}{\Delta t} - \left(\Phi_{\text{lat}}|_{i-1/2,j,t}\Delta\text{lon} + \Phi_{\text{lon}}|_{i+1/2,j,t}\Delta\text{lon} + \Phi_{\text{lon}}|_{i,j-1/2,t}\Delta\text{lat} + \Phi_{\text{lon}}|_{i,j+1/2,t}\Delta\text{lat} \right), \tag{2}$$

where the flux term is $\mathbf{\Phi} = \rho\mathbf{v} = [\Phi_{\text{lat}}, \Phi_{\text{lon}}]$, expressed in [bird/km/h] and Δt, Δlon, Δlat are the grid resolution in time, longitude and latitude respectively.

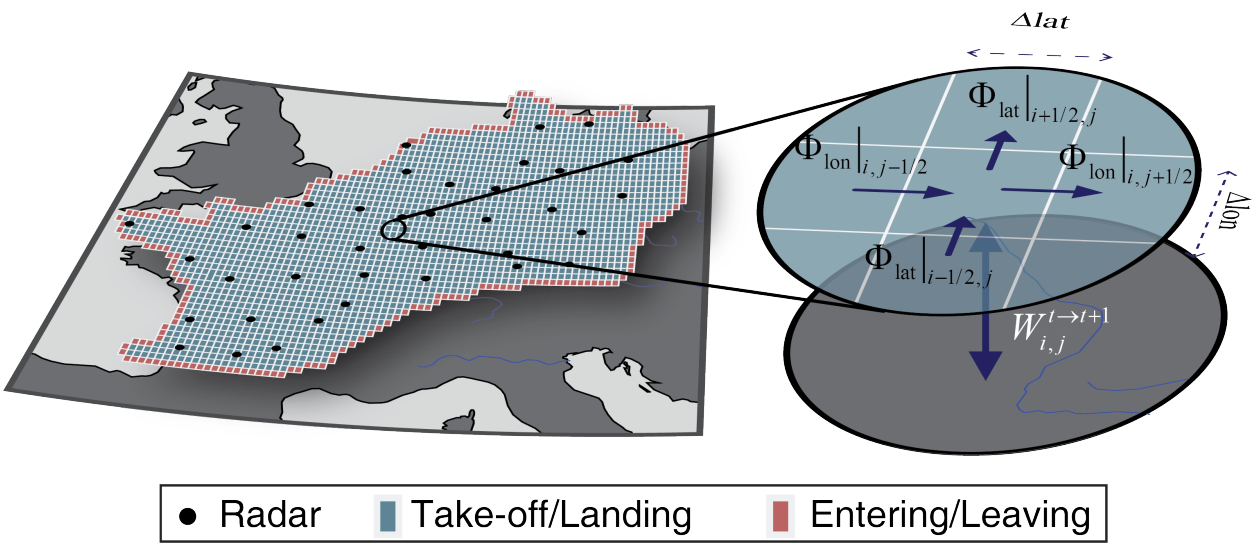

Figure 2. Illustration of the discretization of the continuity equation applied to bird migration. The principle of mass conservation states that the change of bird density over time in each cell (blue square) is equal to the sum of the fluxes ($\mathbf{\Phi}$) between neighbouring cells and the source/sink term (W, i.e. take-off/landing). For the grid cells in the periphery of the study area (red squares), the source/sink term (W) estimates the birds movement entering/leaving the study area.

We apply this model to bird migration by considering bird movement in the air as a fluid. The local fluxes are computed for each grid-cell by multiplying the density with the flight vector (Equation 2). These fluxes are then linearly interpolated to the grid cells' boundaries (Figure 2) for both the longitudinal and latitudinal components. Finally, using Equation 3, the source/sink term is computed for each grid cell at each time step as the change of bird density over time minus the spatial difference of fluxes. The resulting source/sink maps are smoothed to remove small-scale artefacts originating from (1) the sharp edge of rain and daytime masks, or (2) the extrema of bird density visible near radar locations in density maps. This smoothing is performed by the convolution of a 2D Gaussian kernel with isotropic standard deviation of 0.75°. The source/sink term W is composed of birds taking-off and landing (within the study area), as well as birds entering and leaving the study area. These four components are therefore separated by their contribution to the number of birds in the air. Positive values of W correspond to take-off while negative values correspond to landing. Additionally, the values of W at the study area's boundaries are extracted separately as the number of birds entering (positive) and leaving (negative) the study area (Figure 2), thus assuming no take-off nor landing at the boundary cells. Following this procedure, we produced space-time maps of (1) take-off and landing [bird/km^2] and (2) fluxes in lat-lon [bird/hr/km] at the boundaries of the study area..

