biology
letters

Radar aeroecology: exploring the movements of aerial fauna through radio-wave remote sensing

Phillip B. Chilson, Eli Bridge, Winifred F. Frick, Jason W. Chapman and Jeffrey F. Kelly

Biol. Lett. 2012 **8**, doi: 10.1098/rsbl.2012.0384 first published online 23 May 2012

biology letters
Animal behaviour

Biol. Lett. (2012) **8**, 698–701
doi:10.1098/rsbl.2012.0384
Published online 23 May 2012

Meeting report

Radar aeroecology: exploring the movements of aerial fauna through radio-wave remote sensing

Phillip B. Chilson[1,*], Eli Bridge[2], Winifred F. Frick[3], Jason W. Chapman[4,5] and Jeffrey F. Kelly[6,7]

[1]*School of Meteorology and Atmospheric Radar Research Center, University of Oklahoma, 120 David L. Boren Blvd, Norman, OK 73072, USA*
[2]*Center for Spatial Analysis, University of Oklahoma, 101 David L Boren Blvd., Norman, OK 73019, USA*
[3]*Ecology and Evolutionary Biology, University of California Santa Cruz, 1156 High St, Cruz, CA 95064, USA*
[4]*Agro-Ecology Department, Rothamsted Research, Harpenden, Hertfordshire AL5 2JQ, UK*
[5]*Environment and Sustainability Institute, University of Exeter, Penryn, Cornwall TR10 9EZ, UK*
[6]*Oklahoma Biological Survey, University of Oklahoma, 111 East Chesapeake Street, Norman, OK 73019, USA*
[7]*Department of Zoology, University of Oklahoma, 730 Van Vleet Oval, Norman, OK 73019, USA*
**Author for correspondence* (*chilson@ou.edu*).

An international and interdisciplinary Radar Aeroecology Workshop was held at the National Weather Center on 5–6 March 2012 on the University of Oklahoma campus in Norman, OK, USA. The workshop brought together biologists, meteorologists, radar engineers and computer scientists from 22 institutions and four countries. A central motivation behind the Radar Aeroecology Workshop was to foster better communication and cross-disciplinary collaboration among a diverse spectrum of researchers, and promote a better understanding of the ecology of animals that move within and use the Earth's lower atmosphere (aerosphere).

Keywords: radar; aeroecology; phenology; migration

1. INTRODUCTION

The aerosphere supports an enormous abundance of life, but has not been traditionally recognized as 'habitat'. Yet numerous organisms across a broad range of taxa use the aerosphere for migration or foraging. Flows of biomass and genetic information in the aerosphere have important implications in a number of areas, such as pest invasions [1], disease spread [2] and understanding demographic and phenological changes in response to environmental change [3]. Local to regional scale analyses suggest that airborne migrants and aerially foraging animals are highly responsive to environmental change in the aerosphere [4]. Migrants must respond rapidly to their environment to find adequate refugia and acquire enough fuel to endure whatever conditions they may encounter en route. Once these animals reach their destinations, many continue to use the aerosphere to acquire energy for maintenance and reproduction. These behaviours often represent convergent and sometimes co-evolved phenotypic traits, shaped by natural selection to take advantage of predictable shifts in seasonal patterns (phenology) of ecosystem productivity [5]. Observational studies, simulations and experiments relating migration and aerial foraging to food availability or climatic variability have provided compelling evidence for biological responses to changes in climate and land cover on a local scale [6–8]. Such studies help provide insights into individual behavioural responses to environmental changes that will be fundamental to a mechanistic understanding of aeroecological dynamics. However, expanding inferences from these local-scale studies to address continental scale phenomena is a daunting task, and calls for a research infrastructure that can deliver a broad spatial and temporal perspective on how animal movements are affected by environmental change [9], as well as phenological baselines by which the impacts of climatic variability can be investigated [10].

Addressing these challenging yet fundamentally important issues necessitates a fusion of expertise across diverse scientific disciplines, such as atmospheric science, earth science, geography, ecology, computer science, computational biology and engineering. The emerging field of aeroecology represents the union of these fields, in an effort to quantify and understand relationships among flying organisms and their aerial habitats [11]. Because these animals are small, yet capable of rapidly flying over large spatial extents, investigating their behaviour and movements presents formidable challenges, requiring creative integration of novel technological advances for data acquisition and analysis. Radar systems, especially when integrated with other observing and modelling efforts, offer exciting opportunities for investigating ecological processes at spatial and temporal scales that have traditionally thwarted authoritative understanding of ecological dynamics in the aerosphere [1,7,12,13].

