

DO WIND TURBINES AFFECT WEATHER CONDITIONS?

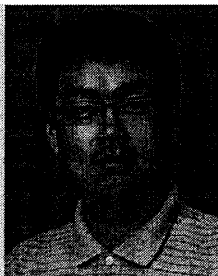
Student Authors

Meghan Henschen, Brittany Herrholtz, Lacey Rhudy, Kathryn Demchak (front), Brian Doogs, Joshua Holland, Erik Larson, Johnny Martin (back, pictured left to right), and Matthew Rudkin (not pictured) are seniors in Atmospheric Sciences at Purdue University. Each member of the group has a passion for studying weather and learning the complexities of our atmosphere. The study started as a research project for a class entitled "Atmospheric Measurements and Observations." They felt the project was a great opportunity and developed an interest for wind energy along the way. In January the group traveled to Seattle, Washington, to present at the 2011 American Meteorological Society Conference. They also won the Student's Choice Award at the 2011 Undergraduate Research and Poster Symposium in the College of Science. Meghan Henschen is the primary author and took the lead in the article submission process.



Faculty Mentor

Dr. Ki-Hong Min is a visiting assistant professor in the Department of Earth and Atmospheric Sciences. Dr. Min's research interest involves improving the prediction of weather and regional climate with emphasis on surface-air interactions using numerical models and observational data. His current research agenda include improving Purdue Regional Climate Model (PRCM) and the Weather Research and Forecasting (WRF) model's surface representation of cold season and the effect of wind turbines on regional climate. Dr. Min is actively involved in atmospheric science education and curriculum development, and he enjoys teaching and mentoring undergraduate students.



Abstract

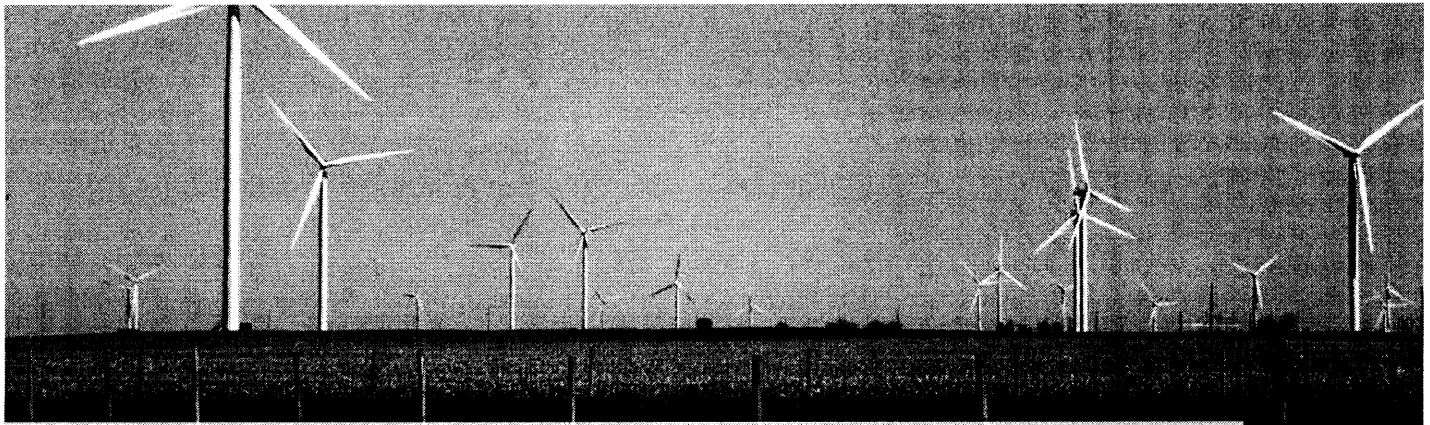
Wind turbines are becoming increasingly widespread in the United States as the world looks for cleaner sources of energy. Scientists, policymakers, and citizens have strong opinions regarding the positive and negative effects of wind energy projects, and there is a great deal of misinformation about wind energy circulating on the Web and other media sources. The purpose of this study is to gain a better understanding of how the rotation of hundreds of turbines can influence local weather conditions within a wind farm and in the surrounding areas. This experiment measures temperature, atmospheric pressure, wind speed, wind direction, relative humidity, and evaporation with five weather instruments at Meadow Lake Wind Farm located in White, Jasper, and Benton Counties, Indiana, from November 4 through November 18, 2010. The data show that as wind passes throughout the wind farm, the air warms during the overnight and early morning hours and cools during daytime hours. Observed lower humidity rates and higher evaporation rates downwind also demonstrate that the air dries out as it travels through the wind farm. Further research over multiple seasons is necessary to examine the effects of warmer nighttime temperatures and drier conditions progressively downwind of the installation. Nevertheless, wind turbines did not negatively affect local weather patterns in our small-scale research and may actually prevent frost, which could have important positive implications for farmers by potentially prolonging the growing season.