Migratory Processes

The produced maps are combined into several by-products to address specific ecological questions. We were particularly interested in characterizing and quantifying nightly migration pulses and stopovers, the accumulation of birds on the ground, and the seasonal migration flows. To achieve this, we proceeded as follows:

- **The nightly migratory pulses and stopovers** are calculated by summing the take-off and landing movements separately over each night, and by visually comparing the maps of landing in the morning with those of take-off the following evening.

- **The year-round accumulation of migratory birds on the ground** is quantified by first aggregating the four fluxes (take-off, landing, entering, leaving) over the whole study area and for each night. Then, the nightly change in the number of birds on the ground is computed as the difference between take-off and landing, or equivalently, between entering and leaving. The cumulative sum of these daily changes corresponds to the number of birds that remained on the ground. We arbitrarily set the starting value of the accumulation to zero because the initial number of (resident and wintering) birds on the ground is unknown. The same procedure is applied to compute the total number of birds

entering (and leaving) the study area over the year.

- **The seasonal flow of bird migration** is quantified by summing the fluxes of birds over spring (February-June) and autumn (August-December). To calculate them, we first computed the **in and out** flows by summing the fluxes of birds entering and leaving the study area. To capture the variability of movements across Europe, we defined six transects along the boundary of the study area according to the major flyways: United Kingdom, the North, the East, the Alps, Spain and the Atlantic (Figure 5). Then, we summed the spatial maps of take-off and landing **within the study area** separately for the two seasons of migration.

Results

Nightly migratory pulses and stopovers

For illustration purposes, we selected a well-defined migration wave spanning from 6 to 10 April, during which birds moved from south-west France to north-east Germany (Figure 3). Over each night, the area between the bulk of take-off and landing has a higher bird density and higher flight speed during the night. More importantly, one night's landing and the following night's take-off are in good agreement (columns in the Figure), which demonstrates that the data and proposed methodology can accurately track a wave of migration over several days. This agreement is particularly striking because most birds were in active migration and stopped over for one day only. This wave of bird migration crossed our study area in four nights performing nightly jumps of around 300km. On April 10, one radar in south-west France is picking up a new wave arriving.

