Wind Farm Effects on Local Weather Conditions

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Introduction

In today's world, the energy landscape is quickly changing, not only by style, but also by sight. All across Texas, farmers are seeing a new product: wind turbines. In exchange for a large sum of money per month, ranchers are renting out acres of their land to allow wind energy companies to place their turbines across the land. Besides the extra pocket change, these farmers are benefitting another way as well. During the winter, their crops finding themselves being protected from frosty conditions. Why? Well, that is exactly what scientists have been investigating, and the facts are being found.

The wind farms springing up all around the world are harboring their own "mini-climate" of sorts. From air temperature to moisture content, meteorologists are discovering just how intricate the links among man, machine, and nature are. Here, we discover the effects that these large wind farms have upon local weather, including wind speeds, air temperature, and dew point, as well as some reasons as to why these processes are affected by the turbines.

Evolution to Modernization

Wind turbines can be found in a fashion going back some thousands of years, to crude yet effective tools that accomplished differing tasks. However, we can find the first truly modern turbines beginning on this side of the mid 20th century, with efforts ramping up by the late 80s and 90s mainly in part by federal funding being the backer of a search for a sensible and renewable energy source of the future (20th Century Developments).

Even so, from the 1980s to today's wind turbines, vast changes have taken place just in the design of the machines. For example, consider that in this time, the height of the towers have increased roughly five times over. Taking it even further (and almost in proportion to the height of the towers), the blade lengths have also expanded dramatically as well. The associated diameter of the average turbine today is about eight times greater than the average diameter going back about thirty years (Krohn et al.). Now, in comparison to the old Brush windmill of the late 1800s, which held a diameter roughly that of the early 1980s turbines, the Brush windmill did good to produce twelve kilowatts of electricity. Those newer style turbines of the early 1980s, with a similar size diameter, could just as easily put out 100 kilowatts of energy (20th Century Devlopments). This demonstrates the advances made in more efficiently converting the kinetic energy of the wind to mechanical energy, although Betz's law guarantees we won't see greater than 59% efficiency in that department (Wind Turbine Power…).

We can also see how much of an increase in wind farm growth has happened in the United States by the amount of power capacity. When compared to the late 1990s, that number has jumped from about 8,000 megawatts to around 300,000 megawatts this year, 2012 (Wind Power Capacity).

Case Studies

In determining the observed effects of large wind farms on weather parameters in the immediate vicinity, I had originally chosen to go through data from several wind farms and determine any obvious trends. However, as I began this research into the wind farm effects, I soon discovered a reality. There is, in actuality, a limited amount of data available, at least to the public. Most wind farms that do have weather stations or towers on site are privately owned, and, therefore, such data as air temperature, dew point temperature, and heat flux is not easily attained. In spite of this, I was able to sift through parts of past research into this theory, that wind farms cause change to local climate, and find several interesting studies that I pooled together along with my own data collection. Below I will attempt to break down the essence of each study as to how it was performed and why it is essential to the question of whether wind farms affect weather.

The first of one of these was a study completed by an undergraduate (senior) research team from the Department of Earth and Atmospheric Sciences from Purdue University, under the leadership of Dr. Ki-Hong Min, a then-visiting assistant professor. Their work was completed in mid-2010 at the Meadow Lake Wind Farm in northwest Indiana. Over a period of two weeks, data was gathered from five geographically separated stations within the wind farm confines. Four are roughly at the corners of the focused area, with the fifth near to center *(Fig. 1)*. Based upon wind direction in time, air temperature and relative humidity was calculated for the locations to determine differences as wind entered and subsequently left the confines of the wind farm. In addition, air pressure, wind speed, and precipitation measurements were taken. It should be noted that measurements were only taken during the late night/early morning time frame when the wind farm effect should be most pronounced, and daytime convection processes are not a factor (Henschen et al. 22, 24).

