3A.1 RECENT EFFORTS TO IMPROVE ESTIMATES OF AND MITIGATION OF WIND TURBINE CLUTTER IMPACTS ON THE WSR-88D

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1. INTRODUCTION

One of the key tools weather forecasters use in preparing forecasts and severe weather warnings is the Nation's network of 159 Doppler weather radars known as the Next Generation Weather Radar (NEXRAD) system, also known as the Weather Surveillance Radar-1988, Doppler (WSR-88D). The federal government invested over $1.4B in developing and deploying the NEXRAD network, and operates and maintains that network to ensure the best possible protection of life and property. In addition, the National Weather Service (NWS) uses Federal Aviation Administration (FAA) Terminal Doppler Weather Radar (TDWR) data to further supplement the forecast and severe weather warning capability.

The federal government is promoting energy independence through the installation of renewable energy sources, and wind energy is a key resource in many parts of the country. In recent years, NEXRAD system operators and data users have noticed an increasing number of wind farms visible in the data and derived products, such as precipitation estimates. This occurs when wind farms are located in a NEXRAD radar beam/radar line of sight (RLOS). The rotating wind turbine blades defeat the radar's clutter filtering algorithm, which only filters energy returned from nearly stationary objects (buildings, terrain, etc.), thus adversely impacting radar data quality and the performance of the radar's internal weather detection algorithms.

Over the next couple decades, the potential for wind farms to interfere with the NEXRAD/TDWR radar networks will increase with the anticipated large growth in wind energy projects. This increased interference will result not only from the growth of the number of wind farms, but also from the increasing size of wind farms and the use of taller turbines, as shown in Fig. 1. The NEXRAD Radar Operations Center (ROC) has evaluated over 800 wind farm projects, some with proposed turbine blade tip heights exceeding 152m (500ft) above the ground. The non-uniform distribution of climatologically-favorable winds for wind energy generation is shown in Fig. 2.

This paper discusses ROC efforts to improve estimates of wind farm impacts and develop options for mitigating wind farm interference issues. Information is presented on:

(1) The NEXRAD system; how wind farms can impact NEXRAD data and forecast/severe weather warning performance;
(2) How the ROC has changed its assessment of potential impacts; recent ROC initiatives to provide additional tools to field forecasters;
(3) Recent efforts for research, education, and collaboration with the wind energy industry; and
(4) Finally, there are considerations for a way forward that allows both the wind industry and the NEXRAD program to meet their national goals…promoting renewable energy and public safety/resource protection.

2. NEXRAD RADAR NETWORK OVERVIEW

The 159 operational NEXRAD radars are located across the contiguous United States (Fig. 2), Alaska, Hawaii, Puerto Rico, and select overseas sites. The radar transmits a 10-cm wavelength (S-band), horizontally polarized 1° beam at 750 kW peak power. It was 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.

The system received a state-of-the-art digital signal processor upgrade in 2006, and is scheduled to be upgraded with dual polarization starting in 2011. Operationally, the radar automatically scans the atmosphere in pre-defined coverage patterns from 0.5° to 19.5° elevation above the horizon, then processes

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The views expressed are those of the authors and do not necessarily represent those of NOAA or the NWS.