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Late-filed Exhibit J – Do wind turbines affect weather conditions
Concerned Citizens of Stark County (CCSC)



DO WIND TURBINES AFFECT WEATHER CONDITIONS?:

A Case Study in Indiana

Meghan Henschen, Kathryn Demchak, Brittany Herrholtz, Matthew Rudkin, Lacey Rhudy, Erik Larson, Brian Doogs, Joshua Holland, and Johnny Martin, Atmospheric Sciences

Image 1. The Meadow Lake Wind Farm in Benton County near Fowler, Indiana, contains over 300 wind turbines (image courtesy of Erica A. Morin).

Introduction

Wind is a beneficial source of energy for the United States. Unlike fossil fuels, wind energy is clean, efficient, and abundant. Wind projects are springing up across the country, but some individuals and communities are unfamiliar with wind turbine devices and nervous about potential effects. More research is needed to address this uncertainty and minimize local opposition to wind farm proposals. The purpose of this study is to gain a better understanding of how the rotation of hundreds of wind turbines can influence weather conditions immediately within a wind farm and the surrounding areas. More specifically, we hypothesize that the motion of multiple turbines in a cluster will lead to mixing, which will cause isolated air currents, or eddies, to form downwind on the lee side of the site. The mixed air may create warmer nighttime conditions at the site and produce dryer areas downstream of the wind turbines, thus preventing or delaying frost at night and in the early morning. If these theories prove to be accurate, they could make for a longer growing season for farmers whose land lies near the wind farm—a positive, unintentional side effect of an already clean, productive source of energy.

How do wind turbines create energy?

According to the U.S. Department of Energy, “a wind turbine works the opposite of a fan. Instead of using electricity to make wind, like a fan, wind turbines use wind to make electricity. The wind turns the blades, which spin a shaft, which connects to a generator and

makes electricity” (U.S. Department of Energy, 2010). A wind turbine has three blades that are aerodynamically designed to create a rotating movement as air blows (Roulston, Kaplan, Hardenberg, & Smith, 2003). The basic rotation occurs when the wind blows, causing the blades to create lift, much like the wings of an airplane. The shaft is set at a low speed and will rotate 30 to 60 times per minute. The shaft is then connected to a gearbox that accelerates to 1,000 to 1,800 rotations in a minute. The high-speed shaft drives a generator to produce electricity. Finally, the generator is connected to a power plant that stores the electricity and sends it to the grid.

Existing research on wind turbines and weather

In terms of weather studies, Roy and Pacala (2004) determined that as wind moves through the wind turbines’ rotating propellers, it is mixed with the air above and below, which have different starting conditions (such as higher or lower temperatures and moisture content). When the two different air types are mixed, the air mass is modified and will either warm or cool and moisten or dry out the original air properties. Furthermore, they state, “Turbulence generated in the wake of the rotors can enhance vertical mixing that significantly affects the vertical distribution of the temperature and humidity as well as surface sensible and latent heat fluxes” (Roy & Pacala, 2004). In other words, depending on the time of day, rotations from the blades pull warmer or cooler air toward the surface and bring cooler or warmer surface air up, which mixes the air.

Data reviewed by Roy and Traiteur (2010) suggest that, “near-surface air temperatures downwind of the wind farm are higher than upwind regions during night and early morning hours, whereas the reverse holds true for the rest of the day.” Many wind farms are built over agricultural land, so the turbines can actually have beneficial effects, such as the nocturnal warming of ambient air to protect crops from frost. This causes a pressure gradient to flow from warmer east air to the cooler west air, resulting in surface radiation cooling of the ground and in a drier climate that is strongest in the early morning hours and decreases throughout the day (Roy & Traiteur, 2003).

