HOW THE WSR-88D AND ITS NEW DUAL POLARIZATION CAPABILITY CAN BENEFIT THE WIND ENERGY INDUSTRY

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1. INTRODUCTION

The primary weather radar network for the U.S., consisting of 160 Weather Surveillance Radar-1988, Doppler (WSR-88Ds), is owned and operated by the Departments of Commerce, Defense, and Transportation. Data from this radar network -- both real time and archived -- are readily available to the wind energy industry and their private sector weather service suppliers to support the wind energy's weather-sensitive operations. The WSR-88D data can be used by the wind energy industry to improve efficiency of power generation and siting decisions.

Real-time WSR-88D data can improve short-term (0 to ~2 hour) forecasts to support wind energy production and resource protection decisions during "ramp events." Radar data are also used to initialize numerical weather prediction models operated by the National Oceanic and Atmospheric Administration's National Weather Service (NOAA's NWS). Archived WSR-88D data can be useful for several wind energy industry needs (e.g., wind climatology studies, forensic cases, and bird/bat migration patterns).

We have reported on the potential benefits of WSR-88D for increasing wind energy production efficiency before (Vogt et al. 2010). However, now the WSR-88D network is being upgraded with dual polarization capability, which will provide even further benefits to weather forecasters and the wind energy industry. This paper will provide a brief overview of those benefits.

2. WSR-88D NETWORK

Operational WSR-88D systems were installed at 160 locations across the contiguous United States, Alaska, Hawaii, Puerto Rico, and select overseas sites between 1991 and 1997 (Fig. 1). Wind energy developers can obtain the location and elevation of one or more WSR-88D systems by sending a request to wind.energy.matters@noaa.gov.

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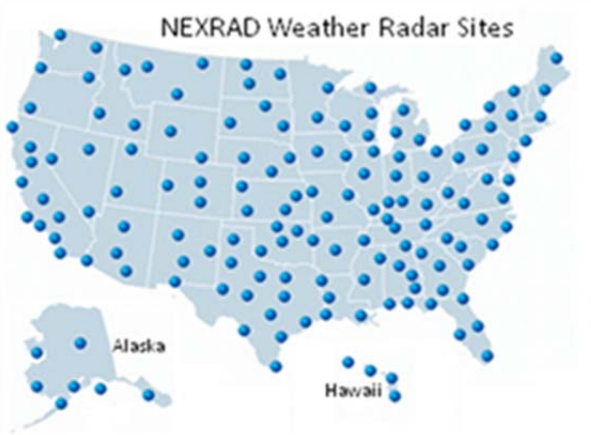

Fig. 1. Location of WSR-88Ds (aka NEXRAD) in all 50 states. There are six additional WSR-88Ds beyond this map.

The WSR-88D is a high-power Doppler radar system designed to detect weather targets and storm-scale winds at long ranges. In addition, its receiver is sensitive enough to detect clear-air (without the presence of clouds or rain) boundaries such as temperature and humidity discontinuities, fronts, gust fronts, etc. The WSR-88D transmits a pulsed ~10 cm wavelength signal, with a 1° beam spread at a peak power of 750 kW. (Vogt et al. 2009) Operationally, the WSR-88D automatically scans the atmosphere with pre-defined coverage patterns from 0.5° to 19.5° elevation above the horizon, then processes and distributes reflectivity, mean radial velocity, and spectrum width (a measure of the variability of radial velocities in the resolution volume) data. (FMH-11, Part A) From these data, computer algorithms generate a suite of meteorological and hydrological products and data that forecasters utilize in preparing short-term forecasts, advisories, and warnings for significant weather events such as tornadoes, hail, wind shear, downbursts, and flash floods.

The WSR-88D radar network is being upgraded with dual polarization capability, replacing the current single (horizontal) polarization beam (Fig. 2). Over 130 WSR-88Ds have been upgraded as of the end of January 2013. The last operational WSR-88D will be upgraded in June 2013. Dual polarization will provide more accurate radar-estimated precipitation accumulations, improved detection and delineation of liquid/frozen/melting precipitation (areas of snow, sleet,

freezing rain), higher quality data, improved avian/bird migration detection, improved hail size estimation, and the ability to detect lofted tornado debris (confirming tornado touch down).