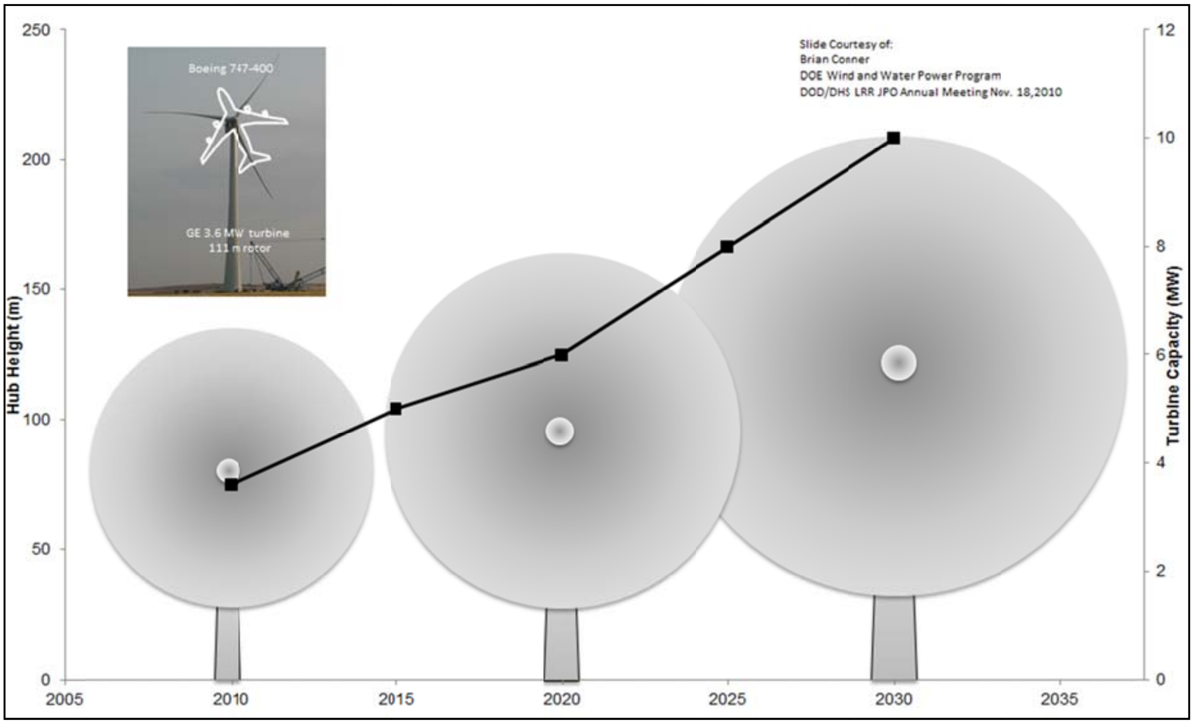

Fig. 1. U.S. Department of Energy projected increases in wind turbine height (top dead center) and turbine capacity (black line) from 2010 to 2030. The upper-left depiction of an airplane outline over the hub of a turbine represents the radar cross section a turbine can have, approximately the same as a 747 airliner.

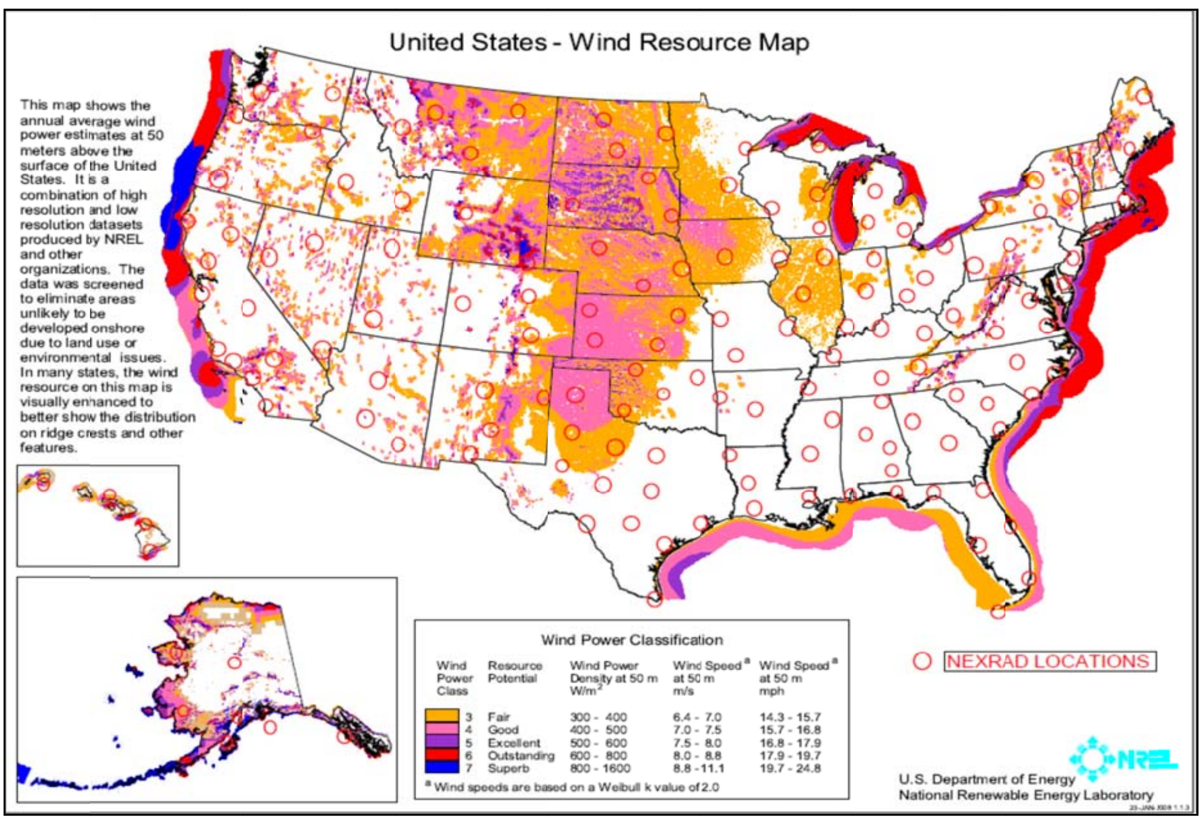

Fig. 2. U.S. Department of Energy 50-meter wind resource map showing areas (colored) favorable for wind energy development with NEXRAD locations (red circles) overlaid.

