NEW CRITERIA FOR EVALUATING WIND TURBINE IMPACTS ON NEXRAD WEATHER RADARS

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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 NEXRADs are located across the contiguous United States (Fig. 1), Alaska, Hawaii, Puerto Rico, and select overseas sites. The Federal government invested over $1.4B in developing and deploying the NEXRAD network, and operates, maintains, and continually upgrades that network to ensure the best possible protection of life and property. In addition, the National Weather Service (NWS) uses data from the Federal Aviation Administration's (FAA) 45 Terminal Doppler Weather Radars (TDWR) to further supplement their forecast and severe weather warning capability.

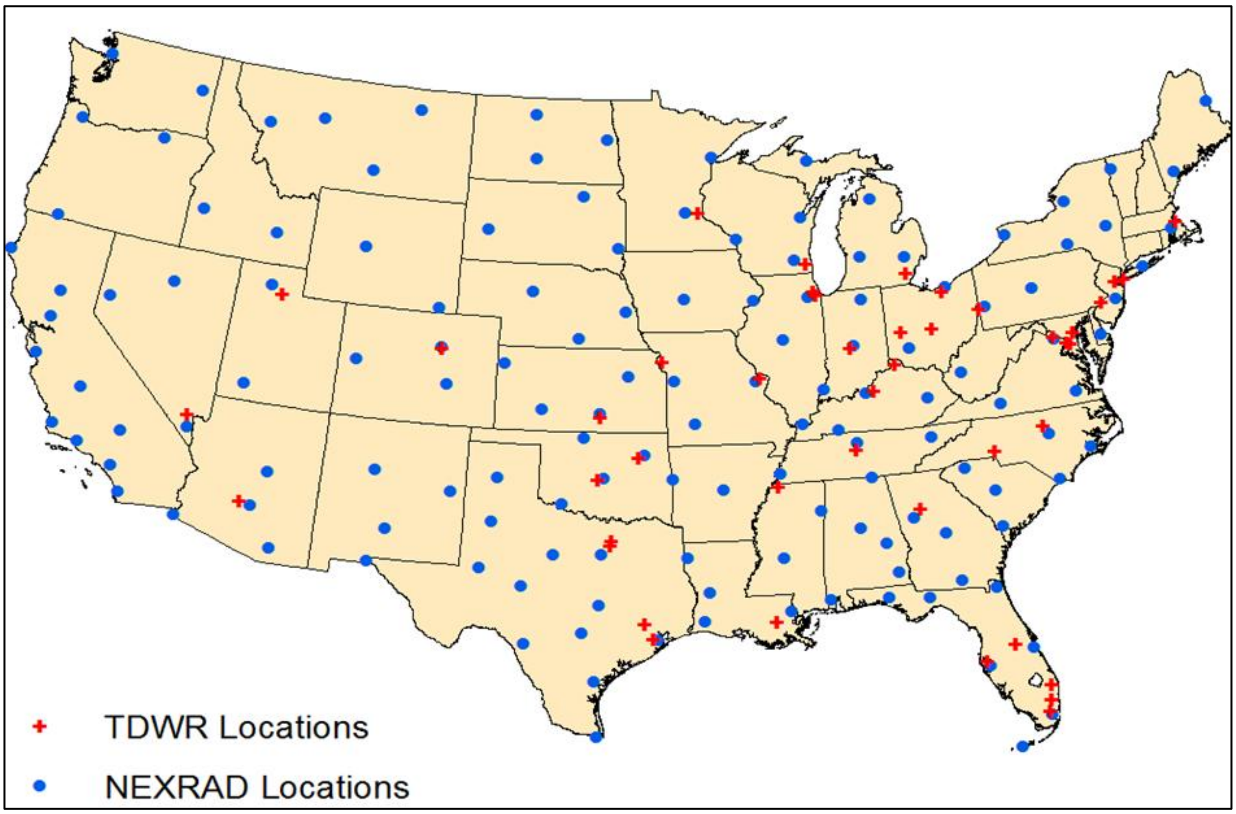

Fig. 1. Map of NEXRAD and TDWR radar locations in the Continental United States. Twelve additional NEXRADs are located in Alaska (7), Hawaii (4), and Puerto Rico (1).

