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Essay

Meteorological Data Policies Needed to Support Biodiversity Monitoring with Weather Radar

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ABSTRACT: Weather radar networks have great potential for continuous and long-term monitoring of aerial biodiversity of birds, bats, and insects. Biological data from weather radars can support ecological research, inform conservation policy development and implementation, and increase the public's interest in natural phenomena such as migration. Weather radars are already used to study animal migration, quantify changes in populations, and reduce aerial conflicts between birds and aircraft. Yet efforts to establish a framework for the broad utilization of operational weather radar for biodiversity monitoring are at risk without suitable data policies and infrastructure in place. In Europe, communities of meteorologists and ecologists have made joint efforts toward sharing and standardizing continent-wide weather radar data. These efforts are now at risk as new meteorological data exchange policies render data useless for biodiversity monitoring. In several other parts of the world, weather radar data are not even available for ecological research. We urge policy makers, funding agencies, and meteorological organizations across the world to recognize the full potential of weather radar data. We propose several actions that would ensure the continued capability of weather radar networks worldwide to act as powerful tools for biodiversity monitoring and research.

KEYWORDS: Ecology; Radars/Radar observations; Animal studies; Biosphere-atmosphere interaction; Economic value; Policy

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The global rate of biodiversity loss has been raising serious concerns worldwide and ambitious international goals have been set to halt further biodiversity loss and restore biologically diverse and well-functioning ecosystems (Díaz et al. 2020). Informing and assessing biodiversity policies, designed to meet international and national goals, require large-scale and long-term monitoring programs that quantify spatiotemporal changes to biodiversity and identify their drivers. Yet, despite the breadth of potential biodiversity indicators, standardized biodiversity monitoring is still a major challenge worldwide (Pereira et al. 2013). Traditionally, biodiversity indicators such as species abundance are measured in situ, often through extensive monitoring schemes relying on trained (citizen) scientists following standardized protocols (Proença et al. 2017). In addition to these in situ measurements, remote sensing, which is often standardized across large spatial scales, has become an efficient and effective approach for sampling abiotic and biotic properties of extensive areas and providing information on ecosystem structure and functioning (Pereira et al. 2013; Proença et al. 2017; Skidmore et al. 2021).

Weather radars are uniquely positioned to provide automated and long-term monitoring of aerial biomass flows, an often unrecognized service to society (Bauer et al. 2017). While operational weather radars are deployed worldwide to provide essential meteorological data for near-real-time observations, atmospheric and climatological research, and meteorological services (Saltikoff et al. 2019b), they also detect biological targets such as flying insects, bats, and birds (Chilson et al. 2012) (Fig. 1). Existing networks of weather radars can therefore play a pivotal role in long-term and standardized monitoring of the abundance, biomass, activity, and movement patterns of the aerial fauna at continental scales (Bauer et al. 2017; Shamoun-Baranes et al. 2021).

In the United States, federal legislation ensures open access to public data and this, together with the National Oceanic and Atmospheric Administration's (NOAA) Big Data Partnership and developments in cloud storage and computing, has resulted in an historical archive of polar volume NEXRAD data (Ansari et al. 2018). Consequently, NEXRAD data have been used for large-scale and long-term aerial biodiversity research, for example, to identify and quantify long-term trends in bird migration phenology in relation to climatic drivers (Horton et al. 2020), large-scale avian productivity (Dokter et al. 2018), and the massive decline in the North American avifauna (Rosenberg et al. 2019) (Fig. 1), as well as the impact of weather and climate on bats (Frick et al. 2012; Haest et al. 2021), the effects of artificial light on