and distributes reflectivity, mean radial velocity, and spectrum width (a measure of the variability of radial velocities in the resolution volume) data. From this data, computer algorithms generate a suite of meteorological and hydrological products and alerts used for determining short-term forecasts, advisories, and warnings for significant weather events such as tornadoes, large hail, wind shear, downbursts, flash floods, and other weather phenomena. National Weather Service and Department of Defense (DoD) weather forecasters use NEXRAD data to provide life- and resource-saving information to support: public, military operations, and inform resource protection decision makers (e.g., emergency managers). The data are also used for the safe and efficient operation of the National Airspace System - NEXRAD data are displayed on FAA air traffic controllers' screens and sent directly to many airborne aircraft. Additionally, the commercial weather industry has experienced rapid growth in the last decade, due in part to the availability of and use of real-time NEXRAD data. Television broadcasters rely on both their own weather surveillance radars and data collected from the NEXRAD network to inform their viewers of evolving weather conditions.

The general public may access the radar data from private companies and the Internet (e.g., http://radar.weather.gov/). Detailed information about the NEXRAD radar is available in (Federal Meteorological Handbook No. 11, Parts A – D; http://www.roc.noaa.gov/FMH_11/default.asp).

There are important differences between weather surveillance radars, such as NEXRAD, and air surveillance radars (ASRs), such as those operated by the FAA, Department of Homeland Security (DHS) and DoD. While they both operate on similar principles, their targets of interest and signal processing are significantly different. ASRs look for large, hard, point targets (aircraft) and process the data to mitigate weak environmental returns. In contrast, weather surveillance radars look for very small, widely distributed targets (e.g., water droplets, aerosols, atmospheric particulates) and perform signal processing to remove or mitigate strong, point targets. Therefore, ASR-wind turbine clutter (WTC) mitigation techniques may not be applicable to weather radars. Also, the identification and removal of WTC is likely to be more difficult for weather radars since the many rotating blades of a wind farm return signals appear very similar to real weather (Fig. 3).

3. IMPACTS OF WIND FARMS ON THE NEXRAD RADAR

The types and severity of impacts is dependent on distance, intervening terrain, height of the turbines relative to the radar beam, and size of the wind farm. In general, the impacts begin to dramatically increase when wind farms are sited in the RLOS within approximately 18 km of the NEXRAD (Fig. 4). Severe impacts can occur if they are sited in the RLOS within 3 km of the radar. Wind farms can impact NEXRAD radars in four ways:

(1) When the turbine blades are moving and they protrude into the RLOS, they can reflect unfilterable energy back to the radar system and appear as clutter in the base data (reflectivity, velocity, and spectrum width). Unfortunately, this corrupted data is then used by other radar algorithms to detect certain storm characteristics, such as rotation (tornadoes) and storm motion, and to produce a suite of weather products, including precipitation estimates, vertical wind