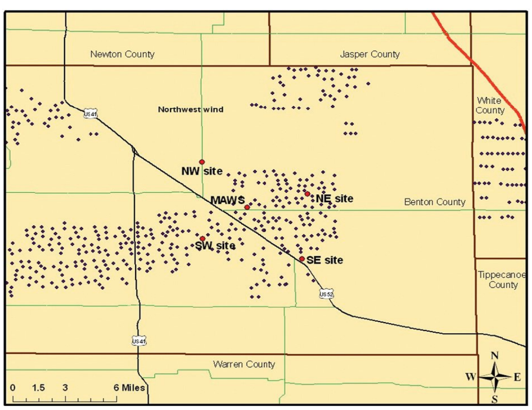


Fig. 1: Five sites located near Fowler, IN as a part of wind farm weather effect research conducted by Purdue undergraduates in 2010. (Courtesy of Henschen et al.)

The second area of focus was centered on the San Gorgonio wind farm in between Palm Springs, CA and Beaumont, CA, and along the I-10 corridor *(Fig. 2)*. Not only was observational data taken and analyzed, but simulations were also ran to determine effects of a theoretical wind farm under certain conditions.

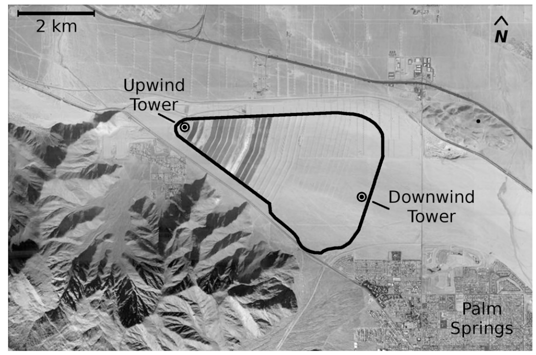


Fig. 2: The location of the study area in the late 1980s of the San Gorgonio Wind Farm. (Courtesy of S. Roy & J. Traiteur)

Somnath Baidya Roy and Justin Traiteur were both conductors of the analyses of the observed and simulated data from this case study. It should be pointed out that this region has an extremely hilly terrain, so care has to be taken to ensure data is not corrupted by any downslope effects. The collectors of data were careful in doing so, as they made sure the information was only taken when wind flow became northeasterly, which would ensure it was reaching the large group of turbines before running into the mountainous hillside.

Roy and Traiteur stated that , at that time, they used the only known available data recorded from a wind farm, which was data recorded from the San Gorgonio during June and August of 1989. This information included near-surface air temperatures from both upwind and downwind locations in relation to the concentration of the wind turbines. The objective was to study this collection of data and determine if it supports a hypothesis that a large group of wind turbines does indeed affect local weather variables. For this case, we are able to test correlation with near-surface air temperatures in the valley (Roy and Traiteur 1-2, 5).

In order to better understand the impacts of wind turbines on the flow of wind in the general area, we can investigate the simulations conducted by Somnath Roy, S. W. Pacala, and R. L. Walko in the early 2000s. Considering a large wind farm located in Oklahoma, they used the Regional Atmospheric Modeling System (RAMS) to study the effects upon near-surface air temperature, moisture content, sensible heat flux, wind speed, evapotranspiration, and turbulence. Assumptions associated with this experiment are that the turbines are 100 meters high, with a rotor diameter of 100 meters. Also assumed is that the turbines are spaced 1000 meters apart from one another, and in a 100 by 100 grid concentration. Instead of using an estimate on the amount of drag at the surface, they set the turbine itself to be of no mass, but a "sink of resolved kinetic energy (RSE) and source of TKE", or turbulent kinetic energy (Pacala 2). Below, *Fig. 3* is an example of the domain their model used to perform the simulations of the wind farm's effects on local weather parameters.