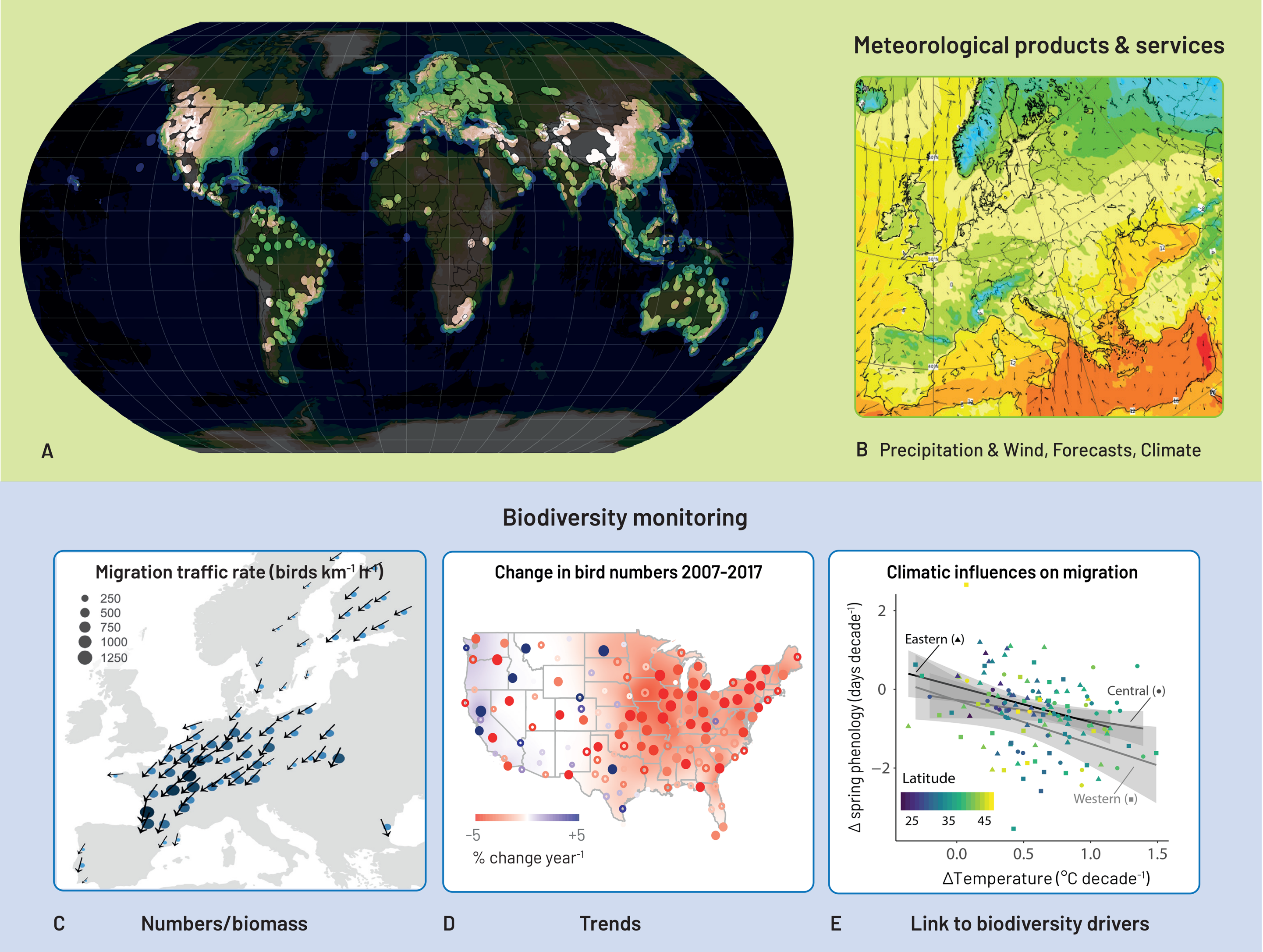

Fig. 1. (a) Weather radar networks exist in many places across the globe and (b) primarily provide data for meteorological products and services. (c)–(e) Weather radar data can also be used for biodiversity monitoring, for instance, for (c) the quantification of aerial biomass flows during migration, (d) the identification of trends in numbers/biomass over time, and (e) their relation to biodiversity drivers. (c) Bird migration intensity over northwestern Europe in autumn 2016 from (Nilsson et al. 2019); (d) changes in the number of migratory birds over a 10-yr period identified significant declines over most of the United States (Rosenberg et al. 2019), and (e) changes in temperature regimes over the United States led to changes in migration phenology (Horton et al. 2020). Credits: World map of weather radars from Saltikoff et al. (2019b); wind forecast from European Centre for Medium-Range Weather Forecasts for 7 Jan 2021.

insects (Tielens et al. 2021), and the long-term decline of insect abundance (Stepanian et al. 2020). In Europe, major steps have been taken in data standardization and data sharing for meteorological purposes, especially for the development of high-quality precipitation products, through the activities of Operational Programme for the Exchange of weather Radar Information in Europe (OPERA) under the governance of European Meteorological Services Network (EUMETNET) (www.eumetnet.eu/activities/observations-programme/current-activities/opera/) (Huuskonen et al. 2014).

