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Extracting bird migration information from C-band Doppler weather radars

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Although radar has been used in studies of bird migration for 60 years, there is still no network in Europe for comprehensive monitoring of bird migration. Europe has a dense network of military air surveillance radars but most systems are not directly suitable for reliable bird monitoring. Since the early 1990s, Doppler radars and wind profilers have been introduced in meteorology to measure wind. These wind measurements are known to be contaminated with insect and bird echoes. The aim of the present research is to assess how bird migration information can be deduced from meteorological Doppler radar output. We compare the observations on migrating birds using a dedicated X-band bird radar with those using a C-band Doppler weather radar. The observations were collected in the Netherlands, from 1 March to 22 May 2003. In this period, the bird radar showed that densities of more than one bird per km^3 are present in 20% of all measurements. Among these measurements, the weather radar correctly recognized 86% of the cases when birds were present; in 38% of the cases with no birds detected by the bird radar, the weather radar claimed bird presence (false positive). The comparison showed that in this study reliable altitudinal density profiles of birds cannot be obtained from the weather radar. However, when integrated over altitude, weather radar reflectivity is correlated with bird radar density. Moreover, bird flight speeds from both radars show good agreement in 78% of cases, and flight direction in 73% of cases. The usefulness of the existing network of weather radars for deducing information on bird migration offers a great opportunity for a European-wide monitoring network of bird migration.

Keywords: altitude profile, bird migration, bird radar, comparison, flight speed, radar ornithology, verification scores, weather radar.

INTRODUCTION

Radar has been used in bird migration studies for more than 60 years (Lack & Varley 1945) and is able to detect birds at long ranges, during day and night. It provides information about bird track direction and speed, migration intensity and, depending on the type of radar, also flight altitude and wing-beat patterns (Bruderer 1997a). Disadvantages of radar mainly concern the lack of detection of low flying birds in the landscape (Buurma *et al.* 1986) and of target identification. The impact of radar on studies of bird migration is tremendous (Eastwood 1967, Alerstam 1990, Buurma 1995, Bruderer *et al.* 1995b, Bruderer 1997a, 1997b, Gauthreaux & Belser 2003) and it is therefore unfortunate that a radar network for continuous monitoring of bird migration has not yet been developed in Europe. A radar network could provide, for example: (1) a more complete spatial and temporal picture of migration patterns, and the possibility to (2) compare simultaneously the impact of external factors such as weather and landscape features, (3) identify important stopover areas during migration, (4) monitor the number of migrants and provide a large-scale early warning system for flight

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safety and (5) track the potential spread of avian-borne disease or for wind energy mitigation (see also Ruth *et al.* 2005).

Dense European meteorology and military radar networks already exist; however, most radars are not equipped with bird detection systems. Real-time bird strike warning systems based on surveillance radar exist only in the Netherlands (Buurma 1995), Germany (Ruhe 2005) and recently at Belgium military sites. These bird strike warning systems aim to reduce the number of bird strikes during low level training by guiding aircrafts to avoid areas with high bird migration activities as measured with radar.

A national network of Doppler capable weather surveillance radars (WSR-88D) covers much of the USA and is used to monitor bird movements (Gauthreaux & Belser 1998, Diehl & Larkin 2005). During the development of the system, automatic bird detection algorithms were developed but not implemented, primarily for financial reasons (Larkin 1994). An empirical relationship was found between reflectivity and bird densities based on moon-watching calibration (Gauthreaux & Belser 1999), and semi-automatic data processing of radar output has made it possible to monitor seasonal patterns of bird migration at the regional and national scale (Gauthreaux & Belser 2003). However, some human image interpretation remains necessary. In addition to reflectivity data, the weather radar wind profile products produce speed and direction data for different altitudinal layers (Browning & Wexler 1968). These measurements are known to be contaminated with biological targets (Larkin 1991, Gauthreaux *et al.* 1998, Koistinen 2000). Bird echoes bias wind estimates as they have a high velocity component, whereas insects drifting with the wind or flying at low air speeds minimally influence wind estimates (Riley 1999). Currently, discrimination between real wind measurements and bird-contaminated measurements is not routinely applied. Recent progress has been reported for the automatic discrimination between real wind versus biologically contaminated measurements to improve the quality of weather radar wind profile data (Koistinen 2000, Holleman 2005, Liu *et al.* 2005). To take advantage of existing radar systems for migration monitoring, an essential initial phase of development is the comparison between data collected by the radar being tested, for example weather radar and data collected by a system with known bird detection properties.

The primary aim of this study is to assess how bird migration information can be deduced from Doppler weather radar wind measurements. The network of these radars in Europe (Operational Programme for the Exchange of weather RAdar information, OPERA) covers many countries and is expanding quickly (Huuskonen 2006). If these radars can be used successfully to study bird migration, then the existing radar network offers a great opportunity for European-wide monitoring of bird migration. In our study, we compare vertical profiles of migration speed and direction measured by a radar adapted for bird flight monitoring with observations by an operational C-band Doppler weather radar. For this procedure, we had to assume that the intensity of bird migration as well as flight speed and direction at different altitudes as observed by the bird radar represent an accurate estimate of the true values for the observation domain of the weather radar. We address the following research questions: (1) Can the times and altitudes of bird migration be measured with the C-band Doppler weather radar? (2) Can migratory bird density at different altitudinal bands be estimated by the weather radar? (3) Can bird speed and direction at different altitudes be deduced from wind profile measurements? Furthermore, to demonstrate the capability of the C-band Doppler weather radar, we present two detailed examples of the type of migration information that can be extracted from it.

