9R.6 **OBSERVATIONS OF INSECTS AND BIRDS WITH A POLARIMETRIC PROTOTYPE OF THE WSR-88D RADAR**

Pengfei Zhang, Alexander Ryzhkov, and Dusan Zrnic*

CIMMS, University of Oklahoma, Norman, Oklahoma
*NOAA/National Severe Storms Laboratory, Norman, Oklahoma

## 1. INTRODUCTION

Biological echoes are treated as contamination like ground or sea clutters by radar meteorologists as they estimate rainfall intensities or assimilate radar reflectivity into numerical forecast model. Doppler velocity measured by radar in the presence of small insects well represents air motion because small insects are considered as passive tracers. But in the presence of birds especially migrating birds, Doppler velocities measured by radar are different from air velocities (Jungbluth et al. 1995; Gauthreaux et al. 1998a, b).

On the other hand, biological echoes are very useful for ornithologists to study the migration, dispersion pattern and flight behaviors of insects and birds especially during nighttime. As early as 1969, Schaefer (1969) had successfully used radar as an entomological tool to study the flight trajectories of locusts. Now more and more information has been published in the fields of radar entomology (http://www.ph.adfa.edu.au/a-drake/trews/) and radar ornithology (http://virtual.clemson.edu/groups/birdrad/).

The application of polarimetric technique on weather radar provides more information about biological scatterers. It has been shown that polarimetric radar has capability to recognize birds and insects (Zrnic and Ryzhkov 1998). Azimuthal dependencies of differential reflectivity $Z_{dr}$ observations have been used to determine the occurrence of migrations of birds and insects in the clear air when the radar observed wind was analyzed (Wilson et al 1994). Achtemeier (1991) used local minimums of $Z_{dr}$ to conclude that insects in the updraft region are in evasive flight and cannot be treated as passive tracers. Recently, Lang et al. (2004) reports that CSU-CHILL polarimetric radar observed quasi-symmetric echo patterns of reflectivity and $Z_{dr}$ in clear air. It is obvious that polarimetric radar become a very useful tool for researchers to learn about the characteristics of different scatterers in the clear air. Dual-polarimetric capability will be implanted on the currently operating WSR-88D weather radar network in the near future. It will benefit not only meteorological studies and weather forecast but also ecology studies.

Clear air observations with the KOUN polarimetric radar in 2004 provide unique opportunity for us to study the spatial distribution and temporal variability of the echo from birds and insects in the planetary boundary layer during daytime and nighttime. The analysis of observations on 8 September 2004 is presented in this paper.

## 2. OBSERVATIONS ON 8 SEPTEMBER 2004

It is well known that in order to escape from unfavorable living conditions in both space and time and colonize themselves in a region with favorable conditions, insects and birds migrate polewardly in spring and summer and equatorwardly in autumn every year. Different types of synoptic weather provide favorable airflows for the migrations of insects and birds (Drake and Gatehouse 1995; Dingle 1996). Most passerines migrate during night (Corral 1989). These nocturnal migrants fly dispersedly rather than concentrate or narrow their route around land formation like diurnal migrants. Thus, radar often observe relative smooth “disk-like” echo in fall and spring (Gauthreaux et al. 1998a; Zhang et al. 2005).

On 8 September 2004, a high pressure system set up over Oklahoma and slowly moved to the east. Atmosphere was quite stable and north-northeast wind dominated the lower atmosphere. It provided favorable airflows for southwardly migrating birds and insects in the fall season. The KOUN radar continuously operated on 8 September 2004 and recorded

