The response of birds to abrupt natural hazards as observed using weather radar

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1. Introduction

Numerous studies have addressed the important question of how species are impacted by seasonal variability, climate change, urbanization and land use effects, and other anthropogenic and natural shifts in habitats (Rosenzweig et al. 2008, Root et al. 2003, Parmesan 2006). However, far fewer investigations have considered how animals respond to abrupt natural hazards: earthquakes, severe weather, flash floods, tidal waves, and so forth. This is due in part to challenges involved with being able to deploy appropriate instrumentation to observe wildlife under these conditions. However, one can utilize existing networks of remote-sensing instruments, which provide a near-continuous data stream with the needed spatial and temporal resolution. As we discuss, operational weather radars can be used in this regard. Indeed, our ability to discriminate between weather and biological entities is being significantly enhanced through polarimetric radar capabilities (Zrnić and Ryzhkov, 1998, Moissev et al. 2008). As dual-polarization weather radars become more common, we should be considering how to better utilize these instruments beyond just weather observations.

2. Methodology

It is well established that scanning microwave radar is a highly effective means of detecting and tracking weather systems, estimating amounts of precipitation reaching the Earth's surface, and measuring many other valuable atmospheric parameters. The U.S. National Weather Service (NWS) maintains a network of 157 weather surveillance Doppler radar (WSR-88D) installations with approximately 130 of them distributed across the continental U.S. known as NEXRAD (Crum et al. 1998, Crum and Alberty 1993, Serafin and Wilson 2000). In addition to weather phenomena, these radars also regularly detect scatter from airborne biological organisms (so-called "bioscatter") (Gauthreaux and Belser 2003, Chilson et al 2012). Although not typically associated with weather radars, bioscatter can sometimes account for the overwhelming majority of signal detected by NEXRAD. Consequently several individuals and research groups have already begun employing data from NEXRAD for biological studies (e.g., Russell et al. 1998, Diehl et al. 2003, Kelly et al 2012, Horn and Kunz 2008, Bonter et al. 2009, O'Neal et al. 2010) and there has been considerable progress in the development of radar as a broad-scale biological observing tool.

Once identified as bioscatter, radar echoes can be used to detect and characterize the presence and movements of birds, bats, and insects, which then can be integrated into a host of biologically and ecologically motivated studies [Gauthreaux et al. 1998, Bridge et al 2011, Larkin and Diehl 2012, Dokter et al. 2010, Kelly et al. 2012). This is an example of the evolving scientific discipline of radar aeroecology (Chilson et al., 2012). The objective of aeroecology is to broaden understanding of ecological patterns and processes that result from the behavior of organisms in the aerosphere (Kunz et al. 2008).

Our ability to discriminate between biological and non-biological scatter and among different biological taxa in radar data is being greatly facilitated by the polarimetric upgrade to the NEXRAD network, which is currently in progress (Doviak et al. 2000). Similar to hydrometeor classifications based on dual-polarization characteristics that are currently in use (Straka et al. 2000), several biological classification algorithms are being developed (Mueller and Larkin 1985, Moisseev et al. 2010).

Here we present and discuss two examples of how weather radar can be used to observe biological response to sudden natural phenomena, namely the sudden mass movement of birds initiated by earthquakes and severe weather. Observational data from several weather radars, including those with dual-polarization capabilities, are used to quantify these biotic responses. The primary objectives of this study are to i) discuss the utility of weather radar data for biological studies, ii) demonstrate how these data provide insight into the response of animals to abiotic drivers, iii) examine how dual-polarization radar data can be used to discriminate between scatter from biological entities and weather, and iv) explain why such observations are important for both meteorologists and biologists.

3. November 6th Earthquake

On the evening of 6 November 2011 at 0353 UTC (22:53 local time) a magnitude 5.6 earthquake occurred in central Oklahoma with the epicenter estimated to be at 35.54°N, 96.75°W and 5 km below the surface. See Fig. 1 for details. Immediately after the earthquake, the Oklahoma City NEXRAD station (KTLX) recorded a rapid increase in radar



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backscatter at the lowest elevation angle (0.52°) in the vicinity of the radar. At the time, the radar was running in a clear-air volume coverage pattern (VCP) known as VCP 32 (OFCM-2006). In Fig. 2 we show two plan position indicator (PPI) plots of radar reflectivity factor (Z) for the lowest elevation angle recorded around 0350 and 0353 UTC. The radar backscatter likely resulted from birds, which abruptly took flight in response to the earthquake. There have been visual accounts of birds becoming confused and suddenly taking off during the onset of earthquakes (e.g., Moncrief 1930), but we are not aware of any observations of this behavior using radar. However, Shamoun-Baranes et al. (2011) have documented similar behavior of birds being suddenly startled by New Year's Eve fireworks during three consecutive years using operational weather radar in the Netherlands. Similarly, in Beebe, Arkansas, numerous blackbirds were killed in flight (presumably as a result of mid-air collisions with one another) after having been startled by the fireworks on New Years' Eve of both 2011 and 2012. These events were detected by NEXRAD.

