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Review

The role of radar wind profilers in ornithology

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In the past 70 years radar technology has been increasingly applied in ornithological research in various geographical areas worldwide and has contributed greatly to a better understanding of bird migration. Many different radar types have been used, such as tracking, ship or weather radars. However, radar wind profilers (RWPs) have been largely neglected in avian research. RWPs continuously measure three-dimensional winds and, despite the low frequency range at which these systems operate, available literature provides evidence that birds are recorded at many sites. So far the potential of RWPs in ornithological research has not been fully explored and studies deal predominantly with birds in the context of clutter removal. However, based on their broad implementation in networks (e.g. E-PROFILE in Europe) situated in areas that are strategically important for bird migration, they could offer a valuable complement to already established or planned large-scale bird monitoring schemes by radar. The objective of this paper is to serve as a reference for those who wish to consider RWP data in a biological context. To that end, we provide an overview of the evolution and establishment of operational RWPs as well as of their mode of operation, in order to depict their role in meteorology and to evaluate their potential in ornithology. The assessment is based on available literature on RWPs and radar ornithology outlining the past, present and potential future role of wind profilers. In the past, birds were discarded as contamination and eliminated as far as possible from the meteorological data. Only recently have the echo signatures of biological targets been scrutinized thoroughly in raw data and used successfully for ornithological investigation. On this basis it is possible to consider the potential future utility of this promising data source as a complement to other remote-sensing instruments and other sampling techniques used in avian research. Weather independence of ornithological information was found to be a particular benefit. However, as the development of the bird-specific method is only in an early stage, more detailed studies are necessary in the future to fully assess the potential of this type of radar.

Keywords: birds, clutter removal, ground truth, migration traffic rates, remote sensing.

RADAR HISTORY AND OUTPUT IN ORNITHOLOGY

A wealth of radar studies have been performed in various regions worldwide to study bird migration dynamics. These include Casement (1966) and Bruderer and Liechti (1999) in the Mediterranean, Biebach *et al.* (2000) and Schmaljohann *et al.* (2007) in the Sahara desert, Gudmundsson (1993) on Iceland, and Gauthreaux (1970, 1971), Richardson (1976, 1982) and Cabrera-Cruz *et al.* (2013) in America. Gürbüz *et al.* (2015) provided a recent overview of the state-of-art of radars used in studies on airborne organisms. Many of these ornithological studies employed adapted tracking,

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fix-beam and marine radars with only a limited range. However, to understand long- and short-range migratory patterns, it is necessary to tap into networks of operational atmospheric radars, which can help obtain greater spatial coverage.

There are two basic types of atmospheric radars, those horizontally scanning and those vertically pointing. The horizontally scanning variety uses almost exclusively X-, C- and S-band, while the vertically directed radars use mainly L- to VHF-band. In ornithological studies, horizontally scanning weather radars have mostly been used (Gauthreaux 1971, Gauthreaux & Belser 1999, Dokter *et al.* 2011). These radars are organized in large networks worldwide, such as NEXRAD in the USA and OPERA in Europe. Operational weather radars run continuously and provide large spatial and temporal coverage. There are increasing efforts to use these data sources for biological purposes, e.g. in the COST action ENRAM (European Network for the Radar Surveillance of Animal Movement; Memorandum ENRAM). It is highly valuable to investigate the potential of these networks for ornithological or more general biological research given the diversity of airspace users and potential interference between them (e.g. bird strike) or for large-scale surveillance (e.g. pest control, migratory movements). This potential can only be evaluated through dedicated qualitative and quantitative studies.

In contrast to the efforts related to horizontal weather radars, vertically pointing atmospheric radars, such as radar wind profilers (RWPs), play only a marginal role in biology, if any, even though they have been known to detect biological targets (Wilczak *et al.* 1995). Thus the question arises whether the globally operational RWPs could be employed in a similar way as weather radars for both local and large-scale ornithological research.

The aim of the present paper is to provide an overview of the development, state of the art and mode of operation of past and current RWPs in order to understand their role in meteorology and potential contribution to ornithology in the future. This should serve as a starting point for further studies that envisage the use of this radar type and its data source.

HOW DOES A RADAR WIND PROFILER WORK?