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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 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). Wind turbine and weather spectra can span the same Doppler frequencies and share a similar dynamic range, causing conventional radar clutter filtering algorithms, which only filter energy returned from nearly stationary objects (buildings, terrain, etc.), to fail in isolating the weather signal. The unfiltered wind turbine clutter can adversely impact 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 Figure 2. The NEXRAD Radar Operations Center (ROC) in Norman, OK has evaluated 844 wind farm projects, some with proposed turbine blade tip heights exceeding 152m (500ft) above the ground.

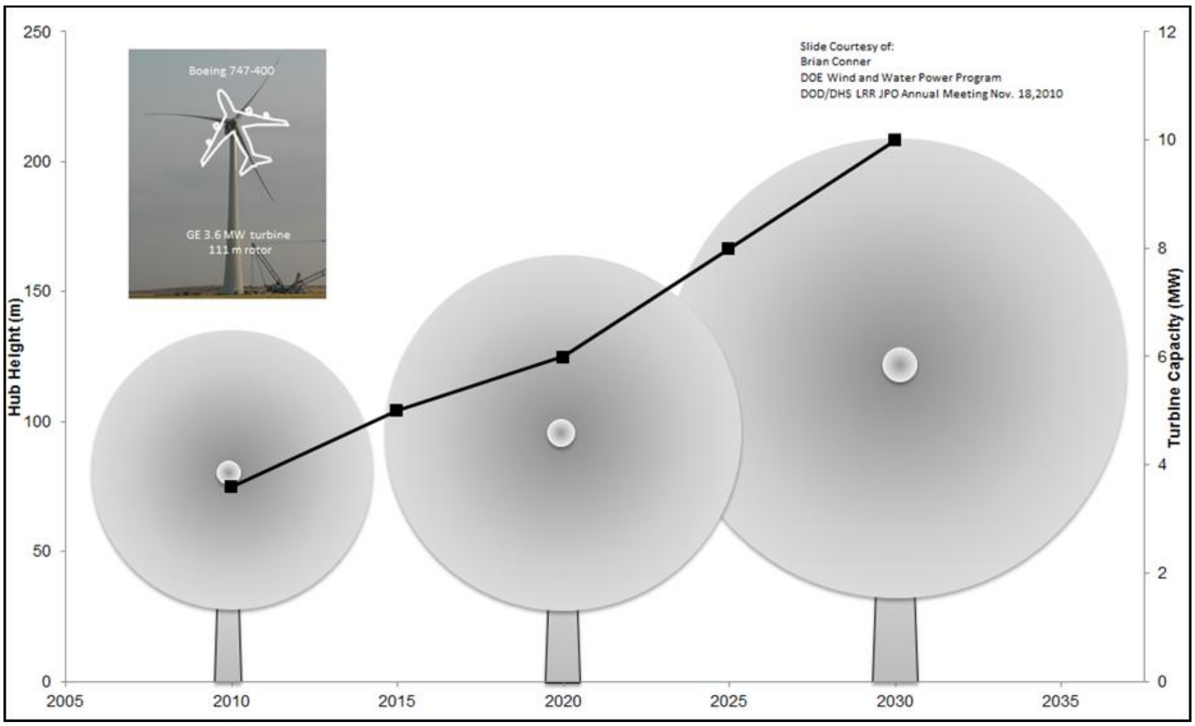

Fig. 2. U.S. Department of Energy projected increases in wind turbine height (top dead center) and turbine capacity (black line) from 2010 to 2030. The upper-left depiction of an airplane outline over the hub of a turbine represents the radar cross section a turbine can have, approximately the same as a 747 airliner.

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) 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 SYSTEM OVERVIEW

The NEXRAD 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 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. 3b).