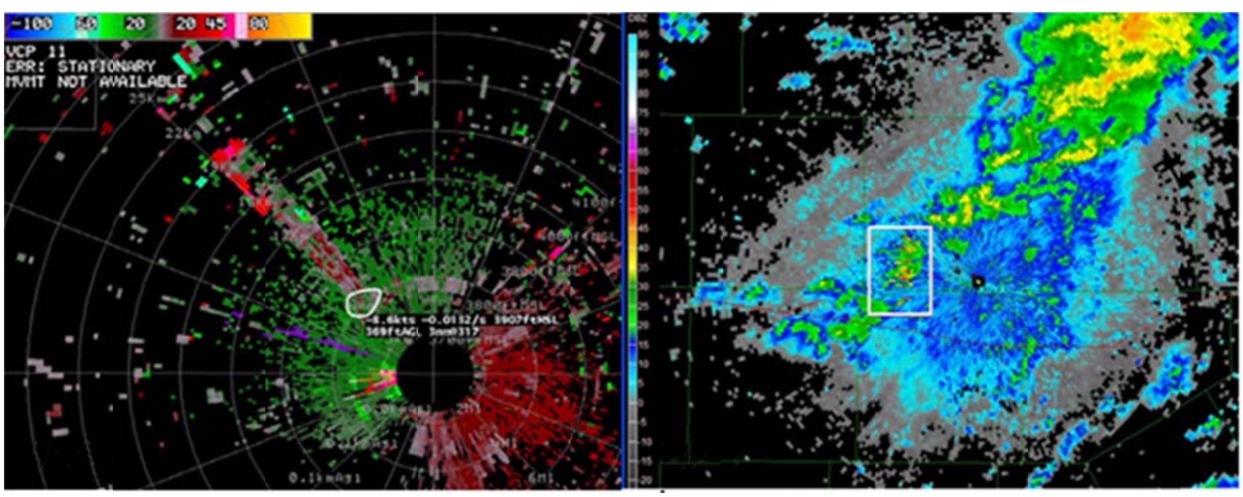

Fig. 3a. This Velocity image (0.5 degree scan) from the Great Falls, MT WSR-88D (KTFX) on February 9, 2006 at 1859 GMT shows how only a few turbines very close to the radar can cause a relatively large impact on radar data. The 6 turbines are approximately 6km from the WSR-88D and in the RLOS. The velocity data is contaminated in azimuth for 9 degrees and out beyond 20km due to multi-path and inter-turbine scattering. **Fig. 3b.** This Reflectivity image (0.5 degree scan) from the Dyess AFB, TX WSR-88D (KDYX) on September 9, 2008 at 1044 GMT shows how a large area of wind turbines (west of radar and in the white box annotation) can look similar to weather returns. Note that weather returns down range of the wind farm do not appear to be affected by attenuation due to the wind farm. Potential blockage/attenuation of radar signals by wind farms must be analyzed on a case-by-case basis.

profiles, and severe weather alerts. Turbines sited within 18 km of NEXRAD begin to impact multiple elevation scanning angles and create multipath scattering returns that show up as spikes of enhanced reflectivity down range of the wind farm.

(2) When turbines are within 3km of the radar, wind turbines' large nacelles (hubs) can physically block a significant percentage of the radar's narrow beam, attenuating the radar signal and impacting data throughout the entire range of the radar.

(3) Radar energy reflected from towers and turbine blades can damage the radar receiver and cause other severe impacts. If turbines are sited in the radar's near field, which for the NEXRAD is within 1500m of the antenna, then they can damage the radar receiver and/or cause unpredictable impacts to radar beam formation.

(4) When turbines are sited within 200m of a NEXRAD, there is potential for construction or maintenance personnel to be exposed to microwave energy exceeding OSHA (Occupational Safety and Health Administration) thresholds.

Examples of how wind farms appear on operational NEXRADs are shown in Fig. 3. These and other examples are available at: http://www.roc.noaa.gov/windfarm/windfarm_impacts.asp

Figure 4 depicts the relative notional impact of wind farms on NEXRAD radars as a function of distance if wind turbines are in the RLOS. Impacts increase exponentially as wind farms are sited closer to the radar, especially within 18km, and radar operator workarounds become more difficult. Determination of RLOS and impact distance are highly dependent on local terrain, requiring site-by-site analyses. Wind turbine clutter has not had a major negative impact on forecast or warning operations, yet. However, with more and larger wind turbines coming on line, experience gained to date strongly suggests that negative impacts should be anticipated -- some sufficient to compromise the ability of radar data users to perform their missions.

4. RECENT EFFORTS TO IMPROVE WIND FARM IMPACT ASSESSMENTS

The ROC learns of potential wind farm developments through formal and informal methods. Formally, the Department of Commerce's National Telecommunications and Information Administration (NTIA) acts as a clearinghouse for developers to voluntarily submit wind farm proposals for review by several Federal agencies, including NOAA. This formal process is in the American Wind Energy Association's (AWEA) Wind Siting Handbook (AWEA 2008). Informally, the ROC learns of wind farm projects from local weather forecast offices, through local news articles or web links to news stories referencing planned wind farms. The ROC proactively contacts the developers if the project appears to have potential impacts to the nearby NEXRAD. Also, developers can anonymously analyze a potential wind farm project for NEXRAD impacts early in the planning process using a GIS tool located on the FAA's Obstruction Evaluation/Airport Airspace Analysis web site at https://oeaaa.faa.gov/oeaaa/external/portal.jsp. This tool is currently being upgraded to reflect the ROC's new analysis criteria.