**Corresponding author address:* Pengfei Zhang, CIMMS, University of Oklahoma, Norman, OK 73019; e-mail: pzhang@ou.edu

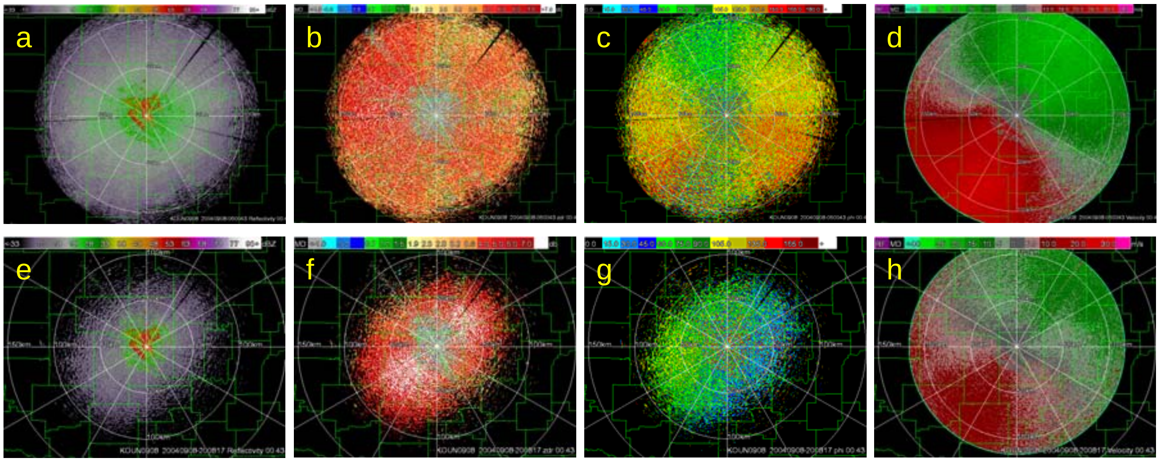


Fig. 1 KOUN radar observations at 0.5$^o$ elevation angle at 06 UTC (upper panels) and 20 UTC (lower panels). Panels (a) and (e) represent reflectivity Z; (b) and (f) differential reflectivity $Z_{dr}$; (c) and (g) differential phase $\phi_{dp}$; (d) and (h) Doppler velocity $V_r$. Radar is located right at the center of each panel. Two white range rings indicate 50 km and 100 km ranges from the radar.

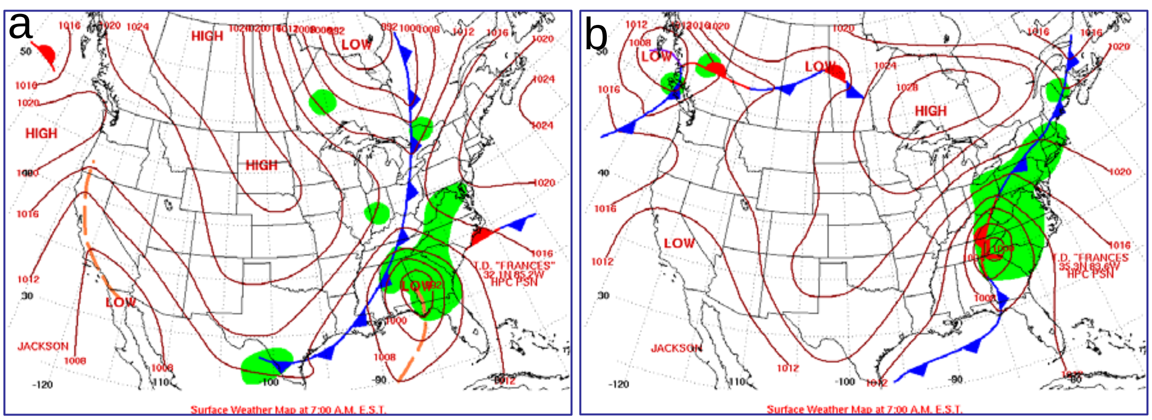


Fig. 2 Surface weather maps at 12 UTC on (a) 7 September and on (b) 8 September 2005.

valuable data. Fig.1 shows reflectivity Z (a and e), differential reflectivity $Z_{dr}$ (b and f), differential phase $\phi_{dp}$ (c and g), and Doppler velocity (d and h) observed with the KOUN radar at 0.5$^o$ elevation angle at 06 UTC (upper panels) and 20 UTC (lower panels). It is obvious that the echo coverage is larger in the upper panels (06 UTC) than in the lower panels (20 UTC) except (d) and (h). The average reflectivity Z is also stronger at 06 UTC than 20 UTC. The echoes within 30 km from the radar are attributed to ground clutters. Larger coverage and stronger echoes indicate more scatterers and they reach higher altitude (about 1800 m ASL) at 06 UTC. The obvious visual differences in $Z_{dr}$ and $\phi_{dp}$ imply the sizes of dominated scatterers are clearly different. The wind direction from Doppler velocity $V_r$ (d and h) at 06 UTC and 20 UTC indicates northeast wind through lower boundary layer (below 1.5 km) that is consistent with rawinsonde observations and weather pattern shown in the weather map (Fig. 2).