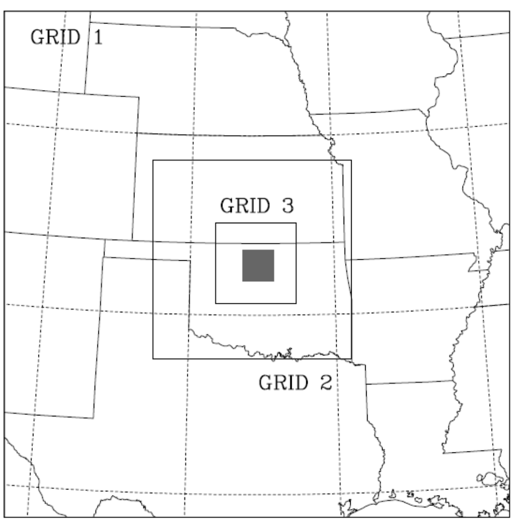


Fig. 3: The shaded area, GRID 3, is the domain the RAMS used for the location of the simulated wind farm.
(Courtesy of S. Roy, S. Pacala, & R. Walko)

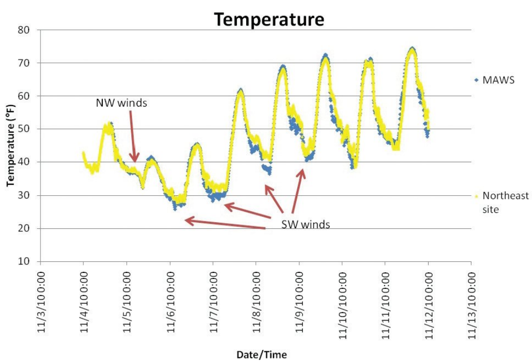
For the data retrieved concerning how wind speeds changed during the time period in July, the model was run using a control and two more scenarios. The first scenario consisted of the model assuming that a turbine is simply a sink of resolved kinetic energy, while the second scenario was for the model to assume not only a turbine acting as a sink for resolved kinetic energy, but also for one to be a source of turbulent kinetic energy (Roy, Pacala, and Walko 1-5).

The final source of data comes from my own gathering from NOAA's National Climatic Data Center (NCDC). Using it, I found the three closest weather stations to the Buffalo Gap Wind Farm near Abilene, Texas, that had simultaneously available data for four weather parameters, air temperature, dew point temperature, wind speed, and wind direction. I used this collection of numbers to plot out the changes in each for three days, January 1-2, 2010, and February 15, 2010. Two of the three days were free from any synoptic fronts, with high pressure dominating the region. For the third day, a cold front was situated to the north of the three stations, and by evening the cold front was moving through. The three selected locations were Abilene, TX, Sweetwater, TX, and San Angelo, TX. In relation to the Buffalo Gap Wind Farm, Abilene is on the northeast corner, Sweetwater is on the northwest corner, and San Angelo is to the south. I must make a reference to the fact that there is another large wind farm, the Roscoe Wind Farm, extending out from the northwest side of Sweetwater. This is important to know when determining trends in the data based upon wind direction. The data collected was for on-the-hour observations and for all twenty-four hours of each day. Buffalo Gap Wind Farm had a production capacity of 524 megawatts of energy in 2008, placing it as the ninth largest onshore wind farm in the United States. Additionally, the average rotor diameter for the farm's turbines was eighty meters.

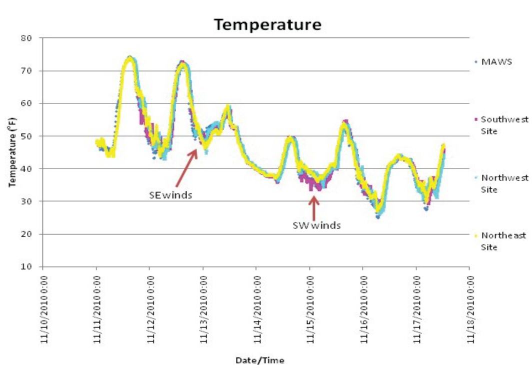
Outcomes & Consequences

Taking a look at what may be the most mentioned parameter, air temperature, and how it is affected in areas with large wind farms, we can start with the research done by the senior undergraduate team from Purdue University. For the period from

November 4-18, 2010, air temperature was plotted for the different stations within the Meadow Lake Wind Farm site (Henschen et al. 25-26). When overlaying the temperature recordings from each site on top of one another, we can see that only at certain instances of time do we see a defined variance in values. From there, we can go and determine the direction of wind at those instances. When that is done, we can see from *Fig. 5* that when the wind is blowing from the southwest to the northeast, the northeast station is quite warmer when compared to the southwest station. We also see a peak in the northwest station's reading when the wind direction comes from the southeast.