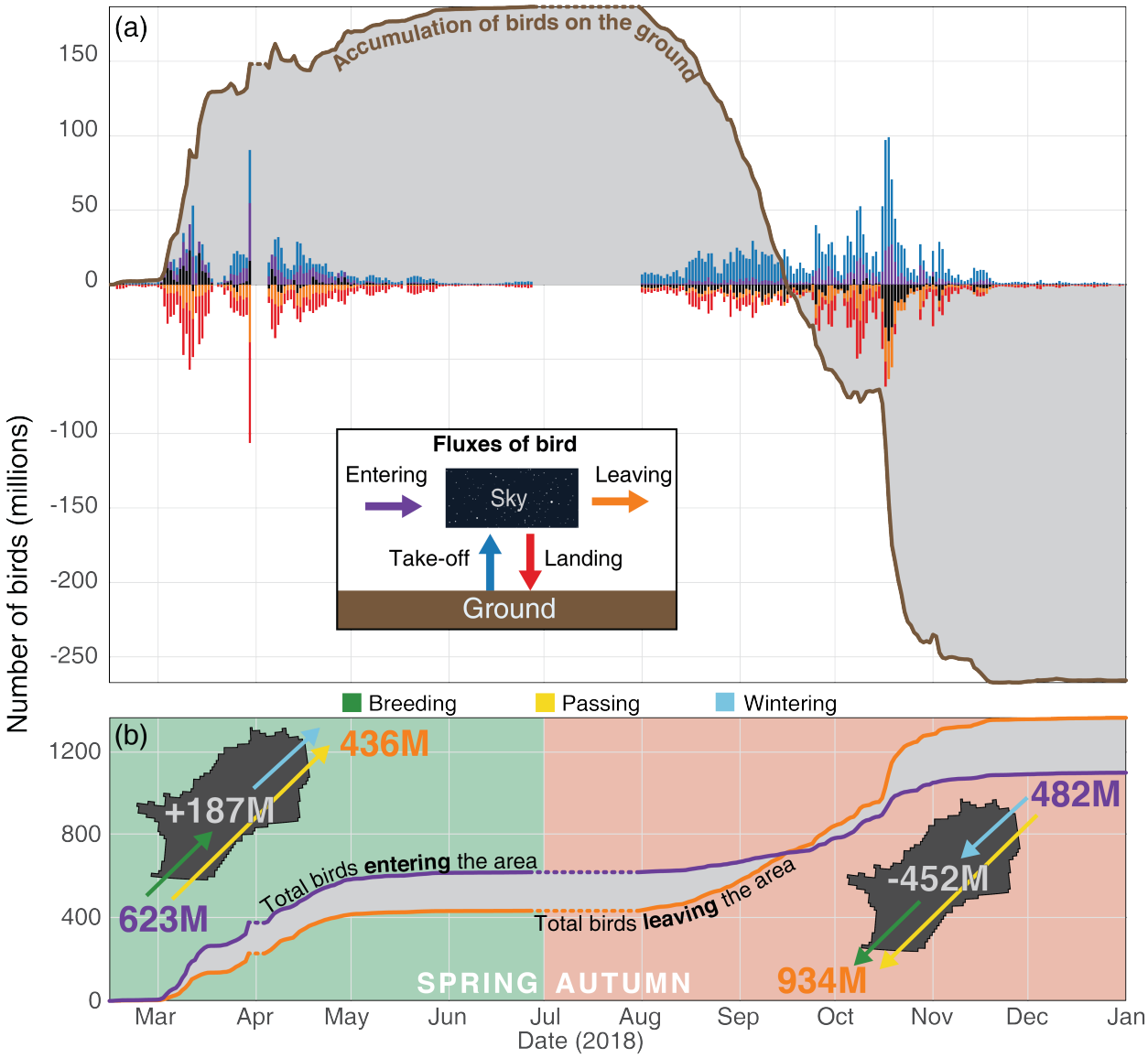

Figure 3. (a) Time series of the daily number of birds taking-off (blue) and landing (purple), as well as entering (red) and leaving (orange) the study area. The changes in the number of birds on the ground (black), and their accumulation (i.e. cumulative sum) (brown line) is calculated as the difference between the number of birds entering and leaving the study area. (b) Cumulative time series of birds entering and leaving the area. The difference between the two lines is equal to the accumulation curve plotted in (a) (grey shaded area). Integrated over a season (spring or autumn), the total number of birds entering to (purple), leaving from (orange), and accumulating in the study area (grey) can be computed. However, the number of birds breeding (green arrow), passing (yellow arrow), and wintering (blue arrow), cannot be disentangled from these Figures. The dotted lines denote absence of data.

Year-round accumulation of migratory birds on the ground

Accumulations of the flow at the daily (or nightly) scale allows us to characterize the year-round changes in numbers of migratory birds on the ground (Figure 4a). The number of birds on the ground rises steeply in March with 150 million more birds entering in the study area than leaving from it. Numbers are declining from August onwards, and culminate in a steep drop in mid-October. As our procedure does not explicitly account for reproduction and death, the overall number becomes negative in autumn as the number of birds leaving includes the new generation and is therefore greater than the number of birds that had entered in spring. The spring migration period is shorter and more condensed (March - May) than the autumn migration (August to mid-November) (Figure 4a), with 50% of all take-offs taking place during 18 nights in spring and 28 nights in autumn. At peak migration, we estimate 90 million birds taking off in a single night in spring (30 March – 1 April) and 99 million in autumn (18-19 October). In spring, 623 million birds entered the study area (breeding + passing) and, at the same time, 436 million left it (wintering + passing), creating a surplus of 187 million birds on the ground within the study area (Figure 4b). Similarly, in autumn, 452 million more birds departed (934M of breeding + new generation + passing) than arrived (482M of wintering + passing, Figure 4b). Our quantification indicates that 1.5 times more birds left the area in autumn (-934M, breeding + passing) than had entered in spring (+623M, breeding + passing). The ratio of the autumn loss (-452M, i.e. entering - leaving) to the spring surplus (+187M, i.e. entering - leaving) is 2.4, meaning that for one additional bird entering in spring, 2.4 more birds left in autumn.