METHODS

Radar scanning protocols

In this study we use data from two different radar systems, a 5-cm C-band Doppler weather radar and a 3-cm X-band bird tracking radar. The observations cover the period 1 March to 22 May 2003. The output from both radar systems has been averaged to hourly means. The C-band Doppler weather radar is operated by the Royal Dutch Meteorological Institute (KNMI) and located at De Bilt (52.10°N, 05.18°E) at an altitude of 44 m asl (in short: weather radar). The C-band radar is a Gematronik Doppler radar (Meteor AC360), with a 4.2-m diameter antenna, a beam width of about 1°, and a rotation frequency of 24° s^{-1}. The peak power and width of the transmitted non-compressed pulses are 250 kW and 0.8 μs, respectively (Holleman 2005). The X-band radar is a Flycatcher tracking radar (Thales group) of the Royal Netherlands Air Force (RNLAF). It is located 80 km SSE of the weather radar at De Peel Air Force base (51.52°N, 5.85°E) at an altitude of 5 m asl (in short: bird radar). The bird radar has a peak power of

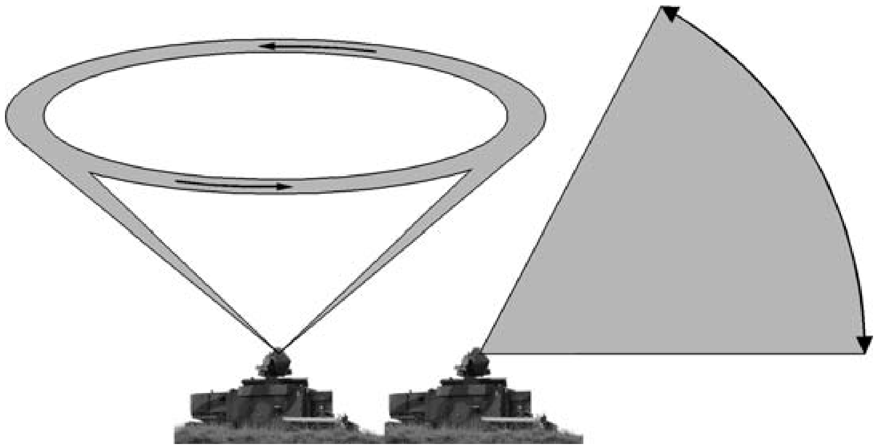

Figure 1. Conical (left) and Range Height Indicator (right) radar scans with tracking antenna of the bird radar.

160 kW and pulse duration of 0.2 μs after compression. It has a pencil beam antenna with an opening angle of 2.4°, a vertical scanning velocity of 30° s^{-1} and a horizontal scanning velocity of 60° s^{-1}.

During this study a dedicated scanning strategy was applied for both radars (Fig. 1). The weather radar uses a conical Doppler volume scan, repeated every 15 min between 0.5 and 25° at 10 different elevations. The 10 elevations were optimized for wind profiling up to an altitude of about 6 km (5–25 km slant range). The bird radar operates with two different scanning techniques. Similar to the weather radar, dedicated conical scans were repeated every hour at seven different elevations between 2 and 30°. Hourly measurements were carried out until 16 April; from then onwards the bird radar was not operational between 12:00 and 17:00 hours. Each hour, data from 10 rotations per elevation (= 1 min), up to a 7 km slant range, are stored. The output from the consecutive conical scans of the bird radar is processed by the ROBIN system, which extracts accurate information about speed, direction and altitude of birds (Buurma 1995, Bouten *et al.* 2003). Between the hourly conical scans we perform two vertical scans perpendicular to the main NE direction of spring migration (NW and SE) to obtain information about bird migration intensity. During a 5-min period the pencil beam scans 60 times vertically between 0 and 60° elevation and a 1–7 km slant range. The ROBIN system detects birds passing through this surface, recording distance to the radar, altitude and echo strength. The problems of such a recording surface have been emphasized previously (Bruderer 1971, 1980, Bruderer *et al.* 1995a) and suggest that when using vertical scans perpendicular to the main direction of migration the number of recorded birds decreases with the size of the bird and the aspect angle of the direction of the bird relative to the recording surface. Using this method, fluxes of birds (Mean Traffic Rate, MTR) are recorded, which have to be transformed into density values by using the direction and ground speed of the birds (Bruderer 1971, 1980). Following the vertical scans we use the pencil beam to track individual targets for signature analysis (Bruderer 1997a).

Data preprocessing

Weather radar

The reflectivity and mean radial velocity data of the conical volume scans are stored and clutter is automatically removed by the Doppler signal processor (Holleman 2005). The strength of radar signals scattered from targets and received by the radar antenna, the so-called radar reflectivity, is used as an indicator of bird intensity. The 10 conical scans overlap in altitude levels at different ranges (measured between 5 and 25 km) depending on the degree of elevation (Holleman 2005). No correction has been applied to compensate for the variation of radar reflectivity with the aspect of birds, nor the decrease of reflectivity with distance. Mean reflectivity per altitude layer is integrated over all 10 conical scans. The radar reflectivity can either be expressed as a linear quantity Z (in $mm^6\ m^{-3}$) or as a logarithmic quantity dBZ. Reflectivity is usually presented on a logarithmic scale, but for calculation of the mean, for example over altitude or time, the linear quantity is used (Doviak & Zrnic 1993, Wilson *et al.* 1994, Gauthreaux & Belser 1999). The parameters Z and dBZ are related as follows (Rinehart 1997):

$$Z = 10^{(dBZ/10)} \tag{1}$$

After calculating the mean over a certain time period (Z_m), the mean logarithmic reflectivity dBZ_m is obtained from Eq. 2:

$$dBZ_m = 10 * {}^{10}\log(Z_m) \tag{2}$$

Integration of the equivalent reflectivity factor, i.e. the factor derived from measured reflectivity (see e.g. Rinehart 1997) over altitude is used to obtain the Vertically Integrated Reflectivity (VIR) (in $mm^6\ m^{-2}$):

$$VIR = \int_{h\,min}^{h\,max} 10^3 \cdot Z_e(h)dh \tag{3}$$

where $Z_e(h)$ is the equivalent reflectivity factor (in $mm^6\ m^{-3}$) as a function of altitude h (in km), *hmin* is the minimum elevation at which migrating birds are detected, and *hmax* is the maximum elevation up to which migrating birds are detected. As no corrections are applied to aspect angle and distance to the radar, VIR is an index of migratory activity over all altitudes.