The ROC provides a case-by-case analysis of potential wind farm impacts on NEXRAD data and forecast/warning operations. In the last 4 years, the ROC has analyzed over 800 wind energy project

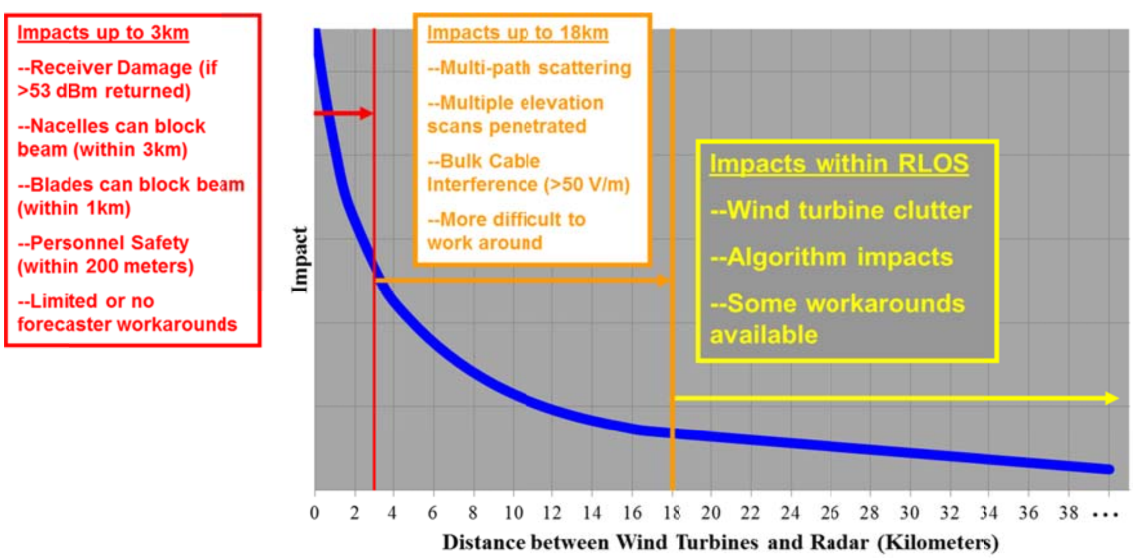

Fig. 4. Estimated impacts of wind farms on NEXRAD radars relative to the separation distance.

proposals on a case-by-case basis. The ROC uses a geographic information system (GIS) database that utilizes data from the Space Shuttle Radar Topography Mission to create a RLOS map specific to the proposal area or turbines under study. The ROC then performs a meteorological and engineering analysis using:

(1) Distance from radar to turbines;
(2) Maximum height of turbine blade tips;
(3) Number of wind turbines;
(4) Elevation of the nearby NEXRAD antenna;
(5) An average 1.0 degree beam width spread; and terrain (GIS database).

From this data, the ROC determines if the main radar beam will intersect any tower or turbine blade based on the Standard Atmosphere's refractive index profile. Finally, the ROC estimates operational impacts based upon type and amount of severe weather in the counties surrounding the wind farm.

Initially, the ROC established the RLOS as a benchmark for seeking further discussions with developers on mitigation strategies. However, our experience over the past few years is that most wind farms in the RLOS, while a nuisance to radar users, have not proven to significantly impact forecast/warning operations. In order to focus our efforts on wind farm proposals that have moderate to high potential for impacts, we have limited mitigation discussions to those wind farms that are within 18km (10nm) (flat terrain) of a NEXRAD. Less than 10% of analyzed wind farm proposals have been projected to be within 10 miles (18km) of a NEXRAD, and only a hand full out of 800 proposals had a wind farm sited within 3km of NEXRAD. So far, most developers are trying to keep a safe distance.

5. RECENT NOAA/NWS WIND TURBINE CLUTTER (WTC) MITIGATION INITIATIVES

In 2010, progress was made in our effort to provide training and tools to NWS field offices to mitigate WTC impacts on the radar. First the NWS Warning Decision Training Branch in Norman, OK developed a 1-hour on-line course for forecasters on identifying and mitigating WTC (http://www.wdtb.noaa.gov/). This training should help raise awareness of the issue within the NWS and help forecasters avoid confusion in the forecast/warning process. Second, the National Severe Storms Laboratory (NSSL) and the ROC jointly developed Geographical Information Systems (GIS) "shape" (*shp*) data files wind turbine locations. "These *shp* files were made available to NWS field offices via NOAA server download in January 2011 and are also available to FAA and DoD WSR-88D users. The files can be used to create Advanced Weather Interactive Processing System (AWIPS) GIS overlays to help Weather Forecast Office and River Forecast Center staff identify potential areas of WTC. The NSSL and ROC plan to release quarterly updates of the shp files.