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. Wind farms can impact NEXRAD radars in three ways:

(1) When the turbine blades are moving and they protrude into the RLOS, they can reflect un-filterable energy back to the radar system and appear as clutter in the base data (reflectivity, velocity, and spectrum width), as shown in Figure 3. 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 profiles, and severe weather alerts. Turbines sited within 18 km of a 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.

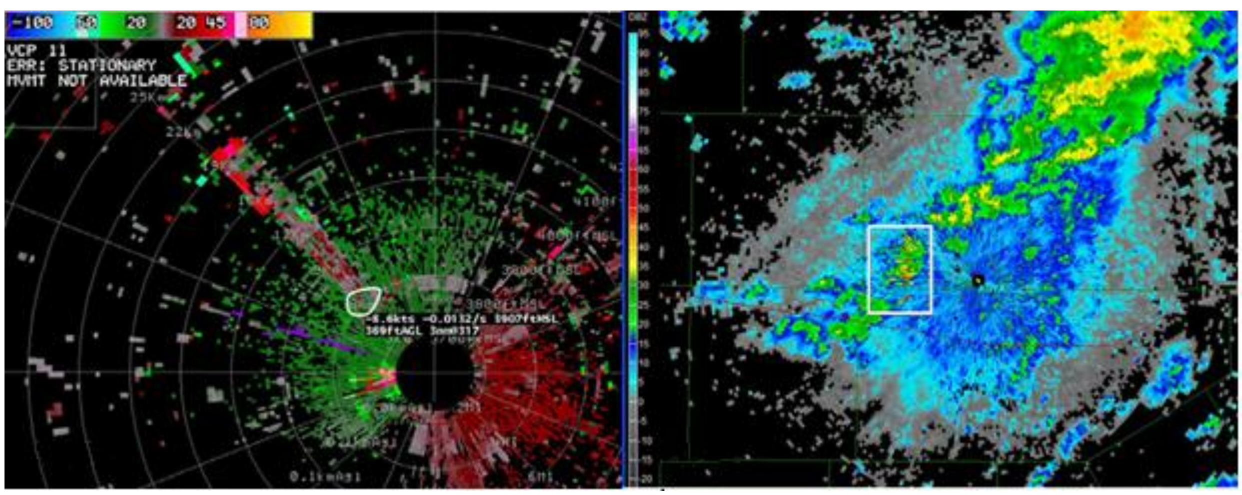

Fig. 3a. This Velocity image (0.5 degree scan) from the Great Falls, MT WSR-88D (KTFX) on February 9, 2006 at 1859 GMT shows how only a few turbines very close to the radar can cause a relatively large impact on radar data. The 6 turbines are approximately 6 km from the WSR-88D and in the RLOS. The velocity data is contaminated in azimuth for 9 degrees and out beyond 20 km 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.

(2) When turbines are within 3 km 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) If turbines are sited in the radar's near field, which for the NEXRAD is within 1500 m of the antenna, radar energy reflected from towers and turbine blades can damage the radar receiver and cause other severe impacts.

Other examples of wind farm impacts 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 18 km, 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.

