Aeroecology meets aviation safety

Early warning systems in Europe and the Middle East prevent collisions between birds and aircraft

van Gasteren, Hans; Krijgsveld, Karen L.; Klauke, Nadine; Leshem, Yossi; Metz, Isabel; Skakuj, Micha; Sorbi, Serge; Schekler, Inbal; Shamoun-Baranes, Judy

DOI
10.1111/ecog.04125

Publication date
2018

Document Version
Final published version

Published in
Ecography: A Journal of Space and Time in Ecology

ECOGRAPHY

Review and synthesis

Aeroecology meets aviation safety: early warning systems in Europe and the Middle East prevent collisions between birds and aircraft

Hans van Gasteren, Karen L. Krijgsveld, Nadine Klauke, Yossi Leshem, Isabel C. Metz, Michal Skakuj, Serge Sorbi, Inbal Schekler and Judy Shamoun-Baranes

H. van Gasteren (http://orcid.org/0000-0002-4810-3899) (jr.v.gasteren@mindef.nl), Royal Netherlands Air Force, Breda, the Netherlands, and Theoretical and Computational Ecology, Inst. for Biodiversity and Ecosystem Dynamics, Univ. of Amsterdam, Amsterdam, Amsterdam, the Netherlands. – K. L. Krijgsveld, Royal Netherlands Air Force, Breda, the Netherlands. – N. Klauke, Bundeswehr Geoinformation Centre, Euskirchen, Germany. – Y. Leshem, Tel Aviv Univ., George S. Wise Faculty of Life Sciences, Dept of Zoology, Ramat Aviv, Tel Aviv, Israel. – I. C. Metz, Inst. of Flight Guidance, German Aerospace Center DLR, Braunschweig, Germany, and Control and Simulation Dept, Faculty of Aerospace Engineering, Delft Univ. of Technology, Delft, the Netherlands. – M. Skakuj, Ekoaviation, Gdańsk, Poland. – S. Sorbi, Aviation Safety Directorate, Belgian Air Force, Beauvechain, Belgium. – I. Schekler, Dept of Evolutionary and Environmental Biology, Univ. of Haifa, Haifa, Israel. – J. Shamoun-Baranes, Theoretical and Computational Ecology, Inst. for Biodiversity and Ecosystem Dynamics, Univ. of Amsterdam, Amsterdam, the Netherlands.

Ecography
42: 1–13, 2018
doi: 10.1111/ecog.04125

Subject Editor: Jason Chapman
Editor-in-Chief: Miguel Araújo
Accepted 5 December 2018

The aerosphere is utilized by billions of birds, moving for different reasons and from short to great distances spanning tens of thousands of kilometres. The aerosphere, however, is also utilized by aviation which leads to increasing conflicts in and around airfields as well as en-route. Collisions between birds and aircraft cost billions of euros annually and, in some cases, result in the loss of human lives. Simultaneously, aviation has diverse negative impacts on wildlife. During avian migration, due to the sheer numbers of birds in the air, the risk of bird strikes becomes particularly acute for low-flying aircraft, especially during military training flights. Over the last few decades, air forces across Europe and the Middle East have been developing solutions that integrate ecological research and aviation policy to reduce mutual negative interactions between birds and aircraft. In this paper we 1) provide a brief overview of the systems currently used in military aviation to monitor bird migration movements in the aerosphere, 2) provide a brief overview of the impact of bird strikes on military low-level operations, and 3) estimate the effectiveness of migration monitoring systems in bird strike avoidance. We compare systems from the Netherlands, Belgium, Germany, Poland and Israel, which are all areas that Palearctic migrants cross twice a year in huge numbers. We show that the en-route bird strikes have decreased considerably in countries where avoidance systems have been implemented, and that consequently bird strikes are on average 45% less frequent in countries with implemented avoidance systems in place. We conclude by showing the roles of operational weather radar networks, forecast models and international and interdisciplinary collaboration to create safer skies for aviation and birds.

Keywords: bird strike, radar, warning system, military aviation, bird migration

NORDIC SOCIETY OIKOS

www.ecography.org

Introduction

The aerosphere is used by billions of birds, moving for different reasons and from short to great distances, spanning tens of thousands of kilometres. The aerosphere, however, is also utilized by aviation, creating increasing conflicts in and around airfields (Sodhi 2002, Zakrajsek and Bissonette 2005, Dolbeer et al. 2015, McKee et al. 2016) as well as en-route, i.e. the phase of flight outside the airfield (Shamoun-Baranes et al. 2005, 2008, van Belle et al. 2007, van Gasteren et al. 2012). Collisions between birds and aircraft, often termed 'bird strikes', cost billions of euros annually (Allan 2002, Anderson et al. 2015, Dolbeer et al. 2015) and, in some cases, result in the loss of human lives and/or destroyed aircraft (Richardson and West 2000, 2005, Thorpe 2003, 2005, 2016). The damage caused by a bird strike is associated with the speed of the aircraft, the mass of the birds, the number of the birds involved, and the location of impact on the aircraft. An analysis of 24 destroyed aircraft reported between 1968 and 2005 showed that 23 of these accidents occurred during departure, with engine ingestion of birds proven in at least 20 of them. Fan and compressor rotor speed are higher during departure than during landing, resulting in higher kinetic energy when birds are ingested into an engine and thus the likelihood of severe damage is higher during departure than during landing (Dolbeer 2008). In contrast, the low-level (i.e. low-altitude) training flights which are customary in military aviation, occur at high speeds and with mostly single-engine fighter jets, result in higher bird strike risks compared to civil aircraft. The latter only briefly cross the low altitudes, where birds generally fly (Bruderer et al. 2018), to reach their much higher cruising altitude. As a result, military bird strikes show a bimodal distribution along aircraft speeds (van Gasteren et al. 2012, Shamoun-Baranes et al. 2017b). Because kinetic energy increases exponentially with aircraft speed, the risk of damage is much higher during low-level flight than during take-off or landing, when aircraft are flying much more slowly (Eschenfelder 2005, Dennis and Lyle 2008, Hedayati and Sadighi 2016).

Bird migration is a world-wide phenomenon between breeding and wintering (or non-breeding) areas. Along the Palearctic-African migration system an estimated 2.1 billion songbirds winter in Africa (Hahn et al. 2009), while 1–2 million soaring birds travelling to and from Africa cross the Mediterranean Sea along its narrowest corridors in southern Spain, Italy or via Turkey and Israel, on their way to Africa (Leshem and Yom-Tov 1996, Newton 2008, Busse et al. 2014, Martín et al. 2016). The most important European migratory flyways stretch between Scandinavia and southwest to southeast Europe as well as between Siberia and western Europe and the UK. Birds migrating through the Middle East are migrating from both sides of the Black Sea (Verhelst et al. 2011) and funnel through Israel (Bildstein and Zalles 2005, Newton 2008). Consequently, the risk of bird strikes is highest during migration, when large concentrations of birds are found in the air. Due to the different nature of bird strikes at airports versus en-route, mitigating the bird strike risk at airports focusses on habitat management to reduce bird numbers in the airport as well as on active bird scaring methodology (Blokpoel 1976, Dekker and Buurma 2003, MacKinnon 2004, McKee et al. 2016). In contrast, measures for low-level flight bird strike prevention, to the authors' knowledge, only exist in military aviation. These measures are based on closing the airspace during peak bird migration, when collision risks are too high. To effectively determine when and where to close the airspace and reduce the risk of bird strikes during low level flight, it is essential to understand where, when and how many birds are most likely to be in the air.

The aims of this study are 1) to provide a brief overview of the bird migration monitoring and warning systems currently used in military aviation to reduce the risk of bird strikes during migration, 2) to provide a brief overview of the impact of bird strikes on military low-level operations, and 3) to estimate the effectiveness of migration monitoring and warning systems in bird strike avoidance. We compare systems in the Netherlands, Belgium, Germany, Poland and Israel; areas that are all crossed twice a year by Palearctic migrants in vast numbers. We conclude by showing the roles of operational weather radar networks, forecast models and international and interdisciplinary collaboration to creating safer skies for both aviation and birds.

Overview of bird monitoring and warning systems

Bird warning systems in military aviation

Since the 1950s, radars have been used to record and monitor bird migration (Lack 1959, Eastwood 1967, Bruderer 1971, Buurma 1995, Gauthreaux-Jr and Belser 2003). The advantage of radar is its capability to detect birds in flight during day and night, quantify the number of birds aloft, and measure flight speed and direction. However, the radars used in military aviation are not able to determine bird species (Eastwood 1967, Bruderer 1997). The first bird warning systems in military aviation were based on reference photos taken from the radar screen of the air surveillance radar (Eastwood 1967, Geil et al. 1974, Buurma and Bruderer 1990, Ruhe 1994). In the Netherlands, a biologist would contact the radar location, to be informed of bird densities on the radar screen. In Denmark, Belgium and Germany radar controllers analyzed the radar images themselves. In Israel, this task was performed by both the radar controllers and, during the migration season, the wildlife control unit in a national center. Their special focus was the so-called Bird-Plagued Zones (BPZ), which carry a heavy risk of bird strikes. If the wildlife controllers detected large flocks of soaring migrants, mainly white storks *Ciconia ciconia*, white pelicans *Pelecanus onocrotalus* and various species of raptors *Accipitriformes* (Leshem and Yom-Tov 1996), they warned

the relevant air traffic control tower and en-route air traffic control units in the respective areas (Leshem 1990).