The shp files included outlines of wind farms, turbine locations from the FAA's "built turbines" database, and turbines identified from digital satellite imagery. The polygon outlines of wind farm locations (Fig. 5, right) were prepared by NSSL using 12-months of accumulated radar Next Generation Qualitative Precipitation Estimation (Q2 QPE) data (visit http://www.nssl.noaa.gov/projects/q2/q2.php for more

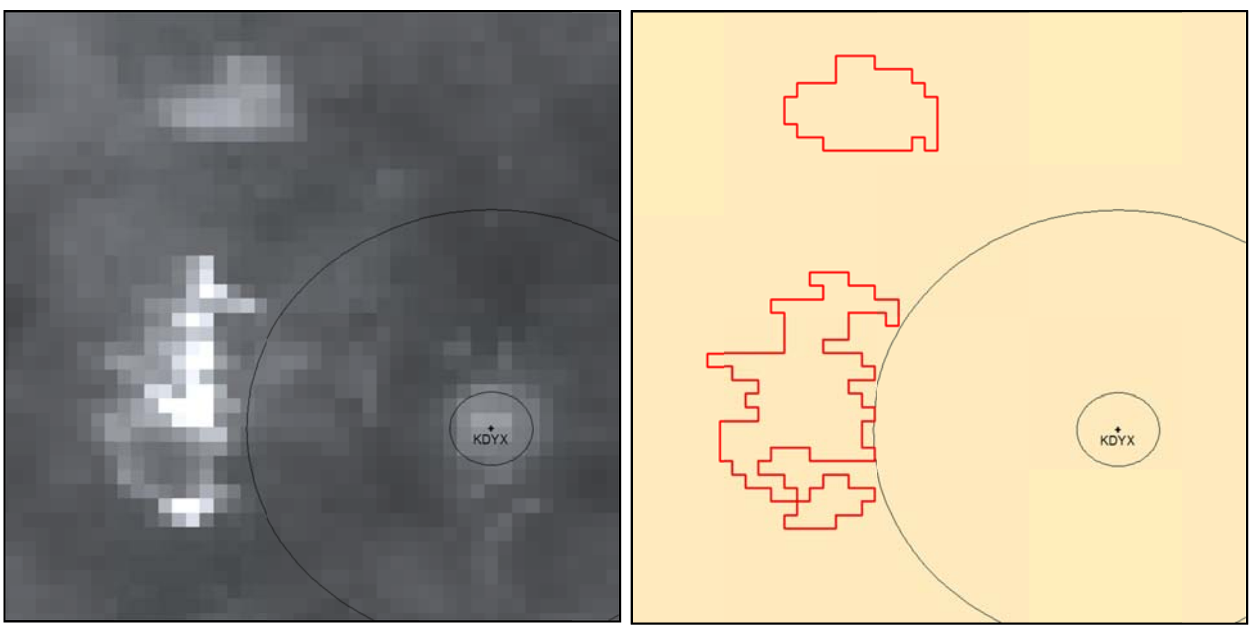

Fig. 5. Left image: 12-month Q2 QPE showing bright "hot spots" west of Dyess AFB WSR-88D (KDYX) near Abilene, TX with 3- and 18-km range rings. Right image: NSSL-generated polygons outlining QPE "hot spots".

Information). The long-term QPE data show a "hot spot" in precipitation accumulation due to the anomalous high reflectivity associated with WTC and other causes (Fig.5, left image). Parameter-elevation Regressions on Independent Slopes Model (PRISM) climate precipitation data for the same 12-month period was used to help flag QPE grid cells with unusually high values. Wind turbine point location data were overlaid on the 12-month QPE to determine if the flagged areas were induced by wind turbine clutter. The NSSL then enclosed these wind-farm-induced hotspots with polygons within a *shp* file.

Along with education and awareness, the ROC continued its collaboration with other Federal agencies to leverage off of their progress. We are working with the DHS, DoD, and FAA to develop a quantitative "Radar-Wind Turbine Interaction Model" that will more accurately and objectively determine the impacts of wind turbines (current and proposed) on various federal radar systems, including the NEXRAD. The contract for this modeling effort was recently awarded. The ROC is also participating in an Interagency Task Force (DOE, DOD, DHS, FAA, NOAA, others) to define the most promising short-, medium-, and long-term strategies for mitigating WTC. The ROC continued to work with some wind energy developers and NOAA's General Counsel Office to develop a Letter of Intent template for brief operational curtailment of turbines in critical weather situations. Operational curtailment is particularly useful in locations with limited severe weather and where wind farms are located between 3 and 18km from the radar.

