5B.7 IMPACTS OF WIND FARMS ON WSR-88D OPERATIONS AND POLICY CONSDIERATIONS

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1. BACKGROUND

The use of wind farms in the United States to generate electricity is growing dramatically (http://www.awea.org/faq/instcap.html). Such installations can have over 100 turbines with blade-tip heights over 120 m (400 ft) above ground level (AGL). Blade-tip heights of over 180 m (600 ft) AGL are expected within a few years.

Figure 1 shows wind farm locations in the contiguous United States (CONUS) as of May 2006. Wind farms now produce enough electricity to power the equivalent of 2.5 million homes.

Continued growth in the number of wind farms is expected. In his 2006 Advanced Energy Initiative, President Bush stated that areas with good wind resources have the potential to supply up to 20% of US electricity consumption. Since wind farms now produce less than 1% of the US electricity consumption, realizing the President’s vision will require deployment of many more (and likely larger) wind turbines.

Data from the national network of Weather Surveillance Radar-1988, Doppler (WSR-88D) systems are a key component in the decision making process of issuing weather forecasts and severe weather warnings, and supporting air traffic safety. Experience has shown that when wind farms are located “close” to weather radar systems, the turbine towers, rotating blades, and the wake turbulence induced by the blades negatively impact data quality and so degrade the performance of radar algorithms.

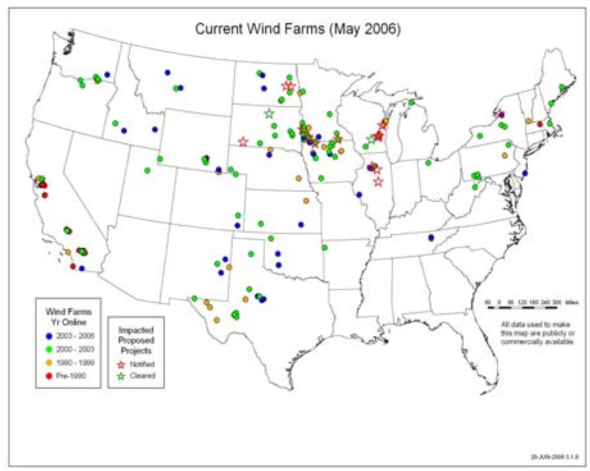

Figure 1. Locations of major wind farms in the CONUS as of May 2006. (Courtesy of U.S. Air Force.)

This paper provides background on the recent dramatic growth in the number of wind farms and examines their characteristics; presents examples of the impact of wind farms on WSR-88D base products; suggests methods to mitigate wind farm impacts on weather radar data quality; and describes efforts to work with the wind energy industry to mitigate the impacts of wind farms on weather surveillance radars.

2. IMPACTS OF WIND FARMS ON WEATHER RADARS

Wind farms “close” to weather radars may block onward propagation of the radar signals, cause reflectivity clutter returns, and produce wake turbulence-induced radar echoes. Clutter, signal blockage, and interference may cause:

- Mis-identification of thunderstorm features in/near wind farm reflectivity signatures
- Meteorological algorithm errors
  - -- False radar estimates of precipitation accumulation;

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-- False tornadic vortex and mesocyclone signatures; and

-- Incorrect storm cell identification and tracking.

Among other locations, wind farms are located near WSR-88Ds at Dodge City, KS; Great Falls, MT; and Des Moines, IA. Images of how these wind farms appear on WSR-88D imagery are shown in Figures 2 and 3 below and Figure 4 at the end of this paper.

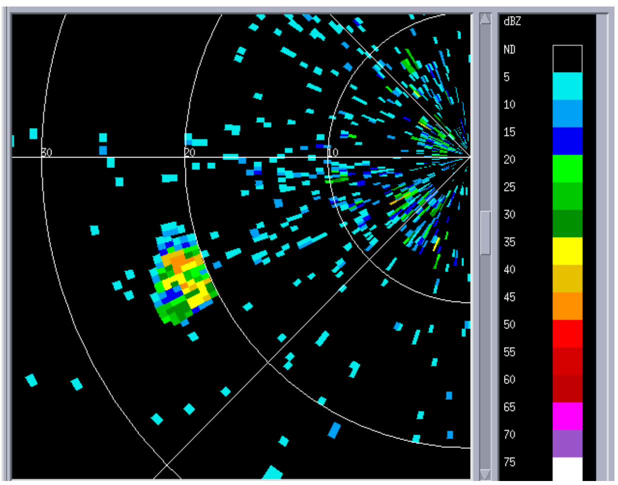

Figure 2. Reflectivity image from the Dodge City, KS WSR-88D showing the returns from a wind farm approximately 40 km southwest of the radar.

