POTENTIAL CLIMATE CHANGE IMPACTS ON WIND RESOURCES IN OKLAHOMA: A FOCUS ON FUTURE ENERGY OUTPUT

By

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CHAPTER I

INTRODUCTION

Oklahoma possesses some of the best wind resources in the world. However, wind regimes are not static; they are dynamic in nature. Wind regimes are sensitive to natural climate variability as well as anthropogenic-driven climate change. The fundamental concern with all renewable energy based on meteorological parameters is determining the variability and reliability of that resource on spatial and temporal scales (Krauze 2009). This study focuses on how climate change could impact future wind resources in Oklahoma, with attention to a gain or loss in power generation resulting from a changing climate.

According to a publication by the Intergovernmental Panel on Climate Change (IPCC), the general scientific community is in agreement that human activity is having a net warming effect on the Earth's average global temperature, which could impact global weather patterns (IPCC 2007). Wind on the local level is influenced by global weather patterns. If global patterns change, local wind patterns might change as well. The purpose of the proposed study is to forecast the change in future wind-energy output in Oklahoma using National Center for Atmospheric Research (NCAR) and Geophysical Fluid Dynamics Laboratory (GFDL) Global Climate Model (GCM) output forced with carbon-dioxide (CO_2) emission scenarios. A *Geophysical Research Letters* study notes that any changes in near-surface wind velocities caused by global climate change could have large societal impacts (Pryor et al. 2006). The study goal here is to analyze data from the North American Regional Climate Change Assessment Program (NARCCAP) within NCAR and forecast potential changes in electricity generation from wind resources resulting from climate change. The study will focus on wind velocity changes on a seasonal basis because wind climates are sensitive to changes in seasons. Moreover, the proposed study will apply the changes to utility-scale wind-farms to speculate how changes in wind patterns will affect the magnitude of electrical output in wind-farms within this study domain. Overall, changes in wind-generated power resulting from climate change might have an effect on future return on investment (over the life of the wind-farm) due to potential energy output changes and availability of wind-generated electricity. The results of the proposed study might be beneficial to many groups of people ranging from investors, managers, and Oklahoma citizens in general and, specifically, to anyone who is connected to Oklahoma's wind power industry.

The current study will first focus on literature in four main areas: (1) past wind climates, (2) Oklahoma wind climate, (3) potential climate change impacts on wind resources, and (4) long term energy production outlooks. Following the literature review, the data used in the current study are described. These include NARCCAP Global Climate Model (GCM) output with the A2 IPCC CO_2 scenario implemented, Oklahoma Mesonet observations, wind-farm characteristics, and a cubic-spline equation that fits the General Electric (GE) 1.5 mega-watt (MW) SLE power curve. Next, the methods used in the current study are discussed including the data processing, analyses, mapping, and power derivations necessary in generating the results. Finally, the findings of the study are reviewed, which will consist of percent changes in future averaged median wind speeds as well as percent change in power generation as a result of the changing wind speeds at two wind-farms in the study domain. These results will show mainly increases in averaged median wind velocities leading to increases in electricity output in future decades at the wind-farms focused on. Furthermore, these results could have great positive impacts on Oklahoma’s wind power industry as well as the economy as a whole.

CHAPTER II

REVIEW OF LITERATURE

Past Wind Climates

Large-scale, global weather is the result of energy transfer from the equator to the poles by atmosphere and ocean. Brazdil et al. (2009) identify the current process of global warming as a significant factor that affects the development of our natural environment at the local, regional, and global scales. Wind is connected to changes in global circulation and so is the resulting wind energy output. Applying these thoughts to wind resources, the local scale is important when comparing the size of wind-farms to nature in general. This suggests the significance of modeling future wind regimes and will be discussed in the next portion of the literature review. Brazdil et al. note statistically significant falling mean wind-speed trends in all months, seasons, and annual values over the time period of 1961-2005 in the Czech Republic (Brazdil et al. 2009). The results Brazdil et al. (2009) present in Europe are important when assessing the results of this thesis.

Decreasing wind speed trends, whether natural or anthropogenic, will decrease wind power density. Wind power density is the industry-standard measurement of wind power potential and is measured in watts per square-meter. Wind power density is a function of the cube of the wind speed, meaning minimal decreases in wind speed could mean significant decreases in wind energy output. Wind power density is defined as

$$W.P.D. = \frac{1}{2} * \rho * V^3 \tag{1}$$

where ρ is air density and V is wind velocity (“Determining Wind Power Density” 2010). Brazdil et al.’s study also reports statistically significant falling trends in relative humidity over the same time period. Although wind power density is not as sensitive to air density as compared to wind velocity, the falling trends in relative humidity mentioned will affect power potential due to the relationship between relative humidity and air density. This study supports the idea that changes in wind climates affect wind power density.

Several studies have been published on past wind climates of the United States. Klink (1999(a), (b)) examines past wind climates stating monthly mean wind speeds are highest in winter and spring when equator-to-pole temperature and pressure gradients are most intense. This is an important statement that supports the decision to analyze the data in the present study by season. Also, due to the characteristics of the power curves of commercial wind turbines, maximum and minimum wind speed climatologies are vital because they provide insight on where the greatest sensitivity exists for potential energy output changes.

A recent study completed by Pryor et al. (2009) provides some motivation for studies on wind climate. They note important past changes in wind climates caused by variation of the global climate system (as well as future changes) are of great importance to the wind industry. The authors go on to state that estimations of power over the 30 year lifetime of the wind-farm are necessary for economic feasibility (Pryor and Barthelmie 2009). Wind industry investors are not safe to assume the current wind regime will be static and compute their return on investment on that basis. An understanding of how the wind regime might change is necessary for accurate return on investment forecasts. Pryor and Barthelmie (2009) show statistically significant declines in wind speeds in all data sets in their study over the period of 1973-2000 across the country. More specifically, the study highlights that negative trends are the largest across the eastern Continental United States (CONUS) and parts of the Plains, but not including Oklahoma. According to another study by Pryor et al. (2007) during the period from 1972-2005 there was a decline in wind speeds across much of the CONUS which resulted in lower average wind power density at the end of the period when compared to the beginning. This research noted more than 30% decreases in average wind power density in some places over the study area. These studies also note climatological maxima and minima in wind speed over the CONUS. Pryor and her co-authors note a winter maximum over the eastern CONUS associated with strong baroclinicity and a spring/summer maximum over the western CONUS (Pryor et al. 2007). It is important to note that these studies do not use observations from a highly dense and accurate network like the current study.

Although some research focuses on changing anemometer technology as a potential cause, the above trends are statistically robust; therefore this cannot fully explain the changes (Pryor and Barthelmie 2009). Other potential causes include hemispheric temperature trends and cyclone frequency shifts (Pryor and Barthelmie

2009). However, these causes would not uniformly affect regional wind speeds because the changes themselves are not uniform.

Regional studies on wind climates can potentially show finer spatial detail in wind climatologies. Areas of the Midwest have experienced a 10% decline in wind speed over the period from 1973 to 1987 (Pryor et al. 2007). On a state-by-state scale, some of the sharpest declines in wind speed occurred in Ohio, Indiana, Kansas, Michigan, Illinois, Louisiana, northern Maine, western Montana, and Virginia (Pryor and Barthelmie 2009). Furthermore, Pryor and Barthelmie (2009) state that wind speeds were decreasing more in the east than in the west, mostly in the northeastern United States and in the Great Lakes Regions, with good theoretical reasoning to believe global warming is the culprit. Wind patterns are globally, synoptically, and locally driven; hence any changes in weather patterns on the global scale could potentially filter down to the regional and local scales influencing climatological variables, such as wind. Yet, there is no evidence to think the changes will be spatially uniform.

Oklahoma Wind Climate

Wind climatology across the state of Oklahoma is highly seasonal where prevailing winds are out of the south during the spring, summer, and fall seasons. Diurnally, from sunrise to sunset to sunrise, winds shift from southeasterly to southwesterly back to southeasterly, respectively. During the winter the winds are bimodal, equally split between northerly and southerly for the most part. These seasonal swings are more dramatic in the northwestern portion of the state (“The Climate of Oklahoma” 2010).

Climatologically, the strongest winds are found in western Oklahoma and the northeastern Texas panhandle due to higher elevation as well as the geography: flat, less-populated areas result in less surface friction to hinder the wind. Also, these areas are lee of the Rocky Mountains where topography can influence the wind. Central and southern Oklahoma and north-central Texas have lower wind velocity magnitudes perhaps due to the further distance from the Rocky Mountains and lower elevation. In areas with more cities and higher populations, there is higher surface-friction that can inhibit the wind as well. Meteorologically speaking, the Rocky Mountains help to funnel disturbances into western areas of the study domain here, and the further east, this effect begins to fade. Moreover, most upper-level storm systems that affect this region of the country move into the study domain from the north-northwest and lift out to the northeast very quickly. This is a result of the polar front jet stream that influences the path of upper-level storm systems (Figure 1).

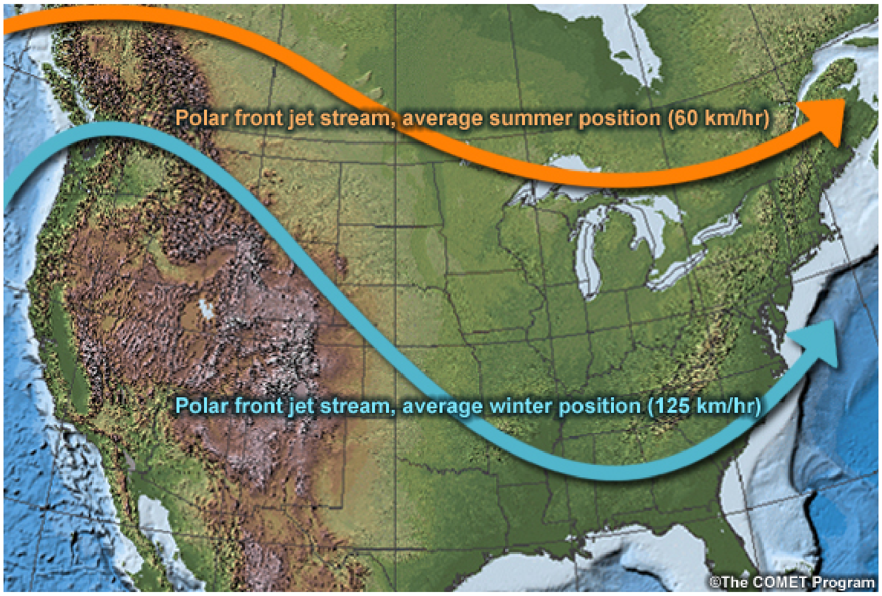


Figure 1: Average jet-stream path for Winter and Summer (“Introduction to Climatology” 2008).