The first electronic systems were operational in Denmark in 1971 and the Netherlands in 1978 (Buurma 1978, Buurma and Bruderer 1990). Both systems were electronic bird migration intensity counters in a number of windows on the radar screen of military air surveillance radars. The next phase in automatic bird detection systems was based on the extraction of bird information from the air surveillance tracking algorithms (Buurma and Bruderer 1990). These tracking algorithms classified aircraft as well as 'other targets'. Most of these other targets were flocks of birds. Information about their velocity, height and direction were visualized in specific software. Systems based on these processed radar data were in place in Belgium (Bird Observation System Semmerzake, BOSS system) (Buurma and Bruderer 1990) and Germany (Ruhe 2008). The German system has evolved into a network of 19 air traffic radars and 32 air surveillance radars from Germany as well as radars of neighboring countries. The advantage of such systems is that all radars connected in the military network produce this data automatically. However, the visualization of birds on the radar screen depends on the system settings which can be changed by the radar controllers. This is disadvantageous, as these settings are not well known to bird control units. Therefore, experts are needed to interpret the data and translate them into bird warnings (Ruhe 2008).

The Robin system in the Netherlands and Belgium was developed to process raw data from the military air surveillance radar for optimal bird detection. To the best of our knowledge, this is the only bird warning system where bird information is extracted directly from the radar (Buurma 1995). Unfiltered raw video is sampled at the highest resolution. Time-lapse images show location, direction and density of bird movement. Improvements to the system have resulted in automatic discrimination between bird tracks (location, speed, direction and size), ground clutter and rain. When computer power increased in the late 1990s, bird echoes could be tracked in the whole radar range of up to 150 km and altitude of up to 5 km (Buurma 1995).

Similar to other types of radars, weather radars are able to monitor biological information, predominantly insects and birds (Wilson et al. 1994, Martin and Shapiro 2007, Bauer et al. 2017, Van Doren and Horton 2018). Weather radars are especially valuable for meteorological products and for the international networks that they can be organized into. This increases the covered area, revealing larger spatial patterns of migration (Huuskonen et al. 2014). Examples of such networks are the NEXRAD system in the USA (Crum and Alberty 1993) and the OPERA system in Europe (Holleman et al. 2008). In the USA and Europe, weather radars are also being used for bird migration warning systems (Gauthreaux Jr and Belser 1998, Koistinen 2000, Shamoun-Baranes et al. 2008). Innovative bird detection algorithms designed for weather radars resulted in an automated method for the detection and quantification of bird migration. With this method, bird density (number of birds per cubic kilometer), speed and direction are measured as a function of altitude (Dokter et al. 2010). The bird detection algorithm is currently operational at the Flysafe bird avoidance model service center (<www.flysafe-birdtam.eu>). It automatically updates the bird density profiles as a function of altitude every half hour for the weather radars in the Netherlands and Belgium. The development and refinement of these bird warning systems have been made possible only through collaboration among radar engineers, ecologists, meteorologists and users.

Bird migration warnings

The output of the bird migration warning systems are issued to pilots as BIRDTAM warnings (BIRD-notice-to-AirMen). This terminology is based on the notice-to-airmen (NOTAM) messages, which are issued by the national aviation authorities to inform pilots about current conditions that might influence the safety of a flight. Similarly, BIRDTAM messages warn pilots of areas with high bird densities and therefore increased bird strike risk. Within the military, the use of BIRDTAMs has been in place since the first publication of the Standard NATO Agreement STANAG 3879 in December 1988 (NATO 2013). Since 1998 all BIRDTAM warnings in northwest Europe have been stored in a database by the German Armed Forces and are used in further analyses below.

Bird densities in the air are measured by radar in Denmark, Germany, the Netherlands and Belgium and translated to a logarithmic BIRDTAM value ranging from 1–8 (Becker 1994). Bird density values measured by weather radar as a function of altitude are likewise translated into BIRDTAM values as follows:

BIRDTAM scale	bird density (in birds km^{-3})
8	> 80
7	40–80
6	20–40
5	10–20
< 5	< 10

Each of these countries has individual regulations regarding the interpretation of BIRDTAM values (Becker 1994). In all countries, the risk of bird strikes is considered acceptable for BIRDTAM values less than 5, while values of 5 or higher are classified differently. Depending on the country, advisory regulations hold for values 5 and 6. Regulations that restrict or prohibit flying are in force for values of 7 and 8 or between 5 and 8. These regulations hold specifically for jet aircraft and other fixed-wing aircraft. This is related to the higher risk of bird strikes as well as higher risk of fatal consequences for fixed-wing aircraft compared to helicopters, as they operate at much higher airspeeds than helicopters (Buurma and Dekker 1992). However, hull losses of helicopters caused by bird strikes do occur (Thorpe 2003, Richardson and West 2005). Therefore, advisory regulations for helicopters do exist; they focus on reducing flight speed (Becker 1994).

BIRDTAM warnings are issued on a daily basis and updated every two to four hours. The extent of the daily BIRDTAM-service differs between countries. In Belgium and the Netherlands, the service is provided during working days. In case of planned night flights, the BIRDTAM-service can be extended respectively. In Germany, BIRDTAMs are issued continuously throughout the day until several hours after sunset, seven days a week. BIRDTAM warnings are provided visually in a $1° \times 1°$ resolution, based on the world geographical reference system (GEOREF) and include the upper limit of the warning in feet above ground level. In the years before the 1990s, BIRDTAM warning text messages were issued through a telex system only and mostly not timely received by pilots. The distribution of BIRDTAM warnings improved when information was presented on a map and distributed through facsimile systems in the 1990s. Nowadays, BIRDTAMs are digitally available in operational planning systems for pilots. Restrictions are furthermore broadcasted on the emergency aircraft frequency (GUARD) to raise the attention of pilots already airborne.

Migration forecast systems

Numerous radar studies have shown how migratory birds behaviour is influenced by weather (Alerstam 1978, Richardson 1978, 1990, Shamoun-Baranes et al. 2017a). The relationship between migratory behaviour and meteorological conditions enable the development of predictive models to forecast bird migration densities and flight altitudes. Once models are developed, weather forecast data are used as model input to predict migration 24–72 h in advance. One of the first predictive models for flight safety was developed in the early 1970s in Denmark, but not used operationally (Geil et al. 1974). The first operational model applied for flight safety was developed in Germany (Ruhe 2001, 2005). The model uses different numeric weather parameters to predict bird strike risk (Ruhe 2008). Currently, this forecast model additionally integrates actual bird migration information from radar systems to fine-tune the prediction. In the Netherlands, a regression model was initially developed based on meteorological data and measurements of migration intensity from two military air surveillance radars in the Netherlands and Belgium (van Belle et al. 2007). This forecast model was in operational use from 2001 to 2012. Subsequently, ensemble forecast models were developed and put into service (Kemp 2012), predicting hourly migration at each radar site. First attempts to use weather radars in a framework to predict migration intensities at multiple sites as well as to forecast flight altitude distributions were developed using radar data of only one year, and thus were not robust enough to deal with environmental stochasticity for operational use (Kemp 2012, Kemp et al. 2013).

The impact of bird strikes on military aviation

In this study, bird strikes are defined as events in which pilots confirmed a collision with a bird, as well as in cases where bird remains were found by ground crew during post-flight inspections. Bird strikes can be defined as local (i.e. take-off and landing) or as en-route (i.e. during level/cruise flight) (Buurma and Bruderer 1990, Shamoun-Baranes et al. 2017b). In this study we focus on the prevention of en-route bird strikes, which is a common flight safety issue in military aviation (Shamoun-Baranes et al. 2005, 2008, van Belle et al. 2007, van Gasteren et al. 2012). Flight phase is reported for each bird strike and the following flight phases were used to identify en-route bird strikes: low-level, cruise, holding and unknown. Earlier studies have shown that unknown flight phases are directly linked to bird strikes occurring en-route (Dekker and van Gasteren 2005). To quantitatively estimate the impact of bird strikes on military aviation, we used bird strike data and information about flight hours from Poland (2005–2017), Germany (1993–2016), Belgium (1997–2016) and the Netherlands (1976–2016). Additionally, bird strike data from Israel (1968–2016) was obtained.