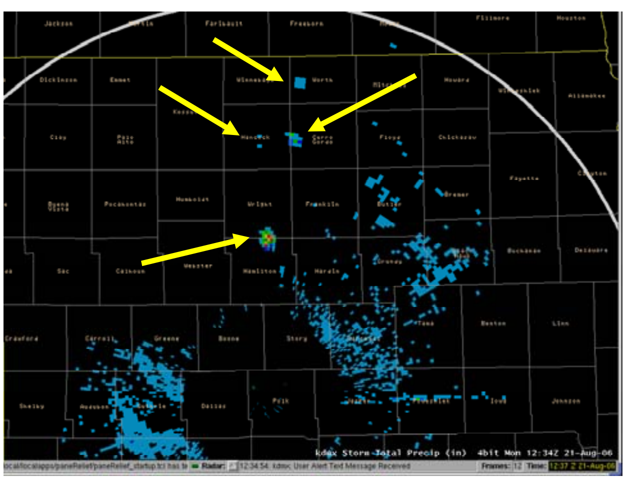

Figure 3. False radar-estimated precipitation accumulations (indicated by the yellow arrows) in a clear air situation due to four wind farms north of the Des Moines, IA WSR-88D. Ducting of the radar beam aided in this incorrect accumulation.

Wind turbine clutter has not been a major negative impact on forecast operations, thus far. However, with more and larger installations – some nearer WSR-88Ds — negative impacts are expected, some potentially sufficient to impact the ability of users of radar data to perform their mission.

3. MITIGATION ACTIONS BEING TAKEN

a. Policy

The wind farms currently in operation were installed without apparent consideration to their impact on weather radars. Permitting for wind farm construction is generally done at a local level. The federal government has no regulatory authority over wind turbine construction on private property. The Federal Aviation Administration is notified of structures over 200 ft tall and determines if the structures are a hazard to aviation via Obstruction Evaluation/Airport Airspace Analysis (Title 14 of the Code of Federal Regulations CFR Part 77).

In January 2006, Congress tasked the Department of Defense (DoD) to determine the impact of wind turbine installations on military readiness and air surveillance radars. The primary finding in the report (DoD 2006), released on 28 September 2006, was that to preclude adverse impacts on defense radars, developers should avoid locating wind turbines in radar line of sight. This can be achieved by distance, terrain masking, or terrain relief. This approach requires a case-by-case analysis. The report deferred to the National Oceanic and Atmospheric Administration's (NOAA's) National Weather Service (NWS) to address impacts on weather radars.

The NWS and the WSR-88D Radar Operations Center (ROC), on behalf of the Next Generation Weather Radar (NEXRAD) Program, are part of a federal interagency working group charged with finding ways to improve collaboration with the wind energy industry. This group will address wind farms impacts on federal interests, including weather radar operations and will develop criteria for wind farm siting and expansion to allow co-existence of both systems with minimal interference.

The limited experience accumulated to date suggest that, ideally, turbines should be at least 40 km (25 nm) from a WSR-88D to preclude turbine blades from encroaching into the main beam of the radar. This distance is dependent on several factors (e.g., radar tower height, maximum turbine height, terrain, elevation of the lowest scan). A case-by-case assessment will be needed.