A recent study by the Atmospheric Radar Research Center ((ARRC): http://arrc.ou.edu) at the University of Oklahoma, with limited funding from the ROC, looked at using base radar data and a fuzzy logic-based algorithm to automatically identify wind turbine clutter in near real time. In addition to detection, the ARRC is exploring signal processing methods based on real-time, wind turbine telemetry-based algorithms. These knowledge-based techniques would exploit wind turbine data of blade rotation rate, orientation, etc., and are a good example of the benefits of collaboration with wind farm operators. Studies have also been conducted on the potential mitigation benefits of phased-array radar (Fig. 6), and other foundational studies are in progress using a controlled laboratory environment with scaled turbine models and dual-polarized scatterometers (Fig. 7).

6. A WAY FORWARD FOR COMPATIBLE WIND ENERGY DEVELOPMENT

Our current strategy is three-fold and consists of education and awareness, the development of short-term mitigation strategies, and the development of long-term solutions. First, we must continue educating the wind energy industry, weather forecasters and other radar users on the potential impacts of wind farms on NEXRAD weather radars. Second, we need to develop radar-based techniques for identifying and mitigating WTC and provide tools to field forecasters. Similarly, we should work with wind energy developers to develop wind farm based mitigation strategies, such as operational curtailment of turbines during severe weather, and the sharing of wind farm meteorological tower weather data. The third strategy involves collaboration with wind energy industry, individual developers, other federal agencies, and academia to fund research on WTC mitigation and develop short-term and long-term mitigation strategies/techniques.

The ROC is supporting a wind industry desire for a national "clearing house" for developers to submit wind farm proposals to all federal agencies with radar assets – e.g. DHS, DoD, FAA, and NOAA. This clearinghouse would function similar to the FAA's Obstruction Evaluation Office for determining obstructions in navigable airspace.

New funding is needed to help develop radar-based and/or wind-turbine based solutions. Radar-based mitigation funding could be used to develop signal processing technology that eliminates WTC (a difficult technical challenge for which there may not be a solution) and, perhaps, build additional gap-filler radars for impacted areas. Wind turbine-based mitigation funding could be used to develop radar-friendly "stealthy" wind turbine blades and towers, provide supplemental surface weather data (precipitation, temperature, dew point, pressure, 10-meter wind speed and direction) transmitted automatically from the wind farm to the NWS to compensate for the wind-farm-contaminated radar data.

7. SUMMARY

NEXRAD is a key tool of the NOAA NWS warning and forecast system, providing critical life-saving and resource protection data to multiple federal agencies and the public. Experience with established wind farms located in NEXRAD RLOS has shown that wind turbine clutter impacts the radar reflectivity, velocity, and spectrum width data as well as internal algorithms that generate alerts and derived weather products, such as precipitation estimates. The severity of impacts depends on many factors, but in general, wind farm impacts to the NEXRAD exponentially increase as the separation distance between them decreases, especially within 18km. NOAA's NWS supports the responsible development of wind energy and wants to work with the wind energy industry to avoid potential impacts to the NEXRAD radar network and to find technical solutions to the radar interference issue. The NWS is collaborating with the wind industry and other federal agencies to develop both radar-based and wind-turbine–based mitigation solutions. On the radar side, the NWS has developed tools and training for radar operators and data users to identify WTC. The NWS is funding studies on radar-based signal processing solutions to initially identify and flag wind farm contaminated data, and eventually filter them from the real weather data. The NWS is also working directly with some wind energy developers on wind turbine-based mitigation, including the possible curtailment of turbine operations during severe weather and the