Bird strike ratios are calculated as the number of bird strikes per 10 000 flight hours. As Israeli flight hours are confidential, bird strike ratios are missing for this country. Where bird-aircraft collisions led to damage to the aircraft, we calculated the 'damaging bird strike ratio' as a second statistic. The 'damaging bird strike ratio' is calculated as the number of damaging bird strikes per 10 000 flight hours. Since reporting biases towards incidents where damage occurred are common in bird strike statistics, the 'damaging bird strike ratio' is a more reliable parameter (Linnell et al. 1999, MacKinnon 2004). We assumed that every damaging bird strike is reported.

Bird strike occurrences over time

Thousands of bird strikes were reported over the past four decades within the five Air Forces included in this study (Table 1). By taking into account the flying hours, an average bird strike ratio of 15.0 (SE $\pm$ 3.0) bird collisions per 10 000 flight hours was reported over this period for all countries, excluding Israel. The average 'damaging bird strike ratio' amounts to 3.0 (SE $\pm$ 0.8). The comparison of the two ratios results in one damaged aircraft per five bird strikes (Table 1). An analysis of military aircraft losses from the past showed a total loss of 286 military aircraft in 32 countries for the period 1950–1999 (Richardson and West 2000). For the countries considered in this study, a total of 37 fighter jet losses were reported during the en-route phase since the late 1950s; 26 of these occurred outside the study period defined in Table 1. From the 11 fighter jet losses in the study period, only 1 occurred after 2000. Bird strike ratios were relatively high in the Netherlands and Germany and relatively low in Belgium and Poland. From the late 1970s, bird strike ratios per country and decade decreased significantly over time (2nd degree polynomial, $R^2 = 0.63$, $n = 14$, $p < 0.001$, Table 1, Fig. 1A) to 7 bird strikes per 10 000 flight hours a year. The damaging bird strike ratios per country and decade similarly decreased significantly over time (2nd degree polynomial, $R^2 = 0.77$, $n = 14$, $p < 0.001$, Table 1, Fig. 1A),

Table 1. Overview of bird strikes over the past decades for Air Forces in various European countries and Israel in relation to number of flying hours of fighter jets. A differentiation is made between all bird strikes, bird strikes resulting in damage, and bird strikes resulting in fighter jet losses while they were en-route. Note that flying hours from Israel are confidential and presented bird strike ratios exclude Israel.

		Bird strikes				Bird strike ratios		
Country	Years	all	damage	crash	Flying hours	all	damage	% damage
Data per country and per decade								
Belgium	1997–1999	37	10		53284	6.9	1.9	27
	2000–2009	64	17		150589	4.2	1.1	27
	2010–2016	24	8		85316	2.8	0.9	33
Germany	1984–1989	1711	406	1	539007	31.7	7.5	24
	1990–1999	1986	405		760686	26.1	5.3	20
	2000–2009	636	67	1	392193	16.2	1.7	11
	2010–2016	235	23		202376	11.6	1.1	10
Netherlands	1976–1979	346	97	1	135371	25.6	7.2	28
	1980–1989	1317	294	1	346610	38.0	8.5	22
	1990–1999	470	86		278819	16.9	3.1	18
	2000–2009	175	34		189746	9.2	1.8	19
	2010–2016	76	8		84384	9.0	0.9	11
Poland	2005–2009	40	0		58483	6.8	0.0	0
	2010–2017	55	13		118212	4.7	1.1	24
Israel	1968–1969	25	22					88
	1970–1979	246	185	2				75
	1980–1989	364	56	2				15
	1990–1999	444	36	3				8
	2000–2009	266	24					9
	2010–2016	136	9					7
All years combined								
Belgium		125	35	0	289189	4.3	1.2	28
Germany		4568	901	2	1894263	24.1	4.8	20
Netherlands		2384	519	2	1034930	23.0	5.0	22
Poland		95	13	0	176695	5.4	0.7	14
Israel		1481	332	7				22
All years and all countries combined								
Summed total		8653	1800	11	3395077	21.1	4.3	21

ranging between 0.9–1.1 in the four Air Forces in the latest decade 2010–2016 (Table 1).

Seasonal and altitudinal pattern of bird strikes

The majority of all bird strikes occurred between March and October during the migration season and in summer (Fig. 1B). However, the proportion of damaging bird strikes was highest during the winter months between November and March (Fig. 1B). High concentrations of relatively heavy aquatic birds (e.g. Charadriformes and Anseriformes) in these regions in winter (Hornman et al. 2018) are likely the cause of higher proportions of damage. While bird strike remains are not analysed systematically among the air forces, the information we could gather shows that during the study period virtually all aircraft losses were due to collisions with bird species over 500 g in body mass (Supplementary material Appendix 1). Aircraft speed was reported for 37% of all bird strikes. The average aircraft speed reported for bird strikes was 410 knots (kts; or 211 m s^{-1}). Of the collisions, 71% were reported to have taken place between 400–500 kts (206–257 m s^{-1}) (Fig. 1C). However, bird strikes also occur at lower aircraft speed during landing or take-off (local bird strikes). This is illustrated in the inset of Fig. 1C, showing both en-route and local bird strikes as a function of aircraft speed.

En-route bird strikes occurred mostly at the lower flight altitudes, at an average of 1225 ft (SE ± 328 ft) (i.e. 373 m, SE ± 100 m; Fig. 1D). 86% of all en-route bird strikes with fighter jet aircraft were reported below 2000 ft (i.e. 610 m) and 95% below 3500 ft (i.e. 1067 m). This skewed altitude distribution with relatively more bird strikes at lower altitudes corresponds to the average yearly bird density distributions in NW-Europe (Shamoun-Baranes et al. 2017b, Bruderer et al. 2018). This indicates that military en-route flights sample the airspace equally, with the exception of the lowest 500 ft class, which is only flown on low-level flight routes.

Effectiveness of migration monitoring systems in bird strike avoidance

Bird warnings over time and between seasons

The total number of hours per year with issued BIRDTAM values 5 or higher differed greatly over the years and between air forces. Figure 2 shows the average number of hours with issued BIRDTAM values for the four NW-European