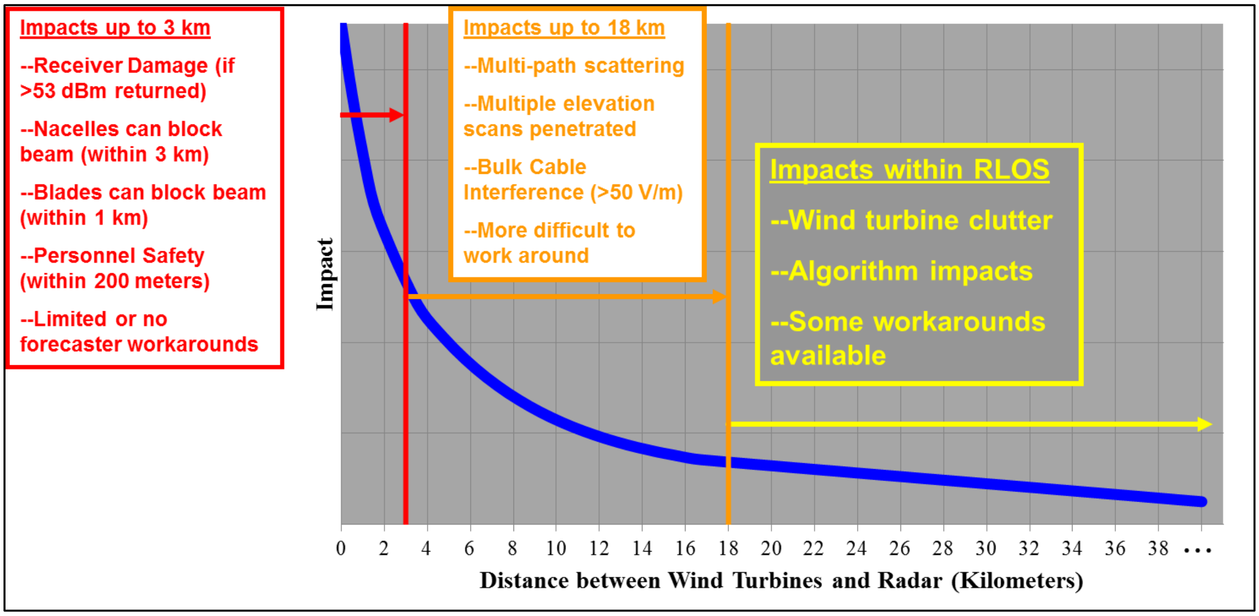

Fig. 4. Inventory of estimated impacts of wind farms on NEXRAD radars relative to the separation distance.

4. THE IMPACT ASSESSMENT PROCESS

The ROC learns of potential wind farm developments through formal and informal channels. 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). 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 new analysis criteria.

The ROC does 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 844 wind energy project 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 the radar to turbines;
(2) Maximum height of turbine blade tips;
(3) Number of wind turbines, or area of development;
(4) Elevation of the nearby NEXRAD antenna;

(5) A 1.0 degree beam width spread; and
(6) 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 the type and amount of severe weather in the counties surrounding the wind farm.

5. RECENT CHANGES TO WIND TURBINE IMPACT CRITERIA

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 a potential for significant impacts, we have limited mitigation discussions to those wind farms that are within about 18 km (10 nm) of a NEXRAD, assuming flat terrain, and whose blades penetrate into the second or higher radar scan angles. Only about 6% of the 844 analyzed wind farm proposals have been projected to be within 18 km (10 nm) of a NEXRAD, and only about a dozen (1.4%) have been proposed to be sited within 3 km (Fig 5). No wind farm has yet been built within 3 km of a NEXRAD, but there are several wind farms operating within 18 km. Despite this, there have been no missed weather warnings, and only a couple of