Figs. 4&5: For the period Nov. 4-10 (above) and Nov. 11-18 (below) , a separation in station air temperatures is evident and correlated to the direction of wind. (Courtesy of Henschen et al.)



As seen in *Fig. 4* above, a similar occurrence takes place as the wind shifts from the southwest between the central (MAWS) station and the northeast station. A pronounced difference in air temperatures is clear over four days, all with the northeast (downwind) site being distinctly warmer than the central (upwind) weather station.

Shifting over to the research by Roy and Traiteur, we focus on their data from San Gorgonio Wind Farm collected by others during June and August of 1989. Again, we see that, on average, the air temperatures from the upwind site are cooler during the late night and early morning hours *(Fig. 6)*. This is on the order of about a degree Celsius. During the daytime hours, the upwind tower is warmer than the downwind tower, as we would expect. Interestingly enough, though, the difference is much more well-defined. Around 13Z local time, the difference in the two temperatures was about four degrees Celsius *(Fig. 6)*.

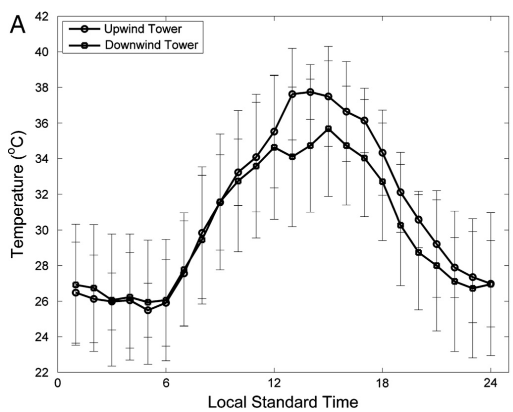


Fig. 6: Air temperature data from two towers on the site of the San Gorgonio Wind Farm in California for a twenty-four hour period. (Courtesy of Roy & Traiteur)

As Roy and Traiteur point out in their own research, the near-surface warming by the wind turbines can be verified from atmospheric sounding data from a nearby location (Roy and Traiteur 1). Specifically, they provided a vertical air temperature profile from the Edwards Air Force Base station for this same time period, as it is the closest World Meteorological Organization (WMO) weather station to the San Gorgonio Wind Farm, according to Roy and Traiteur. The profile gives data for three specific hours during a day, 4 AM, 10 AM, and 4 PM, all local time. As you can see in *Fig. 7*, the near-surface air temperature at 4 AM is cooler than the air temperature is aloft. This corresponds well to the data that shows near-surface air temperature is warmer downwind of the wind turbines than upwind of them. As hypothesized, the turbines mix down warmer air from aloft and mix up cooler air from the surface. As the hours progress, the surface warms up to higher temperatures than those aloft, as seen in the 10 AM and 4 PM vertical profiles. Again, this supports the idea of mixing air by the turbines as we see how cooler air aloft is mixed down to cause the near-surface air temperatures to become cooler than their counterparts at the upwind location.

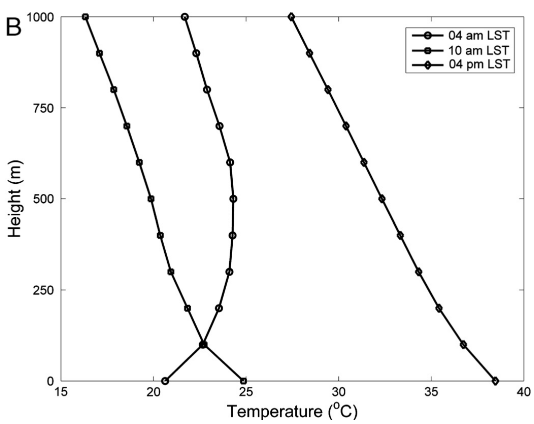


Fig. 7: Vertical air temperature profiles from Edwards AFB for 4 AM, 10 AM, and 4 PM during the San Gorgonio Wind Farm study. (Courtesy of Roy & Traiteur)