Speed and direction information are retrieved from the radial velocity of the weather radar using the Velocity Azimuth Display (VAD) technique (Lhermitte & Atlas 1961, Browning & Wexler 1968). When the mean radial velocity at constant range and elevation over a complete conical scan is displayed as a function of azimuth, the resulting curve has a sine form. The average speed and direction of all the targets within the scanned volume can be determined from the amplitude and phase of this sine by Fourier series decomposition (Fig. 2, top). All radial velocity data are processed in one multi-dimensional linear regression by the Volume Velocity Processing (VVP) retrieval technique (Waldteufel & Corbin 1979). For both VAD and VVP wind retrieval techniques the acronym WRWP (Weather Radar Wind Profiles) will be used from now on. In addition to speed and direction, the standard deviation of the radial velocity is calculated for each altitude (Holleman 2005). In a homogeneous wind field, standard deviations are small, usually less than 0.5 m s^{-1} (Fig. 2, top). However, variation in speed and direction of bird targets can result in standard deviations as large as 6 m s^{-1} (Fig. 2, bottom). Recent studies by Koistinen (2000) and Holleman (2005) have suggested that the standard deviation of the radial velocity is a good discriminator between high quality wind measurements and bird-contaminated wind profiles. Comparison of wind measurements with radiosonde profiles and the Hirlam Numerical Weather Prediction model (Undén *et al.* 2002) resulted in a standard deviation threshold of 2.0 m s^{-1} as an optimal value for high quality and high availability of wind data (Holleman 2005).

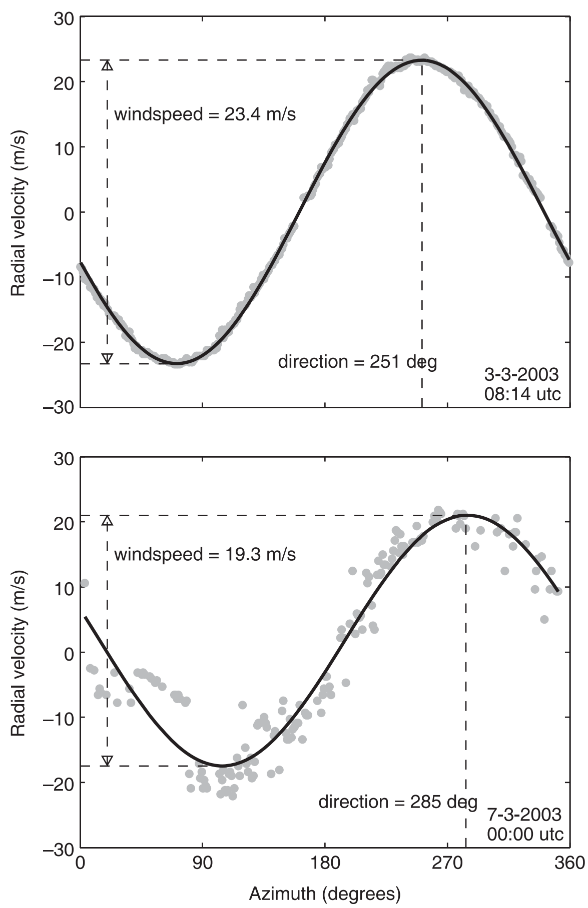

Figure 2. Examples of a Velocity Azimuth Display (VAD) obtained from a volume measurement (Holleman 2005) of a homogeneous wind field (top) and a measurement dominated by birds flying with speeds and direction that vary from that of the wind (bottom). In both graphs the fitted line is a sum of sine curves derived by Fourier series decomposition. Mean speed and direction are defined by the dotted lines.

Bird radar

Unlike the weather radar, which provides a mean reflectivity value per altitude layer over a relatively large integration area, the bird radar provides an echo (which is linked to a lot of information such as reflectivity, altitude, speed and direction) over a very small integration volume. The signal from the bird radar needs to be integrated horizontally as well as over altitude to calculate bird density at the same spatial scale of the weather radar so that it can be compared with the reflectivity value from the weather radar. The bird radar detects birds roughly in the domain 100–7000 m from the antenna with a rapid decrease in the detection rate beyond 4.5 km. The detection probability is a complex function of distance to the antenna and the features (such as size and mass) of the single targets. Bird detection probability decreases with increasing distance from the antenna (Eastwood 1967, Bruderer *et al.* 1995a, Bruderer 1997a) due to decreasing signal strength according to the fourth power law, and with decreasing distance from the antenna due to limited beam width. This leads to two distinct effects: (1) reflectivity decreases with increasing distance from the radar and (2) echoes are lost at larger distances (detection loss) but at a different rate for different classes of reflectivity. We deal with this by assuming that birds of all size classes are expected to be equally abundant at different distances from the radar.

We correct for decreasing reflectivity with increasing distance from the radar by normalizing the observations with the following relationship

$$RD(i,s) = \frac{R_{obs}(i,s)}{\bar{R}(s)} \quad (4)$$

where s is the distance (in m) from the radar, $RD(i,s)$ is the distance-corrected reflectivity of echoes i, and $RD_{obs}(i,s)$ is the observed reflectivity of echoes i. Note that a given echo is localized at a specific distance s. $\bar{R}(s)$ is the expected reflectivity-reduction factor at the distance s. The continuous function $\bar{R}(s)$ is found by averaging the observed reflectivity over the complete observation period, smoothing it with a lowess smoother (Cleveland 1981), and normalizing it so that the maximum of $\bar{R}(s)$ (near the radar) equals one ($0 \le \bar{R}(s) \le 1$).