There is enormous potential for deploying a variety of radars and observing instruments to quantify animal movements, population densities, diversity and species phenologies across a wide range of spatial, temporal and climatic scales. However, as discussed during the workshop, realizing this potential will require advances in (i) validation studies based on theory and experiments in the laboratory to evaluate reflectivity measurements provided by radars; (ii) multi-instrument sampling in the field that can validate approaches across different radar platforms; and (iii) development of tools and techniques for mining radar data in concert with field observations and other remotely sensed data.

The National Weather Center houses the National Oceanic and Atmospheric Administration (NOAA) Radar Operations Center and NOAA National Severe Storms Laboratory (NSSL). NOAA maintains and operates the US network of weather surveillance radars (NEXRAD; see below) and the NSSL is charged with using NEXRAD data for improved weather analysis. The National Weather Center provided a natural venue for biologists, radar scientists, meteorologists and computer scientists to interact and develop better

Received 23 April 2012
Accepted 3 May 2012

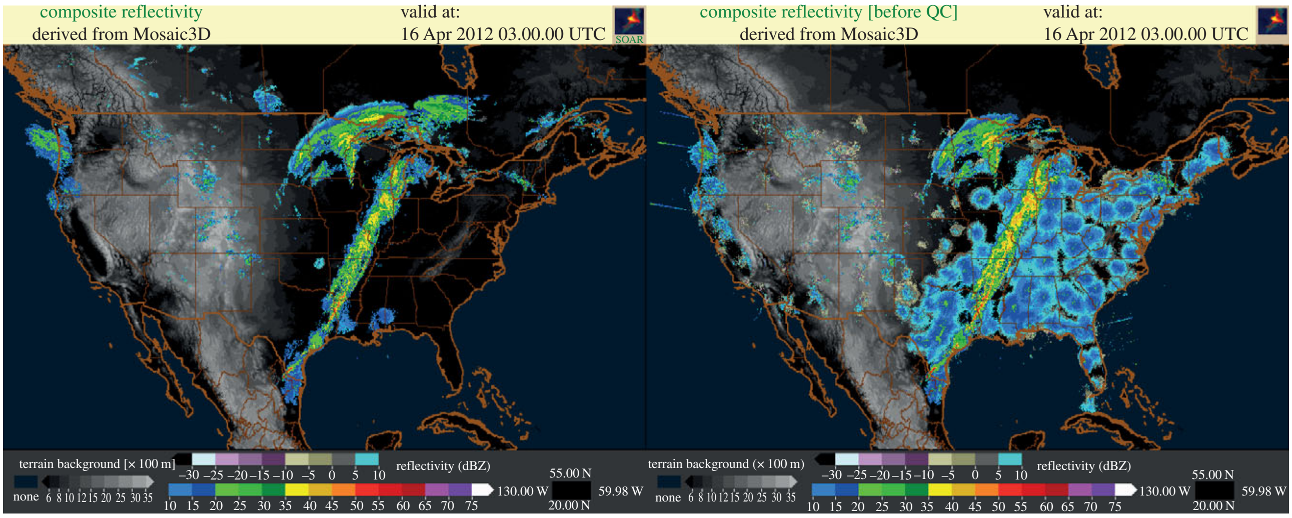

Figure 1. Depiction of the merged radar reflectivity factor after (left image) and before (right image) quality control to remove non-meteorological effects. These images were taken from the SOAR web portal (soar.ou.edu) corresponding to radar observations for 16 April 2012 at 03.00 UT. Flying animals produce much of the data removed during quality control process.

understanding of recent innovations in radar, radar processing and their application to biological studies. To set the stage for discussions and establish a common framework among the international and interdisciplinary group of participants, three keynote talks were presented at the beginning of the workshop: ‘History of radar based biological science’, ‘The future of biological investigations with radar’ and ‘The future of meteorological investigations with radar’.

2. INTEGRATED RADAR NETWORKS AS BIOLOGICAL OBSERVATORIES

It is widely accepted that integrative approaches are needed to allow biologists to investigate foraging and migratory activity of individual animals and scale these data to populations at regional to continental scales [4,7,11,12,14]. During the workshop, we discussed the development and application of technologies involving networks of meteorological radars that can be used to make ecological inferences about scaling from individuals to populations, and from regions to continents [13]. Several countries and confederations of countries already operate sophisticated meteorological radar networks. A prime example is NEXRAD, which provides near contiguous coverage of the lower 10 km of air space for the entire continental United States. NEXRAD data have been collected in a consistent manner every 5 min since the early 1990s and have a spatial grain resolution of 250 m. NEXRAD regularly detects scatter from air-borne biological animals (birds, bats and insects), known as bioscatter (figure 1 and discussion below). As such, it is a powerful tool, and it served as a centrepiece for our discussions on radar aeroecology [13].