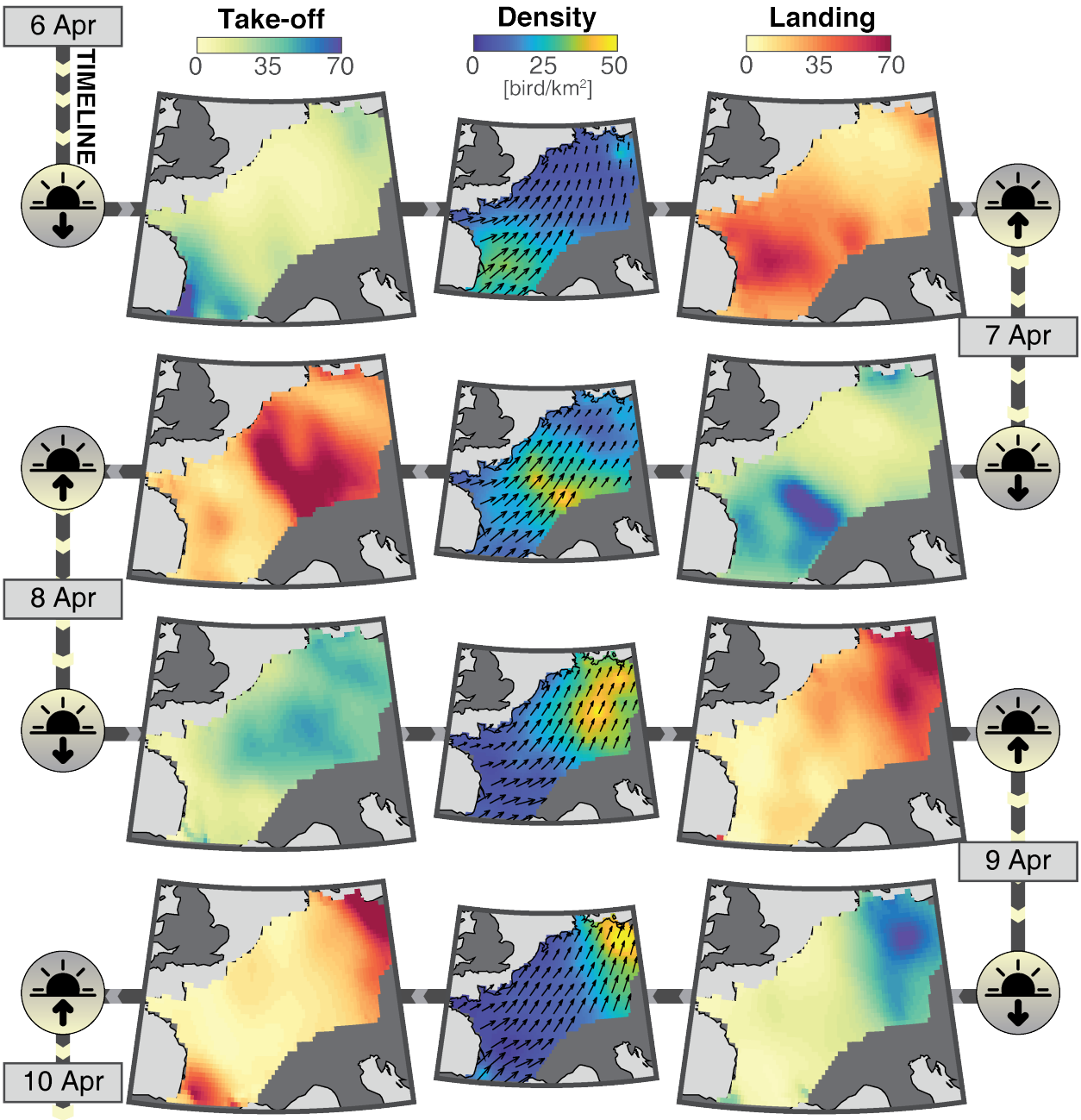

Figure 4. Nightly movements of bird migration between 6 and 10 April 2018. Following the timeline (dashed grey line), each night (row) starts with take-off, then the density and flight speed (averaged over the entire night) and finally the landing. Take-off and landing maps show the sum of take-off and landing over the entire night, respectively.