There are also proposals for adding wind farms in Canada. The Radio Advisory Board of Canada in conjunction with the Canadian Wind Energy Association provides general information to developers on whether a proposed wind turbine or wind turbine farm may negatively affect radio, telecommunications, or radar systems in the vicinity of the turbine's proposed location (RABC/CANWEA 2006). The document provides guidelines for determining "consultation zones" within 80 km of Environment Canada weather radars and how to assess the potential impacts. In addition, several European countries have developed processes for determining the interaction between wind farms and radars.

b. Radar Operation and Interpretation

In collaboration with the University of Oklahoma (OU)/Cooperative Institute for Mesoscale Meteorological Studies, the ROC is evaluating operational impacts of current and proposed wind turbine installations on the data and products produced by the WSR-88D network as well as weather forecast and warning performance. Forecasters in NOAA/NWS Weather Forecast Offices (WFOs) can learn to recognize wind farm weather radar signatures; reduce impacts somewhat through proper radar configuration; and attempt to accommodate or "work around" the wind farm impacts in their decision process. For example, forecasters can:

(1) Establish exclusion zones to limit precipitation overestimation or false accumulations. However, exclusion zones do not remove the contamination from the base data.
(2) Invoke clutter suppression. This approach only excludes stationary targets and is not effective on clutter arising from turbine blades in motion.
(3) Look at higher elevations to "see over" wind farms. This can result in the loss of low-altitude information crucial in some forecast situations, e.g., onset of a tornado.

Although operational forecasters can often distinguish wind turbine clutter (WTC) from weather signals using their experience, a major concern is the effect of these echoes on automated detection algorithms.

c. Mitigation of Wind Turbine Clutter Using Spectral Processing

In collaboration with OU, the ROC is evaluating the impacts of current and proposed wind turbines on WSR-88D signal processing and how these impacts can be mitigated. With the recent Open Radar Data Acquisition (ORDA) upgrade to the WSR-88D network, it is now practical to implement advanced real-time signal processing algorithms. The focus of this section is to provide examples of the unique spectral characteristics of WTC and to propose methods how this might be exploited to mitigate clutter and estimate the spectral moments of a weather echo.

The processing capability of the ORDA allows the calculation of the Doppler spectrum, which is defined as the *power weighted distribution of radial velocities within the resolution volume of the radar* (Doviak and Zrnic, 1993). The resolution volume is defined by the pulse length and the antenna beamwidth of the radar and can be on the order of hundreds of meters in range and several kilometers in azimuth. Given that the azimuthal size of the resolution volume increases with range, it is expected that the resulting Doppler spectra can exhibit a variety of functional forms. For example, the Doppler spectrum from ground clutter is well known to have a large peak at zero radial velocity, since the ground clutter is not moving. Bird echoes can show two distinct peaks in the spectrum due to the opposing motion of the beating wings (Wilczak et al. 1995).

Level II data from the WSR-88D provides the spectral moments of the radar data. Before processing, it is typical to use a ground clutter filter, which is designed to attenuate signals with near-zero radial velocity. Of course, the blades of wind turbines are in motion and, therefore, produce radar signals that are not significantly affected by conventional ground clutter filters. An example of Level II moment data from the Dodge City, KS WSR-88D (KDDC), is provided in Figure 5 (at the end of this paper), with the wind farm location emphasized with ovals. Isolated precipitation was present during the observation time. Note that it is difficult to distinguish the precipitation echo from the WTC in the reflectivity images. Given the motion of the blades, which can be away from or toward the radar, the radial velocity fields appear nearly random. As will become apparent soon, the spectrum width is extremely large in the wind farm region.

As mentioned earlier, the ORDA processor allows the real-time calculation of the Doppler spectrum, which has been used for spectral-based methods of combined moment estimation and clutter filtering (Siggia and Passarelli 2005). WTC has a unique spectral signature, characterized by extremely large radial velocities. In fact, the tips of the turbine blades can travel at speeds of over 70 ms^{-1}. Therefore, severe aliasing can occur resulting in a Doppler spectrum, which encompasses the entire velocity domain. In order to test these ideas, an extensive experiment was conducted in March 2006, with close collaboration among the ROC, OU, and the NWS WFO in Dodge City, KS, using their WSR-88D radar (KDDC). During the experiment, several different experimental modes were used to acquire Level I data. Preliminary results will now be presented from the experiment.