The jet stream is a result of strong temperature gradients which is related to pressure-gradients via the equation of state (or the ideal gas law); the stronger the pressure-gradient force the stronger the jet stream. These patterns are important to understand when analyzing the potential changes in future patterns. This information will be important when addressing the potential causes of changing wind patterns in the future across Oklahoma.

Potential Climate Change Impacts on Wind Resources

Research on potential change in wind velocities ranges from international scales to regional scales. Several studies in northern Europe address how climate change will affect wind energy density in the future. Northern Europe has considerable economic interest in the potential impact of climate change on wind resources (Pryor et al. 2005(a)). A publication by the Finnish Meteorological Institute states how the climate strongly affects the potential power production based on renewable energy sources. The study's main objective is to assess the effect of climate change on wind power by 2020 (Tammelin et al. 2002). This research from the European community shows how important these potential climate change effects are to Europe's wind industry and the concern surrounding the issue. This leads to questions regarding anthropogenic climate change effects' on wind resources (Pryor et al. 2006).

The methodological consensus in these types of studies is to downscale Global Climate Models (GCMs) with output from various carbon dioxide emission scenarios in an attempt to model climatological variables in greater spatial detail and accuracy. This consists of running a reanalysis on the past climate with the model and comparing it to wind observations (from the same time-period) to check model accuracy, and then to compare the reanalysis data with the prognostic-emission scenario data to examine any differences (Pryor et al. 2005(b)). Some data and models include CO_2 emission scenarios from the IPCC as well as scenarios from the Hadley Centre in the UK and scenarios from the UK Climate Impact Programme (Tammelin et al. 2002). All studies reviewed here use similar data and methodology: GCMs are downscaled to output regional-scale climatological variables influenced by a certain level of CO_2 emission. Reanalysis data is three-dimensional forecasting that is initialized with real climate observations such as temperature, wind speed and pressure ("What is Reanalysis Data?" 2010). This reanalysis effort has been fairly successful and model runs showed qualitative agreement with observational data from 1961-1990 (Pryor et al. 2005(b)).

Empirical downscaling, a statistical based method that derives smaller scale climate from larger scale climate through the use of cross-scale relationships using random or deterministic functions, shows the greatest consistency between model reanalysis data and observations (Hewitson and Crane 1996). Also, model outputs show future emission projection-based changes differ from reanalysis modeled data, suggesting anthropogenic-caused climate variation (Pryor et al. 2005(b); 2006). Hadley Centre CO_2 emission scenarios would result in increased average wind speeds of about 7% over the Nordic region. Although variations in wind speed changes with different scenarios exist, the consensus with respect to this study indicates increased wind speeds in the future, mostly in the winter months (Tammelin et al. 2002). On a seasonal time-scale, winter wind speeds could increase as much as 5% to 10% in northern England and Scotland, with slight decreases possible in the summer months (Harrison et al. 2008). These European studies provide good insight on how to apply these ideas to Oklahoma through their data and model selection as well as their methodologies.

Climate change and its impact on renewable resources are being extensively studied in the United States and have produced studies similar to the European ones. Wind power is a fast-growing industry in the United States because of the need to decrease the use of coal-based sources of energy coupled with the fact that the country possesses some of the best wind resources in the world ("Nordex opens for business…" 2010). However, how might potential climate change in the CONUS alter these resources? Due to increased CO_2 emissions, GCMs forecast weakening north-south temperature gradients, the key that drives most synoptic-scale wind patterns (Segal et al. 2001).

Scientists have previously studied the natural variations in wind patterns but are now considering the risk of human-caused climate variation. A study by Breslow and Sailor (2002) implemented GCM data with CO_2 emission scenarios from the IPCC and Canadian Climate Centre to model future changes in climate variables where they found potential 1% to 3% decreases in average wind speeds for the United States over the next half century. As a result, a 3% to 27% decrease in energy output is possible in the near future.

A study by Segal et al. (2001) differed by nesting (embedding) a regional climate model (RegCM2) inside a GCM (HadCM2) to create two ten-year climate simulations, one to model current climate trends and the other modeling enhanced CO_2 output. The GCM data provided coarse resolution (5^o latitude x 5^o longitude), while the regional climate model (and GCM downscaling) provided better spatial resolution (as fine as 1^o x 1^o) of climate parameters.

There are pros and cons when looking at the data and methods of the Segal et al. (2001) and the Breslow and Sailor (2002) studies. It is important to compare reanalysis runs of the model to past observations to justify model accuracy. However, nesting a regional model inside a GCM is an excellent resolution-aiding methodology. A study that combines both methodologies would be appropriate. According to Segal et al.'s study, reanalysis output is consistent with observations overall, but with seasonal variation. Some seasons are underestimated while others model real observations more accurately. The Canadian Climate Centre model forecasts 8% to 10% decreases in winds in the summer, and 4% during the winter months in the future. The Hadley model shows little seasonal variation (Breslow and Sailor 2002). The results of the nested regional-model study are broken up into seasonal daily wind power output and annual average wind power output. The seasonal results indicate an all-season decrease in wind power of up to 20% by 2075, but potentially higher in some states. Furthermore, a decrease in annual average wind power is simulated as well (Segal et al. 2001). Both studies above that focus on the potential for climate change impacts on wind resources were consistent in their findings, even though somewhat varied in methodology. The findings support an overall decrease in wind speeds on a regional scale, with compounded decreases in wind energy density in the future due to the cubic relationship between wind velocity and power generation.

Another study of climate change affecting wind power generation is on a regional scale in the northwestern U.S (Sailor 2008). The study includes Idaho, Montana, Oregon, Washington, and Wyoming. Sailor's study chose a single weather observation station in each state to validate the model(s) used. GCM output was taken from each grid cell nearest to major airports in those states for use. Statistical downscaling was used in this study to aid in the spatial resolution of the data. In the Sailor study, one of the models used includes the Climate of the 20th Century Experiment model run from the Goddard Institute for Space Studies/GFDL. A tree-structured regression based downscaling technique was applied to this model. The model used six GCM output variables including zonal, meridional, and total wind speeds. This tree-structured regression downscaling technique was also applied to IPCC Special Report on Emission Scenarios (SRES) versions A1B and A2 (Sailor 2008). Both scenarios follow the same emission curve (see Figure 3) until the second half of the century, when A1B starts to level off based on policy to inhibit CO_2 emissions and A2 continues to increase emissions. When comparing raw (non-downscaled) GCM data models to one another, strong discrepancies were evident. This acts as a limitation in the confidence in the model output. The raw GCM reanalysis data did not model past wind observations well; however, after the output was downscaled statistically, accuracy improved. The results are similar to the previous U.S. studies. The model results project wind speeds to likely decrease in the Pacific Northwest in summer months, with smaller changes in the winter months (Sailor 2008). Although many of the models differed in how much decrease in wind speeds will be seen (some the equivalent of up to a 40% decrease in energy density), they all showed negative trends.

Before literature on energy outlooks is reviewed, a few studies on the effects of climate change will be reviewed that focus on the same geographical location as this thesis. The goal here is to identify the lack of concentration on changes in wind patterns as well as show the coarse resolution of current studies in this geographical area. According to a publication by Karl et al. (2009), temperatures in the Great Plains (including Oklahoma) are going to increase and precipitation patterns will result in drier conditions. Moreover, the Oklahoma Climatological Survey has published a "statement on climate change and its implications for Oklahoma" based on IPCC output's which states "global climate models are unable to accurately simulate small scale weather events" (Crawford and McManus 2007). The publications note a warming climate and an increase in precipitation extremes. The lack in focus on the effect of a changing climate on wind velocities in the studies above are examples why the current study is needed.

One GCM that was used to come to some of the conclusions in the above research is the United Kingdom Hadley Centre's climate model with a spatial resolution of 2.5° latitude x 3.75° longitude (US EPA 1998). This grid resolution translates into roughly 417 km x 278 km at Oklahoma's latitude. This thesis uses model resolution of 50 km x 50 km and provides insight on regional and meso-level meteorological influences. The present study is timely due to the fact that it focuses on climate change impacts on wind patterns and derives its results from global climate models with much smaller spatial resolution.

Energy Outlooks and Output Impacts

The final portion of the literature review examines natural variation in wind climates affecting wind-energy output and how anthropogenic climate change carries the same potential result. Also, the importance of long-term wind outlooks will be highlighted in an attempt to legitimize the purpose of this study as well as be a means of keeping people aware of the potential for future wind-energy changes.

Variations in weather and climate potentially pose serious challenges to the electricity supply industry (Parkpoom et al. 2005). Anthropogenic climate change might compound these variations; therefore, past natural variation may behave in the same way as future variation. The commonly-used assumption that the future will be similar to the past may not hold (Parkpoom et al. 2005). Long-term variability in wind regimes exists on a sufficient scale to be of concern to the wind industry. Palutikof et al. (1987) notes a variation in wind velocity of roughly two meters per second over a sixty-year period in Britain. These natural variations roughly translate into an 18% decrease in energy output. If the above results were short-term anomalies around a long-term stationary mean, this would not be significant. However, these patterns continually occur and can persist for up to a decade. No matter what purpose or size of a wind-power-generating project, the prediction of expected power output closest to reality is vital (Palutikof et al. 1987). Baker et al. (1990) notes the significant uncertainty in energy estimates from wind-farms due to inter-annual and inter-seasonal variability. In the western United States, almost 80% of the energy from wind-farms is produced in the summer months. Any periods with abnormally weak winds can spell significant reduction in energy output for these wind-farms.

The above example can be applied anywhere. For example, if weakened springtime low-level jets of the southern Great Plains were to persist, Oklahoma wind-farms could experience lower energy output (Greene et al. 2004). This would be a short-term result, but if climate change semi-permanently changes the low-level jet pattern in this region, it could turn into a longer-term impact. Baker et al. (1990) concludes by stating maximum and minimum seasonal energy values can vary naturally by 25% to 50% from the mean seasonal energy value in the Pacific Northwest. That percentage change could really hinder return on investment time scales as well any electric-grid based requirements the wind-farm must uphold.

The importance of long-term wind outlooks is seen through the known relationships between the variation of wind climates and resulting change in energy output as mentioned in the previous portion of this review. A site's wind resource is the driver of many financial income streams including power production agreements, selling wind energy, receiving renewable energy credits, production tax credits, and other sources of revenue from the production of wind energy. Understanding wind power from a financial/economical standpoint is just as important as understanding it from a physical standpoint. Typical investments for a 100 megawatt (MW) wind-farm can be more than 200 million dollars, and any minute long-term variation in wind speed can mean significant financial impacts (Krauze 2009).

Current economic conditions sum up how important studies like this thesis are to this industry. In commenting on the relationship between finances and wind power on a climate time scale, a publication by RMEL Electric Energy states the

> Financial implications of not having wind power forecasts cannot be overplayed…imbalance charges resulting from deviations in scheduled output will steepen project operating costs. Wind power forecasts can help to minimize these penalties (Lerner and Garvert 2009, 39).