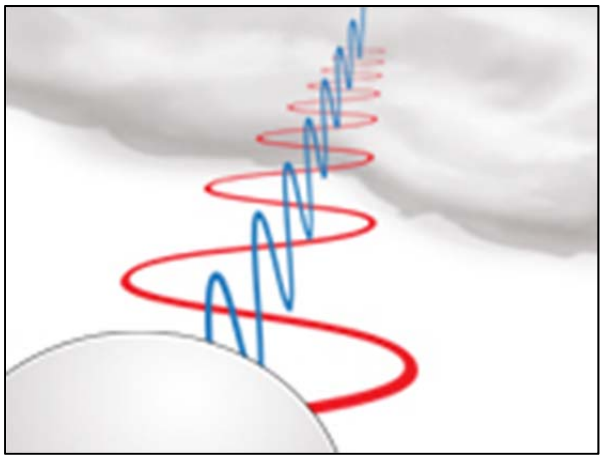

Fig.2 Schematic showing the horizontal and vertical polarizations that constitute "dual polarization."

Three new dual polarization Level 2 variables are available:

- Correlation Coefficient (CC) can help forecasters distinguish precipitation from non-precipitation, and determine whether the precipitation targets have the same shape and type (e.g., all rain or all snow), or if a mixture exists (e.g., rain and snow). Data values range from 0.0 to 1.05. Values indicating precipitation are usually between 0.9 and 1.0.
- Differential Reflectivity (ZDR) is the difference in reflectivity between the horizontal and vertical polarized radar signals. ZDR can help identify the dominant target shape. Spherical, randomly oriented targets (e.g., hail, snow, debris) have values near zero while horizontally elongated targets (e.g., large rain drops) have large positive values.
- Specific Differential Phase (KDP) is computed from the phases of the horizontal and vertical polarized radar signals. KDP units are degrees per kilometer. The greater the KDP, the greater the liquid water content in the radar beam. It can help identify regions of heavy rain.

3. REAL-TIME ANALYSIS/NOWCAST RAMP EVENTS

The WSR-88D system can detect changes in the atmosphere that may not be visible to the naked eye. As a remote sensor, the radar provides thousands of atmospheric measurements in real time and on a continuous basis. Weather radar data can support improved short-term forecasts, also termed "now casting," primarily though visual interpretation of radar product data. Work at the National Center for Atmospheric Research and other centers have/are researching nowcasting and numerical weather prediction approaches for improving forecasts of ramp events using WSR-88D and other remote and in situ sensors. (For example, Sun 2010; Tadesse 2009) The following sections provide examples of weather situations we believe radar data can best support the wind energy industry.

3.1 Detection of Wind Shift Boundaries

The WSR-88D's highly-sensitive receiver enables the system to detect boundaries between different air mass types generated by several different meteorological phenomena. Examples are shown in Fig. 3 and Fig. 4. The WSR-88D can produce "base products" of reflectivity and radial velocity from each scanning angle. Environmental situations include:

- Thunderstorm Outflows: Thunderstorm outflows can cause a ramp event (a sudden increase or decrease in wind direction and/or speed, which in turn can increase or decrease power generation). The wind energy industry needs to be able to predict the outflow onset in order to optimally balance power output going to the power grid. The collapse of a mature thunderstorm pushes cool, dry air to the surface of the earth. When the air reaches the surface it spreads in all directions. Since the air is cooler and drier than the surrounding air, there is a discontinuity between the air masses that WSR-88Ds can detect, as seen in Fig. 3.
- Dry Lines, Sea/Lake Breeze, or Frontal Boundaries: Fig. 4 shows a dry line advancing through Southern Kansas and Northern Oklahoma. The dry line is clearly visible in the radar reflectivity product on the left, while the visible satellite image on the right gives little or no visual indication of the dry line. Knowing where boundaries are occurring and the speed/direction of winds approaching a wind farm can provide advance information on the need to change operation of the turbines and forecast changes in power production. We encourage users to incorporate various sensors in their operations planning and forecasts.

3.2 Detection of Severe Weather

Severe thunderstorms can generate tornadoes, damaging hail and damaging strong winds. Knowing where severe storms are occurring can provide information on the need to change turbine operations to mitigate damage and forecast changes in power production. The path of a suspected or actual tornadic thunderstorm can help focus efforts to determine any damage to equipment. Examples follow:

- Confirmation of Tornado Touch Down: Dual polarization data can be used to help confirm that a tornado has reached the ground. When tornados touch the ground they usually loft debris into the air. The debris returns a specific signature

in the dual polarization data, specifically, low ZDR and CC values. The legacy Reflectivity and Velocity products can indicate a possible tornado, but rarely detect debris from a tornado. This new capability is very useful at night when visual confirmation of a tornado is much more difficult. An example with both legacy and dual polarization products can be viewed in Fig. 5.