Seasonal Flow

In and out

The main flyway of migration in the study area (both in spring and in autumn) is from Spain to Eastern Germany. Indeed, even the migration through the Atlantic transect mostly comprises birds crossing the Bay of Biscay from Spain. In contrast to spring, birds take a more easterly route in autumn, with proportionally more birds flying through the Alps transect (autumn/spring = 105/62 = 1.7) than the Atlantic transect (215/166 = 1.3). Moreover, fewer birds cross the East transect in autumn than in spring (139/171 = 0.8). This suggests a clockwise loop migration where birds migrate to their breeding ground via the Iberian Peninsula in spring and fly south further East in autumn.

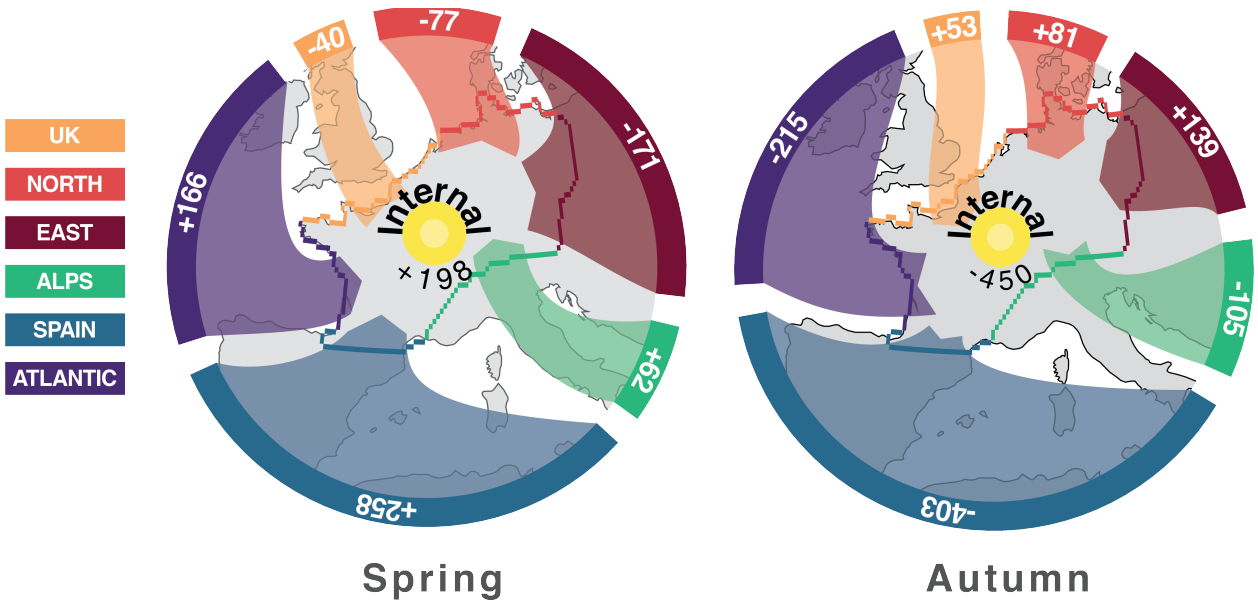

Figure 5. The flow of bird migration (in millions of birds) in spring and autumn are aggregated by six transects representing the major flyways. The direction (in and out of the area) is illustrated by the shape of the flow arrow as well as the sign (+/-) in the pie chart value. The internal accumulation is found by summing all the inward and outward fluxes. The total number of birds entering and leaving slightly differ from Figure 4b because Figure 4b shows the cumulative numbers per grid cell, whereas Figure 5 sums the fluxes over each entire transects flux thus, neutralising cells with fluxes of opposite sign within a transect.