These variations are significant enough to affect power generation over the approximate thirty-year life-time of a wind-farm.

Long-term wind forecasts, possibly showing any changes from climatological means, are very important to this industry. Within the growing United States wind industry, long-term wind energy outlooks will become more and more crucial. It will become increasingly important to consider changes to our climate caused by human activity. A full understanding of the availability, variability, and reliability of wind as an energy source is crucial for the efficient and effective development of reliable and cost-effective renewable energy production (Krauze 2009).

CHAPTER III

DATA AND METHODOLOGY

Data

The spatial domain of this study was the entire state of Oklahoma as well as the Texas panhandle and portions of surrounding states that creates a “rectangle” of latitude and longitude. Data used in this research study were (1) NARCCAP GCM runs that simulate past climate from 1990 through 1999, (2) NARCCAP GCM data from 2039 through 2070 with CO_2 emission scenario A2 from the Intergovernmental Panel on Climate Change’s (IPCC) Special Report on Emissions Scenarios (SRES) (2007), (3) current wind-farm locations in the domain that fall in locations where wind velocity changes are greatest, (4) Oklahoma Mesonet wind velocity data from Mesonet stations closest to each wind-farm, and (5) the industry standard 1.5 MW General Electric SLE wind turbine power-curve used to forecast specific changes in electricity output over the temporal range for this project.

NARCCAP

The heart of this thesis consists of simulated past climate data as well as projected future wind speeds from NARCCAP which implements certain GCMs that are forced with the A2 SRES emission scenario. The goal of NARCCAP is described as follows:

> NARCCAP will systematically investigate the uncertainties in regional scale projections of future climate and produce high resolution climate change scenarios using multiple regional climate models (RCMs) nested within multiple atmosphere ocean general circulation models (AOGCMs) forced with the A2 SRES emission scenario, over a domain covering the conterminous US, northern Mexico, and most of Canada. The plan also includes an evaluation phase through nesting the participating RCMs within reanalyses of observations (Mearns 2007, 2).

More specifically, a portion of NARCCAP focuses on ‘time-slice’ experiments concentrating on two slices of time: one in the past and one in the future. This study will concentrate on this ‘time-slice’ portion of NARCCAP. Two different GCMs are used for each time slice, the first time-slice represents ‘historical’ conditions (1969-2000) which was modeled by the atmospheric component of the Geophysical Fluid Dynamics Laboratory’s (GFDL) GCM, known as the AM2.1 (“FMS AM2 Model” 2010). The second time-slice (2039-2070) is modeled by the third version of the Community Atmosphere Model (CAM 3.0); this is a portion of NCAR’s GCM called The Community Climate System Model (CCSM), a coupled climate model for simulating the earth's climate system (“The NCAR Community Climate Model (CCM3)” 2010). Both of these sub-models contain only one component of each parent GCM, as explained below:

> In the time-slice experiments, the atmospheric component of an Atmosphere-Ocean Global Climate Model (AOGCM) is run without the full-coupled ocean component of the model. Instead, the boundary conditions for sea surface and ice for the historical run are based on observational data, and boundary conditions for the scenario run are derived by perturbing the same observed sea-surface temperature and ice data by an amount based on the results of a lower-resolution run of the full AOGCM (“NARCCAP Time-Slice Experiments” 2010, 1).

This is done because the computational requirements of the simulations are lower, resulting in higher resolution of the output.

The output from each time slice is 50 km x 50 km. In this thesis, the GCM output will be represented with a grid of 228 points across the study domain. Each point represents the centroid of each grid box (Figure 2). The grid-point pattern is comprised of centroids of 50 x 50 km grid boxes across all 228 latitude/longitude pairs.

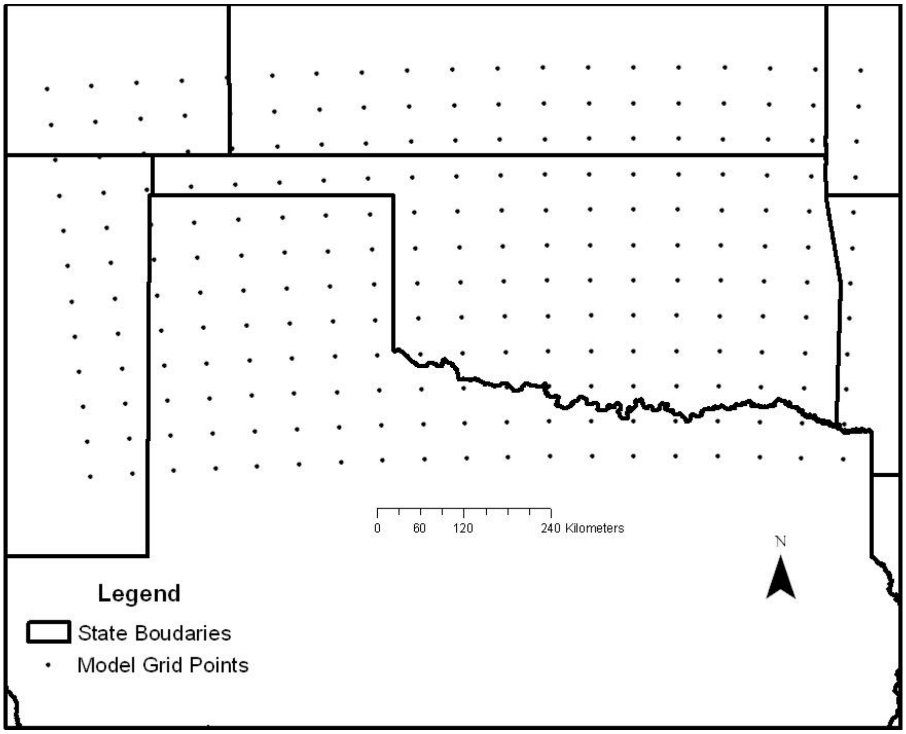


Figure 2: Study domain showing NARCCAP GCM output grid-points

Historical Time-Slice (GFDL CM2.1)

The model that provided the simulated past output from 1969-2000 is the atmospheric component of the GFDL GCM. The coupled-model is known as the CM2.1, however, the atmospheric component alone is known as AM2.1. These models were developed to simulate the new IPCC Fourth Assessment (AR4) findings. In 2004, new global coupled AOGCMs (the CM2.x family) were used to conduct climate research studies at NOAA's GFDL ("GFDL's CM2.0 & CM2.1 Models…" 2010). The models are the result of an effort to expand upon the capabilities of past GFDL GCMs. One of the main goals was to create models that can realistically simulate phenomena from diurnal-scale fluctuations and synoptic-scale storms up to multi-century climate change (Delworth et al. 2006). The AM2.1 simulates past climate based on dynamic and thermodynamic equations that represent atmospheric conditions very similar to real conditions of the past. A more detailed description of how these models simulate past climate can be found below:

> These simulations were driven by a rather realistic set of external forcings, which included the known or estimated history of a range of natural and anthropogenic sources, such as variations in solar output, volcanic activity, trace gases, and sulfate aerosols (Reichler and Kim 2008, 304).

Although both models in this study represent state-of-the-art climate modeling, there are issues and limitations with these models (Reichler and Kim 2008). For example, there are many issues with clouds and moist convection as well as the lack of simulation of the stratosphere ("Global Atmospheric Model Development" 2009). More specifically, while the root mean square error decreased from 1.54 K to 1.16 K for CM2.1 (which AM2.1 is a part of), there remained issues with respect to temperature and precipitation bias between CM2.0 and CM2.1 (Delworth et al. 2006). With biases still present in the precipitation and temperature patterns, it is important to note that some biases could exist in the wind pattern simulations as well.

Climate Change Scenario

NARCCAP focused on one IPCC SRES emission scenario; A2 was the chosen scenario due to its overall acceptance in the scientific community at the time when

NARCCAP was being developed. The quotation below explains the characteristics of this emission scenario in more detail:

> The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines. (IPCC 2007, 18).

The A2 scenario (Figure 3) is described by heterogeneity where self-reliance and local identities are emphasized and population increases continuously.

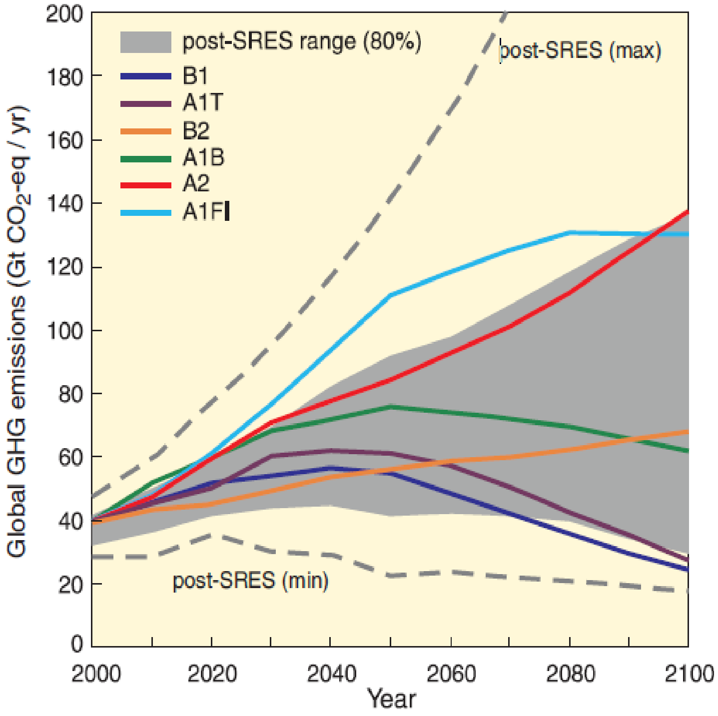


Figure 3: IPCC SRES CO_2 emission scenarios (IPCC 2007)

In fact, the scenario projects global population to rise over 10 billion total by 2050. Economic development is regional and technology development is relatively low in comparison to other scenarios. This scenario seems to be on track with its forecast of population and regional economic development; however, the lack of technological development might be a weakness due to concepts such as Moore's Law that states how the processing power of a microchip doubles every year and a half (Moore 1965).

Future Time-Slice (NCAR CCSM3)

The Community Atmosphere Model (CAM3) is the sixth-generation of atmospheric general circulation models (AGCMs) that have been developed by the climate community and NCAR. It was released to the climate community in June 2004 (Collins et al. 2006). Like many of the GCMs that preceded it, CAM3 was designed to be a modular and versatile model that would be suitable for climate studies by the general scientific community (Collins et al. 2006). CAM3 can either be run as a stand-alone AGCM or as the atmospheric component of the Community Climate System Model (CCSM). Due to the fact that NARCCAP is focused on anthropogenic climate change, the stand-alone version is implemented in the time slice experiments. Further reasoning for this can be found below:

> The stand-alone mode is particularly suitable for examining the response of the atmospheric circulation and state to observe patterns and changes in sea-surface temperature and can also be used to estimate the equilibrium response to external forcings, for example anthropogenic increases in carbon dioxide (Collins et al. 2006, 2145).