To foster the use of weather radar networks for monitoring, understanding, and predicting aerial biomass flows, the European Network for the Radar surveillance of Animal Movement (ENRAM) was established with 24 participating countries including experts in ecology, meteorology, and information science (Shamoun-Baranes et al. 2014). This interdisciplinary collaboration resulted in a data license agreement between ENRAM members and the OPERA network that allows the use of weather radar data for ecological research, the implementation

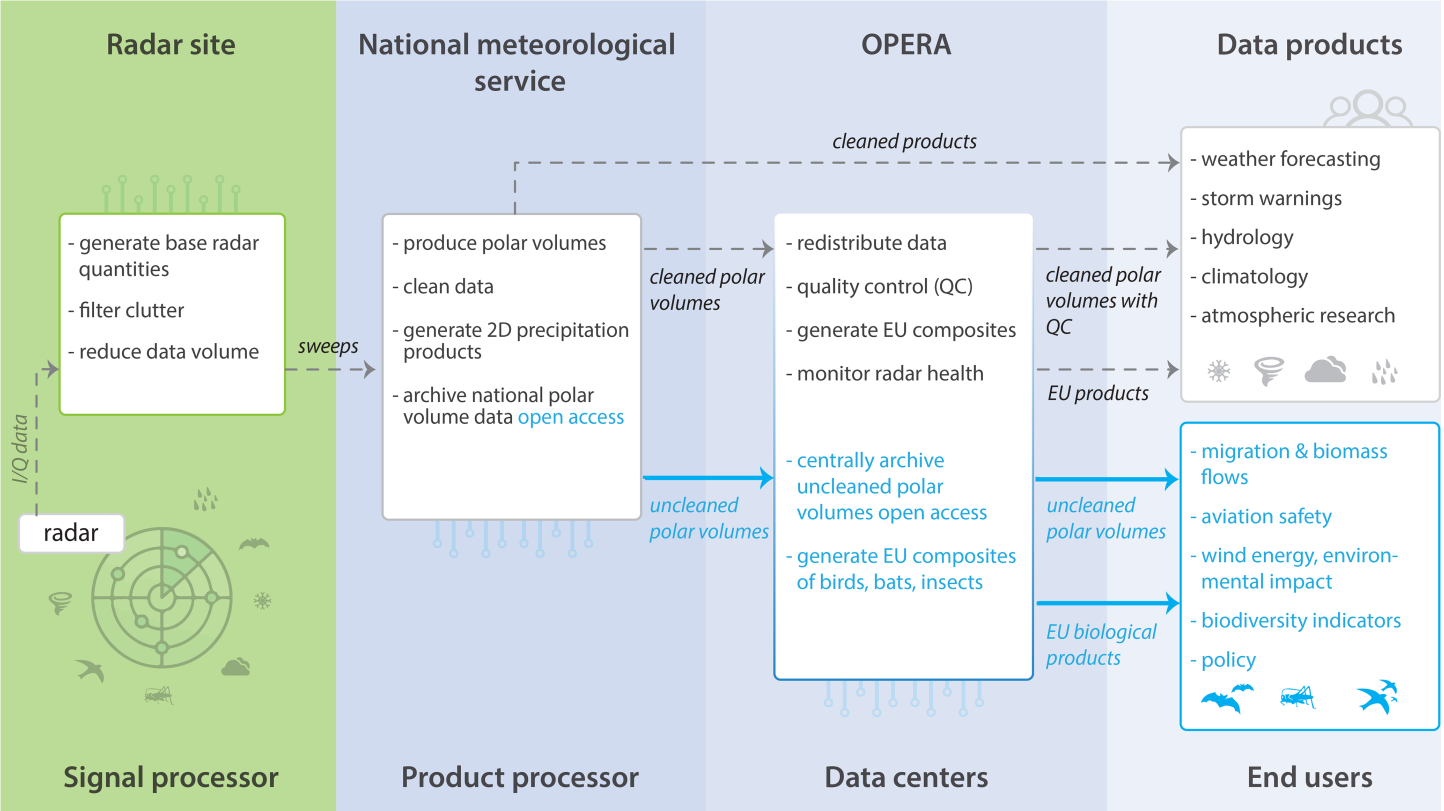

Fig. 2. Current (black font) and suggested (blue font) flow of weather radar data in Europe. At the *radar site*, data are digitally recorded by the radar receiver [I/Q data; the rawest form (level 0) of radar data] and converted to radar variables by the radar's signal processor. Sweeps are sent to *national meteorological services*, where they are processed to create both *uncleaned* and *cleaned* polar volumes and meteorological products. Note that generating polar volume data from sweeps is sometimes done at the radar site. After data processing, most national centers send *cleaned* polar volume data to the central *OPERA data centers*, yet, for biodiversity research and applications, *uncleaned* polar volume data are required. Ideally, uncleaned data would be centrally archived at OPERA's data centers and openly accessible to diverse *end users*.