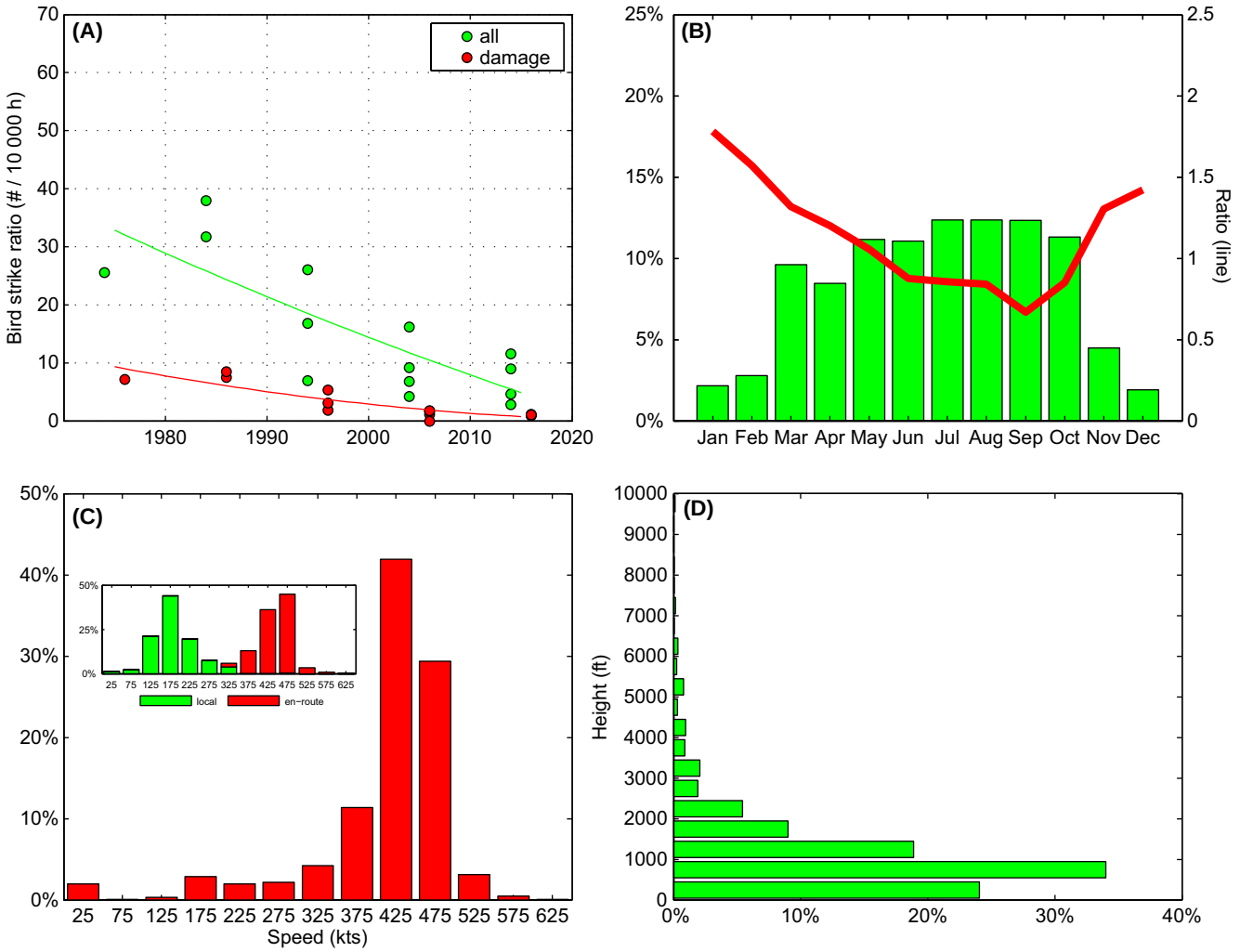

Figure 1. Summary of en-route bird strikes with military jet fighters from Poland (2005–2017), Germany (1993–2016), the Netherlands (1976–2016), Belgium (1997–2016) and Israel (1968–2016). (A) bird strike ratios for all bird strikes combined and for damaging cases only, shown per decade in the period 1976–2016 (no data from Israel). (B) Percentage-distribution of bird strikes throughout the year (bars, left axis) and relative distribution (ratio) over the year of bird strikes resulting in aircraft damage (red line, right axis). The ratio is calculated as the percentage-distribution of damaging bird strikes divided by the percentage-distribution of all bird strikes. (C) Distribution of en-route bird strikes over aircraft flight speeds (n = 3161). Inset shows speed-distribution for all bird strikes (local on airbase and en-route) for the Netherlands (1976–2016, n = 2354). (D) Height distribution of en-route bird strikes with military jet fighters (n = 3328).

countries between 1998 and 2016. The Danish warning system was only active until 2008, which explains the steep decline after 2008 (Fig. 2A). In Germany, the BIRDTAM-service (comprising evenings and weekends together with increasing awareness, improved radar data supply as well as more and better radars) led to an increase in hours with active warnings (Fig. 2B). In the Netherlands, the number of BIRDTAM hours per year decreased slightly from 2010 onwards (Fig. 2C) whereas the number of BIRDTAM hours per year was relatively constant in Belgium (Fig. 2D). Maximum BIRDTAM values were rarely issued in all countries and decreased to very few occasions in the last decade.

Over the season, BIRDTAMs were most frequently issued during the migration periods in spring (March–April) and autumn (September–November) in Belgium, Germany and the Netherlands (Fig. 3). Flight restrictions related to the highest BIRDTAM values were absent during the summer and winter months. The Danish data deviates considerably from this pattern, with high numbers over the entire year, including flight restrictions to the highest BIRDTAM values.

Figure 4 provides a geographical overview of issued BIRDTAM warnings for the periods from 1985 to 2005 and from 2010 to 2016. The largest difference in provided warnings can be found in Germany and Denmark. Due to the diminishing warning system in Denmark in 2008, BIRDTAM warnings are missing for this country in the second period. On the other hand, improvements in the bird warning system in Germany, with steadily increasing availability of radar data, probably led to an increase in hours with active warnings in the second period. In general, the majority

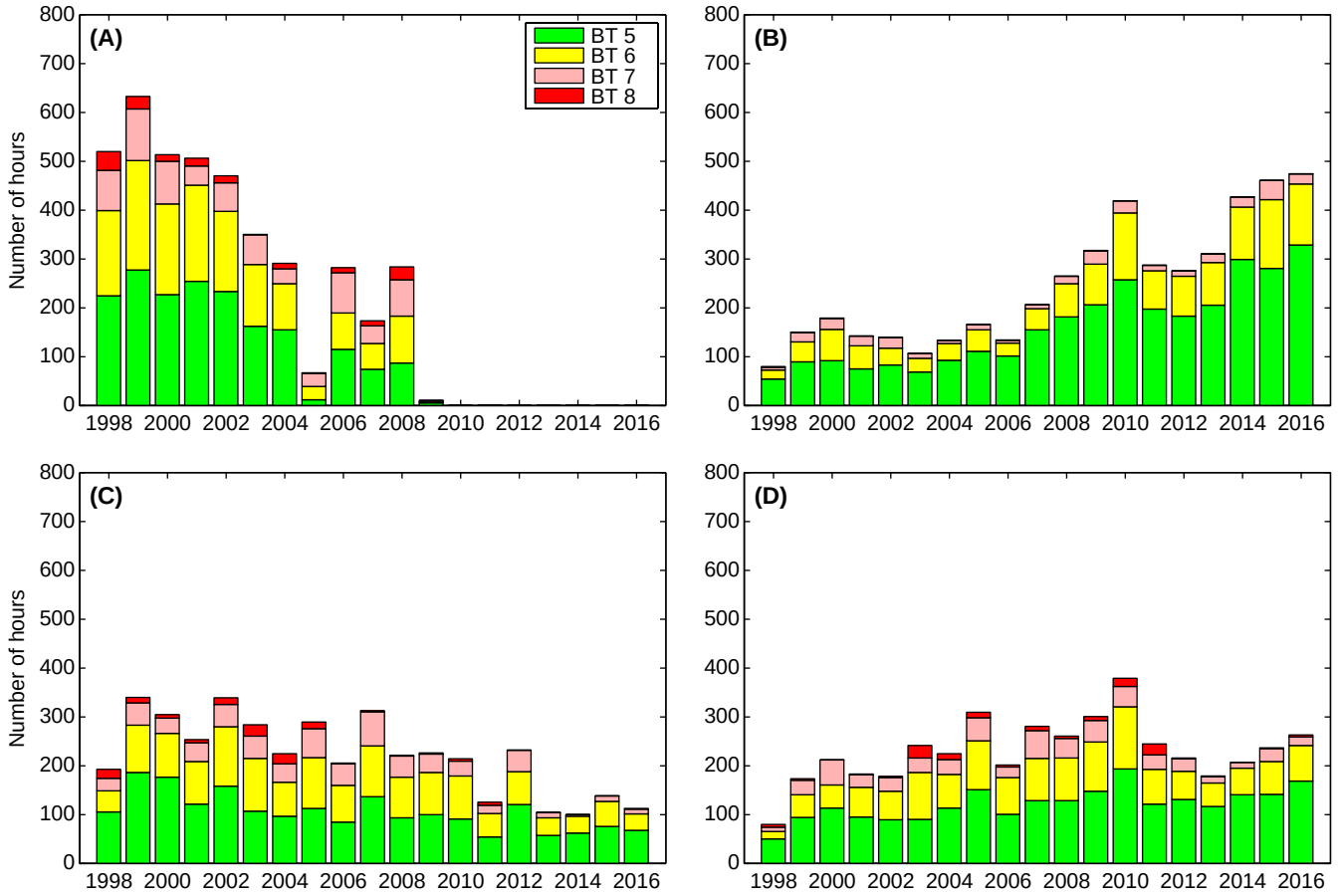

Figure 2. Number of hours during which BIRDTAMs were issued with values 5–8, per year for all GEOREF squares in Denmark (A), Germany (B), the Netherlands (C) and Belgium (D). Legend is equal for all figures. Note that Denmark published BIRDTAMs only until 2008; Germany provides a 24/7-service in publishing BIRDTAMs. The Netherlands and Belgium provide warnings between 08:00 and 16:00 during workdays as well as during planned night flight hours.

of the BIRDTAM warnings were issued in Denmark, northern Germany and the Netherlands in the first period from 1985 to 2005. These regions correspond to the wetlands, the Wadden Sea and lower parts of NW-Europe where millions of aquatic birds are present (Hornman et al. 2018). Figure 4 shows a dominance of intermediate values (6–7) for their regions. In the period from 2010 to 2016 the number of BIRDTAM hours are highest in northern and western parts of Germany with decreasing average number of hours to the southeast. The average values for the Netherlands and Belgium only changed slightly between both periods in general. However, a decrease regarding the higher BIRDTAM values, especially above the North Sea area, can be observed.

The number of issued BIRDTAM values of 5, and to a lesser extent of 6, increased in Germany and Belgium (Fig. 2B, D). In contrast, no increase took place in the Netherlands (Fig. 2C). These low BIRDTAM values only warn pilots of potential bird strike risk and do not result in flight restrictions in the Netherlands. Therefore, the reduced number of low BIRDTAM warnings indicates that the Netherlands consider their publications as less relevant than Germany and Belgium, where BIRDTAM values of 5 and 6 lead to flight restrictions.