We correct for echo detection loss for seven reflectivity classes separately. These seven classes are chosen such that the frequency histogram per class of the number of echoes (y-axis) over distance from the radar (x-axis) is as distinct as possible from the histograms of the other classes. We refer to each of these reflectivity classes with the letter c. We consider altitude bands of 200 m, with a range of 200–4000 m. An altitude band is denoted by h. We denote the *observed* number of echoes that fall within reflectivity class c and altitude band h by $NEobs_{c,h}$. This value is calculated by summing the number of observed echoes over reflectivity classes within a given layer h and integrating over the distance that is considered in this study (see below):

$$NEobs_{c,h} = \int_s \delta_{c,h}(s)ds \quad (5)$$

where $\delta_{c,h}(s)$ is a Dirac function that takes a value of one if an echo falls within reflectivity class c, altitude band h and is located at distance s, otherwise it is zero. The observed number of echoes needs to be corrected because the chance that an echo is detected is a reflectivity class-dependent function of distance. We call this function expected detection loss ($\bar{D}_c(s)$) and derive it by averaging the observed number of echoes of reflectivity class c over the complete observation period, smoothing it and normalizing it so that the maximum of $\bar{D}_c(s)$ equals one. Now the *expected* number of echoes per reflectivity class and altitude band ($NE\exp_{c,h}$) can be calculated as:

$$NE\exp_{c,h} = \int_s \frac{\delta_{c,h}(s)}{\bar{D}_c(s)}ds \quad (6)$$

where $\delta_{c,h}(s)$ is the same Dirac function as in Eq. 5. Finally the expected number of echoes is divided by the sampled volume of the radar beam and the total bird density is calculated by summing over the seven reflectivity classes.

$$BD_h = \sum_c \frac{NE\exp_{c,h}}{V_{c,h}} \quad (7)$$

where BD_h is the bird density for layer h, and $V_{c,h}$ is the sampled volume by the radar beam whose calculation is described in Skolnik (1980), Bruderer *et al.* (1995a) and Chapman *et al.* (2002b). Interestingly $V_{c,h}$ is a function of reflectivity class c as well as altitude layer.

In this study only birds in the range from 2 to 4.5 km are analysed. Distances up to 2 km are excluded from analysis due to the small sample volume and the presence of insect targets. When using the bird radar, most insect targets are excluded by the sensitivity time control (STC) filter. As a consequence, not only the majority of insect echoes are removed but also a proportion of small birds. Signature analysis of tracked echoes (Bruderer 1997a) still shows a very small proportion of insect echoes (< 1%). This proportion was zero in March and increased slightly in May. Therefore we have to assume that a very small proportion of the bird radar samples are related to the detection of insects. This problem is reduced when using the weather radar as it is using a larger wavelength. Bats are not common in the study area (Limpens *et al.* 1997) and are therefore unlikely to influence measurements. The 60 vertical scans during a 5-min period are treated as 60 different, but dependent, samples to calculate bird densities (in nr km^{-3}) for each 200-m altitude layer. This method assumes a rather precise definition of the radar beam in contrast to calculating bird densities from mean traffic rate as mentioned by others (Bruderer 1971, Bruderer *et al.* 1995a). However, our method is feasible without information on bird speed and direction, which was often the case in this bird radar dataset. Mean bird speed and flight direction extracted from the conical scan are only calculated when three or more bird tracks per altitude class are available. Calculations of mean direction are made according to standard circular statistical methods (Batschelet 1981).

Radar comparison

We compared the two radars with respect to bird migration activity per 200-m altitude layer. We also compared vertically integrated densities measured by vertical scans of the bird radar over all altitude layers (VID in number km^{-2}) (Eq. 8) with VIR:

$$VID = \int_{h\min}^{h\max} BD_h dh \qquad (8)$$

where BD_h is the bird density (number of birds km^{-3}) as a function of altitude h (in km), $h$min the minimum elevation at which migrating birds are unambiguously detected by radar, and $h$max the maximum elevation up to which migrating birds are detected within 200–4000 m. To compare VID with VIR, observations from both radars, (BD_h and Z(h)) have been smoothed by a moving average filter (window size of 3 h) for each altitude band of 200 m in the range of 200–4000 m. The upper limit of 4 km is high enough to cover practically all bird migration normally occurring above land (Bruderer 1997b). The lowest altitudinal layer (0–200 m) is not taken into account because birds migrating at low altitudes follow preferable habitats (Buurma *et al.* 1986, LWVT/SOVON 2002), causing spatially heterogeneous flight paths. This can introduce a slight bias between radars at different locations up to flight altitudes of 50 m. Moreover, non-migratory movements, recognized as movements in all directions, generally also occur in this altitude layer. Furthermore, strong ground clutter is not completely suppressed, which causes a bias in the mean radial velocity towards zero in Doppler weather radars (Holleman 2005). Data are only compared when available for at least 30% of the altitude profiles of both radars per 3-h window.