For the case of the 6 November event, KTLX initiated a new VCP scan soon after onset of the earthquake. A full scan in VCP 32 mode normally requires about 10 minutes; however, the earthquake caused the radar to begin a new scan before the previous one was complete. Therefore we have observations at the lowest elevation angles with a temporal separation of only about 3 minutes. Moreover, since two consecutive scans are performed at the lowest elevation angle of 0.5° in VCP 32, we have four sets of observations within a time period of roughly four minutes at low elevation. This provides a fortuitous opportunity to observe the birds as they were just departing.



Fig. 1 Location and distributed intensity of the magnitude 5.6 earthquake recorded in Oklahoma on 6 November 2011. Plots are from the United States Geological Survey (http://earthquake.usgs.gov/earthquakes/eqinthenews/2011/usb0006klz).



Fig. 2 Values of Z measured using KTLX corresponding to the lowest elevation angle (0.52°) before (left panel) and after (right panel) the occurrence of the earthquake. The start times of the VCP scans before and after the earthquake are 0350 and 0353 UTC, respectively.

In addition to data from KTLX, we also have data from KOUN during the event. KOUN is the prototype dual-polarization WSR-88D located in Norman, Oklahoma and operated by the National Severe Storms Laboratory. Shown in Fig. 3 are observations of Z in the upper two panels, and differential reflectivity (ZDR) and correlation coefficient (ρ_{hv}) in the lower two panels. During this time, KOUN was operating in VCP 12 (OFCM-2006). Here again the VCP was interrupted by the earthquake and restarted. The texture in ZDR and low values of ρ_{hv} associated with the enhanced values of Z near the radar are clearly indicative of bioscatter, which further supports the claim that this radar signature is the result of birds.



Fig. 3 PPI plots of radar reflectivity factor for the lowest elevation angle observed before (upper left panel) and after (upper right panel) the earthquake. Start times for these scans were 0352 and 0354 UTC, respectively. Measurements of differential reflectivity (lower left panel) and correlation coefficient are shown in the lower left and lower right panels, respectively. These data are for the lowest elevation angle and just after the earthquake.

4. November 7th Severe Weather Event

On the day following the earthquake (November 7), a series of severe thunderstorms moved through the southwest corner of Oklahoma, which produced several tornadoes, large hail, flooding, and damaging winds. Shown in Fig. 4 is a depiction of the general path of storm system along with preliminary tornado tracks as provided by the National Weather Service (http://www.srh.noaa.gov/oun/?n=events-20111107). Additional information pertaining to the storm can be found through NOAA's Storm Prediction Center (http://www.spc.noaa.gov/climo/reports/111107_rpts.html). The longest-lived and most intense tornado was observed around 2038 - 2113 UTC (Track #1 in Fig. 4). The next longest duration, but less intense, tornado (Track #4) moved through the Wichita Mountain Wildlife Refuge from approximately 2159 to 2218 UTC. Tornado track #7 corresponds to a time of about 2245 UTC and the tornado near Fort Cobb (Track #8) occurred at 2300 UTC.

Here our focus is not on the tornadoes themselves, but rather two unusual radar signatures observed in data collected from KOUN, which could be attributed to the movement of birds in advance of this system of severe weather. The signatures are

characterized by a spatial region of radar data having low values of ρ_{hv} accompanied by enhanced standard deviations in the differential phase (Φ_{DP}) and ZDR. For brevity, we will simply refer to these signatures as " ρ_{hv} -minimum signatures." For the two cases considered, the region of potential bioscatter cannot be identified through radar reflectivity alone. That is, the polarimetric data are necessary.



Fig. 4 Map of Oklahoma showing the approximate track of the storm system (left panel) and the approximate tornado tracks (right panel) for November 7. Also shown in the right panel are the locations of the two reservoirs discussed in the text.