The effectiveness of operational warning systems in reducing damaging bird strikes

This study focuses on countries that have been operating bird migration warning systems since the 1980s. In NW-Europe, not all air forces have put bird migration warning systems into service. For example, France and the UK to date have never implemented such a service. To demonstrate how the use of bird migration warning systems have affected bird strike ratios, we analysed bird strike values reported from countries that do and countries that do not use bird migration warning systems. Damaging bird strike ratios were reported for different air forces over the period 1991–2000 (Dekker and van Gasteren 2005). They are summarized in Table 2. Flying at low altitudes was common in the 20th century in all air forces operating in NW-Europe. Therefore, one might expect bird strike risk to be in a comparable order of magnitude for all these countries, located in the same bird migration system of NW-Europe. However, the air forces without an operating warning system experienced on average 7.47 damaging bird strikes per 10 000 h (Table 2). Air forces operating a warning system experienced on average 4.10 damaging bird strikes 10 000 h^{-1}. This corresponds to a 45% reduction of

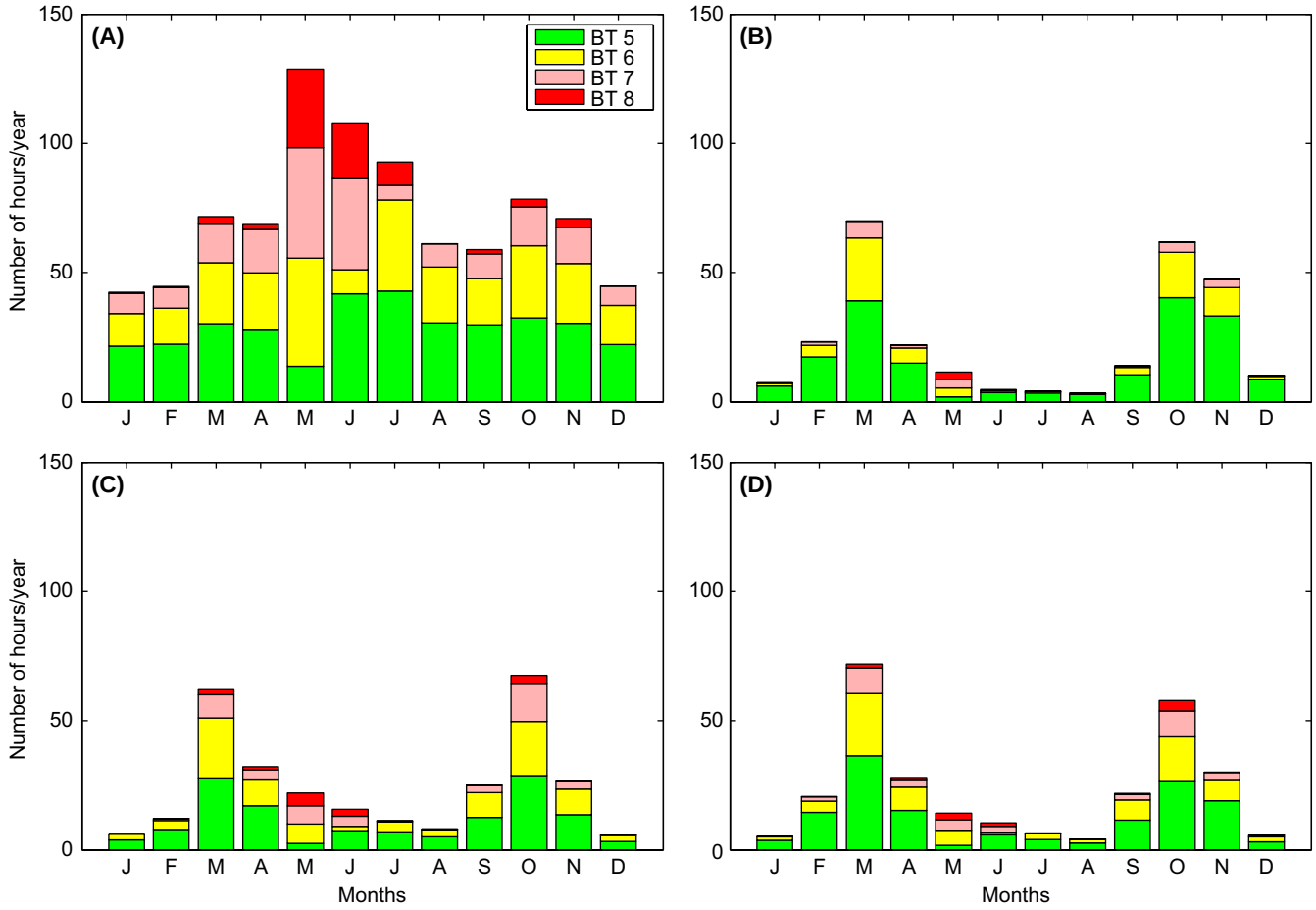

Figure 3. Average number of hours with BIRDTAM values 5–8 issued per month for all GEOREF squares in Denmark (A), Germany (B), the Netherlands (C) and Belgium (D) (1998–2016, Denmark 1998–2008). Legend is equal for all figures.

damaging bird strikes in air forces where warning systems are present.

After the introduction of the Bird-Plagued Zone in Israel in 1983, the percentage of damaging bird strikes decreased by 81% (Ovadia 2005). Following the expansion of the Bird-Plagued Zone regulations after two severe accidents in 1995 and 1997, no fighter losses have been reported in Israel (1968–1997: 7 losses; 1998–2016: 0 losses).

The costs resulting from damaging bird strikes are difficult to estimate and only published for the military in the USA. The USA approximated the costs of bird strikes between 2011–2017 for class A, B and C accidents (cost ranges above US$ 50 000, see classification in (AFSEC/CV 2018)) around US$182 million for the air force and US$ 64.8 million for the navy, which is close to US$ 0.5 million per accident (Insinna 2018). Their accident classes D and E (costs below US$ 50 000) were not taken into account. Based on this data, we estimated the total annual costs of damaging bird strikes for Europe for the period 1991–2000 (Dekker and van Gasteren 2005). We assumed a conservative average cost of US$ 100 000 for each damaging bird strike, which corresponds to a class C accident. To calculate the costs, we multiplied the damaging bird strike ratio by the average flight hours per year and by the assumed costs of an average damaging bird strike of US$ 100 000 (Table 2). The estimated costs of damage range between US$ 1–4 million for countries with an operating warning system. In the countries without a system, the resulting costs lie between US$ 10–11 million.

The operational role of the weather radar network

A substantial improvement of the BIRDTAM warning system lies in using Europe's weather radar network as input for this system rather than individual weather radars (Ginati et al. 2010). By applying the same algorithms for the prediction of bird migration, the output of the individual countries' systems would become comparable. Furthermore, by connecting the systems, the covered range would increase substantially. In Fig. 5, an example is given of bird densities and the resulting warning (BIRDTAM value and validity to maximum altitude) using a weather radar network. In this example from Belgium, pilots are not allowed to fly in the airspace with BIRDTAM values of 5 to 8 (i.e. not below 2.6 km in the evening of 11 October 2015).

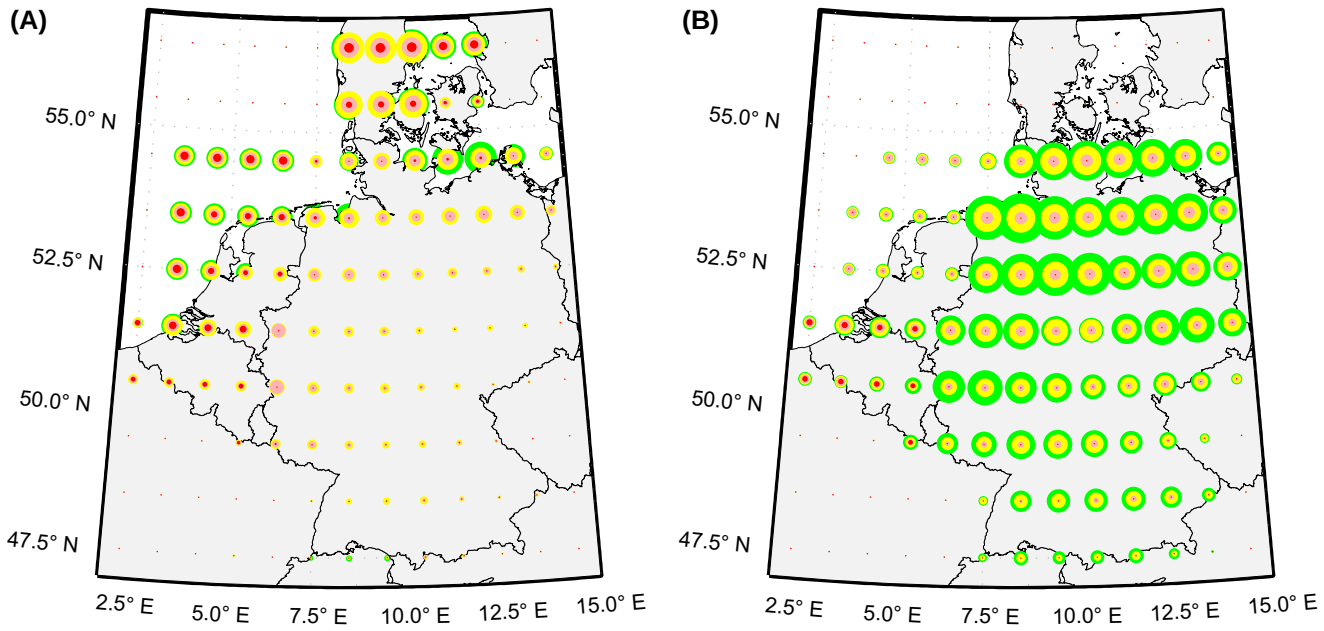

Figure 4. Average number of hours per year with BIRDTAM values 5–8 issued in Denmark, Germany, the Netherlands and Belgium for two time frames (A) 1998–2005, (B) 2010–2016. Colours reflect the BIRDTAM levels as in Fig. 2 and Fig. 3.