of a data processing pipeline, and the establishment an open access data repository of vertical profiles of bird migration (https://enram.github.io/data-repository/). Although the spatial and temporal extent is still limited in Europe, this collaboration has inspired research on spatiotemporal patterns of avian migration (Nilsson et al. 2019; Nussbaumer et al. 2021b), the impact of environmental conditions on migration (Aurbach et al. 2020; Kemp et al. 2013), and forecasts of avian migration to improve aviation safety (van Gasteren et al. 2019).

The threat

Management of weather radar data for meteorological and hydrological applications across Europe is coordinated by OPERA, which serves as a central hub for access to these data and coordinates data exchange between national meteorological services (Huuskonen et al. 2014). Through the central data hub, users of weather radar data can make one request for data across international borders rather than contacting each meteorological service separately. However, because of budget constraints, recent changes in OPERA data exchange policies prioritize meteorological applications, especially to ensure high-quality precipitation products (Saltikoff et al. 2019a), and the implementation of these changes threatens the viability of European weather radar data for biological monitoring. To understand this threat, we define the types of data that are produced at various points in the radar data production chain (Fig. 2). At its starting point, the radar signal processor integrates pulse data into rays to ultimately produce sweeps, which are sent to a central radar product processor at the national meteorological service where they are combined into *polar volume* data. Base radar quantities (generated by the signal processor; see Fig. 2) that are available in polar volume data include reflectivity factor and radial Doppler velocity recorded at different antenna elevation angles, which are essential for extracting biological information (Dokter et al. 2011, 2019). If available, dual-polarization quantities, which provide better estimates of target size, shape, and distribution, and therefore improve the quality of meteorological products and the ability to identify biological targets (Kilambi et al. 2018; Stepanian et al. 2016), are also provided. Dual-polarization information may also be used by the national meteorological services to remove any nonmeteorological echoes from the polar volume data to create *cleaned* polar volumes. The resulting *cleaned* polar volume data yield better meteorological products such as precipitation composites; however, they are of no use for biological products (Fig. 3). The only type of data that is useful for extracting biological information is *uncleaned* polar volume data.

The original OPERA intent of requesting basic data from members was to enable consistent and systematic quality control for generating continental products from a heterogeneous radar network. However, infrastructure and budget limitations for transmission of all dual-polarization variables to OPERA severely limit systematic quality control for meteorological applications. Consequently, OPERA has changed its data exchange policy from requesting *uncleaned* polar volumes from national meteorological services to requesting *cleaned* polar volumes to realize the benefit of the national investments on dual-polarization technology and developments of data quality procedures for meteorological and hydrological applications (Saltikoff et al. 2019b). The ramifications of the current data exchange policy are profound and imply that most progress and investments toward unifying the European weather radar network for biodiversity monitoring will be undone, jeopardizing all Europe-wide biological applications of the network.

Proposed solutions

OPERA is currently establishing new data centers for European weather radar data that could serve as the ideal access points for users and stakeholders outside the meteorological community (Fig. 2). Access to uncleaned polar volume data at these data centers would extend the use of national weather radars beyond their core functions for meteorological services—particularly for aerial biodiversity monitoring and other multidisciplinary applications. We, therefore, urgently call for the following changes to be made: 1) national and international funding schemes (e.g., the European Union) recognize and support the full potential of the data that meteorological institutes are generating, 2) data policies and data infrastructure are updated to sharing all uncleaned polar volume data (including dual-polarization data) necessary for both meteorological and biological applications across national borders, initially prioritizing inclusion of uncleaned reflectivity and radial velocity data in addition to the cleaned data currently shared, 3) the new OPERA data centers establish an open access data archive to facilitate long-term multidisciplinary research and biodiversity monitoring, and 4) data quality needs for biological application are considered and incorporated. Ideally, national meteorological services would provide as many radar variables to OPERA as the radars record, and OPERA would compile these into *cleaned* and *uncleaned* polar volume data. Products would be made available for multipurpose research with an international and open access archive adopting findability, accessibility, interoperability, and reusability (FAIR) principles (Wilkinson et al. 2016). These solutions would prevent the irreversible cleaning of meteorological data before archiving or exchange; data cleaning would then be tailored to specific application products. We also suggest that, with the right financial structure in place, tools will be developed for a range of stakeholders (e.g., predictive models of migration for aviation, wind energy, or agriculture) that could be converted into sustainable services run by meteorological institutes on national or international platforms. A shift in data policy likely requires a commitment at the national and international level to provide funding and