Experiment procedures and site description

We chose to conduct this experiment at the Meadow Lake Wind Farm in White, Jasper, and Benton Counties, Indiana. This large wind energy project is approximately 30 miles northwest of the campus of Purdue University. The entire Meadow Lake site consists of 121 Vestas V82 1.65 MW wind turbines, 66 Acciona AWs 1.5 MW —turbines, 69 model sle GE 1.5 MW turbines, and 47 Suzlon S88 2.1 MW turbines, for a combined total of over 300 turbines. In coming years, Horizon Wind Energy Company will install Phase V and VI for an estimated total of around 600 turbines and nameplate capacity of nearly 1,000 MW once the entire project is online (Horizon Wind Energy, 2011). These turbines are arranged in a cluster pattern and range from approximately 135 feet tall to 380 feet tall, thereby creating a significant distance between the blade rotation and ground area.

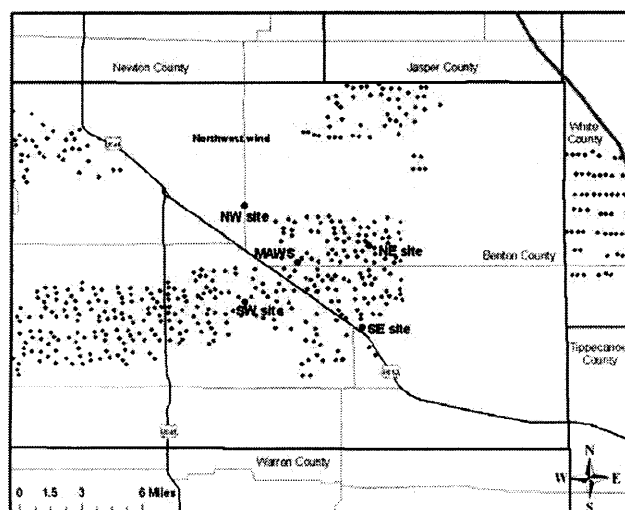


Figure 1. This map shows the experiment site in Benton County. The red dots represent the location of weather instruments, and the blue dots represent each wind turbine.

For this experiment, the weather equipment used to collect the data consisted of four WXT-510 weather instruments that measure different surface parameters, one MAWS101 weather station to measure surface conditions, and three evaporation containers. The weather equipment was set up in diverse spots in Benton County, Indiana, and arranged in a square formation with all of the weather instruments approximately equal distances apart. There was a WXT-510 at each of the four corners of the square, with the MAWS101 located in the center of the square. Parameters measured for this experiment were temperature, air pressure, wind speed, wind direction, relative humidity, and rainfall amount.

The MAWS101 weather station was positioned in the center of the designated research area, approximately 4,500 meters away from each corner site, in a cornfield and away from roads and houses. The MAWS101 was set up near a few wind turbines in order to collect potential data supporting the hypothesis that wind turbines affect the temperatures and moisture within the wind farm (see Figure 1).

Each site had technical problems collecting data due to laptop computer errors, but data were successfully collected by the weather instruments for 13 days starting from November 4 to November 18, 2010. Each instrument was set to retrieve data every two minutes for each day. Data were collected from November 4 to November 11 for the MAWS and northeast sites and, after obtaining new laptop computers, the MAWS, southwest, northwest, and northeast sites were able to retrieve data from November 11 to November 17.

The evaporation containers were put out at the MAWS, northwest, and northeast sites on November 5. The evaporation containers were filled with water and measured upon initial placement at the sites, again on November 11, and at the terminus of data collection. Measurements accounted for the amount of precipitation that fell during the experiment time. Rainfall at the sites was recorded daily and added into the containers’ total amount while winds were averaged each day to create an “average wind direction” for the day.