One of the main goals of this model is to use accurate and detailed physics schemes that have been updated and adjusted from previous models that are "designed to maintain the fidelity of the simulations over a wide range of spatial resolutions and multiple dynamics" (Collins et al. 2006, 2158). The major changes in the physics from past

NCAR GCMs and the new CAM3 are plentiful. Some of the changes include: the treatment of cloud condensed water using prognostic treatment, updated thermodynamic package for sea-ice, explicit representation of fractional land and sea-ice coverage, new treatment of geometrical cloud overlap in radiation calculations, new parameterization of long-wave absorbtivity and emissivity of water-vapor, updated absorption by water-vapor schemes, updated atmospheric chemistry schemes to represent current atmosphere composition, evaporation of convective precipitation, and finally careful formulation of vertical diffusion of dry static energy (Collins et al. 2006). Further enhancements include a new sea-surface temperature boundary data-set as well as clean and clear separation between physics and dynamics.

Moreover, the CAM3 has technological improvements from the previous version that includes an optional message-passing configuration which allows the model to work in parallel tasks within distributed-memory environments ("The NCAR Community Climate Model (CCM3)" 2010). This improvement sounds simple; however the increased computational power this model has compared to its previous version is order of magnitudes greater.

Mesonet Data/Wind-Farm Locations

In order to apply the results to specific wind-farm projects the percent changes in averaged median wind velocity, derived from the NARCCAP GCM output, was multiplied by the Oklahoma Mesonet wind observations for each respective season and decade in order to show percent increase or decrease in power output. In this thesis, 'averaged median' wind velocities simply refer to the average 'wind velocity value' on a decadal basis; the ‘wind velocity value’ is the statistical median of all 3-hour simulated wind velocities throughout the whole year. Figure 4 below shows a map highlighting where all points are relative to one another.

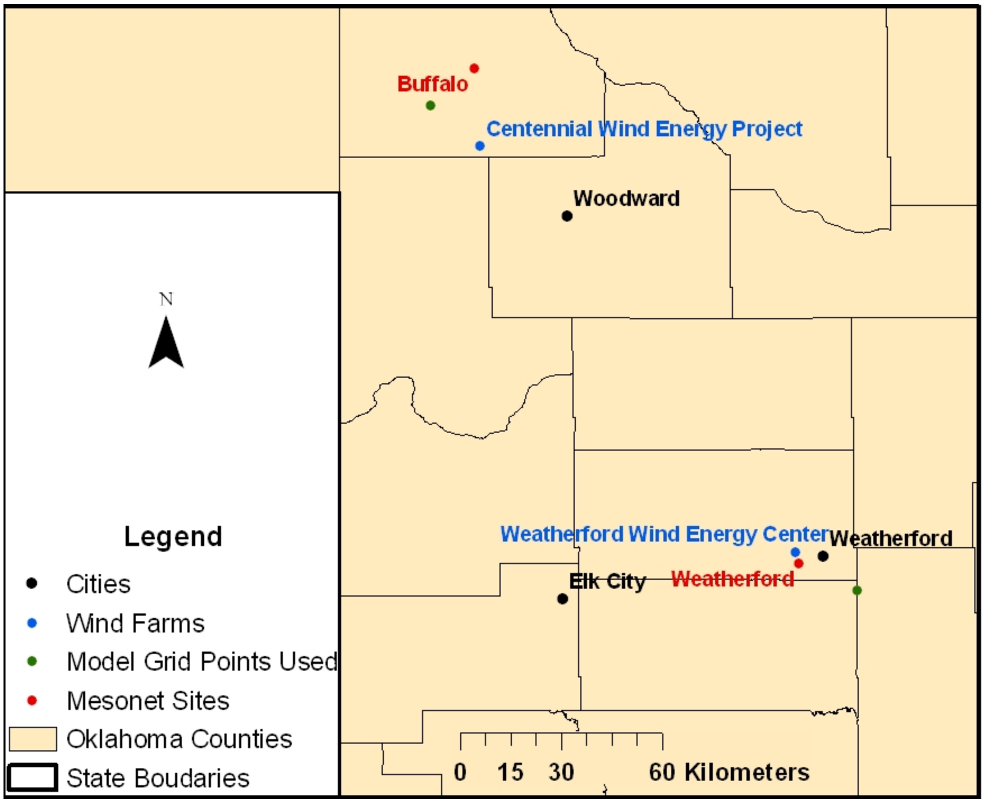


Figure 4: Wind-farm locations and Mesonet sites

The Oklahoma Mesonet is a network of 120 automated meteorological observation stations across all 77 counties in Oklahoma (“About the Mesonet” 2010). Two wind-farms were chosen due to their location in the study domain as well as where they were located with respect to the most dramatic wind velocity changes shown in the NARCCAP output. Furthermore, the closest Mesonet station to each wind-farm was chosen to represent an every five-minute time-series of wind velocity for a year.

In the northern portion of the study domain, the Centennial wind-farm and the Buffalo Mesonet station were chosen. In the southern portion of the study domain, the Weatherford Wind Energy Center wind-farm and the Weatherford Mesonet station were chosen; see Table 1 for wind-farm information and Table 2 for Mesonet site information. The Methodology section will give a more complete explanation of how these sites are used in this study.

Name	**Location**	**Capacity**	**Units**	**Developer**	**Owner**	**Power Purchaser**	**Online**
Weatherford Wind Energy Center	Custer County	147 MW	98 GE 1.5 MW	NextEra Energy Resources	NextEra Energy Resources	AEP - Public Service Company of Oklahoma	May 2005
Centennial Wind Farm	Harper County	120 MW	80 GE 1.5 MW	Invenergy LLC.	Oklahoma Gas & Electric	Oklahoma Gas & Electric	December 2006

Table 1: Oklahoma Wind Power Initiative wind-farm information sheet ("Oklahoma Wind Farms" 2010)

Name	**County**	**Latitude (˚)**	**Longitude (˚)**	**Elevation (meters)**
Buffalo	Harper	36.83	-99.64	+ 559
Weatherford	Custer	35.50	-98.77	+ 538

Table 2: Oklahoma Mesonet station characteristics

The Oklahoma Mesonet is considered high quality data due to a vigorous quality control process (Shafer et al. 2000). Many meteorological variables are measured either on or near a 10-meter (m) tower where the observations are compiled into an archive with 5-minute observations. For this study, the important variable is average wind speed measured at 10 meters. The average wind speed is semi-independent of wind direction and is measured in meters per second. The instrument is the RM Young Wind Monitor that has accuracy of +/- 0.3 meters per second (“Instruments: WSPD” 2010).

In order to assess any changes in power output generated from the wind-farms selected based on the NARCCAP output, wind speeds must be vertically extrapolated to turbine height. Also, characteristics such as power curves and cut-in and cut-out speeds are used for the turbine used in this study. In this thesis, the 1.5 MW General Electric (GE) SLE wind turbine, the most widely-used turbine in the United States, will be used. The wind power law equation (Pryor and Barthelmie 2009), which extrapolates winds from one vertical level to another, is

$$U= (U_R) * [(Z/Z_R)^{\alpha}] \qquad (2)$$

where the wind velocity (U_R) is the wind velocity at the reference height of 10 m multiplied by the ratio of height desired above the ground (Z=80 M) over the reference height (Z_R=10 M) raised to the alpha (α=.143) which approximates vertical speed sheer in a neutral atmosphere. Here, the average turbine height implemented was 80 meters.

Power Calculation

Once the wind velocities are extrapolated to turbine height, the power generation calculations can begin. Figure 5 below shows the relationship between wind velocity and power generated for the turbine used in this study from a General Electric wind turbine specification document.

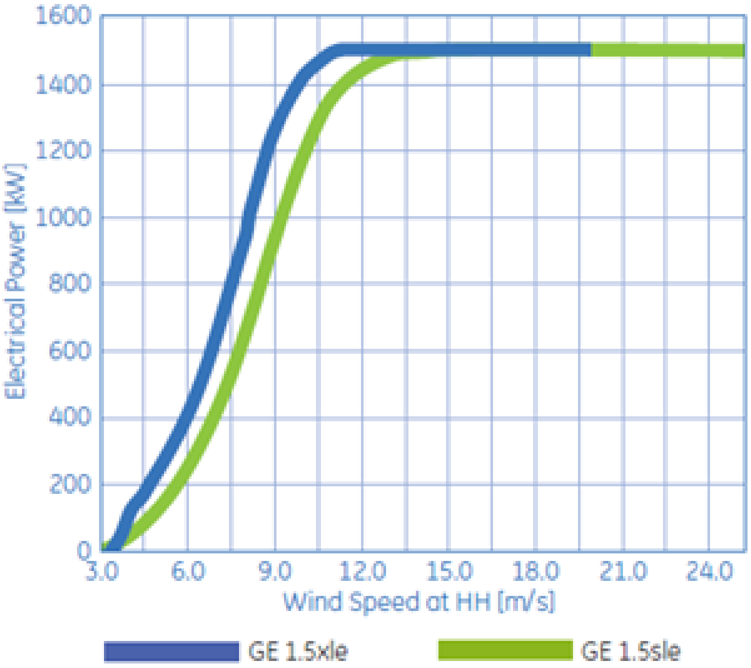


Figure 5: Power curve for GE 1.5 MW turbine ("1.5 MW Wind Turbine" 2010)

In an email message to the author, Ethan Cook provided a cubic-spline equation that represents the GE 1.5 MW SLE wind-turbine power curve (Cook 2010):

$$\text{Power (kW)} = C_1 + C_2*(\text{Speed} - V_1) + C_3*(\text{Speed} - V_1)^2 + C_4*(\text{Speed} - V_1)^3 \qquad (3)$$

where C_1, C_2, C_3, and C_4 are the cubic-spline coefficients for the power curve for this industry-standard commercial wind turbine and V_1 is the reference wind-speed value for each coefficient. Table A.1 in Appendix A lists the information pertaining to this equation. The coefficients in the coefficient table represent values that make up the piecewise polynomial function here. In order to calculate power generated from a certain wind speed, the coefficients associated with that velocity are used.

Methodology

The methodology that was implemented in this research project can be split into four steps. These include: 1) processing the North American Regional Climate Change Assessment Program (NARCCAP) data, 2) performing spatial statistical analyses, 3) choosing wind-farm locations and corresponding Oklahoma Mesonet sites and NARCCAP data grid-points, and, finally 4) calculating total gross power generated at each wind-farm for each time period, by season, as well as percent change over time.