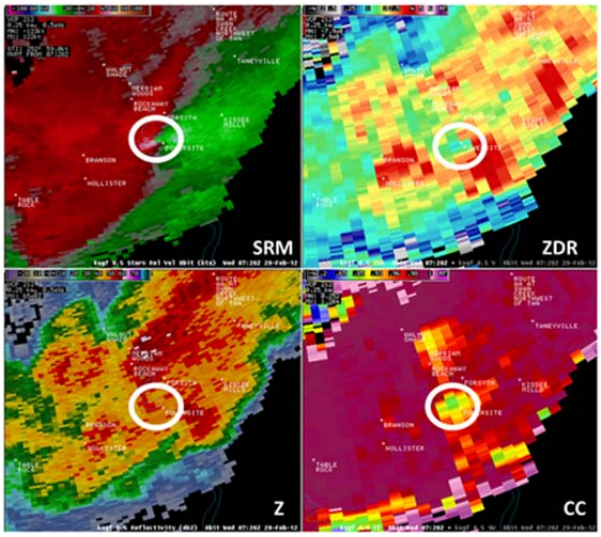

Fig. 5. Reflectivity (Z) and Storm Relative Motion (SRM) Velocity product indicate possible tornado (note hook echo and velocity couplet in circle). Dual polarization data (low ZDR and CC values in circle on right) can detect debris cloud, and help confirm a tornado is on the ground.

- Improved Hail Detection. The WSR-88D contains a Hydrometeor Classification Algorithm (HCA) that utilizes the different dual polarization properties of the various hydrometeor types to better specify the location of hail within storms. Forecasters can also examine the legacy and dual polarization products to detect areas of hail and estimate its size. Hail is associated with areas of high Reflectivity combined with low ZDR and CC values. An example of these products for a storm that produced giant hail is at Fig. 6. Knowing where hail may occur can provide advance information on the need to change operation of the turbines to mitigate damage and forecast changes in power production. The path of a suspected hail-producing thunderstorm can also help with efforts to determine where damage may have occurred.

3.3 Delineation of Freezing/Frozen Precipitation

Combined with other sensors, radars can help identify areas of snow or freezing precipitation. The WSR-88D dual polarization upgrade, which provides a series of new products and algorithms, will boost forecaster confidence in determining the type of products are used by forecasters to precisely determine the changeover from all snow to mixed precipitation in precipitation. In Fig. 7, the dual polarization Correlation Coefficient (CC) and Differential Reflectivity (ZDR) parts of the New York City/Long Island area. High CC values (e.g., >0.95) and/or near zero ZDR values indicate homogenous mixture of precipitation (e.g., all snow or

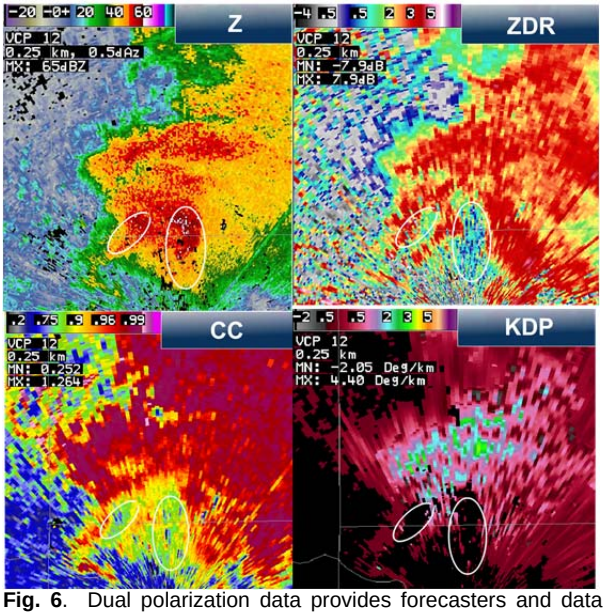

Fig. 6. Dual polarization data provides forecasters and data users additional confidence of the occurrence, location and size of hail. Above, reflectivity (Z) and dual polarization ZDR, CC, and KDP products from the test bed WSR-88D KOUN in Norman, OK during a "giant" (>2 in) hail event in Oklahoma City area on 10 May 2010. "Baseball" size hail at the ground was reported in the white circled areas.