Temperature and relative humidity results

From approximately November 4 to November 6, winds were out of the northwest. Pressure steadily increased throughout these days, and by the end of November 5, the relative humidity was nearing 90 percent. From nightfall until approximately mid-morning on November 6, a short-wave warm front came through that switched the wind direction from northwest to south. When the warm front

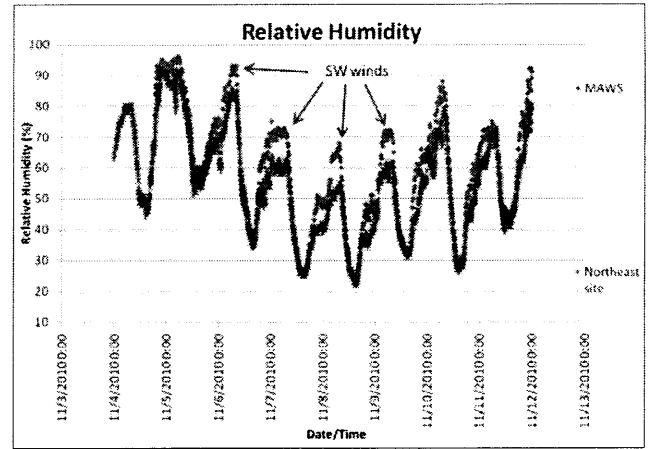
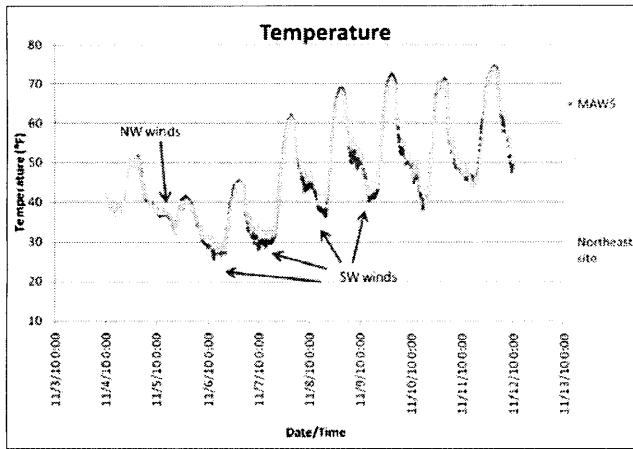


Figure 2 and Figure 3. These graphs show the temperature and relative humidity for the MAWS and northeast site from November 4 through November 12, 2010. The arrows indicate that the southwest and northwest winds had greater nightly temperature and relative humidity differences.

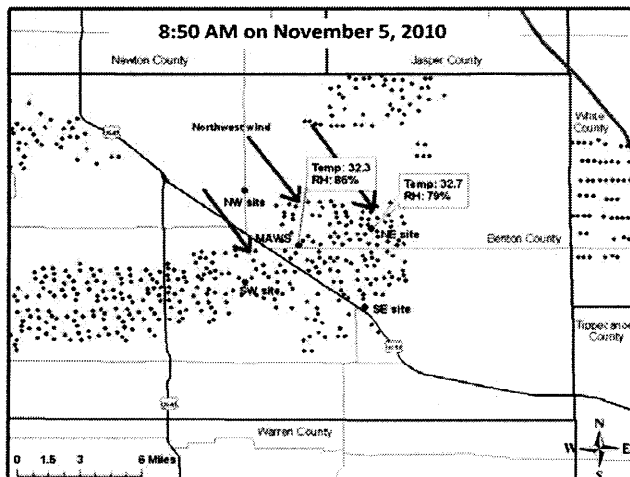


Figure 4. Conditions at the MAWS and northeast sites at 8:50 a.m. on November 5, 2010. Wind from the northwest is indicated by the red arrows. The text boxes contain the temperature and relative humidity at the two sites.