Within the study area

For the entire spring season, birds mainly took-off from France, while landing is more spread-out with many birds landing in southern France and central Germany. As a result, the combined map of spring showed a net increase in the number of birds in Germany and a more heterogeneous pattern in France. Like the landing pattern in spring, many birds took-off from southern France and central Germany in autumn. In autumn,

the landing activity is highest in southern France. Taken together, these maps highlight a higher turn-over rate of birds both in spring and autumn in France than in Germany, while in Germany proportionally more bird staying during the breeding season than passing-by.

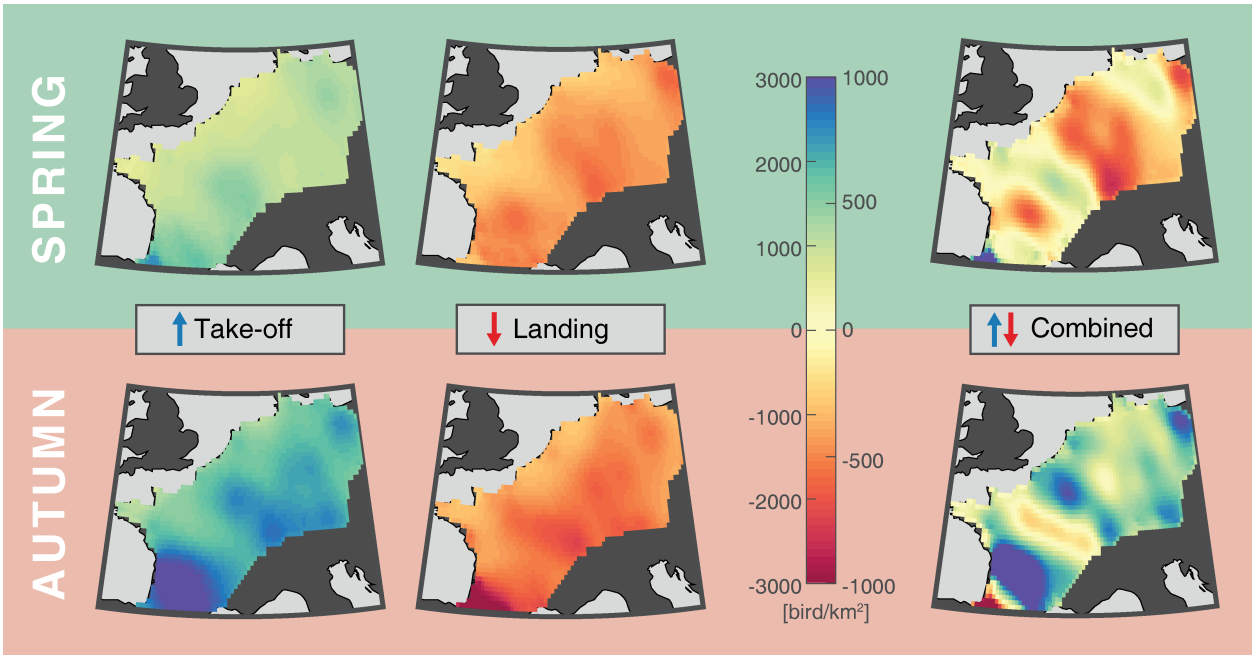

Figure 6. Take-off and landing maps aggregated over spring (top) and autumn (bottom). Different ranges of the colour-scale are used between take-off/landing (left of the colour scale) and the combined maps (right of the colour scale).

Discussion

In this study, we present a novel methodology inspired from fluid dynamics to model the migratory flows of nocturnal migrants, tracking the mass of birds from take-off, during nocturnal flight, to landing. The model produces high-resolution maps that allow investigating the dynamics of migratory movements at various spatial and temporal scales. We used the largest available dataset on the ENRAM data repository to characterize and quantify nightly, seasonal and year-round migration patterns over most of Western Europe.

Model

The model presented in this study builds on the methodology developed in (Nussbaumer et al., 2019) which interpolates point observations of bird densities measured by weather radars into continuous maps. Our new approach uses these maps as the input of a flow model by considering bird migration as a fluid. This allows

us to extract more dynamic information about bird movement, in particular, information about take-off and landing.