Verification scores

We first compared the weather radar data with the bird radar data with respect to presence or absence of birds. A threshold of 1.0 bird echo km^{-3} as measured by the bird radar was used to determine bird presence and absence. This threshold was the optimal value identified by searching for the highest ratio of matching cases and the lowest false positive ratios attained using thresholds between zero and three echoes per km^3 in increments of 0.1 echoes per km^3. The results are presented in a two by two contingency table of bird radar versus weather radar bird presence (Fig. 3). This table is also called an error or confusion matrix. In this table, A and D refer to the number of matching cases for bird presence and absence, respectively, and B and C represent the two possible prediction errors: false positives and false negatives. In rare events, when D is dominant and the correct fraction artificially becomes one, the validity of the parameter is doubtful. In such cases the correct fraction is used in combination with other verification scores that include one of the two prediction errors. As D is dominant in a high percentage of the cases in this study, the correct fraction is used in combination with other verification scores as described above.

Estimation of migratory density

To try to estimate migration density with the weather radar we apply two approaches. In the first approach, reflectivity of the weather radar (linear quantity Z) is compared with bird density (BD) as extracted from the bird radar per 200-m layer using linear regression. In the second approach we compare vertically integrated reflectivity measurements of weather radar (VIR) and the vertically integrated density of the bird radar (VID) using linear regression. For the quantification of migration density we only include those observations of Z and VIR where bird presence is indicated by the weather radar based on the standard deviation of the radial velocity. Although the standard deviation can be used to identify bird presence in wind measurements, discrimination between wind, birds, insects and clutter or rain echoes can be improved to estimate migration density by

		Weather radar YES	Weather radar NO	
Bird radar	YES	A	B	A + B
Bird radar	NO	C	D	C + D
		A + C	B + D	TOT

		Weather radar YES	Weather radar NO	
Bird radar	YES	3290	571	3861
Bird radar	NO	2029	13830	15859
		5319	14401	19700

Figure 3. Two by two contingency table of bird radar vs. weather radar detections. Naming conventions (left) and results (right): each case represents a comparison between both radars per altitude class and hour. *A* and *D* refer to the number of matching cases for bird presence and absence respectively, *B* and *C* represent false negatives and false positives respectively.

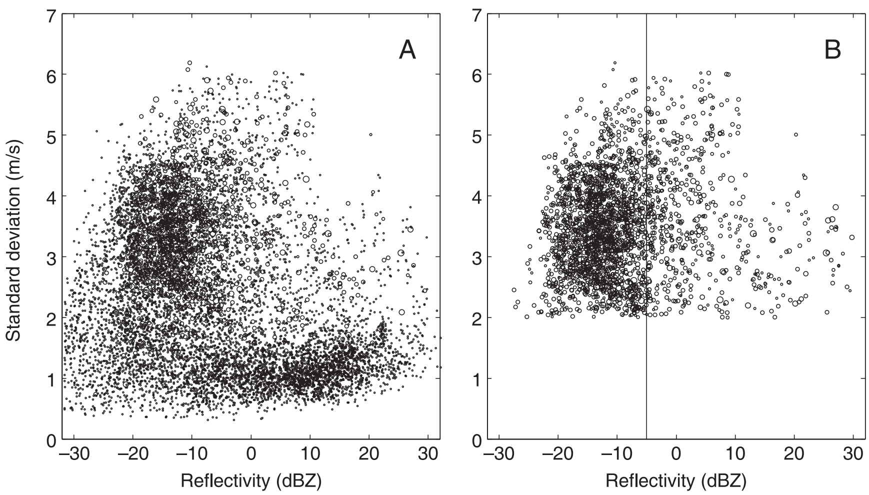

Figure 4. Scatter plots of standard deviation of radial velocity and reflectivity of the weather radar. The circle size represents the bird density as estimated from the bird radar. In (A) all data are included. In (B) only data from the weather radar with a standard deviation larger than 2 m s^{-1} and data from the bird radar with minimum bird density of one echo per km^3 are included. The extra selection criteria of reflectivity ≤ –5 dBZ, used in the estimation of migration density, is indicated with a vertical line in (B).

using additional information about minimum speed (insects, ground clutter) or maximum reflection (rain, ground clutter). Maximum reflectivity greatly affects VIR if wrongly classified as birds. Therefore, we identified the values of maximum reflectivity and minimum speed per altitudinal layer that optimally detect bird presence via cross-validation. A linear regression model between the VIR and VID is derived on the basis of three-quarters of the dataset (calibration set), and the root mean square error (RMSE) is calculated on the remaining quarter (validation set). This bootstrap procedure is repeated 100 times on randomly selected calibration and validation datasets, and for each combination of maximum reflectivity (ranges between –10 and +10 dBZ, with steps of 1 dBZ), minimum speed (ranges between 1 and 15 m s^{-1}, with steps of 1 m s^{-1}) and a minimum radial velocity standard deviation of 2 m s^{-1}. The mean over the 100 evaluations results in a mean RMSE per combination of maximum reflectivity and minimum speed.

By applying the cross-validation procedure, optimum values (minimum RMSE) for the maximum reflectivity threshold and minimum speed threshold are respectively –5 dBZ and 6 m s^{-1}. These selection criteria are used in addition to a minimum radial velocity standard deviation of 2 m s^{-1} (Fig. 4) to define bird presence in the weather radar data for the quantification of migration density.

RESULTS

Presence/absence (Verification scores)

Among 19 700 cases (a case referring to a single altitudinal layer) 70.2% were cases without birds in both radars. This high number is a result of a very low migration density in the upper half of the radar volume and low densities during daytime, which are all eliminated from analysis according to the threshold of one echo per km^3. In 16.7% of all cases both radars showed presence of migration. Adding these two values leads to a correctly predicted incidence (presence/absence) of birds in 86.9% of all cases. If only the cases where the bird radar showed presence of migration are considered (19.7% of all cases), the probability of detection of the weather radar is 85.2%. On the other hand, the false-positive ratio of 38.1% is rather high ($C/(A + C)$, Fig. 3).