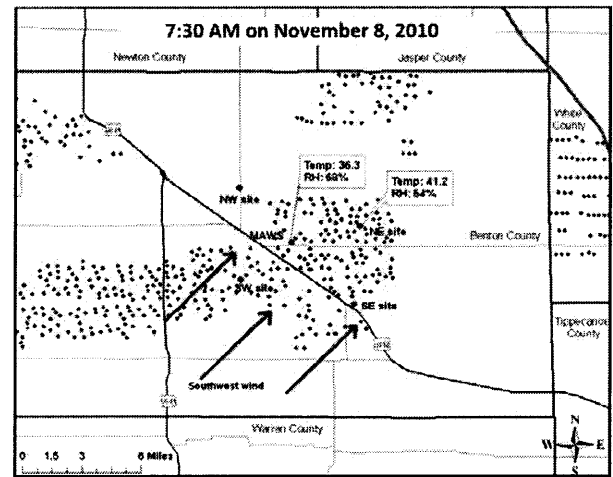


Figure 5. Conditions at the MAWS and northeast sites at 7:30 a.m. on November 8, 2010. Wind from the southwest is indicated by the red arrows. The text boxes contain the temperature and relative humidity at the two sites.

passed, air pressure was steady for roughly two days, and relative humidity dropped to 60 percent during daytime hours. Another front passed through on November 10, shifting winds to the south for the remainder of the period. Figures 2 and 3 show the temperature and relative humidity in this period.

From November 4 through November 11, significant nighttime differences were observed in temperature and relative humidity under the southwest flow. At most other times, the temperature and relative humidity remained fairly consistent between the two sites due to wind direction. In particular, the nighttime mixing was most prevalent for two days during the experiment period. The first of these days was November 5, with observation occurring at 8:50 a.m. (see Figure 4). On this morning, Benton County experienced a northwest wind. The MAWS recorded a temperature of 32.3°F, and the northeast site recorded 32.7°F. At this point, the wind direction was nearly perpendicular to the plane of the two sites, and it is safe to assume that the mixing was nearly identical. The MAWS did, however, record a relative humidity of 86 percent while the northeast site only recorded 79 percent. Throughout the experiment, though, the MAWS consistently recorded higher relative humidity than the other WXT instruments had recorded throughout the duration of the experiment, which suggests a bias in the instrument data. With this said, the two sites were essentially experiencing the same atmospheric environment on that particular morning.

The next date analyzed was November 8, 2010, with observation at 7:30 a.m. (see Figure 5). On this morning, the site location had southwest winds. This flow was favorable to our research because we could compare the surface variables at a site in the center of the wind farm—under the mixing influence of the southwest portion of the wind farm—and a site at the northeast corner of the wind farm. The MAWS recorded a temperature of 36.3°F, and the northeast site recorded a temperature of 41.2°F. Since these two sites are only about 4,500 meters apart, this is a significant temperature difference. There was obvious mixing at the surface due to the wind turbines. Again, we noted that the MAWS recorded higher relative humidity, but at this time the MAWS recorded 68 percent relative humidity, and the northeast site recorded 54 percent. Accounting for the higher relative humidity bias in the MAWS, the relative humidity difference became much greater during the southwest flow, suggesting that these results were due to the bias plus the mixing. These results were significant because they indicated that mixing also reduced relative humidity throughout the wind farm.

From November 11 to November 17, all sites except the southeast site were able to be analyzed. The placement of functioning weather instruments in this period was more ideal, because they covered more ground within the wind farm and provided better spatial results. Starting on November 13, winds changed from southeast to southwest, with wind speeds increasing at each site as winds shifted westward. The pressure dropped dramatically

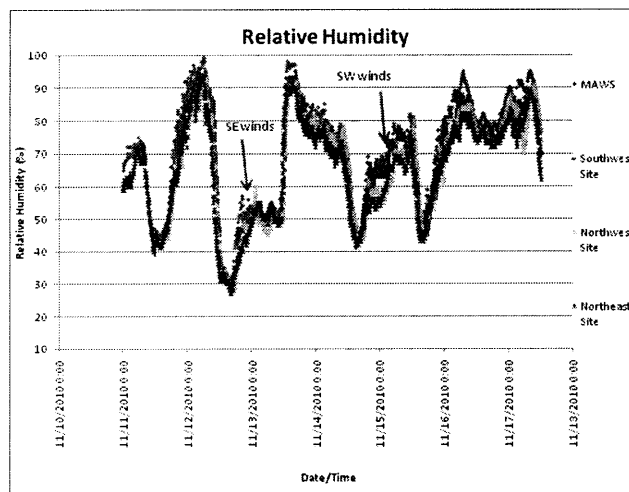
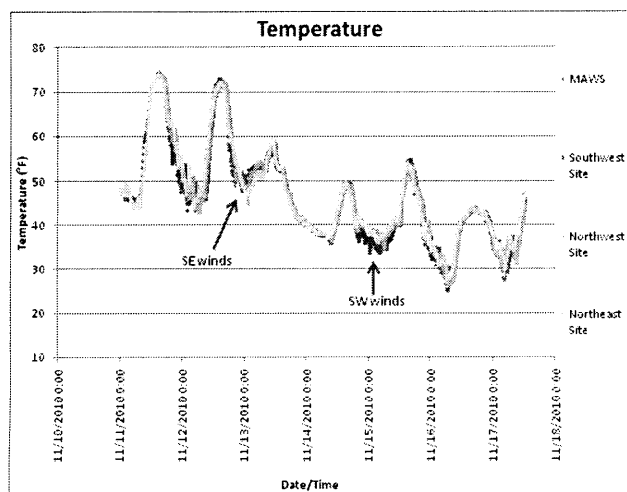