NARCCAP Data Processing

The study domain for this project (shown in Figure 2) has 228 grid-points representing the centroids of all 228 50 km x 50 km NARCCAP output grid boxes. The NARCCAP output for each grid-point represents three-hour averages of 10 m instantaneous wind velocity simulations. In each yearly grid-point file there were 2,920 observations; one observation for every three-hour output. Winter was defined as December through February, Spring was defined as March through May, Summer was defined as June through August, and Fall was defined as September through November as in standard climatological practice. In Figure 6, it can be seen that the distribution at the grid-point at 33.00 N, -103.76 W is not characteristic of a normal distribution; it is skewed to the right. Therefore, the median of all distributions were chosen as a better measure of central tendency.

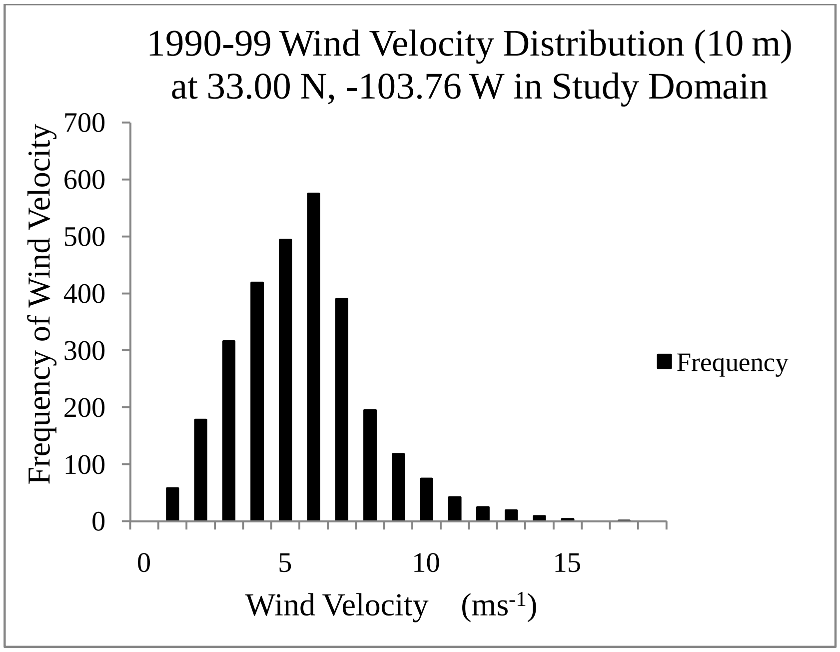


Figure 6: Histogram of 1990-1999 NARCCAP 10 m wind velocity simulations at the 33.00 N, -103.76 W grid-point

Once all of the medians were averaged for each decade per season, percent change in wind velocity median was calculated for all three future decades by comparing them to the 1990-99 decade. The percent change formula is:

$$\text{Percent Change} = [(\text{New Median} - \text{Old Median})/\text{Old Median}] \times 100 \qquad (4)$$

where ‘New Median’ is future data and the ‘Old Median’ is the comparison 1990-99 data.

GIS and Spatial Statistics

Once the NARCCAP data were processed they were input into a GIS for statistical analyses and visual representation. The averaged decadal median wind velocities were mapped by season (4 maps) and by whole decade (1 map), resulting in five maps for the 1990-1999 decade. Initially, the data were mapped in a point pattern by grid-point.

However, in order to analyze spatial patterns a statistical spatial interpolation technique known as Kriging was used.

In recent decades, Kriging has become a powerful interpolation method and a fundamental tool in geostatistics. The method is described in detail below:

> It is based on the assumption that the parameter being interpolated can be treated as a regionalized variable. A regionalized variable is intermediate between a truly random variable and a completely deterministic variable in that it varies in a continuous manner from one location to the next and therefore points that are nearer to each other have a certain degree of spatial correlation, but points that are widely separated are statistically independent (Lucio 2004, 119).

Based on these statements, Kriging seemed to be a reasonable method for representing the NARCCAP data in this project.

There are three main theoretical assumptions in which Kriging is based: (1) first-order stationarity, where data at one location is not influenced by data at another location; (2) second-order stationarity, where covariance depends only on distance and direction apart, not locations; and (3) the distribution of the data are normally distributed (Ge 2010). With regard to meeting these assumptions Figures 7 through 9 should be examined. Figure 7 shows the z-scores of Local Moran's I, where any values with z-score magnitudes greater than 1.63 show statistically significant clustering (non-random patterns) to the 90% confidence interval. This particular confidence interval was chosen because it represents strong confidence. It is important to be aware of spatial autocorrelation as well as address it. The Local Moran's I spatial autocorrelation statistic was used here to address the first-order stationarity assumption above of no spatial auto-correlation (Anselin 1995). This is known as 'LISA' (Local Indicator of Spatial

Autocorrelation); the results were in a point pattern, so they were Kriged to show the spatial pattern.

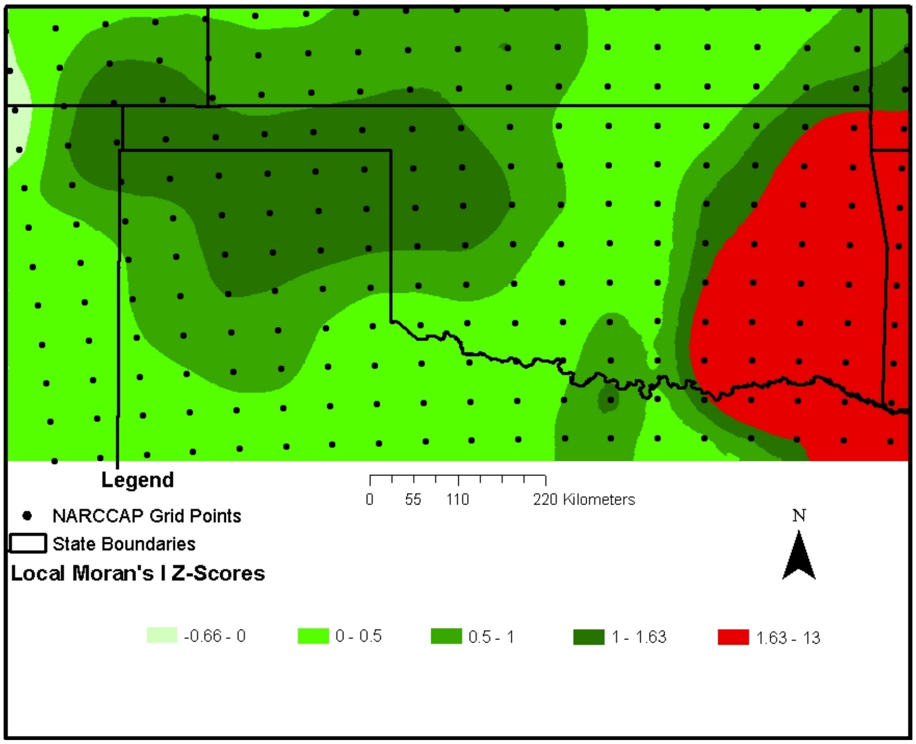


Figure 7: Local Moran's I z-scores for median wind velocity 1990-1999

It is clear from the z-scores that most points show a statistically random pattern (any areas in green on the map above) which meets the first-order stationarity assumption. However, there is clustering in some points in the south and central and northwestern portions of the study domain, but these regions are small when compared to the study domain as a whole.

With respect to the second-order stationarity assumption where the variance in the data should increase as distance increases, Figure 8 should be examined. It is clear that as distance (from a selected point to all others) on the x-axis increases, gamma (γ, represents semi-variance on the y-axis) increases; this relationship meets this assumption.

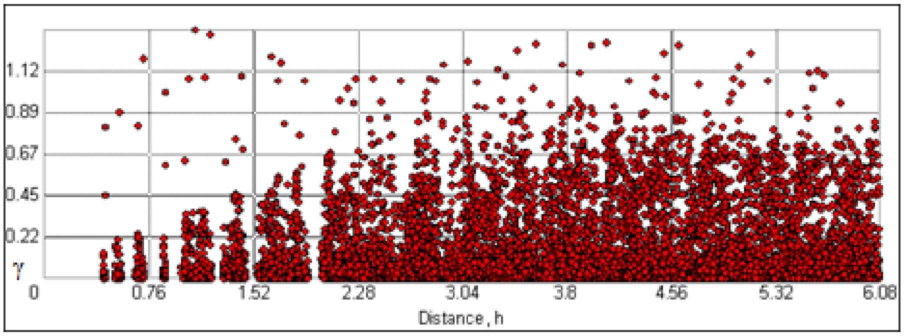


Figure 8: Semivariogram for 1990-1999 median wind velocities

Finally, the normality assumption can be addressed by examining as histogram of the data (Figure 9 below).

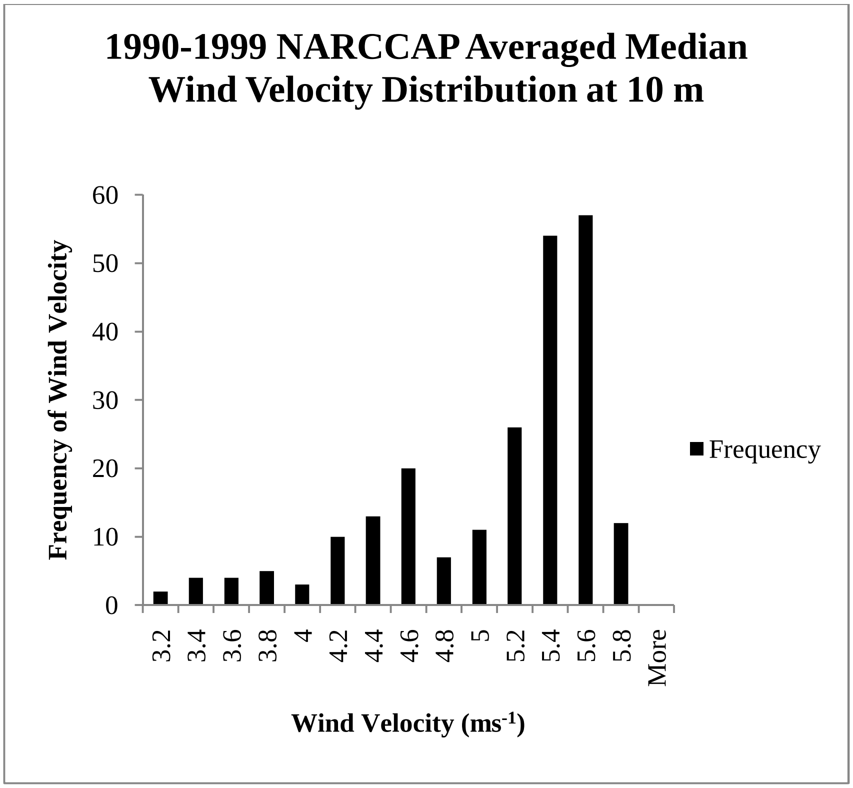


Figure 9: Histogram of 1990-1999 NARCCAP averaged median simulated wind velocities at 10 m over all 228 grid-points

The data distribution is the averaged median wind velocity value for each grid-point from 1990-1999 over the whole study domain (for all 228 grid-points); the distribution is not normal. This is shown here because this is the data the Kriging was performed on. Different transformations were applied to the data, but none improved the distribution in a useful way. Although non-normality may be a limitation in this study, the assumptions for Kriging have largely been met here.