3. RADAR AEROECOLOGY AT SMALL SPATIO-TEMPORAL SCALES

In addition to the broad-scale perspective offered by networked radars, many biologists also look to mobile/transportable radars to observe behaviour of aerial fauna at smaller spatial and temporal scales [1,7,15]. Additionally these radars can be used to help validate observations from larger radar facilities such as NEXRAD [16,17]. As an example, we discussed the capabilities of the vertical-looking entomological radars with polarization rotation and beam nutation developed by Rothamsted Research in the UK, which provide continuous data on the physical characteristics (body shape, mass and wing beat frequency) and flight parameters (altitude, heading, speed and direction of movement) of individual high-flying insect migrants [1]. The ability to study the flight behaviour of actively migrating individuals of named species has led to significant advances in our understanding of their capabilities and migration strategies [18]. The development of radars with similar technical capabilities aimed at the study of identifiable bird and bat species is theoretically possible, and we discussed the potential design and development of such a radar.

4. HARNESSING RADAR DATA FOR ECOLOGICAL RESEARCH

Among the grand challenges in radar aeroecology are (i) discriminating biological scatter from other radar signals; (ii) identifying species or taxa through radar observations and possibly other supporting data; and (iii) quantifying animal densities using bioscatter. There has been considerable progress towards attaining these goals [15,17,19,20]; however, more work is desperately needed. Establishing progress along these lines will require a fusion of technologies across multiple disciplines. The workshop provided an excellent venue to allow the interdisciplinary cadre of participants to address these difficult, yet important topics. Areas in which more targeted investigations are needed include: concerted multi-instrument experiments dedicated to quantification and validation, improved understanding of how radio waves interact with animals in flight, development of radar simulators based on realistic agent-based behavioural models, and rigorously derived estimates of measurement uncertainties associated with radar derived biological products.

5. MOVING FROM RADAR DATA TO BIOLOGICAL PRODUCTS

More extensive use of weather radar data such as those from NEXRAD is currently hindered by the fact that accessing and processing the data require significant computational skills and time investment. At present, the extensive archive of NEXRAD data is exploited only by a relatively small subset of specialists within the biological community. To address this issue, workshop participants explored a variety of different biologically relevant products, which could be derived from networked weather radar data and provided to the general public (e.g. bioscatter maps, migration trajectories, phenology curves). Typically, weather radar data are intensively filtered to remove non-meteorological signals. However, through collaborative work between biologists, computer scientists and researchers at NOAA NSSL, we have begun to develop tools to visualize non-filtered NEXRAD data (e.g. surveillance of the aerosphere using weather radar—soar.ou.edu; figure 1). These tools are valuable for ecological research, because they enable biologists who are interested in the collective behaviour of airborne organisms to observe phenomena over a wide range of spatial and temporal scales in a manner not possible with other existing technologies [12,21]. Within this framework, biological products can be evaluated in connection with meteorological observations to explore meteorological influences on animal behaviour in the aerosphere. One example is the effect of synoptic scale weather patterns on migration as depicted in figure 1.

6. CONCLUDING REMARKS

The Radar Aeroecology Workshop fostered collaboration among diverse research communities to promote a better understanding of phenology, distribution, density and diversity of animals in the aerosphere. It also helped to strengthen integration between two emerging communities within the US and Europe dedicated to the advancement of radar aeroecology: Aeroecological Interdisciplinary Research and Education (AIRE) and European Network for the Radar Surveillance of Animal Migration (ENRAM).

Additional information about the workshop, including slides from the keynote presentations can be found at http://arrc.ou.edu/raw2012/. We thank the participants for their help in making this a very successful workshop through their lively and engaging discussions. We are also grateful for support from the Oklahoma Biological Survey, OU's Atmospheric Radar Research Center, and the National Science Foundation (IOS-0541740 and EPS-0919466).