Figure 6 and Figure 7. These graphs show the temperature and relative humidity for the MAWS, southwest site, northwest site, and northeast site from November 11 through November 18, 2010. The arrows indicate that the southeast and southwest winds resulted in the greatest temperature and relative humidity differences.

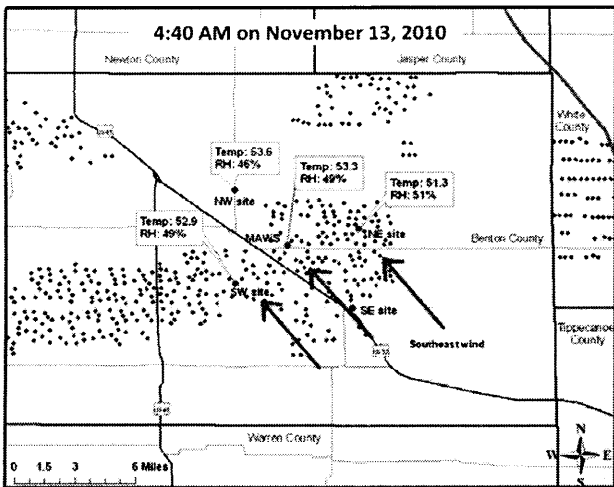


Figure 8. Conditions at the southwest, northwest, northeast, and MAWS sites at 4:40 a.m. on November 13, 2010. Wind from the southeast is indicated by the red arrows. The text boxes list the temperature and relative humidity at the four sites.

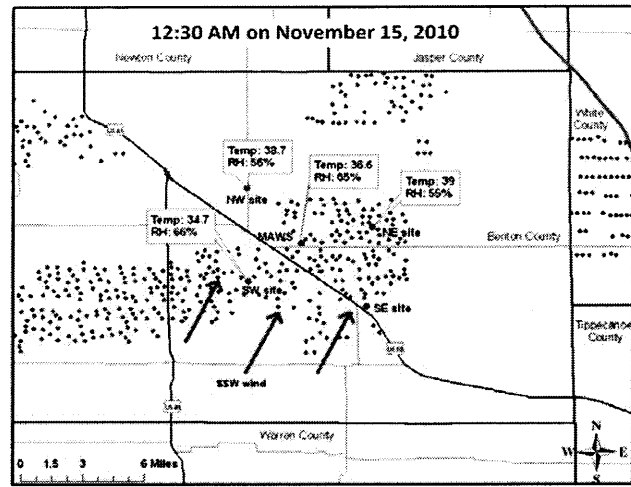


Figure 9. Conditions at the southwest, northwest, northeast, and MAWS sites at 12:30 a.m. on November 15, 2010. Wind from the south-southwest is indicated by the red arrows. The text boxes list the temperature and relative humidity at the four sites.

from November 12 to November 13, and then became steady until November 15 at 8:00 p.m.. Winds also shifted dramatically during this time. Southwest winds became southerly, and then shifted to easterly by November 16. On November 18, winds were blowing from the north in the morning and from the west by midday. This was indicative of a cyclonic flow due to a low pressure system. During this time frame, the air pressure dropped from about 984 hPa to 973 hPa. Figures 6 and 7 show the temperature and relative humidity in this period.