Another important factor to consider is how the moisture content of air changes based upon potential impacts from large wind farms. Starting with research from the Purdue University team again, we take a look at the data collected on relative humidity changes in time based upon wind direction shifts. For the same time period, November 4-18, 2010 at the Meadow Lake Wind Farm, we can seen that for the central (MAWS) station, relative humidity is much greater than at the northeast station for southwesterly flow *(Fig. 8)*. This same event happens on several occasions over the two week span (Henschen et al. 25-26). One particular day saw a difference of almost fifteen percent (55% to 70%). Therefore, the same pattern indicates that as air moves through the area where the wind turbines are located, the air progressively dries out. In the study conducted by Roy, Pacala, and Walko, scenario #2 from the model simulation also showed a drying out of near-surface air (via the near-surface total mixing ratio) as vertical mixing took place in time (Roy, Pacala, and Walko 5). This coincides well where the dew point temperature decreases with height, that drier air may be mixed down to the surface.

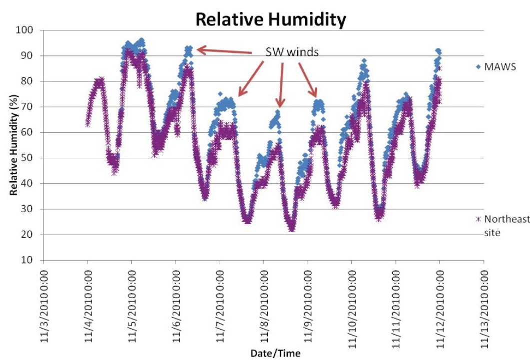


Fig. 8: The blue line shows RH change with time for the central (MAWS) station, while the purple line show RH change at the northeast site. The arrows indicate when the wind is southwesterly. (Courtesy of Henschen et al.)

Staying with Roy, Pacala, and Walko, we now shift gears to effects seen on wind speed. First of all, we can say again that the effects will be seen most distinctly during the early morning hours. This is in part due to the low-level jet that becomes established during the nighttime period over the eastern and central parts of the U.S. (Haby). This keeps the turbines operating at a higher efficiency than during the daytime period. Knowing this, we evaluate the two scenarios established in the model run over the Great Plains (Roy, Pacala, and Walko 4). In relation to the control run, both scenarios reveal a decrease in wind speed for air that has passed through the turbine field. In fact, scenario #2 shows a greater decrease in wind speed, when factoring in the turbines being a source of turbulent kinetic energy *(Fig. 9)*.

Also of interest is the authors' analysis of the air currents around any one turbine. For their simulation, they described the method in which as air passes by a turbine, it slows in speed. As flow decreases in velocity, a turbine may reach its cutoff speed. At that point, because of the turbulent flow surrounding the turbine, momentum from above and below the turbine may help to build speed back up until the turbine begins rotating once again (Roy, Pacala, and Walko 3, 5).

hours. I was wary of using data for individual days, and it is nearly impossible to collect time-averaged data for this type of analysis, so I averaged out the three days' data myself, but to no avail. In fact, the trends that were established became even less. At first, as you may imagine, the results were less-than-satisfying and quite disappointing. An immediate explanation escaped me, so I continued going over the data for days. Eventually, however, after further research and insight into these processes, I believe the answer has become much clearer. As I mentioned before, these three weather stations are located in three close-by towns, and are the closest with full

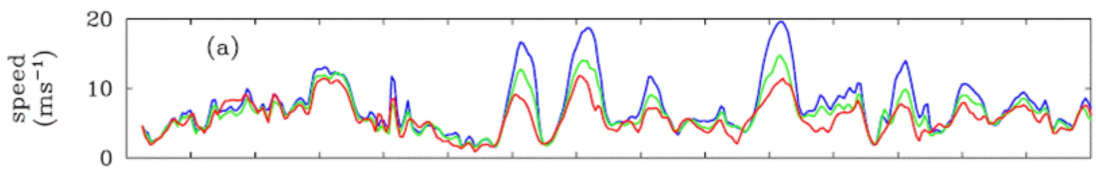


Fig. 9: Simulated wind speed in time as it passes through wind turbines, with blue indicating the control run, green as scenario #1 and red as scenario #2. (Courtesy of Roy, Pacala, & Walko)

It is important to point out, however, at least in this case, that the slower wind speed is most expected near the turbine's height above the surface. In actuality, with a nocturnal low-level jet overhead, the vertical mixing caused by the wind farm may bring faster wind speeds down to the surface, not slower ones.