Generally there are two types of RWPs – boundary layer and tropospheric RWPs. Boundary layer RWPs typically emit electromagnetic waves in the L-band (wavelength 15–30 cm) and UHF (wavelength 0.1–1 m) range, whereas tropospheric RWPs operate in the VHF range (wavelength 1–10 m). These radars are designed to detect irregularities of the refractive index of particle-free clear air (Dibbern *et al.* 2003). Such irregularities are caused through variations in the prevailing temperature, pressure and moisture that affect the propagation of waves and the degree of scattering. To be able to detect these irregularities, which can span from a few centimetres to many metres in size (Wright 1998), the wavelength of the radar must be in the same range (Vaisala 2002). Thus the L- to VHF-band is an optimal frequency range for clear-air measurements. In comparison, weather radars designed to detect hydrometeors (water droplets) rather than air itself typically operate in the frequency ranges of the S- (wavelength 7.5–15 cm), C- (wavelength 3.75–7.5 cm) and X-band (wavelength 2.5–3.75 cm). Even though weather radars can also detect scattering from refractive index irregularities, they are not sensitive enough for such routine measurements as provided by RWPs and are more effective in detecting small particles of precipitation (Hogg *et al.* 1980, Vaisala 2002, Zrnic & Doviak 2005).

RWP specifications are customized based on site-specific requirements and conditions. In operation, the system typically produces wind profiles by one (or two different) electromagnetic pulse(s). If two pulses are specified, independent wind profiles for two height ranges will be calculated, with two different vertical resolutions (low mode with smaller sampling volumes vs. high mode with larger sampling volumes; Fig. 1). If a pulse encounters a target, the electromagnetic energy is scattered and a fraction of this so-called backscatter is registered by the radar. Based on the time lag between the transmission of the pulse and the reception of its backscatter, the distance of the target can be computed. This information is obtained for many height levels (range gates) in the sampled vertical air column above the radar and is finally represented as wind profiles (Dibbern *et al.* 2003, Japan Meteorological Agency (JMA) 2012).

Wind profiles are obtained by a beam, which is emitted by antenna panels, switching between three or five directions, one vertical direction and two (four) inclined by 15°. Data from at least three directions are needed to calculate the three-

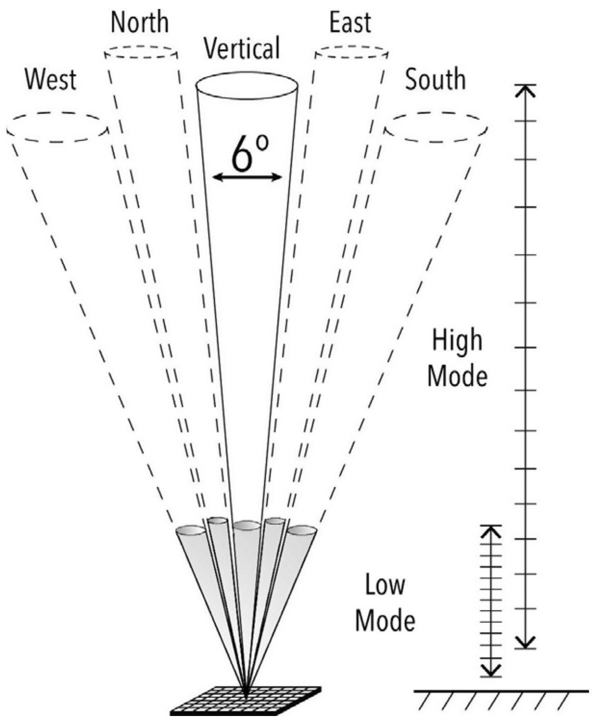

Figure 1. Scheme of a radar wind profiler with four RASS (Radio Acoustic Sounding System) containers and two sampling heights (low and high mode).

dimensional wind vector. Just as in other Doppler radars, only objects moving along the direction of the radar beam (either skywards or earthwards in the present case) yield radial velocity and hence are visible to the radar.

Signal processing of the collected data is divided into two main parts, the time-domain stage and the frequency-domain stage (Fig. 2). In the time-domain stage, a time series (unfiltered raw data with all atmospheric and non-atmospheric signals) of the reflected signal is received for each detection height along the beam during a specified time, in which the beam remains in the same position (so-called dwell time). Each time series is then converted to a frequency plot (Doppler velocity spectrum) via a mathematical inversion algorithm (fast Fourier transform). These spectra represent the first output in the signal processing chain (Strauch *et al.* 1984). In the subsequent spectral averaging process, several consecutive spectra are used to calculate a mean spectrum. The peak of the spectral data, which exhibits characteristics most similar to atmospheric echoes, is selected according to the signal processing settings in order to calculate the moment data. This moment data consist of signal-to-noise ratio (SNR), radial velocity and spectral width, which represent the second processed output. Finally, consensus averaging by a consensus algorithm (Fischler & Bolles 1981, Dibbern *et al.* 2003) is applied to radial velocity data as a final filter to remove erroneous values. Subsequently, the wind vectors (speed and direction) are calculated as the vector sum of the mean radial velocities for each detection height (range gate). The final product, the wind data (consensus data), is then visualized as time–height plots with three-dimensional wind barbs. These measurements run continuously.