By calculating the Doppler spectrum for each range gate, for a particular azimuth angle, the spectral content versus range can be studied. An example of just such measurements is shown in the top panel of Figure 6. For ease of interpretation, the WTC and the weather echo have been denoted in the figure. The radial velocity is plotted along the abscissa over the range +/-26 ms^{-1} and range is represented on the ordinate axis. Note that the weather signal shows the expected range continuity and gradual variation but generally exhibits a radial velocity of approximately -15 ms^{-1}. The wind farm is located at ranges of 37-40 km and is seen to have an extremely wide Doppler spectrum. The tower, which supports the turbine, is stationary with the expected near-zero Doppler velocity. The lower panel of Figure 6 shows a similar variation in Doppler spectrum but now as a function of azimuth angle, rather than range. Again, the wind farm echoes exist only over limited azimuth angles and an obvious distinction can be made between the WTC and the weather echo. It is this exact distinction that can be exploited to extract the weather echo from the contaminated composite signal.

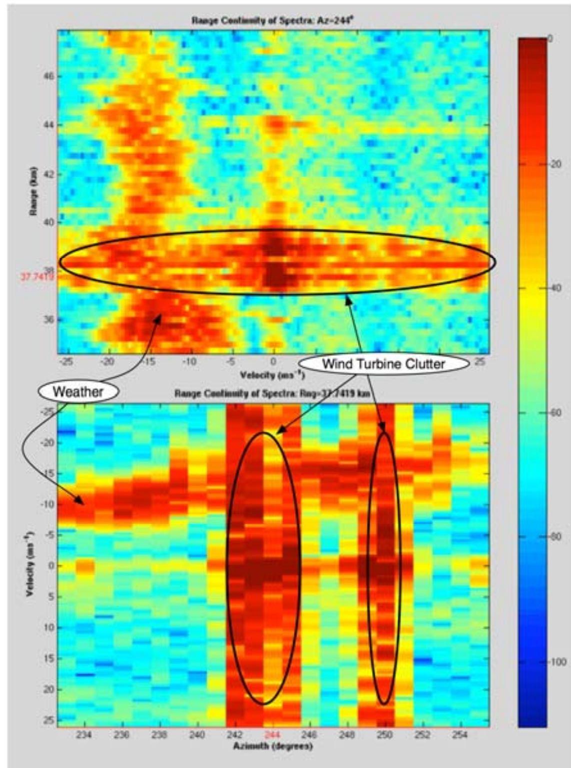

Figure 6. Example Doppler spectra from the Dodge City WSR-88D. The top panel shows the spectra as a function of range and the bottom as a function of azimuth angle.

The next steps in the mitigation phase of this study will include the development of an automatic algorithm for the removal of WTC from the Doppler spectrum. The algorithm will use the obvious range/azimuth continuity of the weather echo (see Figure 6), which is not observed in the WTC signal. Although relatively obvious in Figure 6, the extraction of the weather echo will be hindered by short dwell times, due to the rapidly scanning radar antenna. In addition, large wind farms, which encompass an area over which the continuity assumption would be invalid, will present a particular challenge. Currently, wavelet-based methods are being studied to exploit the non-stationarity nature of WTC as functions of range and azimuth. More advanced image processing methods will also be investigated to mitigate the undesired WTC signal.

4. SUMMARY

The rapidly increasing number of wind farms used to generate electricity is beginning to impact weather surveillance radar data. To date, the impacts appear to be minimal. However, experiences to date indicate the expected near-exponential growth in the number of such installations is cause for concern. NOAA's NWS has become involved in studying the impacts of wind farms and mitigation opportunities to ensure the network of WSR-88Ds can continue to provide mission-critical support to forecast and warning operations.

5. ACKNOWLEDGMENTS

The support of the Dodge City, KS WFO staff, particularly Larry Ruthi, Meteorologist in Charge, were key in collecting the Level I data from the KDDC WSR-88D and in monitoring the impacts of the wind farms on the WSR-88D and forecast/warning performance. Steve Brueske, NWS Western Region Headquarters provided the photos of the Great Falls, MT wind farm and its impact on the Great Falls WSR-88D data. Karl Jungbluth, NWS Des Moines, IA WFO, provided the imagery from the Des Moines WSR-88D.