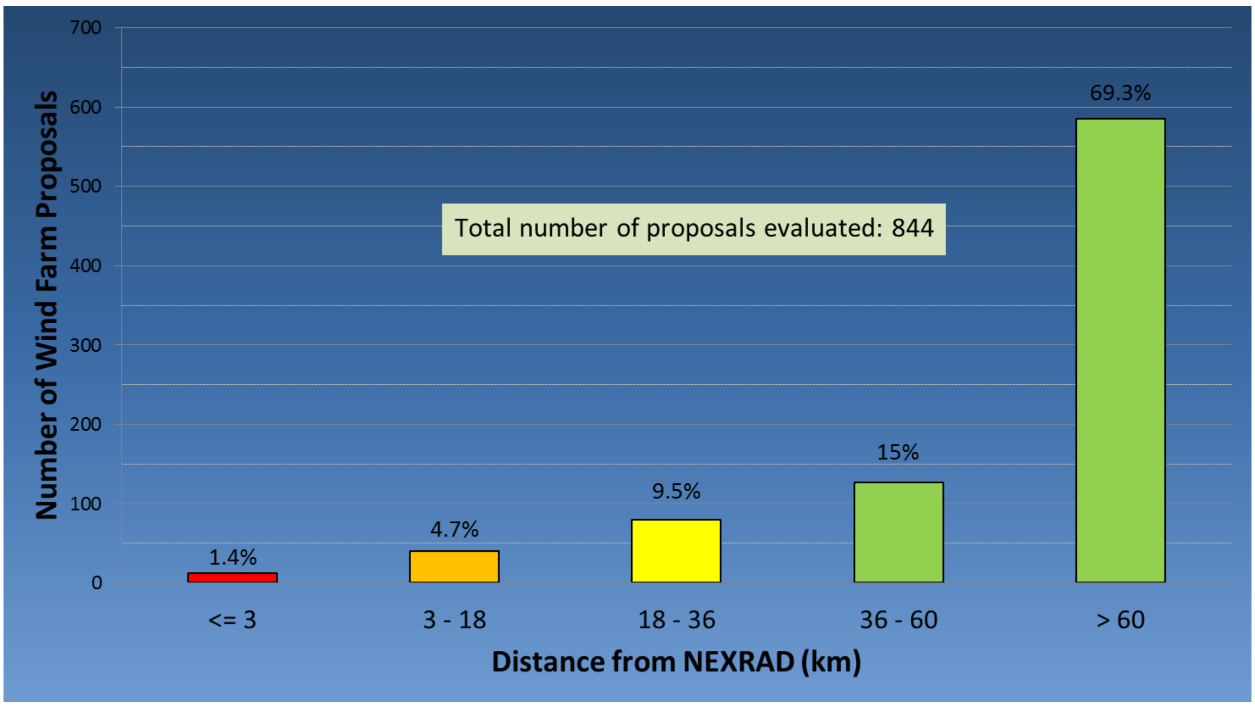

Fig. 5. Number of wind farm proposals as function of distance from a NEXRAD radar.

instances of false weather warnings attributed to wind WTC. Also, when WTC is confined to the first elevation scan, forecasters can generally verify WTC by looking at the next higher scan angles. These finds have allowed us to relax our evaluation criteria. As a result, in the past year, the ROC has settled on new impact criteria and is changing how we communicate the impacts to developers.

Figure 6 below shows our current and planned changes to the radar line-of-sight model output for the Bismarck, ND NEXRAD. Current output indicates that impacts to radar operations are either "highly likely" or "likely" and that further study is required. Project developers did not find this very helpful. They desired more action-oriented output. Can we, or can't we build there? Are you going to request impact mitigation? The new output communicates our expectations and answers those questions. The new radar line-of-sight output is divided into four zones: No-Build (3 km red circle), Mitigation (orange), Consultation (yellow), and Notification (dark green) Zones. The zones are terrain dependent, except for No-Build, which is a fixed 3 km-radius circle centered on the radar. Also, the Consultation Zone is limited to 36 km unless the turbines penetrate the second elevation angle, in which case it is extended up to 60 km from the radar. The Notification Zone extends to the edge of the radar's line of sight. The intention of this zone is simply to get developers to notify NOAA that they intend to build there. A wind farm built in the Notification Zone will likely be visible in the radar data, so NOAA needs to know it's out there and warn forecasters ahead of time. For wind farms planned in the Consultation Zone, NOAA wants to stay in touch with the developers and track the project to completion. We want developers to keep us informed of any changes to the numbers of turbines, turbine height, or turbine locations. Turbines located in the Mitigation Zone will likely cause significant impacts to the radar data and limit forecaster workarounds. Therefore, we would want to discuss potential options for mitigating impacts. Finally, for projects located in the No-Build Zone, we would want to discourage a developer from building in that area. Work-arounds are few and impacts are likely to be great. There are some radars in the mountainous terrain of the Western US where developers may be able to build within 3 km of the radar and still stay out of the radar's line of sight, but they are few.