## 3. EVOLUTIONS OF POLARIMETRIC VARIABLES

Four sectors centered at four different azimuths 30$^o$, 120$^o$, 210$^o$, and 300$^o$ at 0.5$^o$ elevation angle are selected in order to study the characteristics of radar moments along and perpendicular to the ambient wind direction (Fig. 3). The width of each sector is 30$^o$. The ranges from 30 km to 70 km are selected. The reasons are 1) to avoid contaminations of ground clutter near the radar; and 2) to gather most available

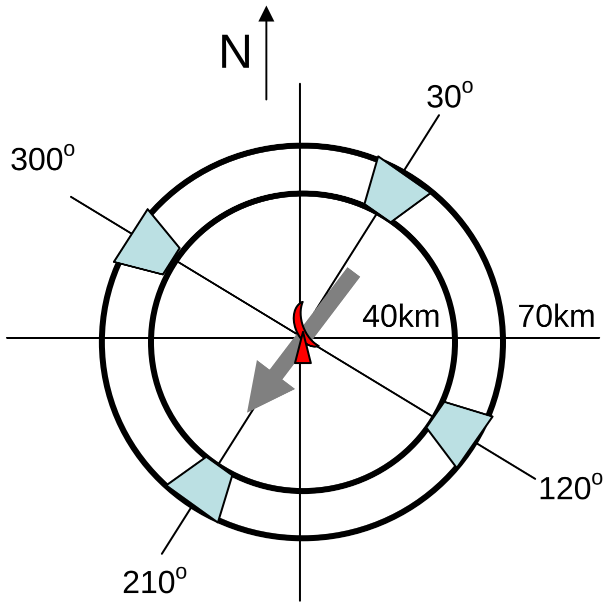


Fig. 3 Schematic diagram for the locations of four sectors (cyan trapezoid). Radar is right at the center of range rings. The gray arrow indicates the direction of ambient wind.

valid observations because clear air echo beyond 70 km in the daytime (see Fig. 1 lower panel) is quite weak.

Average Z, $Z_{dr}$, and $\phi_{dp}$ for the four sectors are calculated and the evolution of these variables is illustrated in Fig. 4a, b, and c. Note that straight lines between 15 UTC and 17 UTC in Fig.4 correspond to the lack of observations. In Fig. 4 all the radar variables show abrupt changes just after sunset and before sunrise. The sunset time is 00:46 UTC and sunrise time is 12:08 UTC on 8 September 2004. For example, average Z at azimuth 210° quickly drops to -13 dBZ after sunset and then climbs back and reaches its maximum of 22 dBZ in about 1 hour. Just before sunrise, it suddenly drops to its minimum -18.4 dBZ at 11:46 UTC and bounced back to 15.4 dBZ at 12:03 UTC. The abrupt changes of radar variables at sunset and sunrise in the clear air day during migrating season are common. Similar pattern is also found in the observations from the KOUN radar on 8-9 May and 12 June 2004 (not shown). It implies that the birds and insects dramatically change their flight behavior as the sky light changes.

Radar ornithology studies (Lincoln et al. 1998) have found that nocturnal migrants fly at different altitudes at different times during the night. Shortly after sunset, migrants generally take off and rapidly reach their maximum altitude. They keep flying at the peak altitude until around midnight and gradually descend until sunrise. Our observations (Fig. 4a) show similar evolution pattern. For the average Z of all four sectors, they rapidly reach their peak in about 1.5 hour after sunset and then gradually decrease.