A general description of the operational aspects of RWPs can be found in Dibbern *et al.* (2003) and JMA (2017). A more in-depth account about the technology can be found in Balsley and Gage (1980), Strauch *et al.* (1984), Ecklund *et al.* (1988), Vaisala (2007) or Lehmann (2010).

EVOLUTION OF TECHNOLOGY

The discovery by Atlas *et al.* (1966) that radars can detect air turbulence paved the way for the first wind measurements by Doppler radars (Dobson 1970, Browning *et al.* 1973, Woodman & Guillén 1994). The first RWPs were introduced in Europe (Czechowsky *et al.* 1976) and in the USA (Green *et al.* 1975) shortly thereafter. From the 1980s onwards, RWPs were widely adopted for a variety of operational applications in weather forecasting (Balsley & Gage 1982, Strauch *et al.* 1984). Van Zandt (2000) highlighted the capability of measuring vertical winds as a unique feature of RWPs. In addition to wind measurements, RWPs have been used to measure precipitation (Ecklund *et al.* 1995a). As an optional add-on, virtual temperature is provided through the Radio Acoustic Sounding System (RASS) that merges radio and acoustic techniques (May *et al.* 1989).

Once RWPs had become operational for atmospheric measurements, it soon became clear that these radars also register non-atmospheric targets (Ecklund *et al.* 1990). The quality of wind measurements was heavily affected in nights during the bird migration season (Fig. 3a–c). As the reflectivity of clear-air signals is greatly inferior to the reflectivity of all other targets (e.g. precipitation, birds), wind data are completely masked in the presence of stronger scatterers such as birds. By contrast, bird signals are not affected by atmospheric signals, such as wind or precipitation, and

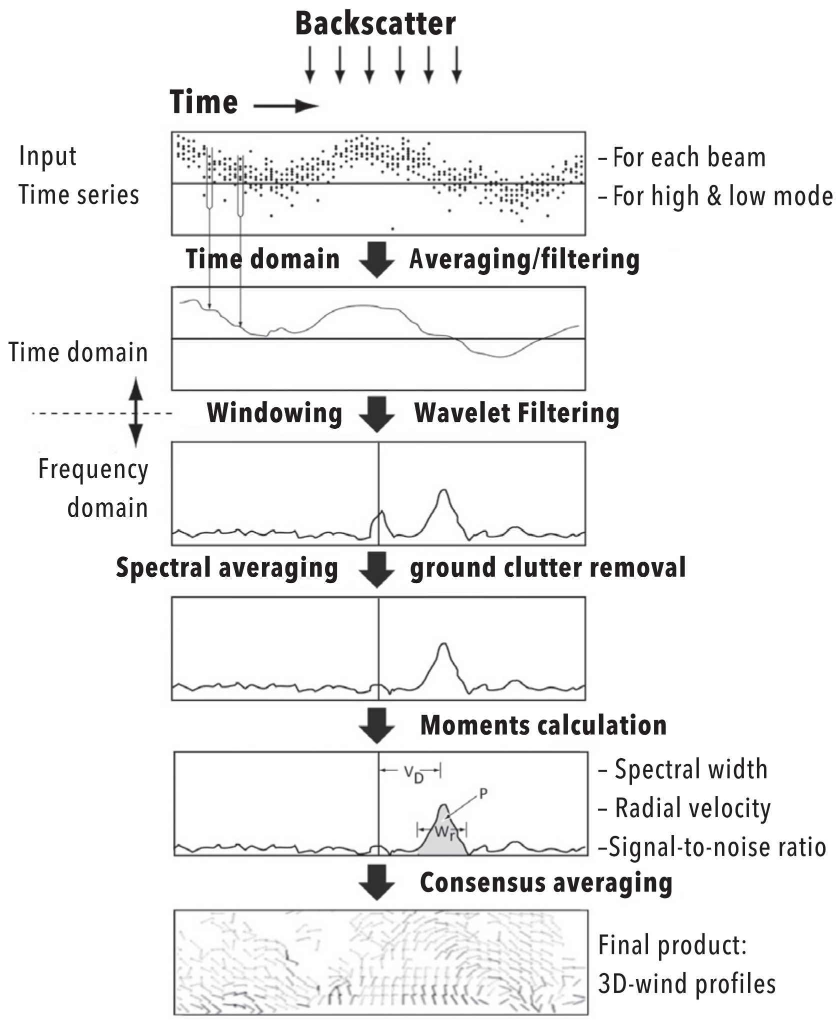

Figure 2. Signal processing chain from raw data (time series) to final wind data (adapted from Vaisala 2007).