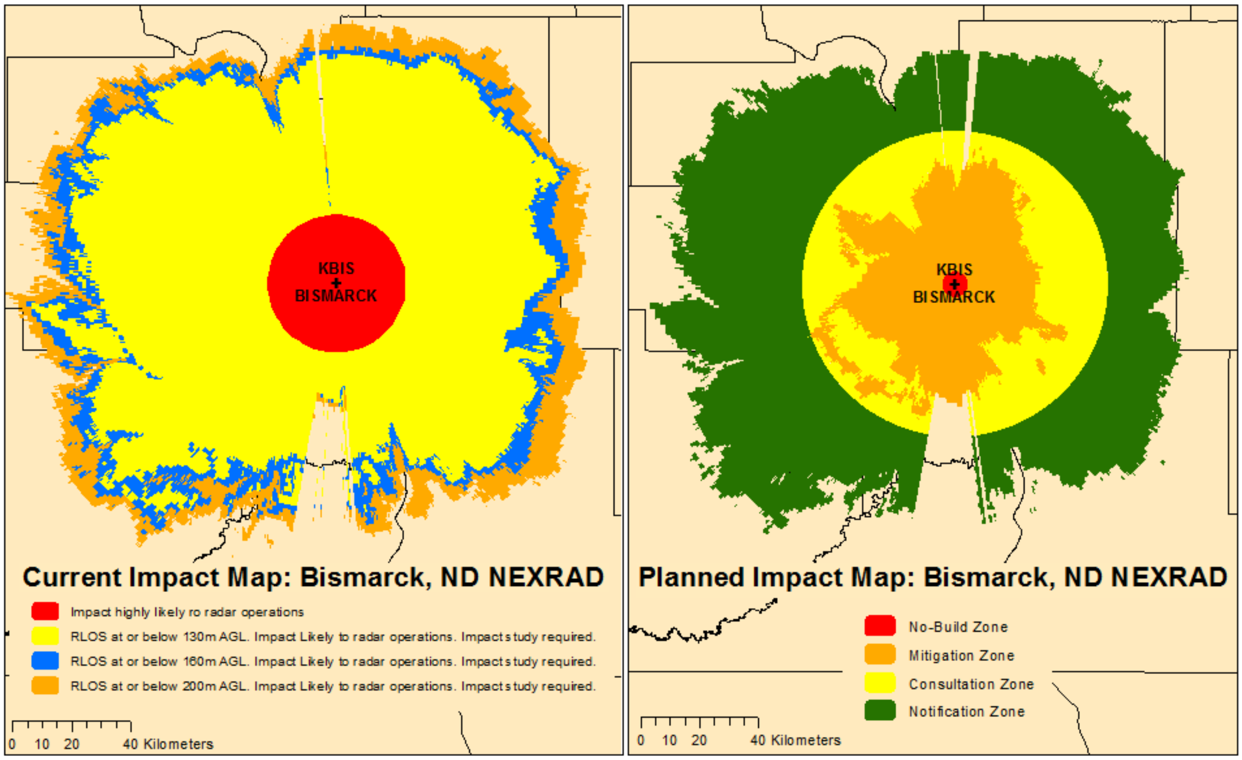

Fig. 6. Example of changes to impact maps for Bismarck, ND NEXRAD

6. RECENT NOAA/NWS WIND TURBINE CLUTTER 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 a 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. 7, 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 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. 7, 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.