The proportion of cases per day with birds present is in most cases below 0.5, which indicates that even in the period of heavy bird migration the percentage of single measurements with birds is usually far below 50%. This high fraction of measurements without birds leads to a constantly high fraction of correctly identified cases, i.e. the radar does not falsely detect birds.

Bird migration intensity

When considering the 20 altitudinal layers separately, a good relationship between Z and BD could not be found. The question remains whether reflections of the weather radar can be translated into bird densities for individual altitudinal layers. Bird density integrated over altitude may be similar, even if density profiles are not the same at 80 km distance. The regression model for bird density integrated over altitude indeed proved to be significant. The best model between VID (in number km^{-2}) and VIR (in $mm^6\,m^{-2}$) is a linear relation ($R^2 = 0.47$, $n = 986$, $P < 0.001$).

$$VID = 0.600 + 0.087 * VIR \qquad (9)$$

At migration peaks the selection criterion of maximum reflection interferes with the analysis. Based on the relationship shown in Eq. 9, the maximum reflectivity value of –5 dBZ in one altitudinal layer corresponds with an estimated density of 30.8 birds km^{-3}, assuming all birds are flying in one 200-m altitudinal layer, which is a realistic value during migration peaks. However, observations with reflectivity values higher than –5 dBZ are now wrongly identified as rain and removed from the data used to quantify bird density, effectively lowering the predicted total bird density.

Assessing speed and direction

In contrast to bird presence, speed and direction can only be compared when both radars observe birds at the same time. Mean bird direction measured with the bird radar and weather radar agreed within 15° bins in 73.3% of the cases ($n = 1451$). Speed agreed within 3 m s^{-1} bins only in 47.1% of the cases ($n = 1451$). Mean speed measured by the weather radar is significantly negatively biased (*t*-test for paired samples; $t = 46.70$, $P < 0.001$, $n = 1451$), with an average underestimation of 3.44 m s^{-1}. Correcting for this bias by adding 3.44 m s^{-1} to the weather radar speed measurements improved the correspondence between both radars to 78.0%. The agreement between the bird direction and (corrected) speed as measured by the two radars increases with altitude up to 600 m and remains constant at higher altitudes (Fig. 5).

Examples of weather radar capability

An example of the information that can be extracted from the weather radar used in this study is given in Figure 6. It shows the incidence and densities of

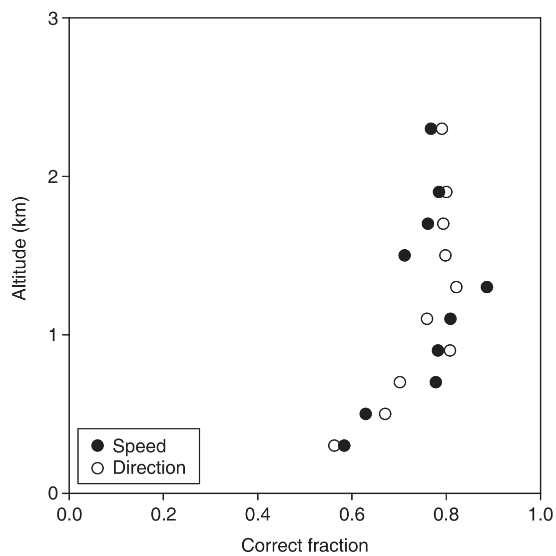

Figure 5. Correspondence between bird and weather radar measurements for speed and direction as a function of altitude.

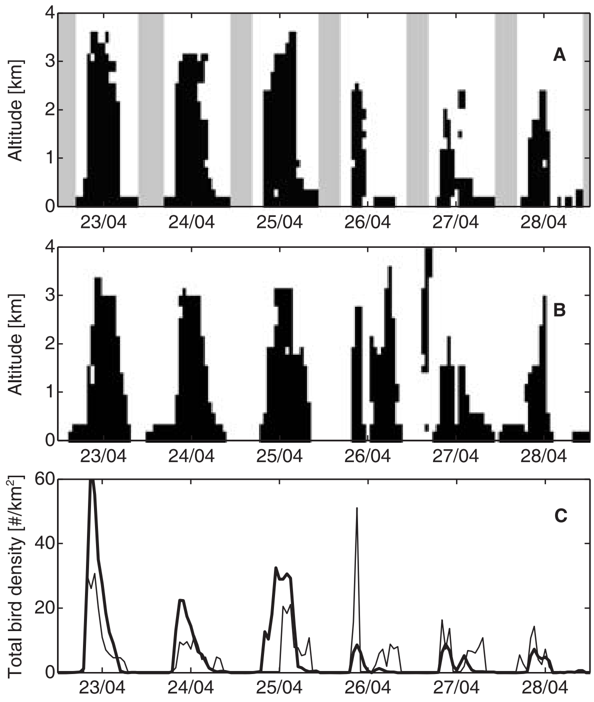

Figure 6. Bird information assessed from weather and bird radar on 22–28 April 2003. Bird presence per altitude layer in bird radar (A), weather radar (B), and bird density integrated over altitude for bird radar, VID (thick line) and estimated density for weather radar (thin line) (C) per hour. The shaded areas in (A) denote periods with no measurements.