More information about biological scatterers is provided by polarimetric variables (Fig. 4b and c). Vaughn (1985) suggested that prolate spherical water drop is a better model for birds and insects as radar scatterers than spherical water drops (Riley, 1985). Usually the ratios of width-to-length are between 1:2 and 1:3 for birds and between 1:3 and 1:10 for insects (Vaughn, 1985). Due to the difference in shape and size, the polarimetric signatures of insects and birds are different. Based on the studies of Zrnic and Ryzhkov (1998), as polarimetric radar scatterers birds have lower $Z_{dr}$ and higher $\phi_{dp}$ than insects. Fig. 1 and 4 indicate that $Z_{dr}$ is roughly lower in the nighttime (between 00:46 UTC to 12:08 UTC) and $\phi_{dp}$ is lower in the daytime (between 12:08 UTC to 24:00 UTC). Hence, dominant scatterers are birds in the nighttime and insects in the daytime. Note that we use term "dominant scatterers" here. Actually we found that birds and insects frequently coexist in a radar resolution volume (Bachmann and Zrnic 2005).

Fig. 4 also demonstrates that the spatial and temporal variations of average $Z_{dr}$ and $\phi_{dp}$ are obviously larger than average Z especially in the nighttime. Average Z for all four sectors (Fig.4a) gradually decreases with time from their peak value at about 02:00 UTC in the nighttime. However, average $Z_{dr}$ and $\phi_{dp}$ show distinct diurnal differences among four sectors. This is likely because $Z_{dr}$ and $\phi_{dp}$ are independent of the concentration of scatterers but are dramatically affected by their size, shape and orientation (Doviak and Zrnic 1993). Also reflectivity is less sensitive to the size change of scatterers than

Lewis and Taylor (1965) have studied about 400 species of insects and found that different species fly at different times of the day or night. Ornithologists found that average migration distances for different birds vary from 50 km/day to 110 km/day when they migrate across northern America (Dingle 1996). Assuming that average flight speed relative to the ground is 15 m/s, it only takes about 1 to 2 hours of continuous flight for individual bird to finish its one day migratory journey.