In a pre-review of sorts for the three main parameters we have studied, air temperature, moisture content, and wind speed surround large wind farms, I am going to lastly focus on the data gathered from the National Climatic Data Center for the Buffalo Gap Wind Farm in Texas. For the three days of data collected in Abilene, Sweetwater, and San Angelo, based upon the direction the wind was blowing, I expected to also see a general trend favoring the discussion we have had on the three atmospheric variables. What I instead found was at best some slight indication of trends, and somewhat sporadic throughout the day. Even this mostly came with the air temperature modifications in the morning

data available simultaneously (Maps|NCDC…). This is in contrast to the above-mentioned data. Those were either simulated in the wind farm field or actually taken from within the farms. Differing from the data I collected is that many other influences must now be factored in.

For instance, San Angelo's station is actually at a distance of 50 miles from the southern edge of the Buffalo Gap Wind Farm. Sweetwater's station is roughly 12 miles from the closest point to the farm, and Abilene's station is similarly 10 miles away. Dispersion of the mixed air now certainly becomes an issue, as does near-by influences on the stations themselves. For example, the Abilene station is located at Dyess Air Force Base, the San Angelo station is at San Angelo Regional Airport and also in proximity to Lake Nasworthy, and the Sweetwater station is at Avenger Airfield (Maps|NCDC…). This all may be summed up to poor data quality. However, there are not necessarily any better options. This wind farm was selected with terrain in mind, so that the land is mostly flat and this factor could be eliminated. Other wind farms of this sort had even less available data, though. However, despite this conclusion, there is still an important discovery through all of this. We have seen wind farms have impacts on these atmospheric parameters when studying data from the immediate vicinity, so that is not the question. What is the result, intrinsically, is that when one ventures much outside of this area, the effects from the wind farm are felt much less. Hence, though the large wind farms may alter conditions locally, it can be concluded that, at least in most cases, those effects remain exclusive to that locality. As distance from the wind farms increases, the effects seen plunge rather dramatically.

Summary

In conclusion, what we have discovered is that large-enough wind farms can have an impact on air temperature, moisture content, and wind speed in a limited area, depending upon the spread of the farm's area. Warmer air being mixed down to the surface was evident at the Meadow Lake Wind Farm and the San Gorgonio Wind Farm, and was expectedly simulated in Roy, Pacala, and Walko's study. The amount of moisture in the air was found to have decreased on the downwind side of the Meadow Lake Wind Farm, and again simulated to be lower in Roy, Pacala, and Walko's modeled experiment. Also in their experiment, we saw that winds would decrease at the turbine-height level and increase near the surface, being most pronounced in the early morning hours with an overhead low-level jet in place. In addition, although they were not included as primary components of this research, both sensible heat flux and latent heat flux play a role in the wind farm theory. For instance, in going back to Roy, Pacala, and Walko's experimental model, there was a significant reversal of sensible heat flux as the near-surface air warmed from mixing, leading to heat transfer to the soil from above. Latent heat flux did just the opposite (with evaporation from the soil to the air above), due to the drier air being mixed down by the turbines from aloft (Roy, Pacala, and Walko 5). All of these observations, again, took place within the confines of the wind farms themselves. For the Buffalo Gap Wind Farm, these effects were less evident, although the data was gathered from stations outside of the farm's margins. This would simply signal that though large wind farms cause a change to local weather conditions, it will be limited to the immediate area, as outside factors will become more prominent the farther you get from the wind farm.

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