Wind-Farm Site Selection and Corresponding Mesonet/NARCCAP Grid-Points

Once the percent change in averaged median wind velocity were calculated for each season per decade, two existing wind-farm locations were chosen in the study domain. The wind-farm choices were based on geographical location with respect to the most extreme modeled changes in wind velocity; meaning wind-farm locations were chosen in locations in the study domain where the NARCCAP output showed the greatest change. Other attributes such as locations relative to Oklahoma Mesonet sites and type and number of wind turbines aided in the selection of each wind-farm. Centennial Wind-farm in Harper County (north-central portion of the study domain) was chosen and Weatherford Wind Energy Center (WWEC) Wind-farm in Custer County (west-central portion of the study domain) was chosen (refer to Figure 4). The main reasons these two wind-farm locations were chosen include the similar landscape conditions these locations experience such as open, rural land with low population density (relatively low surface friction), elevation with respect to sea level, and where they were with respect to the NARCCAP output (in areas of the spatial domain where more extreme changes in wind velocity occur). The locations vary in elevation by 21 m and are approximately 142 km apart.

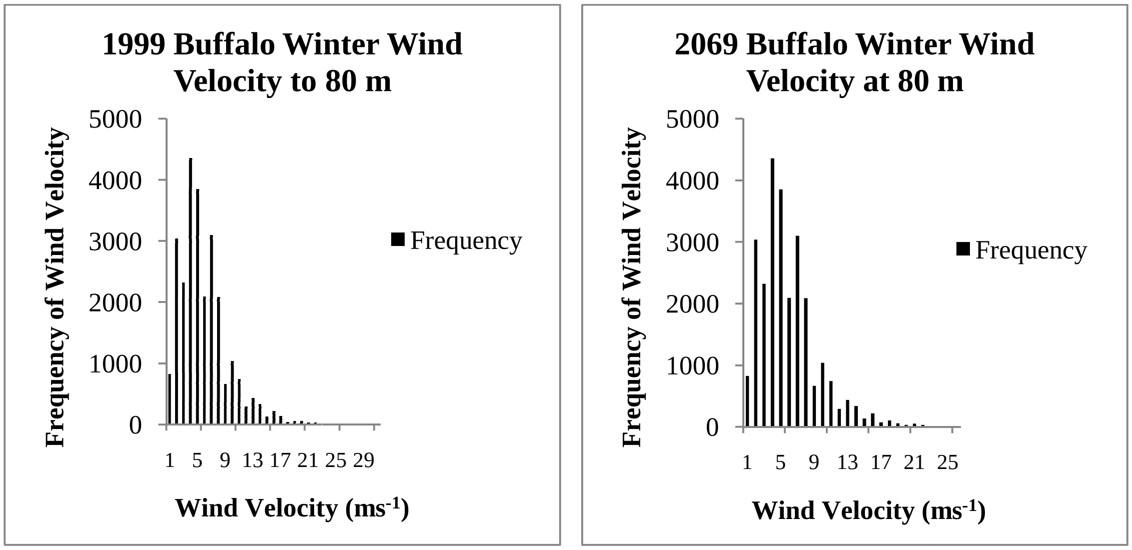
Both wind-farms are very close to Oklahoma Mesonet stations and use GE 1.5 MW SLE commercial wind turbines that are used in the power calculations in the following section. The Buffalo Mesonet site was chosen to represent the yearly wind regime for Centennial Wind-farm and the Weatherford Mesonet site was chosen to represent the yearly wind regime for the WWEC Wind-farm. The terrain at the Buffalo Mesonet site is not nearly as flat as the Weatherford Mesonet site; however, the Mesonet site is on a bluff like Centennial Wind-farm. When calculating power generated from wind velocities, infinitesimally small observation times would be most consistent with theory. However, due to the restraints associated with the lack of such data and the practices of other wind power studies, five-minute observations were used.

The NARCCAP grid-points that were closest to each Mesonet site were chosen to represent the change in wind velocity per season, per decade for future decades. The distance between the Buffalo Mesonet site and Centennial Wind-farm is 23.3 km and the distance between the Weatherford Mesonet site and WWEC Wind-farm is 3.8 km. Furthermore, the distance between the Centennial Wind-farm and the closest NARCCAP grid-point (where the percent-change data was gathered) is 16.9 km and the distance between the WWEC Wind-farm site and the closest NARCCAP grid-point is 19.3 km. These distances are given to provide spatial proximity information with respect to how the results of this thesis were attained.

Power Derivations

Power generation was calculated for the comparison decade of 1990-99 and the future decades of 2040-49, 2050-59, and 2060-69 for each of the two wind-farms. After this was completed, the percent change in power output per decade at each wind-farm was derived.

In order for the total power generated from 1990-1999 at each wind-farm to be calculated, 5-minute wind observations were used for 1999. The 1999 wind observations were multiplied by 10 to represent the average of the whole decade (on a seasonal basis) and while this might be a limitation to this study, the descriptive statistics and histograms in Appendix B show the distributions are not drastically different. The 1999 observations were divided into seasons, and then the wind velocities were used in several equations. After this was done, Equation 2 was implemented to extrapolate the 10 m Mesonet observations to the commercial wind-turbine height of 80 m. The histograms in Figure 10 below provide details on the extrapolated wind velocity distributions from the Buffalo Mesonet site in the winter season over the longest temporal duration of the study (1999-2069).


1999 Buffalo Winter Wind Velocity to 80 m

2069 Buffalo Winter Wind Velocity at 80 m

Figure 10: Histograms showing Winter wind velocity distributions at 80 m at Buffalo Mesonet site in 1999 and 2060-2069

These are examples of the wind velocity values that were used in the power calculations. Upon a comparison of the histograms (beyond inspecting these data distributions for quality control) there is some evidence that perhaps foreshadows how the wind might change over time.

The power law wind profile equation (Equation 2) used includes the exponent alpha (α =.143) (Pryor and Barthelmie 2009), which represents near-neutral and relatively flat, smooth surfaces for the near-surface layer of the atmosphere (the most general state of the atmosphere). Speed sheer changes through the atmosphere (vertically) within other stability conditions were not used because it is quite difficult to estimate it given the existing Mesonet observations and sparse tall tower data from western Oklahoma. The winds extrapolated to 80 meters were used to calculate the power generated from the GE 1.5 MW wind turbine power curve. This was done through the use of Equation 3 and Table A.1 in Appendix A.

Once the wind velocities were inserted into Equation 3, the yearly power generated per turbine was calculated. It was then necessary to divide that total power per turbine by twelve (there are twelve 5-minute Mesonet observation in an hour) in order to get kilowatt hours. Next, the resulting value was multiplied by the number of turbines in the wind-farm, and then multiplied by ten to derive total gross power generated for the whole wind-farm for the decade. The same procedure was done to calculate the total gross power generated for the future decades 2040-49, 2050-59, and 2060-69. However, the percent changes in wind velocity from NARCCAP were applied to each season to represent the changes over time due to climate change. The final step calculated percent change (using Equation 4, except percent change in power instead of median wind velocity) in total gross power generation for each wind-farm based on the seasonal percent changes in the NARCCAP output.

CHAPTER IV

FINDINGS

NARCCAP Output, Power Results, Capacity Factors, and Economic Impacts

This chapter presents the NARCCAP output over the study domain of this project. The 1990-99 decade wind velocity simulations as well as the percent change in wind velocity for the three future decades will be discussed with respect to the characteristics of the output. These characteristics include seasonality and potential meteorological/climatological reasons that might explain the patterns of change in wind velocity in the future. Specifically, only a few seasons will be focused on in detail within the body of the thesis, however maps for every season and decade can be found in Appendix A. With respect to scale in pattern explanations, see the quote below from Christensen et al. (2001, 590):

> RCMs are now used in a wide range of climate applications, from palaeoclimate to anthropogenic climate change studies. They can provide high resolution and multi-decadal simulations and are capable of describing climate feedback mechanisms acting at the regional scale.

The above quote confirms that these regional climate models (nested inside the GCMs in NARCCAP) can simulate regional climatological patterns. Therefore, the explanation of the patterns that result from the analysis in this thesis will be explained on regional and local scales.

Moreover, the power generated for all four decades as well as the percent change in power output for the future decades will be presented and addressed in this chapter. Also, a brief discussion of computed capacity factors is included. This chapter concludes with a speculation on how the change in power output from changes in wind velocity in the future from climate change might affect Oklahoma's wind power industry, including the state's economy and people working in the industry.

1990-1999 Wind Velocities

The NARCCAP output of median wind velocity patterns for the 1990-1999 decade in the region where the wind-farms were chosen are accurate in representing Oklahoma's observed wind climate. This means the patterns found in the simulations are climatologically accurate with the strongest wind velocities in western Oklahoma and decreasing toward the central part of the state. See Figures 11 and 12 below for the decadal average of monthly median wind velocity simulations for 1990-1999 at 10 m as well as average annual 80 m wind velocity, respectively. The results are very similar.

Although Figure has been modeled on a different temporal and spatial scale, if the '5.5-6.0' ms^{-1} wind velocity simulations at 10 M in the darkest blue in the Texas and Oklahoma panhandles in Figure 11 are extrapolated to 80 M, the resulting wind velocity values would be 7.4-8.1 ms^{-1} at 80 m which is similar to Figure 12 in the same region. This comparison provides some insight on the accuracy of the NARCCAP simulations. The decadal average median wind velocity patterns by season for 1990-1999 can be seen in Appendix A figures A.2-A.5.