According to the data collected from November 11 to November 18, temperature and relative humidity differences were less obvious between the four sites during this period and the two sites from the previous period. The most significant nighttime differences were associated with a southwest flow, and we observed two additional dates and times in which the nighttime mixing was most prevalent. The first date was November 13 at 4:40 a.m. (see Figure 8). This wind pattern was not ideal for gathering information, given the placement of the instruments. With the southeast WXT-510 not collecting data, the northeast and southwest WXT-510 and MAWS were positioned almost perpendicular to the wind direction. This scenario provided our research team with less opportunity to determine temperature and relative humidity variation before and after the wind mixing with the turbines. The three functioning weather instruments received wind simultaneously and therefore exhibited roughly the same temperature and relative humidity

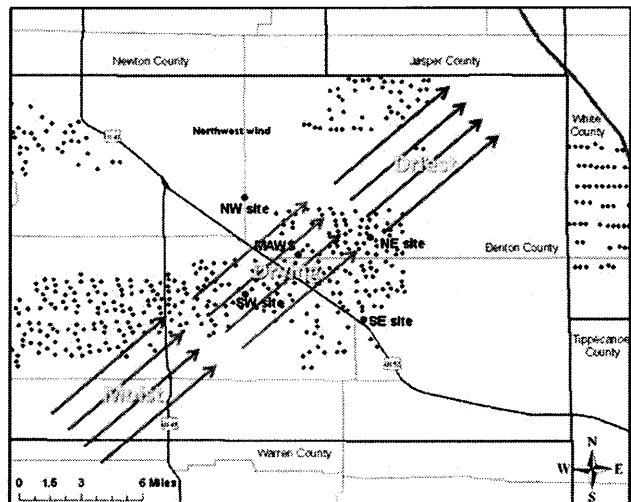


Figure 10. Air begins to dry out as it travels from the southwest to the northeast in the wind farm.

readings. The southwest site recorded a temperature of 52.9°F and relative humidity of 49 percent; the MAWS recorded 53.3°F and 49 percent relative humidity; and the northeast site recorded 51.3°F and 51 percent relative humidity. These were all fairly consistent with only slight variations. The MAWS captured the warmest of the three temperatures, which was also the farthest northwest. To further the results, the northwest site recorded a temperature of 53.6°F and a relative humidity of 46 percent. Even though this site was not within the bounds of the wind farm, this is the highest temperature and lowest relative humidity of the four sites. This implies that wind turbine mixing extends outside the bounds of the wind farm and into the surrounding land.

The second date was November 15 at 12:30 a.m. (see Figure 9). Winds from the south-southwest provided ideal conditions at that time. The southwest site recorded a temperature of 34.7°F and relative humidity of 66 percent; the northwest site recorded a temperature of 38.7°F and relative humidity of 56 percent; the MAWS recorded 36.6°F and 65 percent relative humidity; and the northeast site recorded 39°F and 55 percent relative humidity. One can see that the southwest portion of the wind farm had the lowest temperature, while the northern portion of the wind farm had the highest temperatures. From the southwest site to the northeast site, temperatures varied by 4.3°F and relative humidity varied by 11 percent. These are significant differences given the close proximity of these two sites.

Evaporation results

Evaporation containers were placed at three sites: the northwest site, the northeast site, and the central MAWS site. Rainfall at these sites was recorded daily and added into the containers' total amount, while winds were averaged each day to create an "average wind direction" for the day. Our results demonstrated that relative humidity decreased and evaporation increased progressively downwind of the wind farm.

At the time of initial container placement and up until the first observation, winds came out of the southwest 57 percent of the time, the north seven percent of the time, and the south 29 percent of the time. During the second half of the observation period, winds came out of the southwest most frequently, 57 percent of the time. South winds prevailed 14 percent of the time and southwest winds another 14 percent. Looking at winds for the entire period, it is clear that southwest winds were the