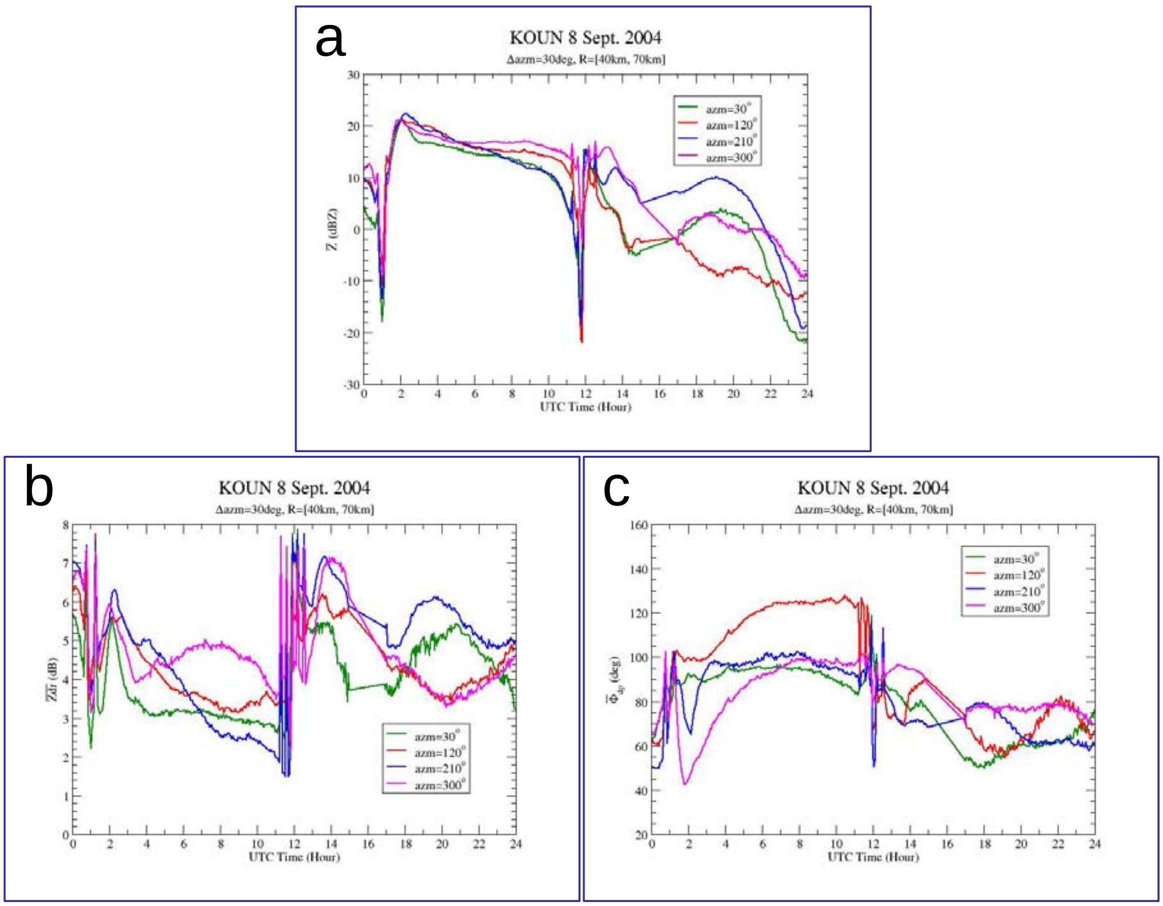


Fig. 4 Time evolution of (a) reflectivity Z, (b) differential reflectivity $Z_{dr}$, and (c) differential phase $\phi_{dp}$ for the four sectors at four different azimuths $30^{o}$ (green), $120^{o}$ (red), $210^{o}$ (blue), and $300^{o}$ (pink).

$Z_{dr}$ and $\phi_{dp}$ (Zrnic and Ryzhkov 1998).

The strong azimuthal variations of $Z_{dr}$ and $\phi_{dp}$ are primarily attributed to the orientation of biological scatterers. Variations in the scatterers size and type is another possible cause of diversity. The latter argument is consistent with conclusions made in some of biological studies.

## 4. AZIMUTHAL DEPENDENCE

Due to preferred orientation of biological scatterers, their signatures would exhibit a well-pronounced azimuthal dependence if they migrate in the same direction with respect to radar. The azimuthal dependencies of $Z_{dr}$ from insects were observed by Mueller and Larkin (1985), Achtemeier (1991) and Lang et al. (2004). Zrnic and Ryzhkov (1998) have compared the azimuthal dependencies of $Z_{dr}$ and $\phi_{dp}$ for reflections from birds with model results for oblate spheroids. The model results showed good qualitative agreement with the observations. The important result of that study is that $Z_{dr}$ and $\phi_{dp}$ reach their maxima as the angle $\theta$ between the direction of incident radar beam and the symmetry axis of prolate spheroid is equal to $90^o$. In the Rayleigh regime of scattering typical for small insects, $Z_{dr}$ and $\phi_{dp}$ monotonically increase to their minima at $\theta = 90^o$. In the Mie regime of scattering typical for large insects and birds, azimuthal dependences of $Z_{dr}$ and $\phi_{dp}$ are more complicated. But their values at $\theta = 0^o$ are still smaller than at $\theta = 90^o$.

Polarimetric observations (Fig. 4) do not exhibit azimuthal dependence predicted by the model. During the nighttime, $\phi_{dp}$ is obviously larger at azimuth $120^o$ (red line) than at other three azimuths. According to the model, $\phi_{dp}$ at azimuth $300^o$ (pink line) should be similar to the one at azimuth $120^o$. But $\phi_{dp}$ at azimuth $300^o$ is much smaller than at azimuth $120^o$. $Z_{dr}$ exhibits more complicated pattern during the nighttime. Before 06 UTC, the pattern of $Z_{dr}$ at four different directions is similar except $Z_{dr}$ at azimuth $30^o$ (green line) is smaller than the others. Between 06 UTC to 10 UTC, $Z_{dr}$ at azimuth $300^o$ becomes the largest among the four directions. There are two reasons to explain why pronounced azimuthal dependence is not observed. First, different birds with different sizes and shapes migrate at the same time. Second, the mixture ratio of birds and insects may be different at different sectors. We speculate that high $Z_{dr}$ and relative low $\phi_{dp}$ at azimuth $300^o$ may indicate more insects are in the sector between 06 UTC and 10 UTC.