are clearly distinguishable in the raw data (Weisshaupt *et al.* 2017). Because of the seasonal occurrence of the presumed bird signals along with deviating wind directions aligned with bird migration directions, increased SNR and apparent higher wind velocities than in the surrounding (bird-free) air space, it was concluded that these signals originated from migrating birds (Wilczak *et al.* 1995). Since then, many studies have dealt with clutter removal and provided different approaches based on spectral (Merritt 1995, Pekour & Coulter 1999, Kretzschmar *et al.* 2003) or time series level (Lehmann & Teschke 2008a,b) to improve the quality of the wind data. However, none of these filters has been able to cope successfully with high bird densities. One of the underlying causes is the nature of signal processing, which relies on the principle of homogeneity between the wind fields in the five beam directions. The density of birds aloft determines the quality of the wind data. In the case of high bird densities, all beam directions register concurrently many birds in the entire air column. As a consequence, the atmospheric signals are masked and the resulting wind profiles are of poor meteorological quality because they do not represent true winds. In the case of low bird densities, birds are considered single erroneous measurements and are removed. A second cause can be the level at which the filter mechanisms were developed. If birds are addressed at the spectral level or later in the signal processing chain, when birds cannot be unequivocally identified, the entire signal processing is based on an unstable foundation with correspondingly unreliable outcomes (Weisshaupt