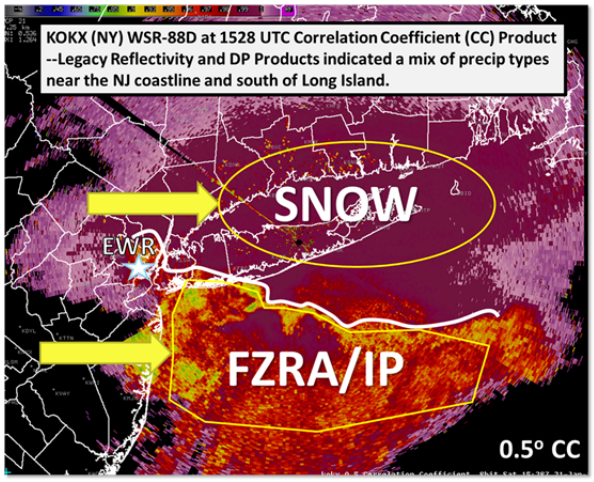

Fig. 7. Very high CC values across Long Island and to the north, close to 0.99, indicate very homogenous mixture (pure snow) in resolution volume. The brighter colored areas (low CC values) of yellow and green to the south indicate a mix of precipitation types, such as sleet and freezing rain. Newark Airport (EWR, at star in image) reported ice pellets at the time, verifying a change over from snow. Overall, dual polarization products provide increased confidence to forecasters on detecting and predicting (in the short term) different types of freezing/frozen precipitation.

all rain), while low CC and high ZDR values indicate a mixture of melting and frozen precipitation.

Knowing where freezing precipitation is occurring may assist wind farm operators when deciding whether operations can continue safely, and/or when determining wind farm power output.

3.4 Winds Aloft

Wind profiles are useful to forecasters monitoring weather events that may soon impact wind energy production. Radar-derived wind profiles can augment other sources of winds aloft to initialize numerical weather prediction models.

The WSR-88D's Doppler capability provides products showing the component of wind velocity coming toward/away from the radar at each scanning angle, as shown in the top left image of Fig. 5. The WSR-88D also provides vertical profiles of wind speed and direction similar to those provided by wind profilers. The WSR-88D has been recently upgraded with an Enhanced Velocity Azimuth Display (VAD) Wind Profile (EVWP) algorithm. The EVWP improves the availability and accuracy of vertical wind profile estimates. An example of this improvement can be seen in Fig. 8.

4. ENHANCED AVIAN/BIRD DETECTION

One of the earliest contacts the NEXRAD Program had with the wind energy industry was from wind farm project siting consultants requesting information on the nearest WSR-88D to aid their bird migration studies. At least one private sector company uses real-time WSR-88D base/Level 2 data to provide bird migration/movement information to customers.

The WSR-88D reflectivity products, especially when used in time-lapse mode, can be used to detect and track migratory or daily roosting movements of birds, but they don't always, by themselves, provide strong avian signatures (Fig 9, left).

The new dual polarization products have the potential to improve avian detection. In Fig. 9, right side, the Differential Reflectivity (ZDR) product is used to identify the direction of migration. This is possible since positive ZDR usually indicates avian head/tail orientation parallel to radar beam while negative ZDR indicates head/tail orientation perpendicular to radar beam. With further research, it may be possible to identify the number and type of birds. Chilson et al. 2012, list the following example biological applications of dual polarization WSR-88D Level 2 data:

- Changes in species phenology
- Population monitoring
- Tracking migratory patterns
- Responses to climate change
- Species interaction

5. 3- TO 12-HOUR AND DAY-AHEAD FORECASTS

WSR-88D data are also used in the generation of numerical weather prediction (forecast) models. Initializing numerical forecast models with radar reflectivity data can increase the accuracy of precipitation forecasts. NWS's National Centers for Environmental Prediction (NCEP) assimilates WSR-88D Level 2 data into the Rapid Refresh Model (RAP) model to improve short-term forecasts. Researchers at NOAA/ESRL/GSD/AMB are developing improved storm-scale models with national coverage, such as the experimental 3-km resolution High-Resolution Rapid Refresh (HRRR) model that will make more use of weather radar data and include forecasts of the 80-meter wind field. The experimental HRRR model output can be viewed at: http://rapidrefresh.noaa.gov/HRRR/. Fig. 10 shows the improvement of HRRR model forecasts when radar data is used. Other modelers may consider adding the WSR-88D data to their data assimilation process.