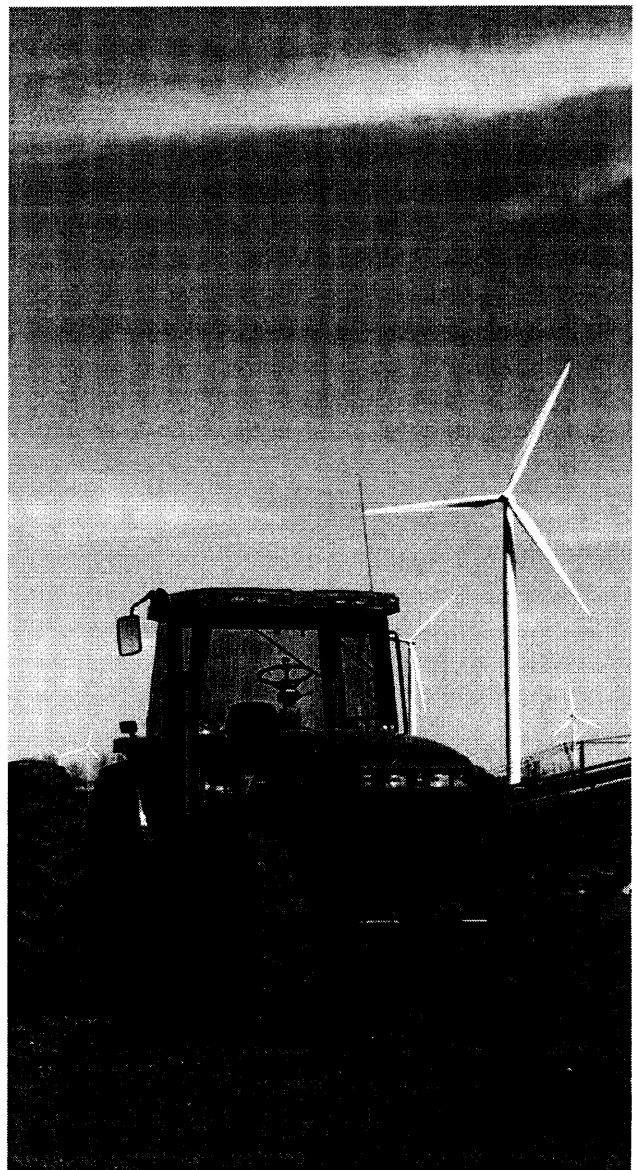


Figure 11. Increases in temperature and relative humidity in the areas surrounding wind farms may prevent frost and increase the growing season for local farmers (image courtesy of Erica A. Morin).

most common, occurring 54 percent of the time. Other wind directions included north at eight percent, south at 23 percent, and northwest at 15 percent of the time. With winds out of the southwest more than 50 percent of the time, we expected more evaporation would occur from southwest to northeast. In other words, the air should have been getting drier as it traveled through the wind farm (see Figure 10).

Evaporation amounts throughout the study show that the northeast site had the most evaporation, with a total of 3.2 mm. The MAWS site had evaporation totals of 1.4 mm, and the northwest site had 1.5 mm of evaporation. The northeast site had 52 percent more evaporation than the MAWS site, which further verifies the results of the study. These results coincide with the relative humidity findings of conditions becoming drier as winds blow through the wind farm.

Conclusion

We found that the constellations of wind turbines in a wind farm impact local climate conditions in and around the wind farm. The results of this study show that as air travels through the wind farm, it is “churned” by the wind turbine propellers, which causes the air at a higher elevation to mix with air at the surface. The data show that the air warms consistently as it mixes throughout the wind farm during overnight and early morning hours. In addition to warming, the air that travels through the wind farm also dries out. The data showed lower relative humidity and higher evaporation where the wind exited the wind farm. Since the air is warming and drying out as it passes through the wind farm, this could potentially prevent frost within the vicinity of the establishment. These effects have positive implications for farmers in the area, as the prevention of frost may help create a longer growing season for crops.

These results show evidence that wind turbines do affect micro-scale weather variables, but it would be appropriate for this study to be reexamined with a longer experimental period through multiple seasons. An additional parameter, such as soil moisture, should also be analyzed to determine differences in soil moisture at wind turbine sites and its possible impact on crops. A study over multiple months would also help reinforce the theory of wind turbine impacts on local climate, as well as help to better distinguish atmospheric variables.

Acknowledgments

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Find out more about Dr. Ki-Hong Min's research in the Department of Earth and Atmospheric Sciences:
<http://go.lib.purdue.edu/pup/min>