1 Chapman, J. W., Drake, V. A. & Reynolds, D. R. 2011 Recent insights from radar studies of insect flight. *Ann. Rev. Entomol.* **56**, 337–356. (doi:10.1146/annurev-ento-120709-144820)
2 Altizer, S., Bartel, R. & Han, B. A. 2011 Animal migration and infectious disease risk. *Science* **331**, 296–302. (doi:10.1126/science.1194694)
3 Parmesan, C. 2006 Ecological and evolutionary responses to recent climate change. *Annu. Rev. Ecol. Evol. Syst.* **37**, 637–669. (doi:10.1146/annurev.ecolsys.37.091305.110100)
4 Shamoun-Baranes, J., Bouten, W. & van Loon, E. E. 2010 Integrating meteorology into research on migration. *Int. Comp. Biol.* **50**, 280–292. (doi:10.1093/icb/icq011)
5 Hedenstrom, A. 2008 Adaptations to migration in birds: behavioural strategies, morphology and scaling effects. *Phil. Trans. R. Soc. B* **363**, 287–299. (doi:10.1098/rstb.2007.2140)
6 Van Buskirk, J., Mulvihill, R. S. & Leberman, R. C. 2009 Variable shifts in spring and autumn migration phenology in North American songbirds associated with climate change. *Global Change Biol.* **15**, 760–771. (doi:10.1111/j.1365-2486.2008.01751.x)
7 Bridge, E. S., Thorup, K., Bowlin, M. S., Chilson, P. B., Diehl, R. H., Fléron, R., Kelly, J. F., Robinson, W. D. & Wikelski, M. 2011 Technology on the move: recent and forthcoming innovations for tracking migratory birds. *Bioscience* **61**, 689–698. (doi:10.1525/bio.2011.61.9.7)
8 Johansson, J. & Jonzén, N. 2012 Effects of territory competition and climate change on timing of arrival to breeding grounds: a game-theory approach. *Am. Nat.* **179**, 463–474. (doi:10.1086/664624)
9 Nathan, R., Getz, W. M., Revilla, E., Holyoak, M., Kadmon, R., Saltz, D. & Smouse, P. E. 2008 A movement ecology paradigm for unifying organismal movement research. *Proc. Natl Acad. Sci. USA* **105**, 19 052–19 059. (doi:10.1073/pnas.0800375105)
10 Smith, M. D. 2011 The ecological role of climate extremes: current understanding and future prospects. *J. Ecol.* **99**, 651–655. (doi:10.1111/j.1365-2745.2011.01833.x)
11 Kunz, T. H. *et al.* 2008 Aeroecology: probing and modeling the aerosphere. *Int. Comp. Biol.* **48**, 1–11. (doi:10.1093/icb/icn037)
12 Robinson, W. D., Bowlin, M. S., Bisson, I., Shamoun-Baranes, J., Thorup, K., Diehl, R. H., Kunz, T. H., Mabey, S. & Winkler, D. W. 2010 Integrating concepts and technologies to advance the study of bird migration. *Front. Ecol. Environ.* **8**, 354–361. (doi:10.1890/080179)
13 Chilson, P. B., Frick, W. F., Kelly, J. F., Howard, K. W., Larkin, R. P., Diehl, R. H., Westrook, J. K., Kelly, T. A. & Kunz, T. H. 2012 Partly cloudy with a chance of migration: weather, radars, and aeroecology. *Bull. Amer. Meteorol. Soc.* (doi:10.1175/BAMS-D-11-00099.1)
14 Kelly, J. F., Shipley, J. R., Chilson, P. B., Howard, K. W., Frick, W. F. & Kunz, T. H. 2012 Quantifying animal phenology in the continental scale using NEXRAD weather radars. *Ecosphere* **3**, art. 16. (doi:10.1890/ES11-00257.1)
15 Schmaljohan, H., Liechti, F., Bächler, E., Steuri, T. & Bruderer, B. 2008 Quantification of bird migration by radar: a detection probability problem. *Ibis* **150**, 342–355. (doi:10.1111/j.1474-919X.2007.00797.x)
16 Diehl, R. H., Larkin, R. P. & Black, J. E. 2003 Radar observations of bird migration over the Great Lakes. *Auk* **120**, 278–290. (doi:10.1642/0004-8038(2003)120[0278:ROOBMO]2.0.CO;2)
17 Dokter, A. M., Liechti, F., Stark, H., Delobbe, L., Tabary, P. & Holleman, I. 2010 Bird migration flight

altitudes studied by a network of operational weather radars. *J. R. Soc. Interface* **8**, 30–43. (doi:10.1098/rsif.2010.0116)

18 Chapman, J. W., Nesbit, R. L., Burgin, L. E., Reynolds, D. R., Smith, A. D., Middleton, D. R. & Hill, J. K. 2010 Flight orientation behaviors promote optimal migration trajectories in high-flying insects. *Science* **327**, 682–685. (doi:10.1126/science.1182990)

19 Zaugg, S., Saporta, G., van Loon, E., Schmaljohann, H. & Liechti, F. 2008 Automatic identification of bird targets with radar via patterns produced by wing flapping. *J. R. Soc. Interface* **5**, 1041–1053. (doi:10.1098/rsif.2007.1349)

20 Lakshmanan, V., Zhang, J. & Howard, K. 2010 A technique to censor biological echoes in radar reflectivity data. *J. Appl. Meteorol. Climat.* **49**, 435–462. (doi:10.1175/2009JAMC2255.1)

21 Root, T. I., Hughes, L., Lovejoy, T. E. & Hannah, L. 2005 Present and future phenological changes in wild plants and animals. In *Climate change and biodiversity* (eds T. E. Lovejoy & L. J. Hannah), pp. 61–69. New Haven, CT: Yale University Press.