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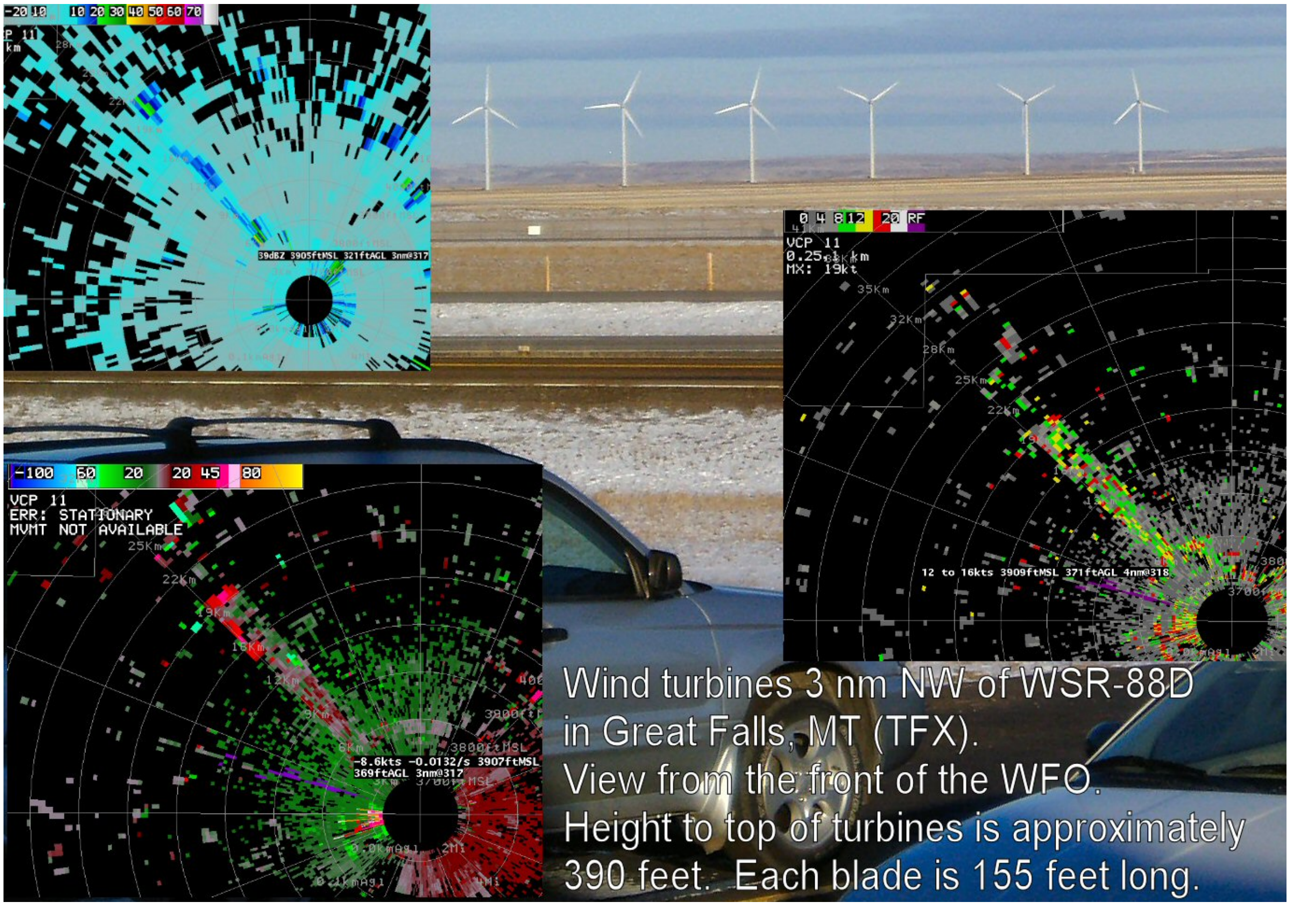

Figure 4. Imagery from the Great Falls, MT WSR-88D and a photo of the wind farm within 5 km (3 nm) of the radar. The photo was taken looking toward the northwest from the Great Falls WFO. In the upper left reflectivity image, the multi-trip echoes from the wind farm results in false reflectivity data displayed down the radials behind the towers. The contamination is also seen in the radial velocity (lower left) and spectrum width (lower right) base products.