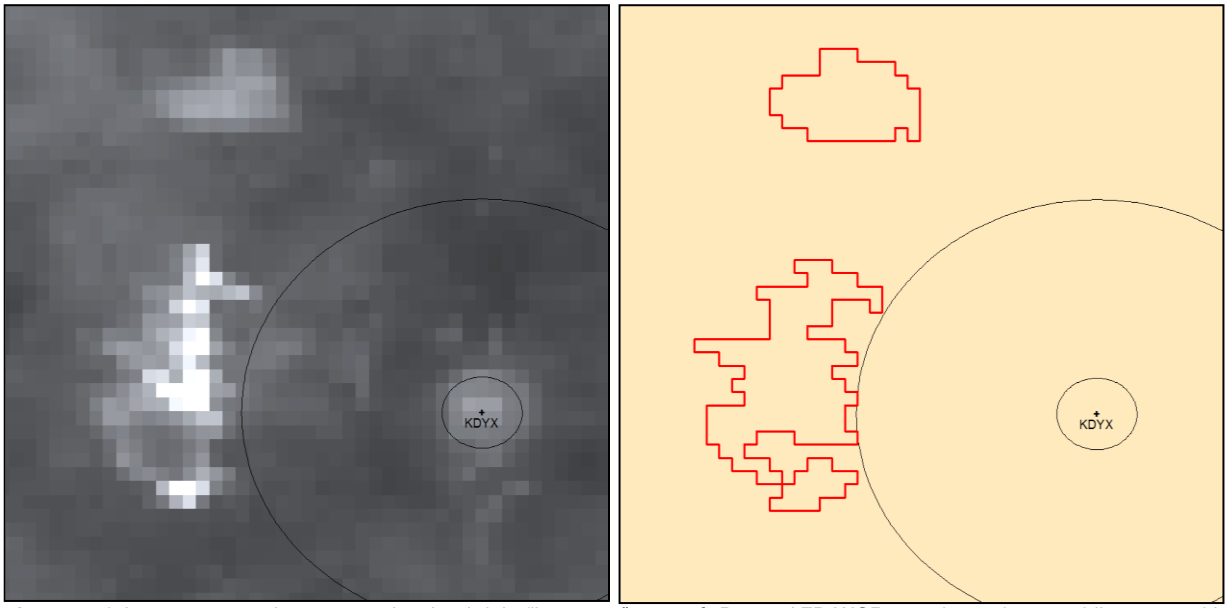

Fig. 7. Left image: 12-month Q2 QPE showing bright “hot spots” west of Dyess AFB WSR-88D (KDYX) near Abilene, TX with 3- and 18-km range rings. Right image: NSSL-generated polygons outlining QPE “hot spots”.

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 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 18 km 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 and other foundational studies are in progress using a controlled laboratory environment with scaled turbine models and dual-polarized scatterometers (Fig. 8).

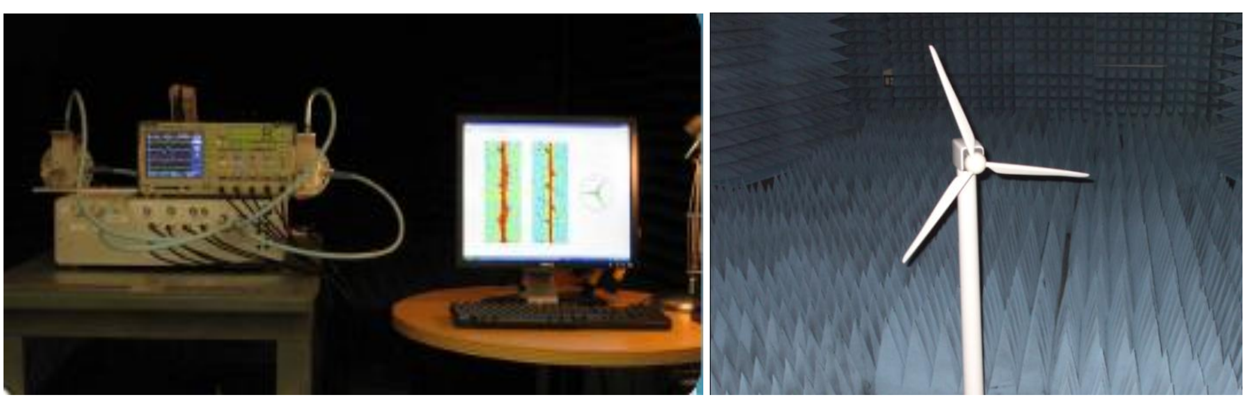

Fig. 8. Model wind turbine (right) and 10 GHz dual-polarized scatterometer (left) in the ARRC Lab at the University of Oklahoma. (Courtesy of the OU ARRC)

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. Based on three years of studying the impacts of wind turbines on the NEXRAD network, the NWS is relaxing its impact criteria and focusing on wind turbines that penetrate into higher elevation scan angles. It is also changing how it communicates the impacts to developers by using zones named with the desired action—Mitigation, Consultation, etc. 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 sharing of wind farm met tower data. The NWS believes 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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