The US Dept. of Energy and NOAA are working together with about a dozen wind energy and other private sector companies to improve numerical weather prediction forecasts of wind, aided by increased use of weather radar data. This project, called Wind Forecast Improvement Project (WFIP), will provide more accurate and reliable wind forecasts for the wind energy industry and the greater weather enterprise.

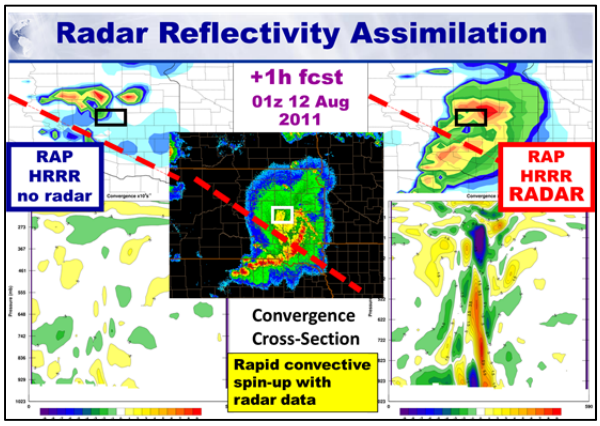

Fig. 10. Experimental 3-km Resolution High Resolution Rapid Refresh (HRRR) model showing improvement in 1-hr forecasts when using WSR-88D Level 2 reflectivity data. Observed radar data is in the center image with the black map background. (Courtesy of Alexander, et al. NOAA/ESRL/GSD/AMB, 2013)

6. HOW TO OBTAIN WSR-88D DATA

The weather enterprise has many vendors that provide commercial customers with value-added products or products as produced by the WSR-88D. Two types of WSR-88D data are available: base data (Level 2) and radar products (Level 3). Level 2 data are the unprocessed stream of radial base data consisting of reflectivity, velocity, and spectrum width, and the three dual polarization variables mentioned above. The Level 2 data are transmitted using the Local Data Manager (LDM) protocol. This enables the amount of Level 2 a requester wants to be from as many or few of WSR-88Ds.

Radar data users need radar product generation

software to process this data and produce viewable products. NOAA's NWS has established an extensive real-time collection and distribution of WSR-88D Level 2 and Level 3 data (Crum et al. 2013 and Kelleher et al. 2007).

6.1 Real-Time Data

Level 2 Data: Real-time Level 2 data are electronically collected from 140 of the 160 operational radars. As of January 2013, the WSR-88D sites on the Level 2 data collection network include all 122 NWS WSR-88Ds, plus 13 DOD and 5 FAA WSR-88Ds. The NEXRAD Program plans to add the 8 remaining CONUS Air Force WSR-88Ds to the NWS Level 2 collection network by mid-2013. Adding the 7 FAA WSR-88Ds in Alaska and the WSR-88D in Guam are dependent on future communications bandwidth and funding availability. Level 2 data are sent to distribution nodes where private sector users can obtain the data. The nodes are at:

- Purdue University,
- Education and Research Consortium of the Western Carolinas (ERCWC), and
- University of Oklahoma.

More information on Level 2 data and how to obtain the data from the above-mentioned sites is available at: http://www.roc.noaa.gov/WSR88D/Level_II/Level2Info.aspx

Level 3 Products: The NWS electronically collects and distributes real-time Level 3 products from 156 of the 160 operational WSR-88Ds (all but four overseas radars). The NWS provides three sources of real-time Level 3 products: Family of Service subscriptions, the satellite broadcast network (NOAAPORT), and anonymous FTP. More information on these sources is available at: http://www.nws.noaa.gov/tg/rpccds.html.

6.2 Archived Data

Archived data can support forensic and climatology studies of significant weather events, wind assessments, bird migration or other studies.

NOAA's National Climatic Data Center (NCDC) WSR-88D inventory and data are accessible electronically. Most requests for archived data can be made at no cost to the requestor, and the data can be downloaded from an FTP site within 6 hours (http://www.ncdc.noaa.gov/nexradinv/).