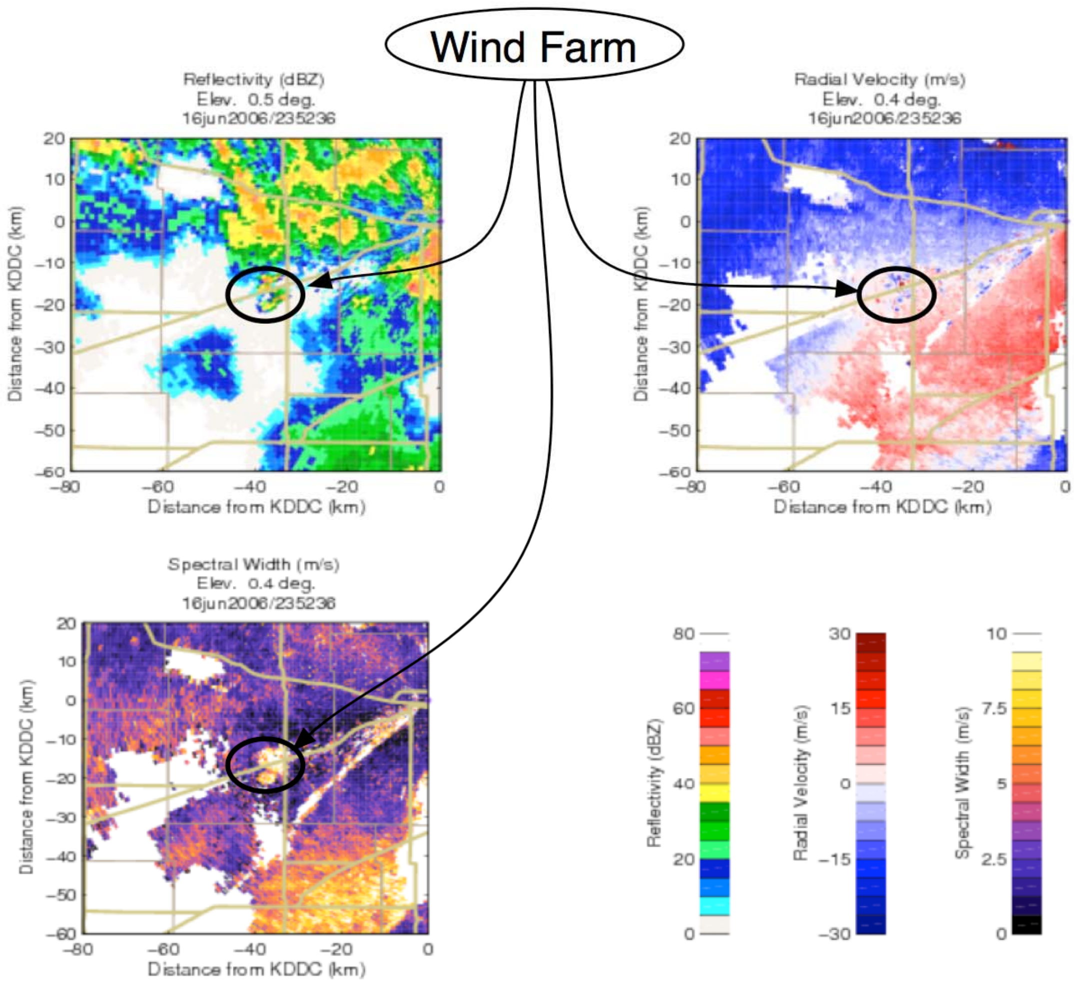

Figure 5. Level II data from Dodge City WSR-88D from June 16, 2006. Echoes from isolated storms mixed with the wind turbine clutter echoes. Turbine signals are characterized by random radial velocity and large spectrum width.