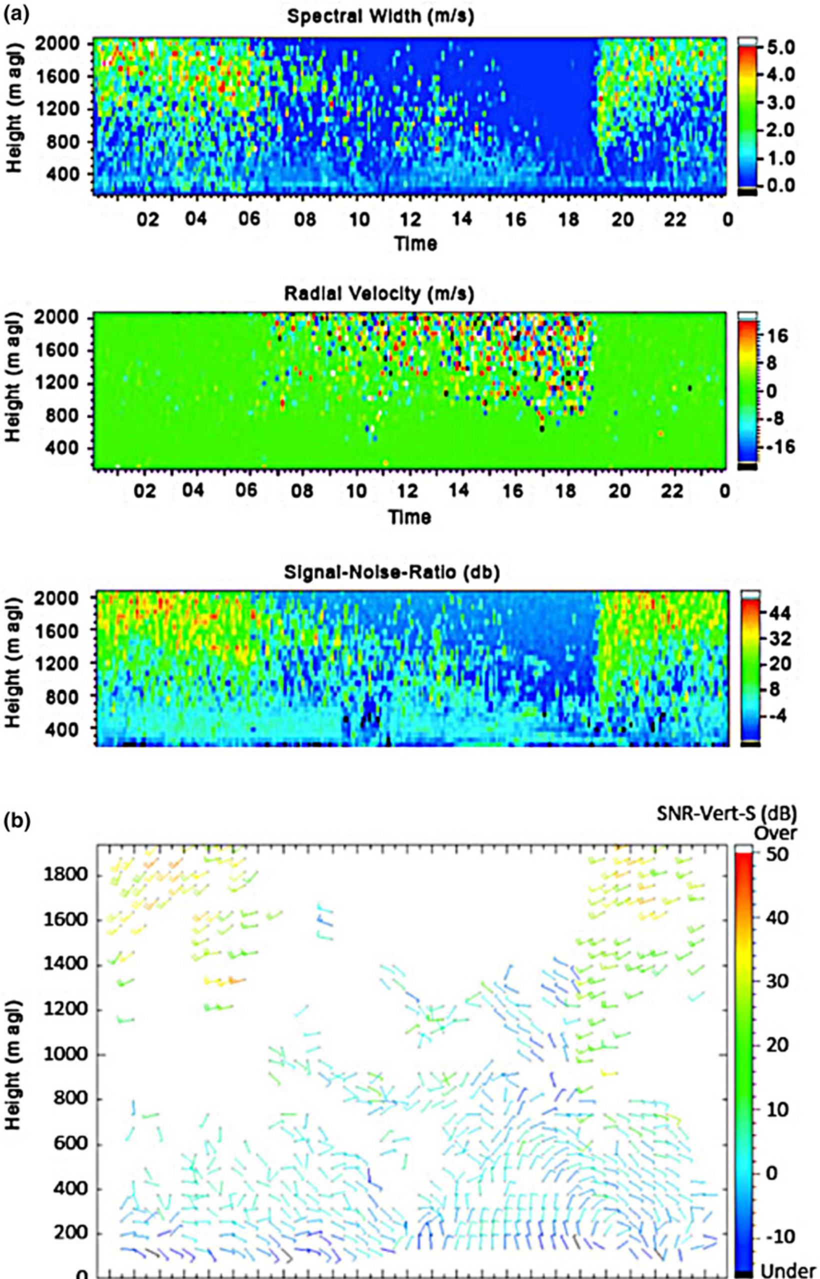

Figure 3. Examples of nocturnal bird migration patterns (00:00–06:00 h and 19:00–00:00 h) in moment (a) and wind (consensus) (b) data, and (c) a mix of birds (sprinkles from 00:00–06:00 h and 19:00–00:00 h), rain (continuous band at 20:00 h) and other atmospheric signals (up to about 800 m). [Colour figure can be viewed at http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1474-919X]

et al. 2017). Therefore, birds have remained a qualitative challenge in wind measurements.

Established RWP networks include the NOAA profiler network (NPN; active from 1992 to 2014) and the Cooperative Agency Profilers (CAP) derived therefrom in the USA, WINDAS in Japan (Ishihara *et al.* 2006), and E-PROFILE with operating sites in Europe, Canada, Australia and Oceania

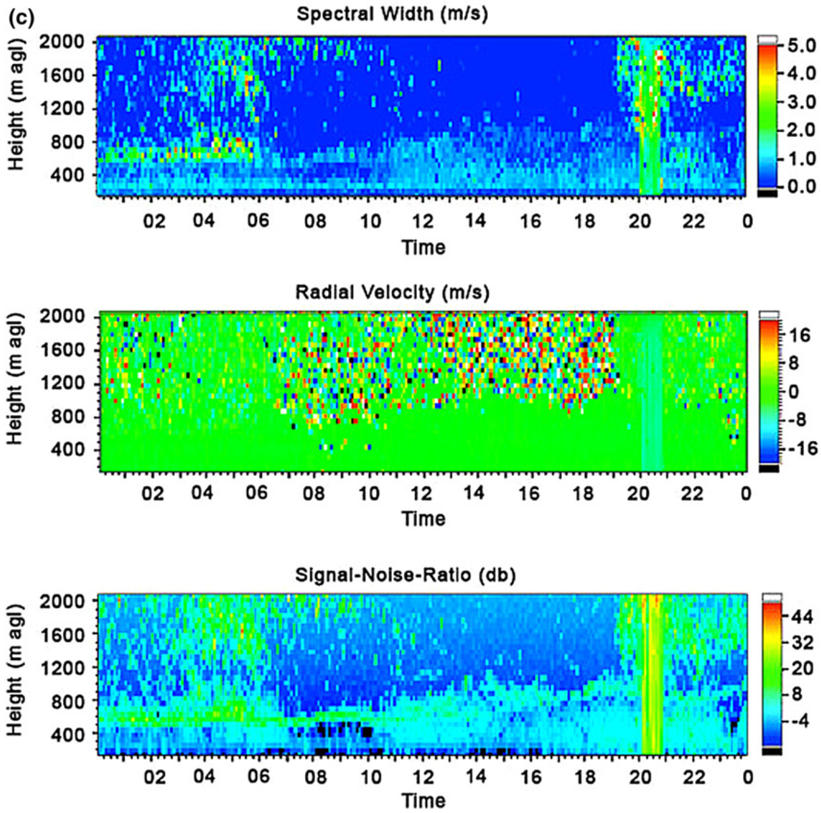

Figure 3. Continued

(Fig. 4). Despite the discontinuation of the NPN, there is still an enormous database available of 22 years that potentially contains information on avian movement. In Europe, networking activities were initiated by two COST Actions (EU-funded programmes to establish interdisciplinary research networks in and outside Europe), COST-74 and COST-76, dedicated to research on operational aspects of RWPs and to improve data quality (Dibbern *et al.* 2003). Two campaigns linked with COST-76 (CWINDE-97 and -99) demonstrated that networking between various radar wind profiler systems was feasible despite their differences in design and purpose and the different operators (Oakley & Turp 2005). CWINDE is today continued by the European Meteorological Services Network (EUMETNET) under the name E-PROFILE (http://eumetnet.eu/e-profile/). The general aim of these networks is to coordinate and improve the quality and usability of meteorological information and to provide support and expertise to both profiler operators and users to render the use of this resource more efficient. Furthermore, E-PROFILE produces daily messages on the status of the network and data quality, which may contain information of ornithological interest on moment and consensus level. According to the UK Met Office (http://www.metoffice.gov.uk/) there are currently 29 RWPs installed in 19 European countries, and more than 150 worldwide (Dibbern *et al.* 2003).