The NCDC provides software (NOAA Weather and Climate Tool Kit) to view the Level II and Level III data. Many private vendors have developed software for displaying and creating value-added products. The tool kit is available at: http://www.ncdc.noaa.gov/oa/wct/

The NWS provides software to read Level II data and emulate the generation of products at WSR-88D sites. The software, called the WSR-88D Common Operations and Development Environment (CODE), is open source and runs on LINUX platforms. (http://www.weather.gov/code88d/)

For more information on downloading Level 2 and Level 3 data visit:
http://www.ncdc.noaa.gov/oa/radar/radarresources.html

7. SUMMARY

The WSR-88D radar network produces data and products that are readily available in real time to the wind energy industry. These real time data can assist industry efforts to improve their energy generation efficiency and resource protection. Archived weather radar data can also be a valuable tool to the wind siting process, and for forensic studies. The ongoing installation of a dual polarization capability, to be completed in June 2013, will provide additional radar products and data useful to the wind energy industry.

8. REFERENCES

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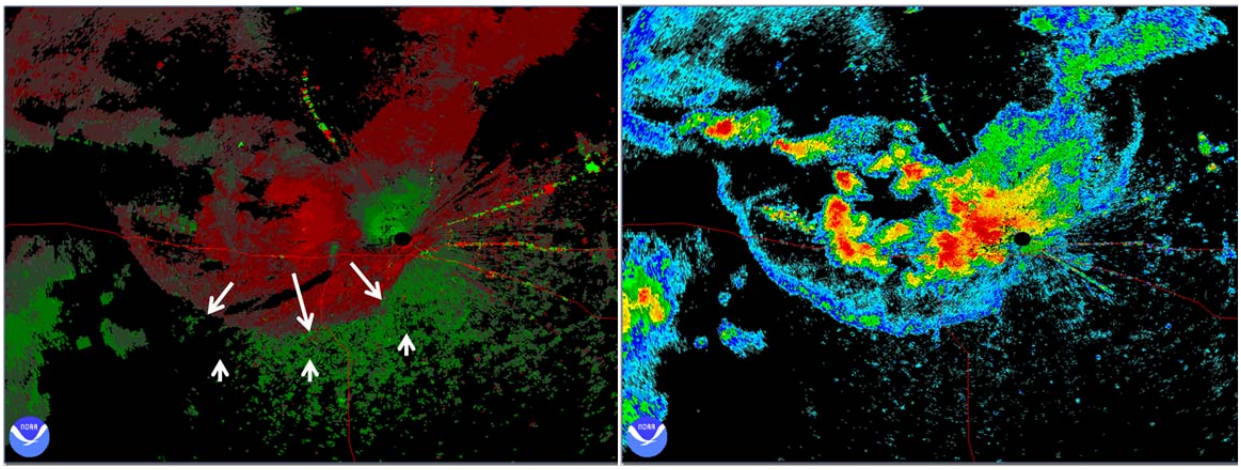

Fig. 3. The WSR-88D can detect thunderstorm outflow boundaries. Comparing sequential reflectivity and velocity products, which are updated every 4 to 5 minutes, allows wind energy companies to estimate the onset of ramp events.