Flight warnings and restrictions derived from the warning system may differ substantially between locations, as visualised in Fig. 6. Here, the BIRDTAM values are shown as measured in the same period at two operational weather radars, one located in the centre of the Netherlands (de Bilt, 52°6′N, 5°10′E) and one located 240 km further south in southeast Belgium (Wideumont, 49°56′N, 5°30′E). Since regulations differ between air forces, we consider in this example BIRDTAM values of 7 and 8 as restrictions and BIRDTAM values of 5 and 6 as warnings. The location in the Netherlands (Fig. 6A, De Bilt) is rich in waterfowl. The second location (Fig. 6B, Wideumont) is in a forested, hilly landscape in Belgium with fewer birds in general and no waterfowl. During night-time, both locations showed high proportions of restrictions in the migratory seasons spring (March–April) and autumn (August–November). Peak migration levels were reached in the first hours after sunset in March and October. On average, flight restrictions occurred during 10% (de Bilt) and 14% (Wideumont) of October nights. This means that in 1 out of 10 and 1 out of 7 nights respectively, bird densities were too high to be considered safe, resulting in flight restrictions issued to pilots. Peak migration levels during daytime, resulted in flight restrictions occurring on only one day a month on average, in March, April and October in both countries. The temporal distribution of flight warnings (BIRDTAM values 5 and 6) differed among the two locations. In the Netherlands, warnings were issued during 39% of the BIRDTAM-service hours (between 8:00–16:00), from March–July, while in Belgium warnings were issued during only 4% of this period. From March to July, these high densities during daytime reflected mostly local, non-migrating birds. These bird movements in the Netherlands, at heights of hundreds of meters, were attributed to lesser black-backed gull *Larus fuscus*, common buzzard *Buteo buteo* using thermal updrafts, black-headed gull *Chroicocephalus ridibundus* and swift *Apus apus* feeding on aerial plankton (Vernon 1972, Shamoun-Baranes and van Loon 2006, Shamoun-Baranes et al. 2006, Ens et al. 2009). These bird species are very common in the Netherlands but nearly absent in the Belgian Ardennes around Wideumont (Hagemeijer and Blair 2002). Furthermore, warnings were issued at night in winter in the Netherlands, while they were nearly absent in Belgium. Nocturnal movements in winter reflect cold weather movements of the approximately 5 million waterfowl wintering in the Netherlands (Hornman et al. 2018) as well as their return flights. Four years (2013–2016) of weather radar data resulted on average in 2187 warning hours in the Netherlands, of which 77 were BIRDTAM values 7 and 8. In Belgium, BIRDTAM values 7 and 8 were in place during 188 of 943 warning hours.

Table 2. Overview of financial costs related to bird strikes in relation to presence or absence of a bird warning system, for four NW-European Air Forces covering the period 1991–2000. Bird strike ratio reflects number of damaged aircraft per 10 000 flying hours. Cost estimates are presented similarly as cost per 10 000 flying hours and as cost per year, and are based on an average of US$ 100 000 per damage case; see text for further explanation. Data from Dekker and van Gasteren (2005).

Country	Warning system	Bird strike ratio	Cost estimate (in M$ US) /10^3 fl.h	Cost estimate (in M$ US) yr^{-1}
France	absent	6.59	0.66	10.3
Great Britain	absent	8.34	0.83	11.3
Germany	present	4.84	0.48	4.1
Netherlands	present	3.35	0.33	0.9

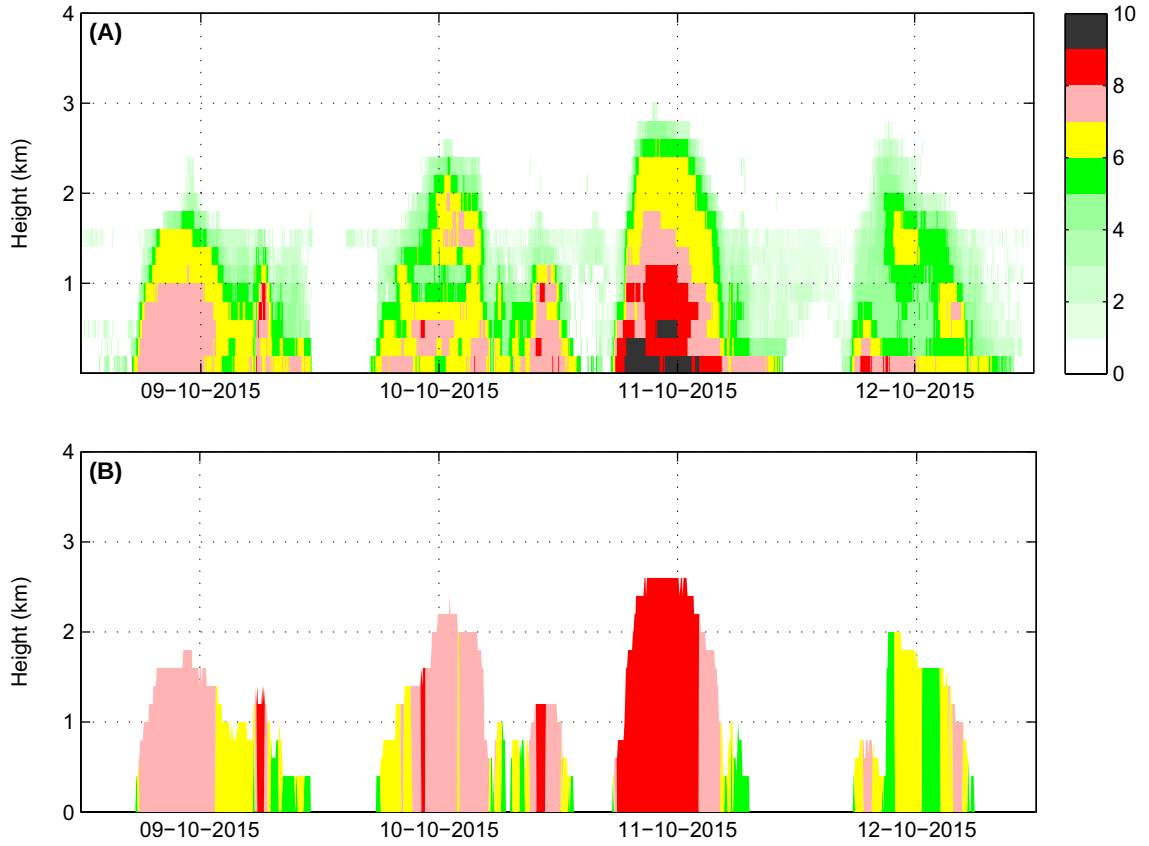

Figure 5. Density and altitude profiles for bird migration on a series of nights in autumn 2015, as measured with the weather radar in Wideumont, Belgium (49°56′N, 5°30′E). (A) Bird density profiles measured by the radar, for 200 m altitude bins, each colour coded in BIRDTAM density values (BIRDTAM density value 9 added as > 160 birds km^{-3}). (B) Bird densities converted to BIRDTAM warnings. The maximum value at a certain timestamp determines the BIRDTAM value, the maximum height with BIRDTAM values 5 and up determine the validity to maximum altitude of the BIRDTAM. BIRDTAM warnings are only issued to pilots for values 5 and up.