The fluid flow approach used here to model bird migration requires several conditions to be met. Firstly, the settings of the spatio-temporal grid must allow numerical convergence such that mass is conserved. This was ensured with a Current number lower than 1, $\frac{u\Delta t}{\Delta x} < 1$ (i.e. bird speed multiplied by temporal resolution must be smaller than the spatial resolution of the grid). Secondly, this approach models bird density rather than the individual birds, which implicitly assumes that the movements of individual birds can be accurately depicted by their averaged quantities (density and flight speed and direction). This condition is also met since the underlying data consists of bird density and velocity field averaged over a 25km radius around the radar location.

Finally, both interpolation and flow modelling require bird migration to be a smooth process, both temporally and spatially. Although this assumption is generally met at the regional and continental scale, there are probably small-scale (<50-100km) variations in bird density and flight speed caused by geographical features (mountains, rivers, sea), weather conditions (e.g. rain), and radar biases (ground scattering, position of the radar in view of the local topography), which cannot be properly accounted for with the current weather radar data (average distance between neighbouring radars is 130km). To address this and avoid a misleading interpretation of the results, we included a nugget effect in the interpolation (more detailed in Nussbaumer et al. (2019)) and a smoothing on the landing/take-off maps. Nevertheless, the analysis of spatial patterns of take-off and landing should always account for the number of, and distance to the nearby radars. Studying the movements of birds at finer scale is best carried out using polar volumes data (i.e., 360° radar scans) (e.g. Kranstauber et al., 2020).

Stopover

In this study, we show how waves of bird migration at the continental scale can be tracked over multiple nights (Figure 3). Our flow model links birds on the ground with birds in the air and can thus quantify take-off, flight and landing. Looking ahead, this example suggests that a forecast system based on a flow model of bird migration could accurately predict bird landings during the night, and perhaps, on a longer term, take-off and landing over a few days.

This method can compute the rates of both take-off and landing in high temporal resolution, and thus to account for birds taking-off and landing at any point during the night. It provides thus more details about the timing of take-off and landing than earlier approaches (e.g. 3hrs after sunset in Buler and Diehl (2009),

interpolation at civil twilight inBuler and Dawson (2014); Buler et al. (2012) or at maximum density within two hours after sunset in Aurbach, Schmid, Liechti, Chokani, and Abhari (2020)). This feature may prove particularly useful in follow up studies that aim at linking movements and stop-overs to geographical features or short, intense weather events. In addition, our quantitative estimation of bird's take-off would also nicely complement studies on species-specific variations in the timing of take-off as retrieved from individual tracking (Müller, Eikenaar, Crysler, Taylor, & Schmaljohann, 2018; Packmor, Klinner, Woodworth, Eikenaar, & Schmaljohann, 2020), and shed new light into the variation in landing behaviour.

Although our model can identify the places and times where birds stop-over, other aspects of stopover dynamics such as stopover duration or survival remain to be tackled in future radar studies. The main obstacle to address this topic is the inability to track birds during the day, i.e. which of the birds landing one day are the ones taking-off the following day(s). A similar problem appears at the seasonal scale, where we cannot identify which birds are wintering, breeding or passing from the birds landing or taking-off. A potential solution would be to model the stop-over duration with a residence time model (Drever & Hrachowitz, 2017). However, this approach requires assumptions of the pattern of individual stopover durations (storage age selection functions) which might undermine the analyses of stopover duration or survival.

Accumulation and seasonal flow

Using our novel methodology and an almost continuous one-year dataset, we assessed the changes in the relative number of birds on the ground. We estimated that in autumn 2018, 723 million birds migrated southwards through Spain and over the Alps (incl. the Atlantic transect). The only previous quantification of migrant bird population estimated that between 1.52 and 2.91 billion long-distance migrants leave the entire European continent in autumn (Hahn et al., 2009). Our estimation is aligned with these numbers if we consider that the breeding area of the migratory birds that flew through our study area (from the British islands to Scandinavia, Finland to Poland, and our study area) corresponds to roughly one third of the European continent as considered by (Hahn et al., 2009). In North America, the number of birds migrating out of the US in autumn was estimated to around 4.72 billion birds (Dokter et al., 2018), which corresponds to an average density of 236 bird/km^2 (19.8 million/km^2 US and Canada). Despite the difference of scale and ecological context, we find a comparable average density of 217 bird/km^2 when we assume again that a third of the European bird population migrates through the southern transect.