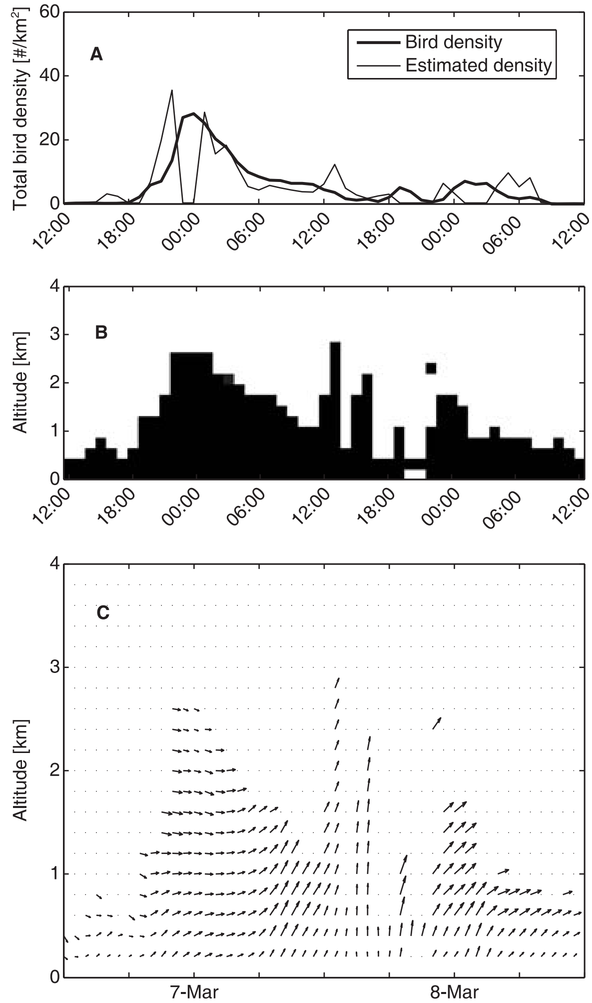

Figure 7. Bird information assessed from weather radar on 6–8 March 2003. Bird density integrated over altitude for bird radar (VID) (thick line) and estimated density for weather radar (thin line): (A) bird presence per altitudinal layer, and (B) mean bird speed and direction per hour derived from the weather radar. In Figure 7C, the arrow length and orientation represents speed and direction respectively where N is upward, E is towards the right.

migrating birds for 6 days in April 2003 measured by the bird and weather radar. During the afternoon (12:00–17:00 UTC) the bird radar was not operational. Both timing and altitude of bird migration are detected well. On 26 April misidentifications of bird presence in the weather radar are related to precipitation. Most of the hours with rain do not show any bird migration (VID) in Figure 6C, where selection on minimum speed and maximum reflections correctly removes those measurements. During this time of year, peaks in both nocturnal and diurnal bird migration occur, but the absence of diurnal migration is confirmed both by radar and by field observations in the Netherlands (www.trektellen.nl).

Another example (Fig. 7) shows the incidence and densities of migrating birds in the weather radar, as well as the mean direction and speed at different altitudes. Migration begins just after sunset (6 March, 18:28 UTC). At low altitudes birds take off in the (normal) northeast direction from southwest Europe towards Scandinavia (Fig. 7C) but at higher altitudes and over the entire altitudinal distribution around midnight, signals of these northeast migrating birds are overruled by birds flying eastward from England towards eastern Europe. In this case, birds crossing the North Sea arrive in our measurement area 3–4 h after sunset and dominate all altitudinal layers. At sunrise, daytime migration starts above land and the mean northeast direction indicates that the arrival of birds from the UK has stopped or has become less important. In this time series, maximum flight altitudes are reached around midnight on 7 March. Altitudinal migration decreases during the course of the night and fluctuates in the afternoon of 7 March. On 8 March the altitude of bird migration is much lower than on 7 March.

DISCUSSION

Detecting bird presence or absence

Our results show that bird presence or absence can be detected with the weather radar using a radial velocity standard deviation threshold of 2.0 m s^{-1}. Weather Radar Wind Profile (WRWP) measurements with high root mean square errors (RMSE) were already identified as bird-contaminated measurements as early as the mid 1990s (Gauthreaux *et al.* 1998, Koistinen 2000, Liu *et al.* 2005). However, no systematic studies had been carried out comparing WRWP measurements and bird migration measurements. The WSR-88D products used in several bird migration studies (Gauthreaux & Belser 1998, 2003) give RMSE values of the WRWP winds in classes of 4.0 m s^{-1} deviations. These classes are too big to conduct a high quality controlled discrimination between real wind measurements and bird migration measurements (Gauthreaux *et al.* 1998), therefore the real RMSE values have to be extracted from WSR-88D products (Gauthreaux & Belser 2003). The use of RMSE as a threshold automatically to discriminate real wind measurements from bird- or insect-contaminated measurements has already been proposed by Koistinen (2000). Koistinen (2000) suggested adding several biological information rules such as seasonal and daily patterns, favourable weather conditions for bird migration and WRWP deviations from numerical weather prediction (NWP) models in weak pressure gradients, but did not implement them into a model. Only recently have automatic quality controls of wind vectors retrieved from WRWP been thoroughly discussed and comparisons made between Volume Velocity Processing and Volume Azimuth Display techniques (Holleman 2005, Liu *et al.* 2005, Zhang *et al.* 2005). The use of multi-criteria quality control parameters resulted in a correct fraction of 94.6% in discriminating between real wind and (bird) contaminated winds (Liu *et al.* 2005, Zhang *et al.* 2005). In our study, based on a single-criterion quality control parameter, a correct fraction of 87% was reached. This value, however, is not very convincing as it consists of 70% cases without migration and only 17% with birds in both radars. Strikingly there is a high false-positive rate in both studies, 37.2% (Liu *et al.* 2005) and 38.1% (this study), that is caused by overlap in discriminating criteria between real wind, insect- and bird-contaminated measurements.