Conclusion and future role of weather radars

While migration warning systems in military aviation have been in existence for several decades in some countries, we have shown that these systems differ among countries, often changing over time as new methods for automated bird detection and warning become available. Furthermore, even though international warning agreements exist via NATO, harmonization in interpretation of migration data is still lacking among many countries (Ginati et al. 2010). This is not

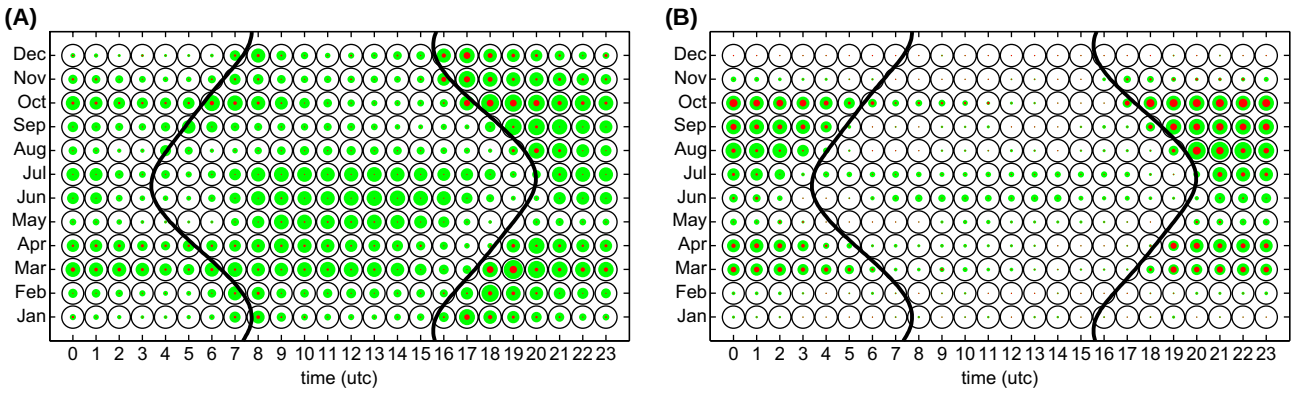

Figure 6. Distribution over time of day and over months of warnings (BIRDTAM 5–6; green) and restrictions (BIRDTAM 7–8; red) if weather radar was used as a 24/7 BIRDTAM-service (2013–2016). (A) BIRDTAMs issued in central Netherlands (de Bilt, 52°6′N, 5°10′E) and (B) in southeast Belgium (Wideumont, 49°56′N, 5°30′E). Shown is the average proportion per hour. The outer black circle indicates the 100% maximum. Thick black lines represent sunrise and sunset.

only due to differences in policy among countries but also to differences among the monitoring systems themselves. The spatial and temporal distribution of warnings varies greatly, not only due to differences in policy and monitoring systems, but also due to actual spatio-temporal differences in aerial bird densities. Clearly, migration is not the only period when the risk of low level bird strikes is high. In some regions this may also occur during other periods when large numbers of birds are present, such as waterfowl overwintering in Dutch and Danish delta areas.

As the capacity to monitor and understand migration improves, so does our ability to reliably forecast migration. Forecast systems provide an additional buffer for military aviation, enabling them to alter flight planning in advance and thereby reducing the cost of last-minute flight alterations. Warning systems which include near real-time monitoring and forecast models have resulted in a clear reduction in bird strikes over time as systems improve. Furthermore, we have shown that bird strike ratios are much lower in countries where warning systems are implemented.

Currently, the utilization of the European weather radar network OPERA for operational bird migration warnings is still in its infancy. Nevertheless, it has great potential for improving flight safety and reducing the risk of collisions between birds and aircraft. As the radars are organized in a network for the development of continental meteorological products, the output could also be utilized for continental-scale migration monitoring and warning systems. On a large scale, it would provide an opportunity for harmonizing measurements and warning protocols among countries. For finer-scale information, for example in and around air force bases, large-scale patterns could be supplemented with local information being provided by dedicated avian radars. As automated algorithms to extract altitude profiles of bird densities, flight speeds and directions from weather radars improve (Dokter et al. 2019), so will the quality of the data and the ability to monitor bird migration using the same methodology across international borders. Utilising an existing sensor network distributed across Europe will also greatly improve our understanding of bird migration and enable us to answer key questions in migration pertinent to flight safety (Bauer et al. 2017, Nilsson et al. 2019). Furthermore, using data archives, data could be processed to develop time series sufficient for designing robust predictive models.

While this study has focussed on the benefits of bird warning systems for military flights, the rapidly developing possibilities of such systems offer a wealth of opportunities in other fields. Any field where potential conflicts between operations and birds may arise may benefit from these developments. Civil aviation, for example, could benefit from the bird warning system by selecting higher routes on arrival and departure as is discussed in the Netherlands for Lelystad airport (Lensink 2018), but also the wind energy industry and offshore oil and gas production in reducing the number of collision victims during strong bird migration. Over the last decades collaboration between military aviation, radar engineers, meteorologists and ecologists has created a unique synergy in which not only the tools to monitor migration, but also our ability to understand and predict migration and apply that knowledge to reduce human–wildlife conflicts, have improved tremendously. We look forward to the possibilities this developing radar network may bring.

Data deposition

Data available from the Dryad Digital Repository: <https://doi.org/10.5061/dryad.78sb41t> (van Gasteren et al. 2018).

Acknowledgements – We acknowledge the support provided by European Cooperation in Science and Technology (COST) through Action no. ES1305, European Network for the Radar Surveillance of Animal Movement (ENRAM), in facilitating this collaboration. We would like to thank Jürgen Meyer for providing and formatting the issued BIRDTAMs, Wilhelm Ruhe for his continuing improvements of the German system as well as providing historic bird strike data and Luit Buurma for his vision and initiative to develop a bird warning system, where bird information is extracted directly from the radar. We would like to thank all air forces for providing their bird strike data. The paper is dedicated to and in memory of Professor Amnon Ginati, who was responsible for the initiation and development of the European Space Agency's Integrated Applications Promotion (IAP) programme and Flysafe.
Funding – We are thankful for the funding provided by the European Space Agency for Flysafe.

References

AFSEC/CV 2018. Air Force instruction 91-204. – Safety investigation and hazard reporting, pp. 1–104.

Alerstam, T. 1978. Analysis and a theory of visible bird migration. – Oikos 30: 273–349.

Allan, J. R. 2002. The costs of birdstrikes and birdstrike prevention. – In: Clarke, L. (ed.), Human conflicts with wildlife: economic considerations. US Dept of Agriculture, Fort Collins, pp. 147–153.

Anderson, A. et al. 2015. Modeling the cost of bird strikes to US civil aircraft. – Transport. Res. Part D 38: 49–58.

Bauer, S. et al. 2017. From agricultural benefits to aviation safety: realizing the potential of continent-wide radar networks. – BioScience 67: 912–918.

Becker, J. 1994. The significance of birdtams/birdstrike warnings for military and civil aviation. – 22nd IBSC Conference. International Bird Strike Committee, pp. 257–262.

Bildstein, K. L. and Zalles, J. I. 2005. Old World versus New World long-distance migration in *Accipiter*s, *Buteo*s, and *Falcon*s. The interplay of migration ability and global biogeography. – In: Greenberg, R. and Marra, P. P. (eds), Birds of two worlds: the ecology and evoloution of migration. Johns Hopkins Univ. Press, pp. 154–167.

Blokpoel, H. 1976. Bird hazards to aircraft. – Clarke Irwin.

Bruderer, B. 1971. Radarbeobachtungen über den Frühlingszug im schweizerischen Mittelland. Ein Beitrag zum Problem der Witterungsabhängigkeit des Vogelzuges. – Ornithol. Beobach. 68: 89–158.