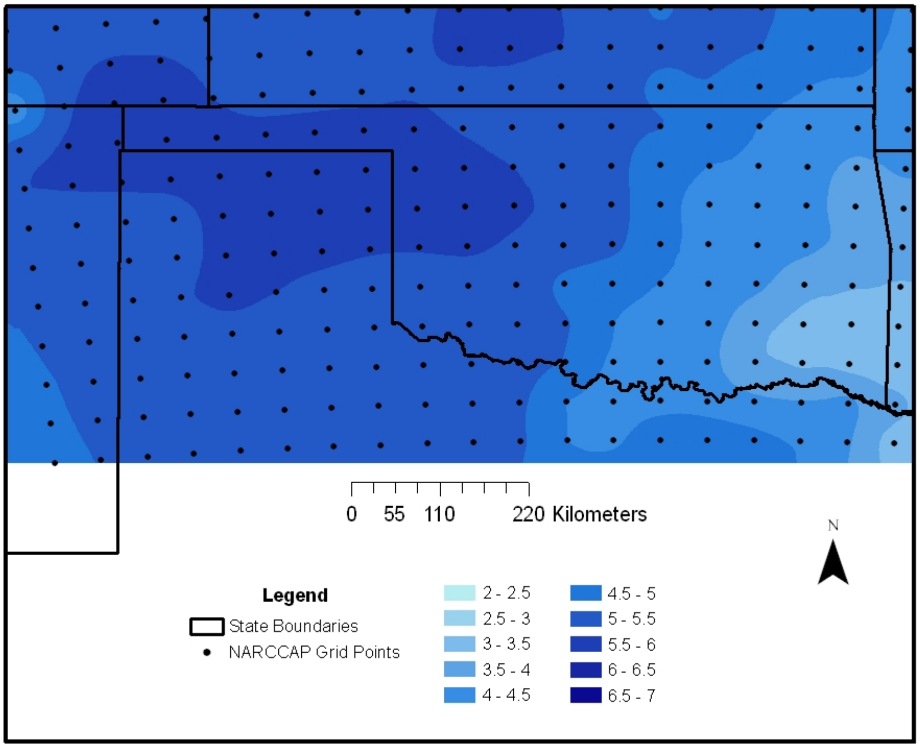


Figure 11: NARCCAP simulated median wind velocities (ms^{-1}) at 10 m for 1990-1999

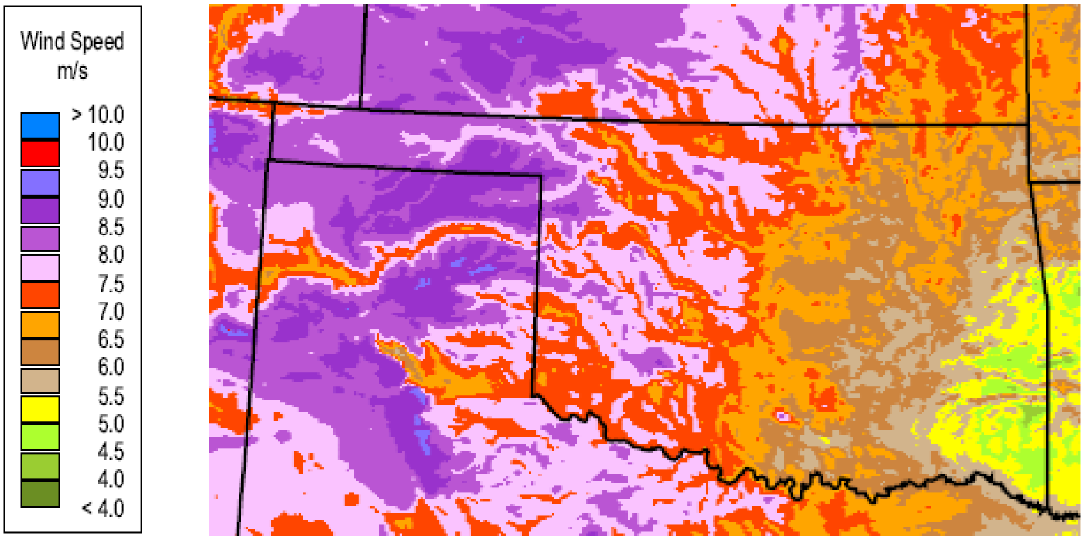


Figure 12: Assesment of annual average wind velocity at 80 m at 2.5 km resolution (AWS Truewind 2010)

2040-2049 Change in Wind Velocity

The overall percent change in median wind velocities between 1999 and 2040-2049 is most drastic in the northern and western portions of the study domain (Figure A.6 in Appendix A). However, change over the different seasons is most important here (Table 3 below). For this decade, spring and summer are the seasons that show the biggest modeled percent change wind velocity at the wind-farms chosen in this study. Table 3 shows the percent change in wind velocity by season for this decade at each wind-farm (seasons of interest shown in bold in percent change tables).

	Centennial Wind-farm		***WWEC***
2040-49	**% Change**	**2040-49**	**% Change**
Winter	0.44	Winter	0.39
Spring	**8.38**	**Spring**	**6.19**
Summer	**6.37**	**Summer**	**5.25**
Fall	1.21	Fall	-1.05

Table 3: Percent change in wind velocity at each wind-farm for 2040-2049 compared to 1990-1999

In spring, there is an increase in wind velocity from southeast to northwest over the entire study domain. This pattern affects both wind-farms, especially Centennial Wind-farm in northwestern Oklahoma. A potential reason for this is a stronger baroclinic zone causing an enhanced spring jet stream; with more intense temperature gradients there are more intense pressure gradients. The jet stream is strongest above areas with strong surface baroclinicity. The region of minimal change in south and southeastern Oklahoma and north-central Texas could be from a lack of changing baroclinicity in that region. See Figure 13 below for the percent change in median wind velocity for the spring season during this decade.

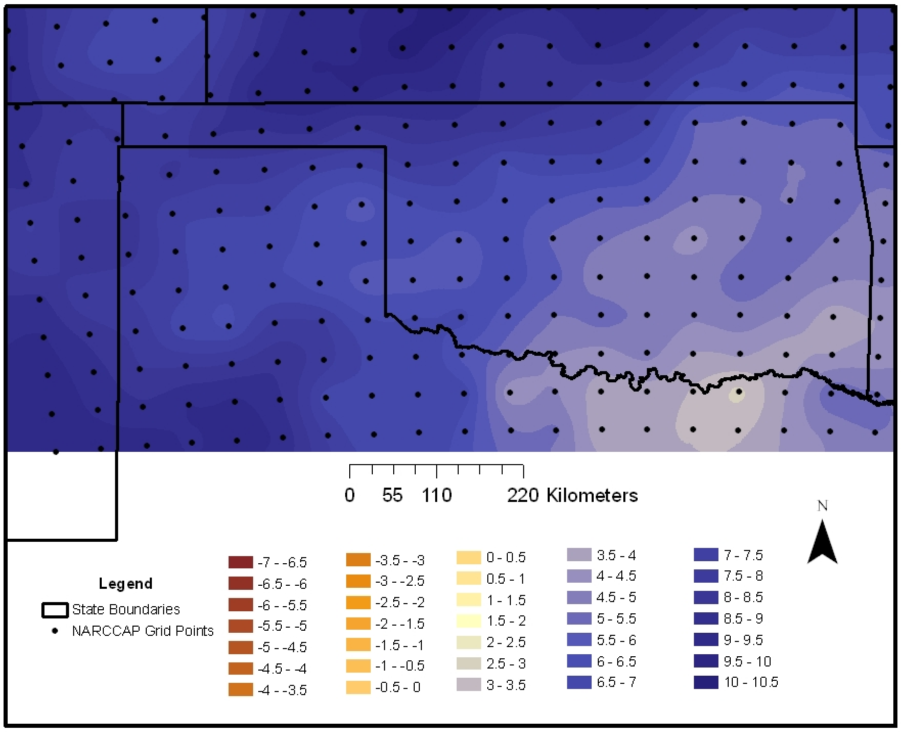


Figure 13: 2040-2049 percent change in averaged median Spring wind velocity simulations (ms^{-1}) at 10 m

In the summer season for this decade, there is increasing wind velocity along a southwest to northeast diagonal linear pattern in the western portion of the study domain that continues eastward toward north-central Oklahoma onward to the eastern portion of the study domain (Figure 14).

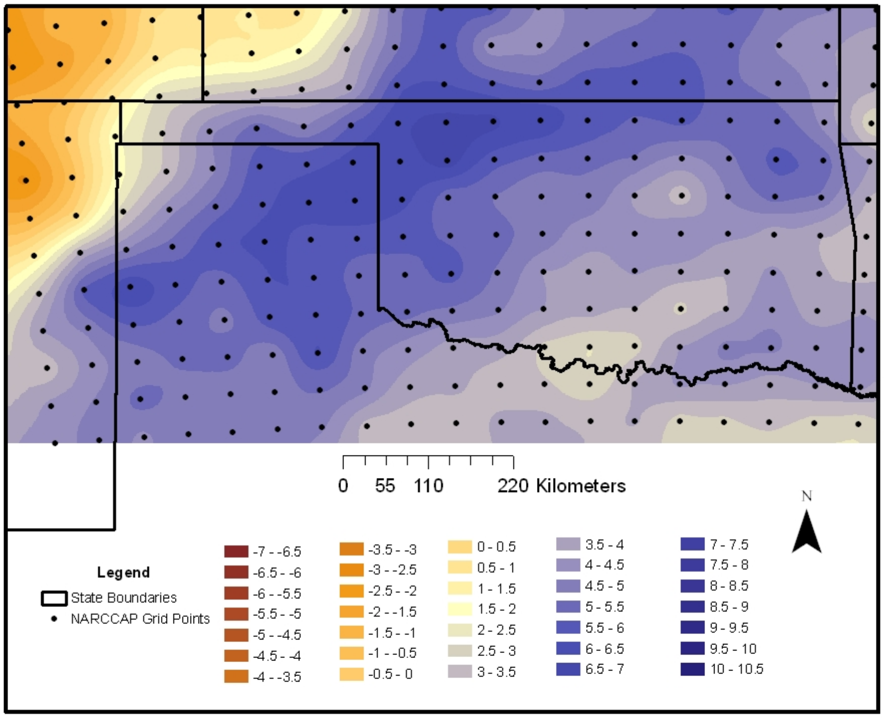


Figure 14: 2040-2049 percent change in averaged median Summer wind velocity simulations (ms^{-1}) at 10 m

With the climatological summer pattern in mind for this region (dominating high-pressure systems), this could be a result of that pattern strengthening. It can be postulated that this near-surface (relative to the thickness of the boundary-layer) pattern of change could be a result of intensified summer climatological patterns resulting from increasing global temperatures. For example, the clock-wise flow that is associated with high-pressure in the northern hemisphere might be strengthened at the surface which might cause this pattern. This could also result from a more ageostrophic (non-zonal) upper-air pattern, which would influence surface wind patterns via jet-stream dynamics. Furthermore, the smaller change toward the south and southeastern portion of the study domain could result from the movement of the strong subsidence associated with a dominating high-pressure pattern (which might account for the non-symmetrical west-to-east versus north-to-south pattern), coupled with increased surface-friction relative to western and northwestern Oklahoma.

2050-2059 Change in Wind Velocity

For this decade, the median wind velocities do not change very much from 1990-1999 over most of the study domain. However, the seasonal variations and change are noticeable (Table 4 below).