Bird migration intensity

Estimating migratory intensity from weather radar measurements was not possible in the current study at a height resolution of 200-m altitudinal bands. The main reason is probably that the sampled volumes were too small and thus the numbers of targets per counting cell and altitude layer insufficient. When integrating the information over altitude, a linear relationship was recovered between the weather radar reflectivity (VIR) and bird density (VID). The radar reflectivity Z depends linearly on the number of point targets per unit of volume and their cross-section reflectivity. Assuming that the cross-section reflectivity of the birds is independent of the number of birds, a linear relation between radar reflectivity Z and the number of birds per unit volume (BD) is expected (Black & Donaldson 1999, Gauthreaux & Belser 1999, Diehl *et al.* 2003). This relation is derived for data with angular velocity standard deviations higher than 2 m s^{-1}, speed measurements higher than 6 m s^{-1} and reflectivity equal or less than –5 dBZ. The reflectivity factor during peak bird migration nights in autumn in the USA can even reach values of +30 dBZ (Gauthreaux & Belser 1998, 2003). These values are also found in our study, but due to our selection criteria on reflectivity they are removed from the analysis (Fig. 4B). Nearly all insect movements are removed by a minimum speed threshold of 6 m s^{-1}, as high insect densities occur in warm, calm weather (with wind speeds much lower than 6 m s^{-1}) and insect speed is close to wind speed (Riley 1999, Chapman *et al.* 2002a, Gauthreaux & Belser 2003). Because we used ground speed measurements in this study, the value of 6 m s^{-1} is specific for our dataset and could be slightly different at other locations. We conclude that weather radar measurements can provide relative values of migration intensity with the exception of high bird densities (when our model leads to under-prediction). During some hours with peak migration (which occurred once every 10–14 days in this spring dataset) bird densities are strongly underestimated, but increasing densities at the beginning of the night and decreasing densities at the end of the night are clear indicators of this underestimation. Improvements in target discrimination algorithms would improve future comparisons between bird detection and weather radars.

Assessing speed and direction

The C-band Doppler weather radar extracts wind speed and direction based on the reflectivity of particles in the atmosphere such as aerosols, aerial plankton, insects and birds. A bird's ground speed and direction, which is measured by the bird radar, is a function of its air speed and direction and the wind speed and direction (Shamoun-Baranes *et al.* 2007). Deviations between the bird's actual ground speed and direction and measurements extracted from the weather radar are expected if we assume that these measurements represent a mixture of wind and bird movements. Bird ground speed, after correction for bias, and direction are estimated with similar accuracy (measured by 78% and 73% correct predictions for speed and direction, respectively). Deviations between the weather and bird radars occur for both parameters. At low altitudes, deviations are caused by insufficient clutter suppression in the weather radar (Gauthreaux *et al.* 1998, Holleman 2005), but also by greater scatter in speed and direction of birds themselves up to altitudes of 0.5 km. Migrating birds at altitudes above 0.5 km generally fly with rather constant speed and direction at a certain altitudinal level. Speed and direction can change with altitude depending on changes in wind direction (Liechti 1993), but at higher altitudes (e.g. above 1 km) birds mainly fly with following winds (Richardson 1990, Bruderer *et al.* 1995b, Liechti *et al.* 2000). Apparently, deviations between wind direction and bird migratory direction are within 15° bins, as approximately 80% of the cases are within this range (altitude 1–2.5 km, Fig. 5). In our study we find that the weather radar measurements of speed are negatively biased by 3.44 m s^{-1}. By comparing radiosonde measurements (weather balloon measurements of wind and temperature) and bird-contaminated WRWP (Fig. 6F in Gauthreaux *et al.* 1998) we show that increasing bird densities lead to higher velocity differences between radiosonde measurements and WRWP. This implies that when observing high bird densities with a WRWP, the measured speeds are a close approximation of the actual bird ground speed, whereas with low bird densities the observed speed is close to wind speed. Therefore, speeds retrieved from WRWP are a mixture of wind and bird movement measurements with a range between wind speed and bird ground speed; as the density of birds increases (and hence the proportion of reflectivity due to birds), the closer the speed estimated by the weather radar will be to the bird ground speed. In contrast, bird radar always measures the actual ground speed of the bird.

Monitoring

The use of weather radars and WRWP in bird migration research has been suggested (Gauthreaux *et al.* 1998 and references therein) ever since the contamination of weather radars and WRWP have been at least partly attributed to birds. Only recently has the network of WSR-88D weather surveillance radars in the USA been used to examine temporal and spatial dynamics of bird migration on a continental scale (Gauthreaux *et al.* 2003). Because of the labour-intensive analytic work involved, only one case of continental bird migration has been investigated (Gauthreaux *et al.* 2003). Only when radar data are efficiently archived in a database and data processing is fully automated, will it be possible to monitor daily and yearly changes in migratory patterns on a more regular basis (Gauthreaux *et al.* 2003). In Europe, an automated system for monitoring bird migration can be established using the network of weather radars in Europe (Operational Programme for Exchange of RAdar data, OPERA: www.eumetnet.eu.org). The capabilities of one of the C-band Doppler weather radars used in this network are presented in this study.

CONCLUSIONS

Contamination of an operational weather radar has been compared with bird migration as observed with a dedicated bird radar. In this study, this so-called contamination of wind measurements can largely be attributed to migrating birds. Bird and weather radar correspond quite well with respect to timing and altitude of bird migration. The total migration intensity reproduced by the vertically integrated reflectivity of the weather radar shows a good correlation with observations from the bird radar. However, in the current study, migration intensity estimated by the weather radar at a specific altitudinal layer could not be matched with bird radar observations. This mismatch is probably due to small sample sizes and the distance between both measurement sites (80 km). Finally, flight speed and direction assessed from the weather radar are closely related to bird speed and direction as observed with the bird radar, especially at altitudes above 0.5 km. We expect that further improvements can be made to weather radar data interpretation by conducting a similar comparison between radars with overlapping coverage, improving algorithms for target discrimination and algorithms to correct for detection loss in the weather radar. The existing European network of weather radars offers great opportunities for bird migration research as well as for developing a European-wide warning system for preventing bird hazards to military aircrafts.

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