RADAR WIND PROFILERS IN ORNITHOLOGY

The presence of birds has been reported from a variety of RWP sites, including in the USA (Wilczak *et al.* 1995, Locatelli *et al.* 1998), Japan (Ishihara *et al.* 2006) and Europe (Kretzschmar *et al.* 2003, Lehmann & Teschke 2004). A general description of signals was provided by Wilczak *et al.* (1995). Bird presence has been described as extensive patterns between sunset and sunrise up to about 4 km, with high spectral width, high SNR, variable radial velocities and resulting wind errors of about 10 m/s (Wilczak *et al.* 1995, Weisshaupt *et al.* 2014, 2017).

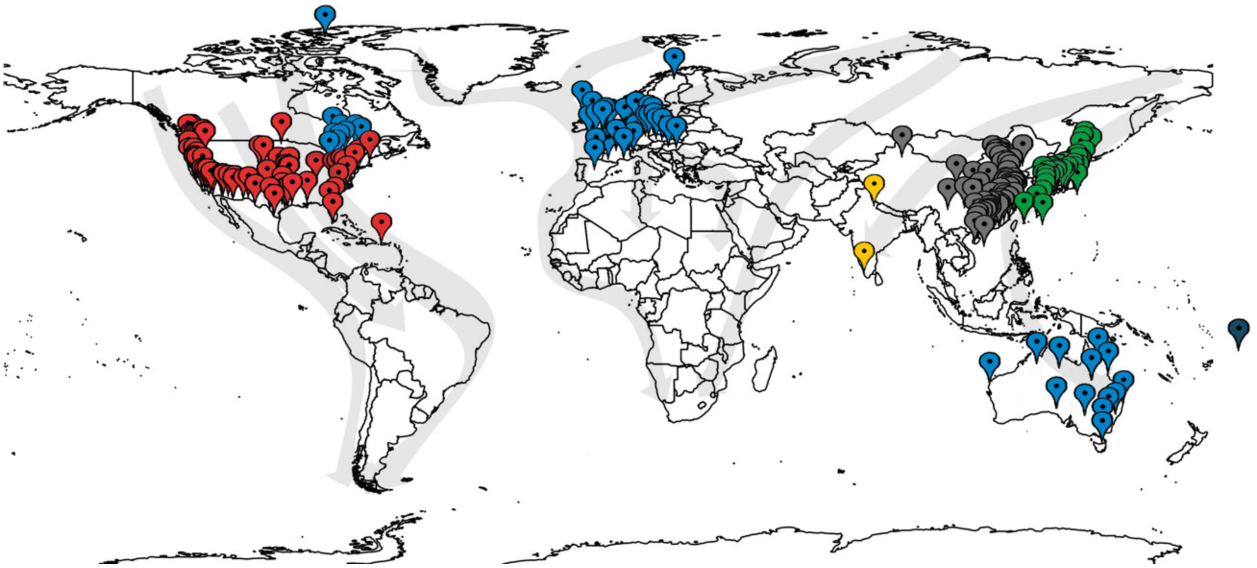

Figure 4. Radar wind profiler networks Cooperative Agency Profilers in the USA (red), E-Profile in Australia, Canada, Europe and Oceania (blue), India (yellow) and China (grey), and WINDAS in Japan (green) with overlaid migratory flyways. [Colour figure can be viewed at http://onlinelibrary.wiley.com/journal/10.1111/(ISSN)1474-919X]

Examples of radar plots during bird migration are given in Figure 3.

When using non-validated radars for biological purposes, initial target verification (i.e. to identify the observed characteristics of echoes and assign them to birds, insects, rain and so on) by means of a secondary system, such as thermal imaging, visual observations or dedicated bird radars, is essential, because target identification by radar alone is insufficient (Schmaljohann *et al.* 2008). If this is not done, then the biological content of the sampled volume remains ambiguous given that not only birds can migrate in high numbers, but also insects and bats (Larkin 1991, Gauthreaux *et al.* 2008, Chapman *et al.* 2011). The unknown content of the sampled volume could potentially bias the study outcomes and affect their reliability. For example, in ecological impact studies this might have major consequences (Schmaljohann *et al.* 2008).