Between 18:00 UTC and 23:00 UTC, $Z_{dr}$ in the sectors perpendicular to the ambient wind direction (azimuths $120^o$ and $300^o$) are clearly smaller than in the sectors along the wind direction (azimuths $30^o$ and $210^o$). Oval-shaped radar echo pattern is observed (Fig. 1e) during that period of time. As we mentioned previously, the dominant scatterers in the daytime are insects. Large $Z_{dr}$ and strong echo along the ambient wind direction imply the orientation of insects is perpendicular to the wind direction. Common orientation of migrating insects, such as grasshoppers and moths, has been observed and studied by entomologists. The angle between the orientation direction of insects and ambient wind direction is defined as “crab angle” by Wolf et al. (1995). Generally, crab angle is less than $90^o$. But in this case, the crab angle is about $90^o$. It is different from the observation of Lang et al. (2004). They found that the insects are flying upwind, so the crab angle is $180^o$ in that case. It is also different from migrating birds. They usually take the advantage of tail-wind and their orientation direction is the same as ambient wind direction.

## 5. COMPARISON BETWEEN RADAR MEASURED WIND AND SOUNDING

The ambient wind directions at 1000 m ASL observed by rawinsonde are $40^o$ and $48^o$ at 00 UTC and 12 UTC separately. Thus, the $V_r$ observations in the sectors centered at $30^o$ and $210^o$ are compatible with the rawinsonde observed wind speed. KOUN radar is collocated with the OUN sounding observation station. With north-northeast wind, sounding balloon drifted to south-southwest of the radar as it ascends. The azimuth of $210^o$ is closer to the balloon than the azimuth of $30^o$. Time evolution of average $V_r$, Z, and $Z_{dr}$ in the sector at azimuth $210^o$ is illustrated in Fig. 5. The wind speeds from rawinsonde observations at 00 UTC and 12 UTC at height 1000 m ASL that is about same as the height of the KOUN radar beam at range 55 km are also marked as blue circles in Fig. 5. The ambient wind directions are slightly different from radar azimuth $210^o$. Thus the wind speeds shown in Fig. 5 are the projections of rawinsonde observations to the azimuth $210^o$. They are 11.3 m/s and 9.2 m/s at 00UTC and 12 UTC. The sunset (00:46 UTC) and sunrise (12:08 UTC) time are also marked with brown dash lines in Fig. 5.