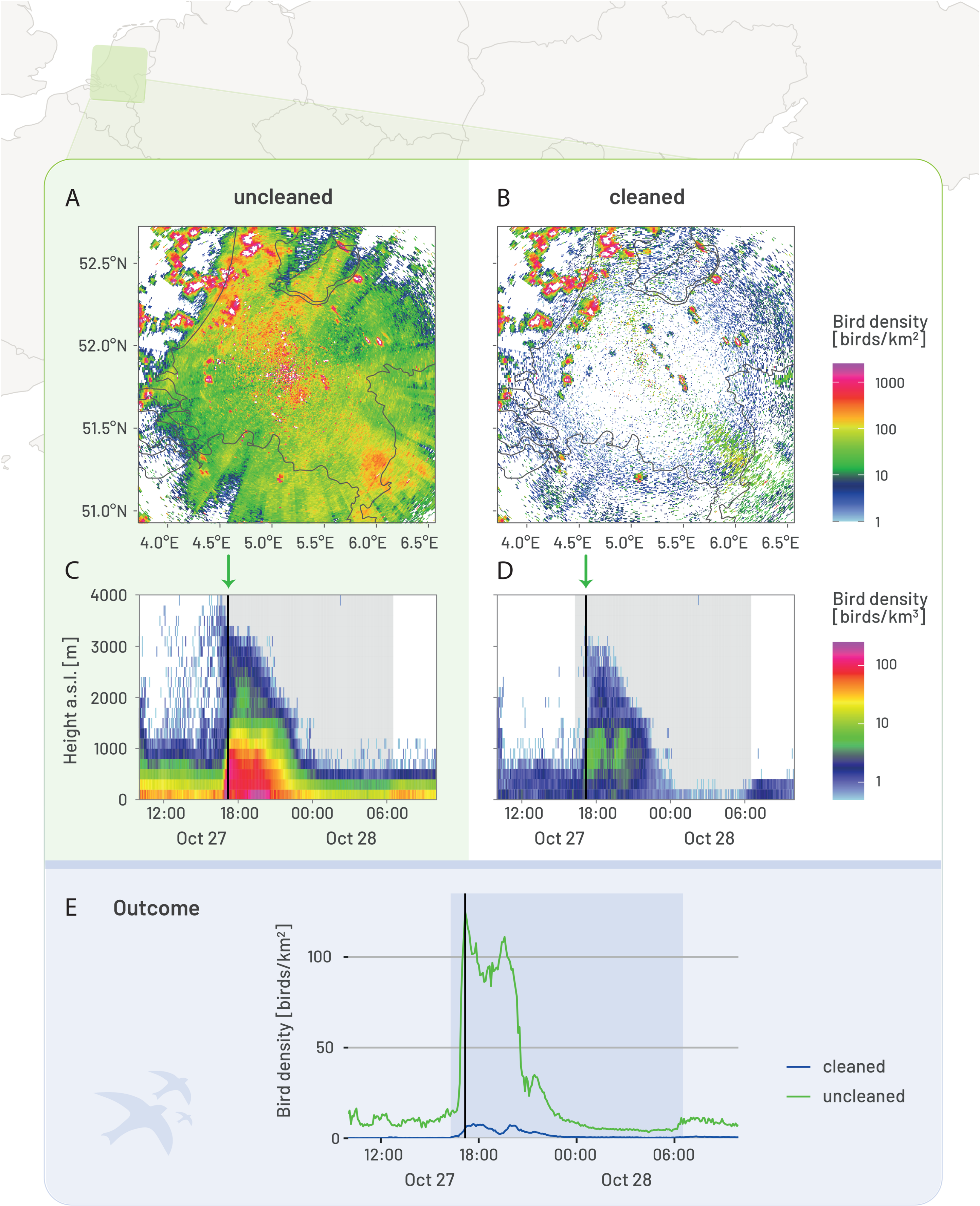

Fig. 3. The effect of cleaning on the bird densities extracted from radar data by comparing (a),(c) uncleaned data to (b),(d) cleaned data. Radar data from the Herwijnen radar (NLHRW) in the Netherlands was used for the night of 27–28 Oct 2017. This night had a high abundance of nocturnal avian migrants. Cleaning has been applied by using the wradlib (Heistermann et al. 2013) implementation of the dual-polarization fuzzy logic algorithm (Overeem et al. 2020) used