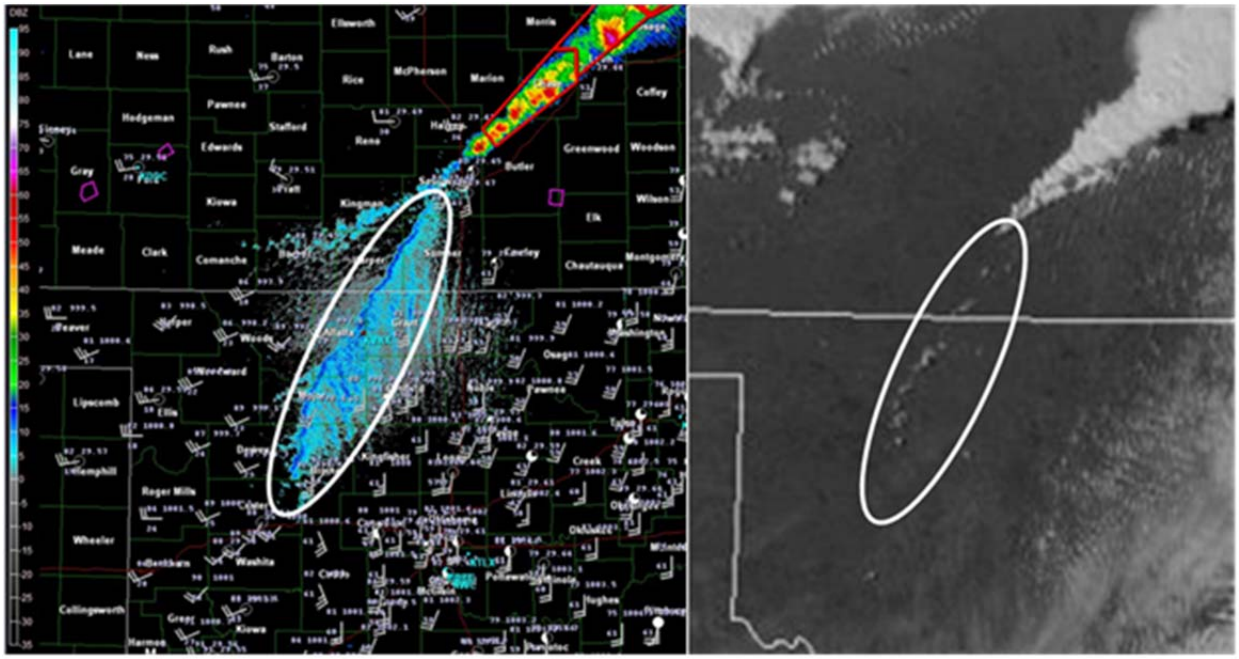

Fig. 4. Left image: Base Reflectivity Product, 0.5° elevation, from Vance AFB, OK NEXRAD (6 Apr 2010, 2040 UTC). The color codes for the reflectivity values are on the left side. The reports from automated surface observations are also plotted and depict a slight wind shift when crossing the boundary. Right image: GOES satellite photo of the Kansas – Oklahoma area on April 6, 2010 at 2045 UTC. The circle annotations are in the same location and highlight the ability of the radar to depict boundaries in the atmosphere (dry line in this case) even though the satellite imagery does not.

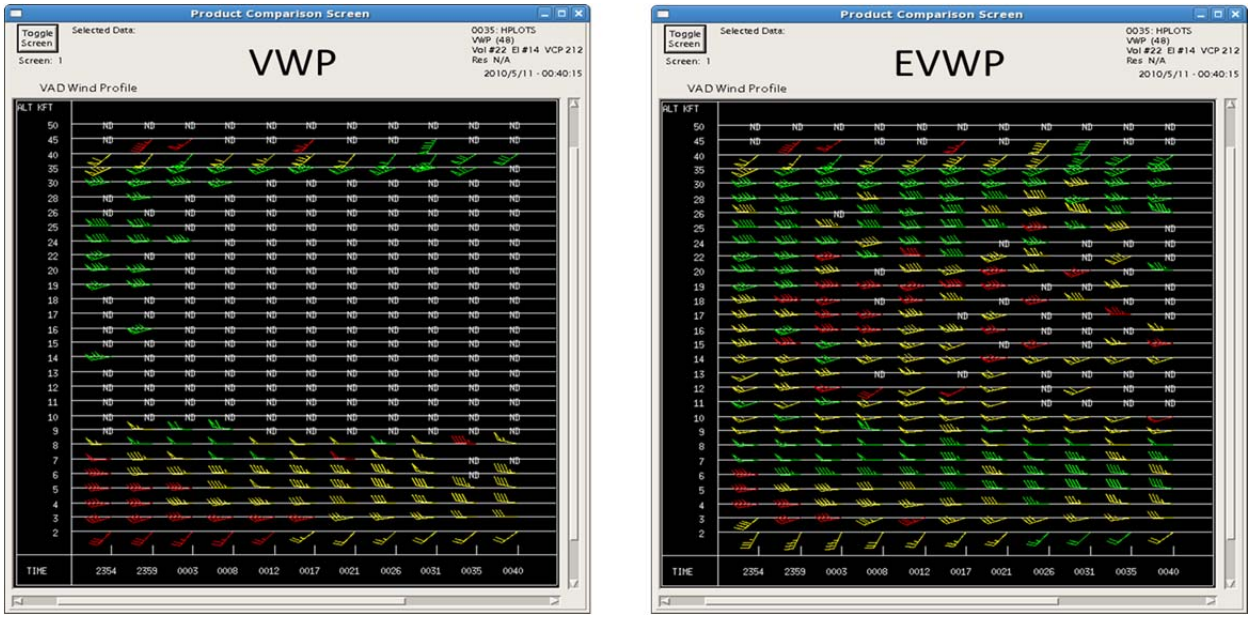

Fig. 8. Comparison of legacy vertical wind profile (VWP) and new Enhanced VWP (EVWP) product. EVWP improves availability and accuracy of wind estimates.