Outside the meteorological realm, there are currently two ornithological RWP contributions by Weisshaupt (2015) and Weisshaupt *et al.* (2017) who employed a thermal-imaging camera as a verification tool. Their findings reveal comparable seasonal and temporal (nightly) occurrence of bird migration in both radar and thermal imaging. Another study dealing with the use of radar wind profilers in an ornithological context assumed nocturnal migration based on general (non-radar) field knowledge without any concurrent target verification (Locatelli *et al.* 1998).

The general lack of target verification could be explained by the minor interest in the biological content of clutter in meteorology where the focus lies on improving the quality of wind measurements and not on obtaining biological data. Overall, birds are considered the major biological cause of deteriorated wind profile quality based on their superior reflectivity and above all their ability to fly actively against the wind (Wilczak *et al.* 1995). However, it has been suggested that insects probably also have an impact on wind measurements (Ecklund *et al.* 1995b, Angevine 1997, Drake & Reynolds 2012). In contrast to birds, spatially extensive movements of insects are usually passively transported by the wind and might therefore serve as wind tracers.

Insect presence and its characteristics have been treated by several studies in connection with weather radars (e.g. Achtemeier 1991, Wilson *et al.* 1994), but there is no such information available from RWPs, even though insects and birds can occur simultaneously. Even though insect activity might be considered a primarily diurnal source of clutter (Angevine 1997), there are also considerable nocturnal movements at heights where birds migrate (Chapman *et al.* 2003). Given the wavelength dependence of Rayleigh scattering, insect contamination might be less of an issue in

L-band to VHF RWPs than in C-band weather radars and has therefore received less attention. However, it remains unknown to what extent the 'birds' observed in RWP studies might be mixed with insects. A first indication of the presence of potential biological non-bird echoes registered in wind profilers is presented in Weisshaupt *et al.* (2017). However, more research is needed to clarify the origin of these signals.

EXPERIMENTAL CAMPAIGNS WITH RADAR WIND PROFILERS AND OTHER RADARS

To validate and calibrate X- to S-band radars, various devices and methods have been used: moon-watching (Lowery 1951, Gauthreaux 1970, Liechti *et al.* 1995, Bruderer *et al.* 2012, Mateos & Bruderer 2012), thermal imaging (Liechti *et al.* 1995), ceilometers (Able & Gauthreaux 1975), mist-netting (O'Neal *et al.* 2010, Desholm *et al.* 2014) and visual observations (Hofmann 1956, Gauthreaux 1970, 1971, Dokter *et al.* 2013). All of these methods provide simultaneous measurements of bird numbers from which migration traffic rates can be calculated (Lowery 1951, Schmaljohann *et al.* 2008), a quantitative reference value for comparing different measurement systems and methods. Moon-watching, mist-netting and visual observations additionally deliver information on bird species composition, and thermal imaging and visual observations provide migration directions. This entire data resource can then be used in combination with the observed radar patterns to aid the interpretation of echo signatures. Once a radar system has been validated, it can be further used as a validated tool itself (Dokter *et al.* 2011). For RWPs, the four existing studies mentioned earlier (Kretzschmar *et al.* 2003, Weber 2005, Weisshaupt *et al.* 2016a, 2017) employed thermal imaging for target verification. Weisshaupt *et al.* (2016a,b) confirm that the majority of the echoes belonged to passerine migrants, with a minor contribution from non-passerines and some insects and bats. Other studies involving RWPs compared the outputs of various non-validated RWPs (e.g. Wilczak *et al.* 1995) and therefore cannot be counted as validations, since comparing several volumes of unknown content will not help clarify the origin of any targets. Therefore, at a biological level, there are still many open questions related to RWPs, in particular in regard to the variety and characteristics of signals present in the databases. However, RWPs could potentially be used as a validating technology for weather radars and vice versa as both are networked radar systems.