Bruderer, B. 1997. The study of bird migration by radar. Part 1: the technical basis. – Naturwissenschaften 84: 1–8.
Bruderer, B. et al. 2018. Vertical distribution of bird migration between the Baltic Sea and the Sahara. – J. Ornithol. 159: 315–336.
Busse, P. et al. 2014. Evolution of the Western Palaearctic passerine migration pattern presentation style. – The Ring 36: 3–21.
Buurma, L. S. 1978. The practical use of bird migration warnings. – 13th IBSC Conference. International Bird Strike Committee.
Buurma, L. S. 1995. Long-range surveillance radars as indicators of bird numbers aloft. – Israel J. Zool. 41: 221–236.
Buurma, L. S. and Bruderer, B. 1990. The application of radar for bird strike prevention. – 20th IBSC Conference. International Bird Strike Committee.
Buurma, L. S. and Dekker, A. 1992. Bird strike hazards to helicopters. – 21st IBSC Conference. International Bird Strike Committee, pp. 51–62.
Crum, T. D. and Alberty, R. L. 1993. The WSR-88D and the WSR-88D operational support facility. – Bull. Am. Meteorol. Soc. 74: 1669–1688.
Dekker, A. and Buurma, L. S. 2003. Zero-tolerance a panacea? – 26th IBSC Conference. International Bird Strike Committee, pp. 419–426.
Dekker, A. and van Gasteren, H. 2005. EURBASE: military bird strike frequency in Europe. – 27th IBSC Conference. International Bird Strike Committee.
Dennis, N. and Lyle, D. 2008. Bird strike damage & windshield bird strike. – ATKINS Limited and the Food and Environment Research Agency, pp. 1–139.
Dokter, A. M. et al. 2010. Bird migration flight altitudes studied by a network of operational weather radars. – J. R. Soc. Interface 8: 30–43.
Dokter, A. M. et al. 2019. bioRad: biological analysis and visualization of weather radar data. – Ecography 42: xxx–xxx.
Dolbeer, R. A. 2008. Feathers in the fan. – Airosafety World 3: 22–26.
Dolbeer, R. A. et al. 2015. Wildlife strikes to civil aircraft in the United States 1990–2014. – Federal Aviation Administration and U. S. Dept of Agriculture, Animal and Plant Health Inspection Service (APHIS).
Eastwood, E. 1967. Radar ornithology. – Methuen.
Ens, B. J. et al. 2009. Onderzoek aan meeuwen met satellietzenders. – Limosa 82: 33–42.
Eschenfelder, P. F. 2005. High speed flight at low altitude: hazard to commercial aviation? – 7th Bird Strike Committee USA/Canada.
Gauthreaux Jr, S. A. and Belser, C. G. 1998. Displays of bird movements on the WSR-88D: patterns and quantification. – Weather Forecast. 13: 453–464.
Gauthreaux-Jr, S. A. and Belser, C. G. 2003. Radar ornithology and biological conservation. – Auk 120: 266–277.
Geil, S. et al. 1974. Forecast models for bird migration in Denmark. – Research Establishment, Univ. of Copenhagen and Royal Danish Air Force, Danish Defence Research Establishment.
Ginati, A. et al. 2010. FlySafe: an early warning system to reduce risk of bird strikes. – ESA Bull. 144: 46–55.
Hagemeijer, W. J. M. and Blair, M. J. 2002. The EBCC atlas of European breeding birds: their distribution and abundance. – T. and A. D. Poyser.
Hahn, S. et al. 2009. The natural link between Europe and Africa – 2.1 billion birds on migration. – Oikos 118: 624–626.
Hedayati, R. and Sadighi, M. 2016. Bird strike. An experimental, theoretical, and numerical investigation. – Woodhead Publishing in Mechanical Engineering.
Holleman, I. et al. 2008. Update on the European weather radar network (OPERA). – WMO Technical Conference, TECO-2008.
Hornman, M. et al. 2018. Watervogels in Nederland in 2015/2016. – Sovon Vogelonderzoek Nederland.
Huuskonen, A. et al. 2014. The operational weather radar network in Europe. – Bull. Am. Meteorol. Soc. 95: 897–907.
Insinna, V. 2018. Wildlife strikes add to Air Force and Navy's mishap count. – <www.militarytimes.com>.
Kemp, M. U. 2012. How birds weather the weather: avian migration in the mid-latitudes. – Inst. for Biodiversity and Ecosystem Dynamics, Univ. of Amsterdam.
Kemp, M. U. et al. 2013. The influence of weather on the flight altitude of nocturnal migrants in mid-latitudes. – Ibis 155: 734–749.
Koistinen 2000. Bird migration patterns on weather radars. – Phys. Chem. Earth B 25: 1185–1193.
Lack, D. 1959. Watching migration by radar. – Br. Birds 52: 258–263.
Lensink, R. 2018. Vormen vliegbewegingen van lokale vogels en trekkende vogels een risico voor het luchtverkeer van en naar Lelystad Airport? – Bureau Waardenburg.
Leshem, Y. 1990. The development of a bird migration real-time warning system for the Isreali Air Force utilizing ground observers, radar, motorized glider and drones; and a preliminary report on the use of transmitters received by satellite as a new warning method. – 20th IBSC Conference. International Bird Strike Committee.
Leshem, Y. and Yom-Tov, Y. 1996. The magnitude and timing of migration by soaring raptors, pelicans and storks over Israel. – Ibis 138: 188–203.
Linnell, M. A. et al. 1999. Biases in bird strike statistics based on pilot reports. – J. Wildl. Manage. 63: 997–1003.
MacKinnon, B. 2004. Sharing the skies: an aviation industry guide to the management of wildlife hazards. – Transport Canada Aviation Publishing Division.
Martín, B. et al. 2016. Trends of autumn counts at Iberian migration bottlenecks as a tool for monitoring continental populations of soaring birds in Europe. – Biodivers. Conserv. 25: 295–309.
Martin, W. J. and Shapiro, A. 2007. Discrimination of bird and insect radar echoes in clear air using high-resolution radars. – J. Atmos. Oceanic Technol. 24: 1215–1230.
McKee, J. et al. 2016. Approaches to wildlife management in aviation. – In: Angelici, F. M. (ed.), Problematic wildlife. Springer, pp. 465–488.
NATO 2013. Stanag 3879. – Wildlife Strike Prevention.
Newton, I. 2008. The migration ecology of birds. – Academic Press.
Nilsson, C. et al. 2019. Revealing patterns of nocturnal migration using the European weather radar network. – Ecography 42: xxx–xxx.
Ovadia, O. 2005. Ten years of birdstrikes in the Isreaeli Air Force. – 27th IBSC Conference. International Bird Strike Committee.
Richardson, W. J. 1978. Timing and amount of bird migration in relation to weather: a review. – Oikos 30: 224–272.
Richardson, W. J. 1990. Timing of bird migration in relation to weather: updated review. – In: Gwinner, E. (ed.), Bird migration: physiology and ecophysiology. Springer, pp. 78–101.

Richardson, W. J. and West, T. 2000. Serious birdstrike accidents to military aircraft: updated list and summary. – 25th IBSC Conference. International Bird Strike Committee, pp. 67–97.
Richardson, W. J. and West, T. 2005. Serious birdstrike accidents to U.K. military aircraft, 1923 to 2004. – 27th IBSC Conference. International Bird Strike Committee.
Ruhe, W. 1994. New developments for improving the German BIRDTAM/bird strike warning system. – 22th IBSC Conference. International Birdstrike Committee, pp. 263–274.
Ruhe, W. 2001. Bird strike risk forecasting: a modelling approach. – Third Joint Annual Meeting Bird Strike Committee-USA/Canada, pp. 68–72.
Ruhe, W. 2005. Bird avoidance models vs. realtime birdstrike warning systems – a comparison. – 27th IBSC Conference. International Bird Strike Committee.
Ruhe, W. 2008. Bird hazard management in the German Armed Forces. – 28th IBSC Conference. International Bird Strike Committee.
Shamoun-Baranes, J. and van Loon, E. 2006. Energetic influence on gull flight strategy selection. – J. Exp. Biol. 209: 3489–3498.
Shamoun-Baranes, J. et al. 2005. Linking horizontal and vertical models to predict 3D + time distributions of bird densities. – 27th IBSC Conference. International Bird Strike Committee.
Shamoun-Baranes, J. et al. 2006. A comparitive analysis of the influence of weather on the flight altitudes of birds. – Bull. Am. Meteorol. Soc. 87: 47–61.
Shamoun-Baranes, J. et al. 2008. Avian information systems: developing web-based bird avoidance models. – Ecol. Soc. 13: art38.
Shamoun-Baranes, J. et al. 2017a. Atmospheric conditions create freeways, detours and tailbacks for migrating birds. – J. Comp. Physiol. A 203: 509–529.
Shamoun-Baranes, J. et al. 2017b. Sharing the aerosphere: conflicts and potential solutions. – In: Chilson, P. B. et al. (eds), Aeroecology. Springer, pp. 465–497.
Sodhi, N. S. 2002. Competition in the air: birds versus aircraft. – Auk 119: 587–595.
Thorpe, J. 2003. Fatalities and destroyed civil aircraft due to bird strikes, 1912–2002. – 26th IBSC Conference. International Bird Strike Committee.
Thorpe, J. 2005. Fatalities and destroyed civil aircraft due to bird strikes, 2002–2004. – 27th IBSC Conference. International Bird Strike Committee.
Thorpe, J. 2016. Conflict of wings: birds versus aircraft. – In: Angelici, F. M. (ed.), Problematic wildlife: a cross-disciplinary approach. Springer, pp. 443–463.
van Belle, J. et al. 2007. An operational model predicting autumn bird migration intensities for flight safety. – J. Appl. Ecol. 44: 864–874.
Van Doren, B. M. and Horton, K. G. 2018. A continental system for forecasting bird migration. – Science 361: 1115–1118.
van Gasteren, H. et al. 2012. The FlySafe project: how weather radars can improve the en-route bird strike warning system. – 30th IBSC Conference. International Bird Strike Committee.
van Gasteren, H. et al. 2018. Data from: Aeroecology meets aviation safety: early warning systems in Europe and the Middle East prevent collisions between birds and aircraft. – Dryad Digital Repository, <https://doi.org/10.5061/dryad.78sb41t>.
Verhelst, B. et al. 2011. South west Georgia: an important bottleneck for raptor migration during autumn. – Ardea 99: 137–146.
Vernon, J. D. R. 1972. Feeding habitats and food of the black-headed and common gulls. Part 2 – food. – Bird Study 19: 173–186.
Wilson, J. W. et al. 1994. Boundary layer clear-air radar echoes: origin of echoes and accuracy of derived winds. – J. Atmos. Oceanic Technol. 11: 1184–1206.
Zakrajsek, E. J. and Bissonette, J. A. 2005. Ranking the risk of wildlife species hazardous to military aircraft. – Wildl. Soc. Bull. 33: 258–264.

Supplementary material (Appendix ECOG-04125 at <www.ecography.org/appendix/ecog-04125>). Appendix 1.