The ratio between autumn and spring fluxes can be used to estimate an index of recruitment into the

migratory population, accounting for both reproduction and mortality (Dokter et al., 2018). For the US, (Dokter et al., 2018) estimated a ratio of 1.36 for a transect along the southern border and 1.60 for a transect along the northern border. In our study area in Europe, the resulting indices are 1.5 in the southern transects (Alps, Spain and Atlantic, Figure 5) and 1.0 in the northern transects (UK, North and East, Figure 5), but these values are unlikely to represent the "true" recruitment because many migrants seem to undertake more easterly migration in autumn than in spring. Instead of computing the ratio of migratory birds flying across non-representative transects, we can take advantage of the flow model to estimate a ratio of migratory birds entering to and leaving from an area of interest, and thereby relate the corresponding recruitment index computed over this area to environmental characteristics. For the entire study area, a recruitment index of 2.4 is computed as the ratio between the relative number of birds that have left in autumn (i.e., leaving minus entering) (450M, Figure 4) with the relative number that have arrived in spring (i.e., entering minus leaving) (187M, Figure 4). However, as the fluxes of wintering and breeding bird populations cannot be distinguished (see discussion on stopover 4.1), this recruitment index also depends on the number of wintering birds that leave the study area in spring and return in autumn with offspring. Therefore, while this recruitment index can characterize the migratory bird population growth, it cannot separate the influence of breeding and wintering populations. A possible avenue to address this challenge is to combine breeding and/or wintering bird atlas data with our accumulation of birds on the ground. This approach could provide absolute numbers of breeding, passing and wintering birds along with their corresponding recruitment indices.

Outlook

In this work, we employed a flow model to quantify migratory fluxes of birds in the air and to/from the ground, connecting for the first time the successive migratory stages of take-off, flight and landing. This output constitutes a first step to monitor and track the mass migration of birds over large distances and periods of time. As such, this work invites several avenues of research. For instance, contrasting regional changes in migratory fluxes would improve our understanding of the effects of climate change on migratory behaviour. Moreover, tracking the biomass movement over distant locations can shed light on avian-induced dispersal of seeds, diseases and nutrients. In future studies, the accumulation of birds on the ground computed by the model could potentially be integrated with ground observations such as ringing, citizen science or breeding/wintering atlas to distinguish species and phenological stages (breeding, migration or wintering). On the methodological side, further improvements could include adding more constraints about bird behaviour and flight patterns, which would refine the model and would ultimately pave the way for a

forecasting model, similar to the numerical weather models used by meteorologists or groundwater models used by hydrogeologists.

The accessibility of historical and near real-time weather radar data has shown to be essential for a continental quantitative monitoring (e.g. Rosenberg et al., 2019), and to enable the development of migration forecasts that can contribute to mitigating conflicts with our society (e.g. Horton et al., 2018). Indeed, much work has been achieved in North America thanks to the National Oceanic and Atmospheric Administration's (NOAA) open data policy for weather radar archive (Ansari et al., 2018). This contrasts with the European situation, where biomass data are discarded, or simply not accessible. We are therefore yearning to unfold the full potential of our model with high quality standardized data available at the continental level, which can only be done with the support of the meteorological community.

Acknowledgements

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Authors' contributions

RN, FL, BS and SB conceived the study, RN, LB, GM designed the flow model, RN implemented the computational framework and performed the analyses, RN, BS and SB wrote the manuscript, with substantial contributions from all authors.

Data Accessibility

- The Github page of the project (`rafnuss-postdoc.github.io/BMM` contains the MATLAB livescript used for preprocessing, interpolation, analysis and creation of the figures (`https://rafnuss-postdoc.github.io/BMM/2018/`).
- The raw weather radar data were available on the ENRAM repository (ENRAM, 2020) (`https://github.com/enram/data-repository`).
- The cleaned vertical time series profile are available on Zenodo (`https://doi.org/10.5281/zenodo.3243397`) (Nussbaumer, 2020)
- The code of the website (`https://bmm.raphaelnussbaumer.com/2018`) are available on the Github (`https://github.com/Rafnuss-PostDoc/BMM-web-2018`)

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