CURRENT SITUATION OF RADAR WIND PROFILERS

Overall, the literature has primarily given evidence of presence/absence of birds, while potential artefacts and effects from filtering procedures are poorly understood. Previous research based on processed data denied RWPs the potential to provide data on exact numbers of birds and flight heights (Weber 2005). However, the recent study by Weisshaupt *et al.* (2017) facilitates a reproducible and objective manual approach to extract ornithological information from raw data. The authors detail echo characteristics of birds vs. meteorological (clear air, precipitation) and other non-bird targets, which allowed calculation of migration traffic rates and flight altitude profiles independent of weather interference. As the study included only one beam direction, it was not able to explore the potential ability of RWPs to quantify migration directions and speed. These findings do encourage, however, further efforts to scrutinize the radar wind profiler data pool in a biological context, in particular in regard to birds, but potentially also other airborne biological targets. Furthermore, it would be interesting to determine which system specifications (e.g. wavelength, height resolution) best depict biological information given the wide variety of radar wind profiler systems. The study of Weisshaupt *et al.* (2017) is based on a height resolution of ±60 m. However, there are frequently height resolutions of ±100 m or considerably more, so it would be crucial to know how bird migration parameters compare between systems operating at differing height resolutions. Furthermore, additional work is needed to evaluate the potential to extract flight directions and speeds from bird-only data. For that purpose, it would be essential to take into account data from the tilted beams. To comprehensively quantify direction and velocity, at least three beam directions are needed. Such a potential extended approach should also consider possible limitations. These include the fact that the radar beam measures the different directions sequentially and not concurrently, and that speed and directional measurements are probably sensitive to bird densities because of the effect of consensus averaging. For example, at low bird densities in which perhaps only one of three/five beam directions registers a bird, it might be removed for lack of consensus between the measurements. However, to date these aspects remain unstudied (see Weisshaupt *et al.* 2017 for further information).

OVERVIEW OF POTENTIAL

Despite the scarce literature on birds in connection with RWP systems, recent studies allow for a preliminary evaluation in relation to other types of radars used for ornithological purposes. RWPs offer high-quality information, unbiased by atmospheric or other targets, in a continuous vertical height profile starting from the lowest sample height throughout the altitudinal range where bird migration takes place. Recent analyses of unfiltered raw data (time series) have proven the ability to obtain reproducible quantitative parameters such as migration traffic rates and flight altitude distributions (Weisshaupt *et al.* 2017). As this study only dealt with the vertical beam, it remains unknown for the time being whether directions and speed can be obtained for birds, as these parameters would require processing bird-only raw data from the tilted beams as well. What is currently visualized in the final wind data is a mixture of atmospheric and biological information after the filtering process and may only be considered a rough approximation of actual migration direction. Also, if considerable presence of biological targets other than birds, e.g. bats, is suspected at a wind profiler site, further research might be required to determine the corresponding echo characteristics by a secondary verification tool. Attenuation with respect to bird echoes is insignificant in radar wind profilers because the reflectivity of the birds is so strong. A clear advantage is the unambiguous differentiation between birds and any atmospheric targets in the raw data, which renders data analysis to obtain migration intensities and altitudinal flight distribution completely immune to any weather conditions. Because of the greatly superior reflectivity of birds, their echoes always dominate the atmospheric echoes in mixed sample volumes (Weisshaupt *et al.* 2017). In contrast, differentiation of birds, insects and water droplets is not always clear-cut in weather radars based on partially overlapping signal characteristics (Koistinen 2000, Weisshaupt 2016). Similarly, short-wavelength (X-band) tracking radars are totally blind to birds during precipitation. RWPs also offer attractive temporal and altitudinal resolution. Raw data can be delivered in intervals of about 5 min and the vertical altitudinal resolution may be as high as ±60 m. In comparison, data from C-band weather radars in Europe, for example, are typically available only every 10–15 min with an altitudinal resolution of ±200 m. Another advantage is the availability of networks often situated conveniently along migration routes. These networks would potentially make data provision to biologists and other interested stakeholders more efficient.

Unfortunately, RWP networks are not as extensive as weather radar networks, so spatial coverage is more limited. Furthermore, the variety of system specifications (different wavelengths, sampling height and height resolution) is greater than in weather radars and might complicate the retrieval of equivalent biological information across systems. It would thus be useful to identify the specifications that correspond best to the needs of avian research so that the interests of both the meteorological and the biological community could be synchronized. In this context, it would also be essential to store raw data, and not only processed data from which the biological component of echoes may have been removed. Today's improved storage capacities would support the establishment of such complete databases. The evaluation of biological content of RWP echoes is still at an early stage, but in future it would be valuable to automate the extraction of bird data, similar to current efforts for weather radars in the COST action ENRAM, to make this data source easily available to scientists and consequently to the general public.

A final barrier to the broad use of RWPs is that few people are familiar with it, its mode of operation and the data it offers, in particular outside meteorology. However, we hope that this last problem will be at least partially alleviated by this review.

Overall, according to the available literature, RWPs represent a promising complementary data source that has remained unexploited in avian radar research. Future work should focus on further studying the various echo signatures in the radar wind profiler data pool to determine the sensitivity of wind profilers to airborne organisms other than birds. Further research is then needed to compare RWPs with different system specifications. Tilted beam directions should also undergo closer investigation potentially to extract speed and directional information from birds-only raw data. The available databases from both currently and historically operating sites represent valuable datasets for these further investigations.

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