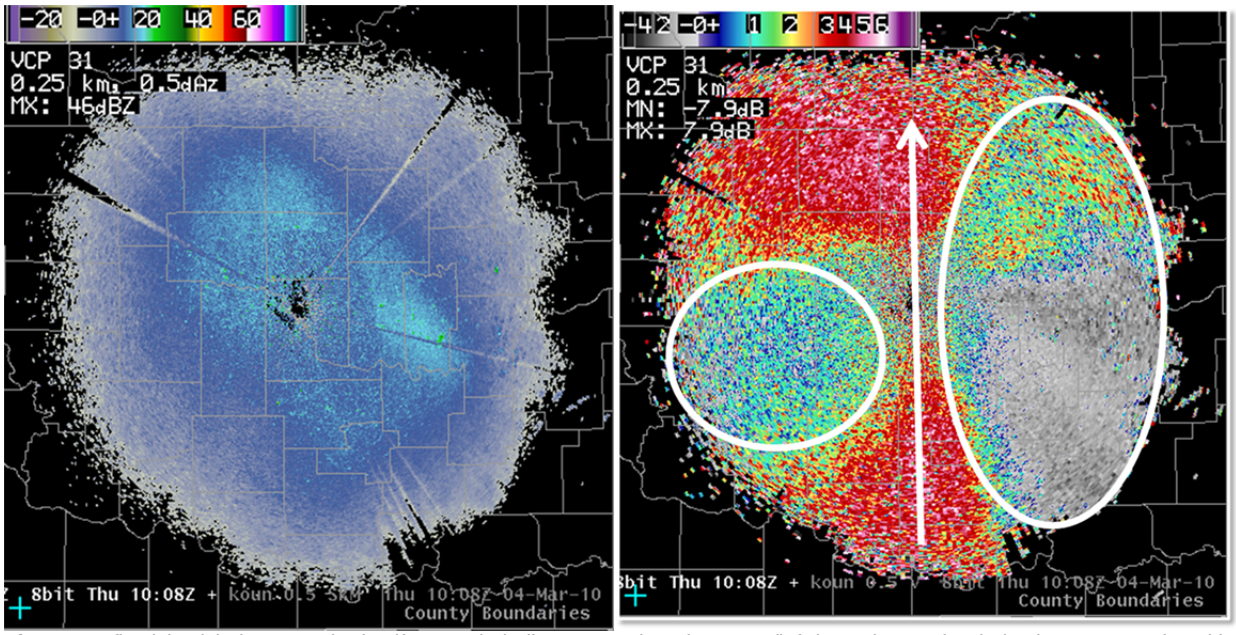

Fig. 9. Reflectivity (Z) does not, by itself, strongly indicate an avian signature (left image). Dual polarization ZDR product (right image) shows a corridor of positive ZDR (arrow) and lobes of negative ZDR (ovals). Positive ZDR usually indicates avian head/tail orientation parallel to radar beam. Negative ZDR indicates head/tail orientation perpendicular to radar beam. Dual polarization can improve bird detection, and potentially help identify number and type.

9. RELATED WEB SITES/USEFUL RESOURCES

- Federal Meteorological Handbook No.11 (FMH-11): **http://www.ofcm.gov/homepage/text/pubs.htm**
- WSR-88D Dual Polarization training materials: **http://www.wdtb.noaa.gov/**
- ERC Real-Time Level II Data Monitoring Site: **http://www.ercbroadband.org/index.php/level-ii-data-status**
- NWS Real-Time Level II Data Monitoring Site: **http://weather.noaa.gov/monitor/radar2/**
- NWS Real-Time Level 3 Product Site Status: **http://weather.noaa.gov/monitor/radar3/**
- NWS Radar Product Central Collection Dissemination Service: **http://www.nws.noaa.gov/tg/rpccds.html**
- NCDC Radar Archive Data: **http://www.ncdc.noaa.gov/oa/radar/radarresources.html**

- WSR-88D Common Operations and Development Environment: **http://www.weather.gov/code88d/**
- WSR-88D Radar Operations Center
  - Home Page: **http://www.roc.noaa.gov/WSR88D/**
  - Interface Control Documents: **http://www.roc.noaa.gov/WSR88D/Program/ICDs.aspx**
  - Level II/Base Data Information: **http://www.roc.noaa.gov/WSR88D/Level_II/Level2Info.aspx**
  - Level III/Product Information: **http://www.roc.noaa.gov/WSR88D/Level_III/Level3Info.aspx**
- NOAA Earth System Research Laboratory: **http://www.esrl.noaa.gov/research/themes/regional/**