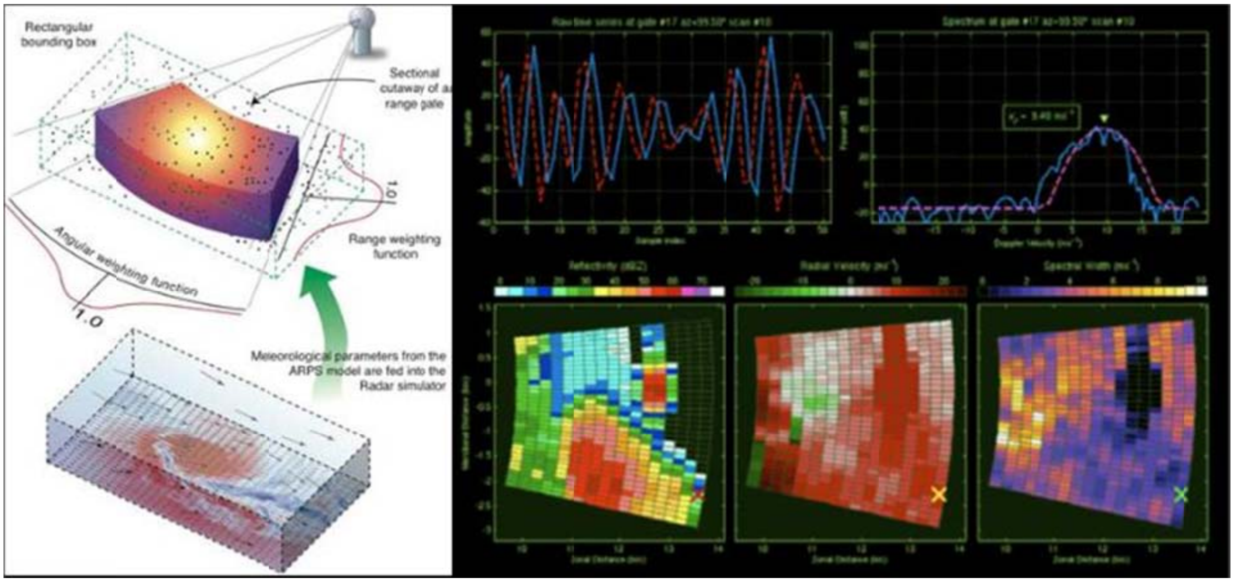

Fig 6. Illustration of numerical simulation scheme used (left) along with typical output from the Simulator (right). Using this method, it is possible to produce individual time series data from each element of a phased array radar (adapted from Cheong et al. 2008). (Courtesy of the OU ARRC)

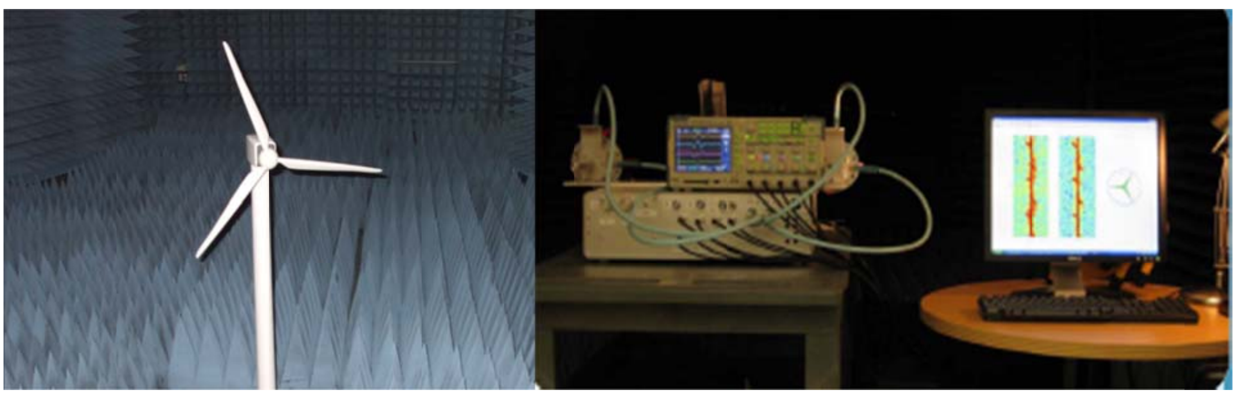

Fig 7. Model wind turbine (left) and 10 GHz dual-polarized scatterometer (right) in the ARRC Lab at the University of Oklahoma. (Courtesy of the OU ARRC)

sharing of wind farm met tower data. Wind energy and weather radars can coexist through cooperation.

Our email is: wind.energy.matters@noaa.gov.

8. RELATED WEB SITES

Federal Aviation Administration Obstruction Evaluation / Airport Airspace Analysis (OE/AAA): https://www.oeaaa.faa.gov/oeaaa/external/portal.jsp

National Telecommunications and Information Administration (NTIA) Interdepartmental Radio Advisory Committee (IRAC): http://www.ntia.doc.gov/osmhome/irac.html

University of Oklahoma Atmospheric Radar Research Center: http://arrc.ou.edu/

WSR-88D Radar Operations Center Wind Farm-Radar Interaction Page: http://www.roc.noaa.gov/windfarm/windfarm_index.asp

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