operationally by the Royal Netherlands Meteorological Institute (KNMI). Maps in (a) and (b) show the estimated vertically integrated density of birds (at 1710 UTC; Kranstauber et al. 2020), with a high density of birds north and southeast of the radar visible in the uncleaned data [(a)] whereas with cleaned data some meteorology is retained but practically all birds are removed [(b)]. The plots in (c) and (d) show estimated altitude profiles of bird densities throughout the night (Dokter et al. 2011). The gray background reflects the period between sunset and sunrise. After sunset, birds ascend and migrate throughout the first half of the night [(c)]. By using cleaned data, densities are reduced by an order of magnitude. (e) The same effect can be seen when comparing the integrated density of birds throughout the night. Vertical black lines correspond to the time for which the maps in (a) and (b) have been drawn (1710 UTC).

additional workforce to implement long-term data storage, processing, and access solutions, part of which might be provided from funding instruments targeting sustainability. However, we expect that the added costs are relatively low compared to the expected benefits of multipurpose use of weather radars. If current data policies remain, ecologists will have to negotiate the extraction of data with many individual national meteorological institutes (which may or may not be able to archive or provide biologically relevant data). Such a decentralized approach will not only hugely increase the efforts required by individual data providers and users, but it will also reduce the data available for biological applications and ultimately stall European-scale biodiversity studies.

The European Union has recognized the need to step up efforts in conserving and restoring biodiversity by addressing the direct and indirect drivers of biodiversity and nature loss and therefore initiated and adopted its Biodiversity strategy (https://ec.europa.eu/environment/nature/biodiversity/strategy/index_en.htm), for which it committed to investing more than EUR 20 billion annually in the accompanying action plan. Ignoring the potential of the often publicly funded operational weather radars for biological monitoring would be a waste of precious resources. Using the existing weather radar networks would be a cost-effective, large-scale, and long-term data stream for biodiversity monitoring that can provide essential data for developing various European policies and assessing their efficacy, such as the Biodiversity Strategy for 2030, Habitats Directive, Birds Directive, Climate Strategy, and Ecosystem Restoration goals, and national and EU-wide initiatives on natural capital accounting. Moreover, monitoring bird or insect movements is highly relevant to stakeholders as diverse as the renewable energy sector, aviation safety, agriculture, conservation, health, ecotourism, and citizen engagement.

We mainly target European policies where a coordinated change of action is urgently needed to counteract changes already made in weather radar data exchange policies. However, the distribution of weather radars in many parts of the world has great potential for establishing a global monitoring network of aerial biodiversity. The data policies we propose would be beneficial in other countries as well, for example, in the Southern Hemisphere, where the utilization of operational weather radars for ecological research is still hampered by difficulties associated with data acquisition, exchange policies and lack of suitable archives (Rogers et al. 2020). The changes we propose would not only benefit monitoring of avian movement but, with appropriate target identification algorithms, would support monitoring and research on insects (Jatau et al. 2021; Nussbaumer et al. 2021a; Stepanian et al. 2020) and bats (Frick et al. 2012; Haest et al. 2021) as well as other multidisciplinary Earth system applications (Gauthreaux and Diehl 2020). Given the connectivity between continents created by the movements of migratory organisms, and international concerns regarding biodiversity and provisioning of ecosystem services, such a concerted international effort will be central to our ability to respond to these concerns. Therefore, our long-term goal is to establish worldwide and long-term monitoring of aerial fauna by working with the World Meteorological Organization (WMO) to implement similar policies in all their regional associations, such that weather radar data suitable for extraction of biological information can be shared globally. WMO's recently approved resolution for a unified policy for the international exchange of Earth system data could be crucial for facilitating access to and use of weather radar data for diverse stakeholders worldwide (WMO 2021).

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Data availability statement. Data used to create Fig. 3 are freely available through the KNMI Data Platform (https://dataplatform.knmi.nl).

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