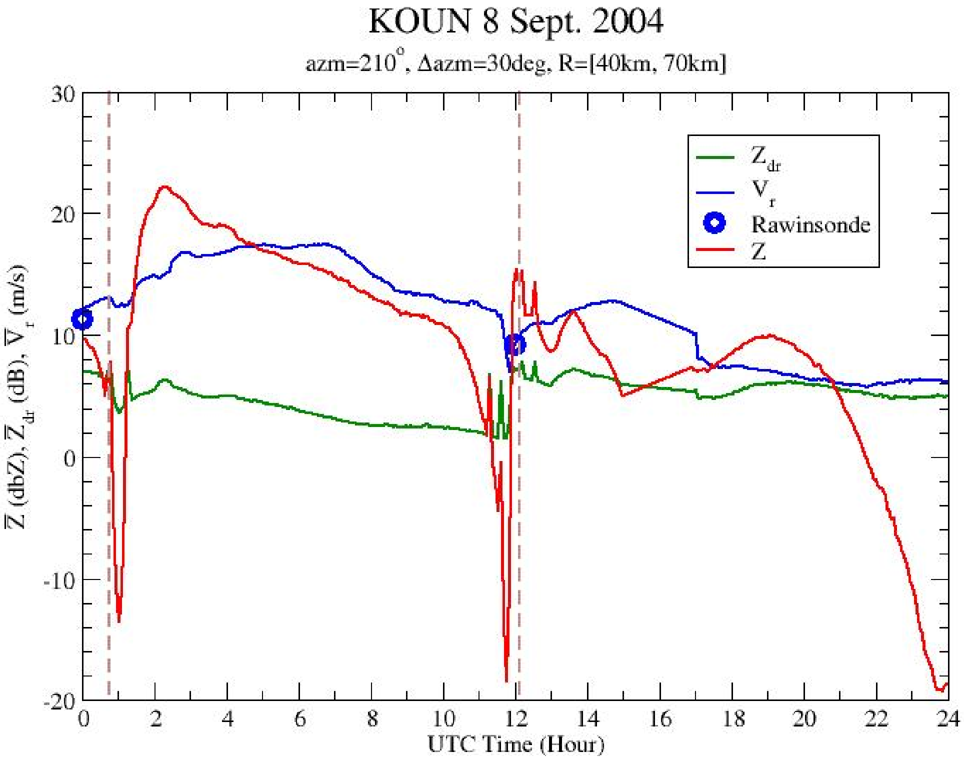


Fig. 5 Time evolution of average Z (red), $Z_{dr}$ (green), and $V_r$ (blue) of the sector at azimuth 210$^o$ for 8 September 2004. Blue circles indicate rawinsonde observations at 00 UTC and 12 UTC. Brown dash lines indicate sunset and sunrise time.

Average $V_r$ slowly increases from 11.3 m/s (the same as rawinsonde observation at 00:00 UTC) to its peak of 17.5 m/s at 06:45 UTC. Then it slowly drops to 10.1 m/s at 11:40 UTC. Average $V_r$ between sunset and sunrise is clearly higher than ambient wind speed observed by rawinsonde at 00 UTC and 12 UTC. Since no other observations rather than Doppler radar are available, true wind speed in the atmosphere is unknown between 00 UTC and 12 UTC. Weather maps (Fig. 2) show the weather pattern does not change much over Oklahoma. We believe that wind speed in the lower atmosphere should not vary much during the night. Hence, the high “wind speed” observed by radar is the sum of ambient wind speed and speed of migrating birds. This conclusion is consistent with the polarimetric observations.

## 6. DISCUSSION AND SUMMARY

Many radar meteorologists consider insects as passive tracers, so radar-measured winds represent ambient air motion. For example, Russell and Wilson (1997) have suggested that insects can be viewed as “aerial plankton”. But other radar meteorologists argue that it may not be true for large insects such as moths and locusts since they can fly at speed 3 to 5 m/s (Riley et al. 1983; Riley 1974). As migrating insects orient and travel in almost the same direction, systematic bias in the radar-measured wind can be induced (Achtemeier 1991; Lang et al. 2004). The studies conducted by Srygley et al. (1996), and Walker and Riordan (1981) indicate that butterfly can adjust their airspeed and flight directions against drift induced by adverse wind in order to migrate to the destination. Time-compensated sun can be used as a compass in insect migrants to navigate them at a preferred geographical flight direction (Oliveira et al. 1998). Thus, it may not be appropriate to treat all insects as passive tracers when insects, especially large insects, migrate.

Checking the azimuthal dependence pattern observed with polarimetric radar becomes an effective way to detect if insects migrate in the same direction.

The observations of diurnal variation of radar variables clearly reflect some behaviors of migrating birds and insects that are in agreement with biological studies. The sensitivity and azimuthal dependence of polarimetric variables provide ample information to distinguish between birds and insects and estimate the orientation of biological scatterers. $Z_{dr}$ and $\phi_{dp}$ measurements might also give a chance to roughly estimate the size of birds and insects once the distinction between them is made.

This work shows the potential of a polarimetric prototype of the WSR-88D radar for detection and classification of biological scatterers. Therefore, polarimetric diversity will benefit data quality control and facilitate assimilation of polarimetric radar data onto weather forecasting models. On the other hand, the biological echoes considered as contamination of weather echoes for meteorologists contain useful information for biologists studying flying behavior of insects and birds. Integrated with other observations such as mark-release-recapture experiments and weather forecast, network polarimetric radar observations can provide vital information regarding insects' and birds' density, their destinations and arrival dates even forecast their behavior for ecology management system.

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