In Fig. 5 we present data from KOUN corresponding to one of the ρ_{hv} -minimum signatures to be discussed. In the leftmost four-panel plot, we see the early stages of the signature as indicated by the yellow oval (2137 UTC). In the next time step (2150 UTC) depicted in the rightmost plot, the signature is becoming more pronounced and the hydrometeor classification algorithm (HCA) has characterized the scatter in this region as resulting from bioscatter. We should note that chaff, storm debris, and other materials could possibly be falsely associated with bioscatter by the HCA. However, these signature is descending. Therefore, storm debris is unlikely. It is worth noting that the ρ_{hv} -minimum signature is first seen near the Tom Steed Reservoir (see Fig. 4) just before the arrival of the tornado- and hail-generating supercell. Although not shown, the signature is seen to track in a northeasterly direction ahead of the storm.



Fig. 5 Two four-panel plots showing Z (upper left), ρ_{hv} (upper right), ZDR (lower left), and hydrometeor classification (HC, lower right). *The times of the four-panel plots correspond to 2137 UTC (left) and 2150 UTC (right). Data were collected with KOUN while scanning at an elevation angle of 0.5°. The yellow ovals denote the location of the radar signature, which might be associated with bioscatter. For the HC data, a color of grey corresponds to bioscatter.*

The second ρ_{hv} -minimum signature is shown in Fig. 6. The features are similar to those provided in Fig. 7. The early onset of the signature (leftmost plot) occurs around 2243 UTC and the next time step (rightmost plot) was observed at 2256 UTC. As before, the signature is detected immediately ahead of the supercell in a region near a reservoir. The location of

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the Fort Cobb Reservoir is shown in Fig. 4. A third ρ_{hv} -minimum signature, which is not shown in the figures, was observed about the time the storm system (Tornado #4) moved across the Wichita Mountain Wildlife Refuge shown in Fig. 4.

Collectively these observations provide compelling, although not conclusive, evidence that the ρ_{hv} -minimum signatures correspond in part to radar scatter from birds that are taking flight to avoid the approaching severe weather. Precipitation from the supercells will also contribute to the radar signal. At the time of the observations, one can expect Canada geese (*Branta canadensis*), snow geese (*Chen caerulescens*), mallards (*Anas platyrhynchos*), and some other less abundant species of ducks to be present at the reservoirs affected. Our preliminary investigations into the flight speeds necessary to account for translation of the observed radar features with time seem consistent with those expected from geese and ducks. It is unlikely that the movement of smaller passerines could have produced the signatures, given their lower air speeds. We are conducting a careful examination of radar data along with meteorological conditions at the time, which will hopefully provide more insight into these observations. Although not shown, data from the dual-polarization NEXRAD installation at the Vance Air Force base (KVNX) reveals similar ρ_{hv} -minimum signatures as those presented here for KOUN; however, given the distance of the radar from location of the storms, these features are more difficult to resolve. The WSR-88D located closest to the storm system (KFDR) was not yet been upgraded for polarimetric operation at the time of the observations.



Fig. 6 Same as Fig. 5 except the times of the four-panel plots correspond to 2243 UTC (left) and 2256 UTC (right).

5. Discussion

Compared to terrestrial and aquatic environments, our understanding of ecological dynamics in the aerosphere is still in its infancy [Kunz et al. 2008, Shamoun-Baranes et al. 2010]. Radar offers an opportunity to investigate the behavior of animals in flight and how they utilize the aerosphere as habitat. Although not yet fully realized, networks of weather radar can be used to monitor how animals capable of flight respond to natural and anthropogenic effects over a wide range of spatial and temporal scales (Diehl et al. 2003, Buler and Moore 2011, Kelly et al. 2012). Here we have briefly examined the utility of NEXRAD to detect and study responses of volant animals to abrupt natural hazards. Many of these are difficult to predict, therefore one must rely on existing networks of instruments to observe the consequences of these phenomena.

These results are preliminary and we are continuing to explore possible causes for the radar signatures discussed in connection with the earthquake and tornadic storms. At present, the most plausible cause appears to be bioscatter resulting primarily from birds. If this is the case, then such observations will facilitate our ability to address a variety of research questions related to animal behavior. For example, what environmental cues do birds use when deciding whether to fly or lay low as severe weather approaches? Flying in rain can be energetically expensive for birds; however, it seems plausible that that they would chose flight over potential exposure to strong winds and hail. Weather radar may provide unique insights into the behavior of flying animals when confronted with abrupt natural hazards.

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