	Centennial Wind-farm		***WWEC***
2050-59	**% Change**	**2050-59**	**% Change**
Winter	0.19	Winter	0.44
Spring	**6.36**	**Spring**	**6.13**
Summer	4.22	Summer	4.74
Fall	**-2.43**	**Fall**	**-2.21**

Table 4: Percent change in wind velocity at each wind-farm for 2050-2059 compared to 1990-1999

More specifically, Spring and Fall display the biggest changes in magnitude of wind velocities for this decade with increases in the Spring and decreases in the Fall.

During Spring (Figure 15), the highest positive increase in wind velocities occurs in the southwestern portion of the study domain as well as some spots in western Oklahoma.

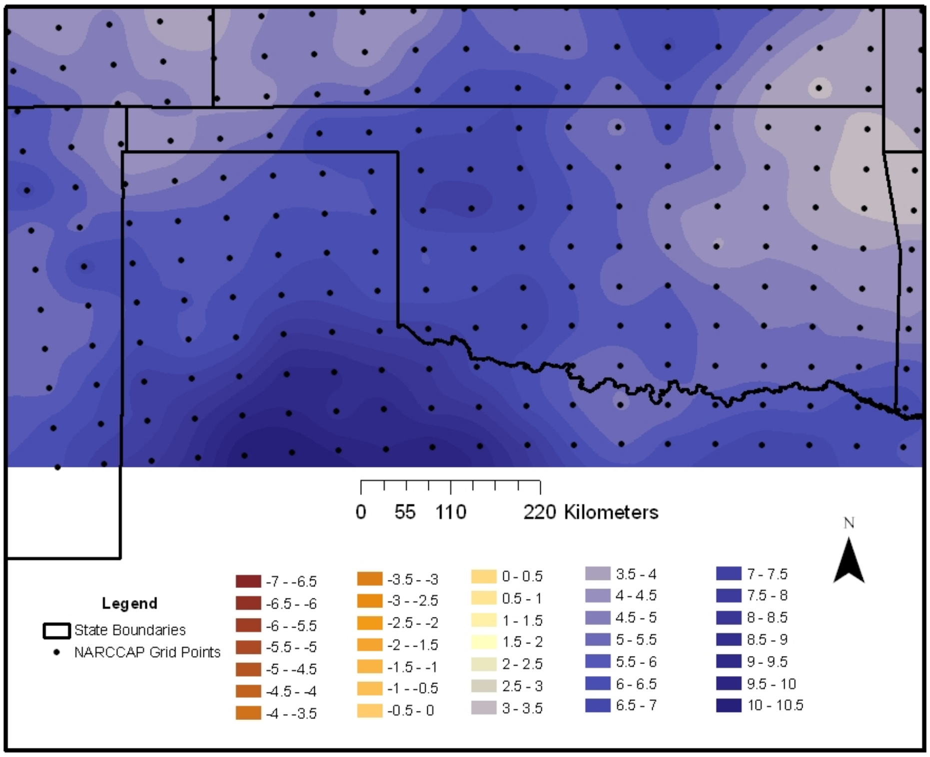


Figure 15: 2050-2059 percent change in averaged median Spring wind velocity simulations (ms^{-1}) at 10 m

Areas where there are small increases in positive percent change include northeastern Oklahoma as well as the northwestern portion of the study domain. These patterns could be a result of baroclinicity being pushed further south as time goes on due to lessening thermal gradients. As cold fronts in the spring move further south and slow down when meeting stronger southerly winds, an increase in near-surface winds (potentially resulting from frontogenesis) could be occurring in areas where the biggest percent change increases exist.

Fall 2050-2059 is opposite of Spring in that the patterns show a negative change in wind velocities over the study domain (Figure 16). The greatest magnitude of change occurs in the far western portion of the study area. This could be a result of upper-level storm tracks shifting further north, therefore not making it into the study domain as often as in the present. Also, there could also be a decrease in adiabatic warming from descending air off the eastern side of the Rockies (down-sloping) which influences wind patterns in the western portion of the study domain. This is logical because most of the disturbances move further northward during the summer with the lifting jet stream, therefore there would be less atmospheric flow perpendicular to the mountains (which is why down-sloping occurs) than in other seasons. This seasonal decrease during this decade could just be an extreme example of natural climatic oscillations. However, it does correlate with Pryor et al. (2009) where they mention that areas of the southern U.S. could see a decline in wind velocities.

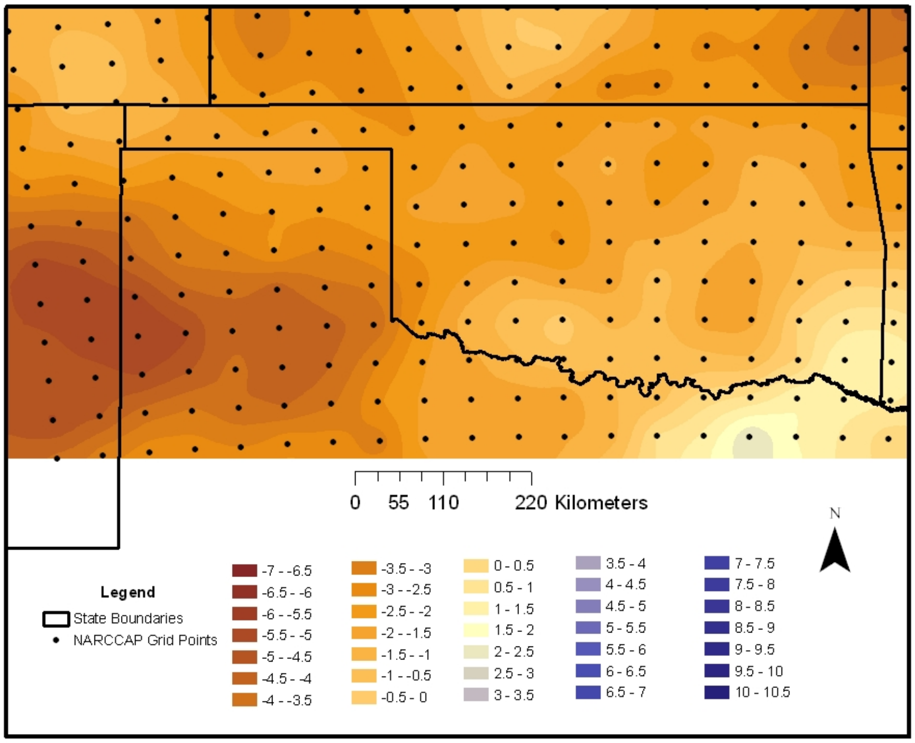


Figure 16: 2050-2059 percent change in averaged median Fall wind velocity simulations (ms^{-1}) at 10 m

2060-2069 Change in Wind Velocity

The final decade examined shows percent change patterns that are the farthest in time and are the most extreme with respect to magnitude when compared to 1990-1999. Even the decadal median wind velocity (i.e. non-seasonal) results show some changes on the magnitude of almost 8% (See Figure A.16 in Appendix A). However, there are seasonal differences to be considered. Here, Spring and Summer will be assessed because they have the largest percent change in median wind velocity. Table 5 shows seasonal percent changes.

	Centennial Wind-farm		***WWEC***
2060-69	**% Change**	**2060-69**	**% Change**
Winter	0.25	Winter	0.68
Spring	**7.32**	**Spring**	**7.7**
Summer	**6.58**	**Summer**	**5.91**
Fall	-1.37	Fall	-1.73

Table 5: Percent change in wind velocity at each wind-farm for 2060-2069 from 1990-1999

The Spring season shows high magnitude percent increases in median wind velocity across the central and southwestern portions of the study domain, including both wind-farm locations chosen for this study. Magnitudes of percent change in wind velocity were somewhat higher for 2040-2049 than 2050-2059 and more similar to 2060-2069.

Before commenting upon what might cause this decadal oscillation, the percent change pattern for 2060-2069 will be assessed. It appears that the baroclinic activity might be over west-central Oklahoma for a larger amount of time during spring over the decade (see Figure 17 below).

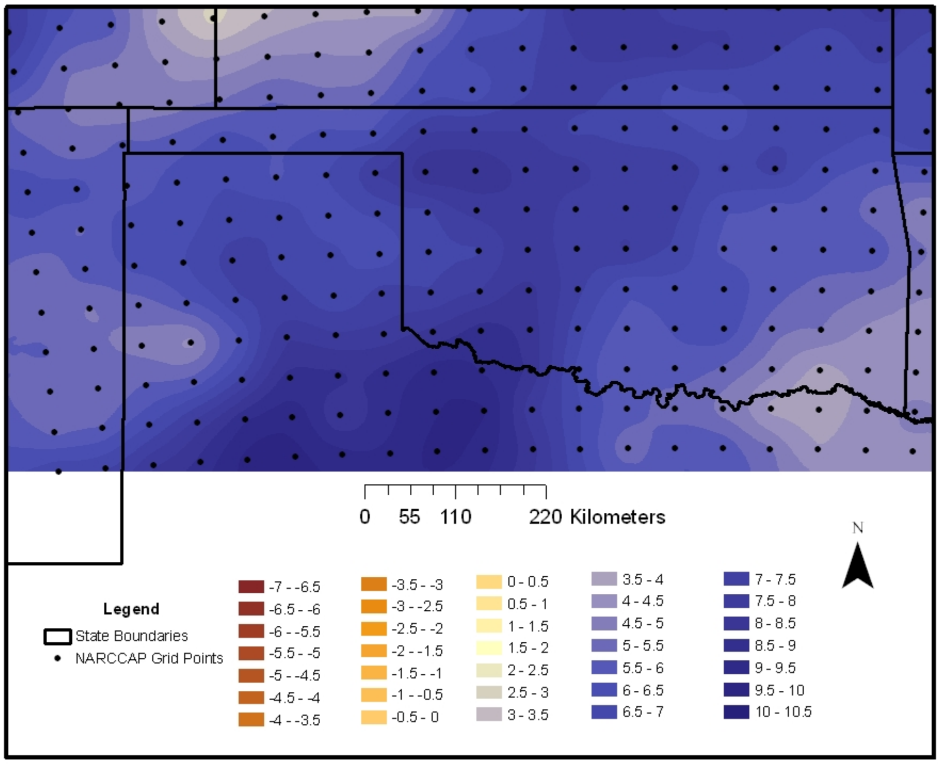


Figure 17: 2060-2069 percent change in averaged median Spring wind velocity simulations (ms^{-1}) at 10 m

The dryline, a diurnal forcing phenomenon that results from the combination of atmospheric mixing and slope in elevation across the study domain, might be a plausible explanation for this positive percent change in wind velocity here. According to an article on dryline thunderstorms, dryline progression eastward throughout the day is accompanied by rapid changes in wind speed (“Dryline Thunderstorms” 2010). For example, if the dryline becomes more active in western Oklahoma, this could explain this pattern of percent increase. Moreover, the numerous eastward bulges embedded in the pattern could also be interpreted as a dryline characteristic as well.

Next, the pattern in the summer seasons during 2060-2069 is similar in the 2040-2049 decadal summer patterns (Figure 18).

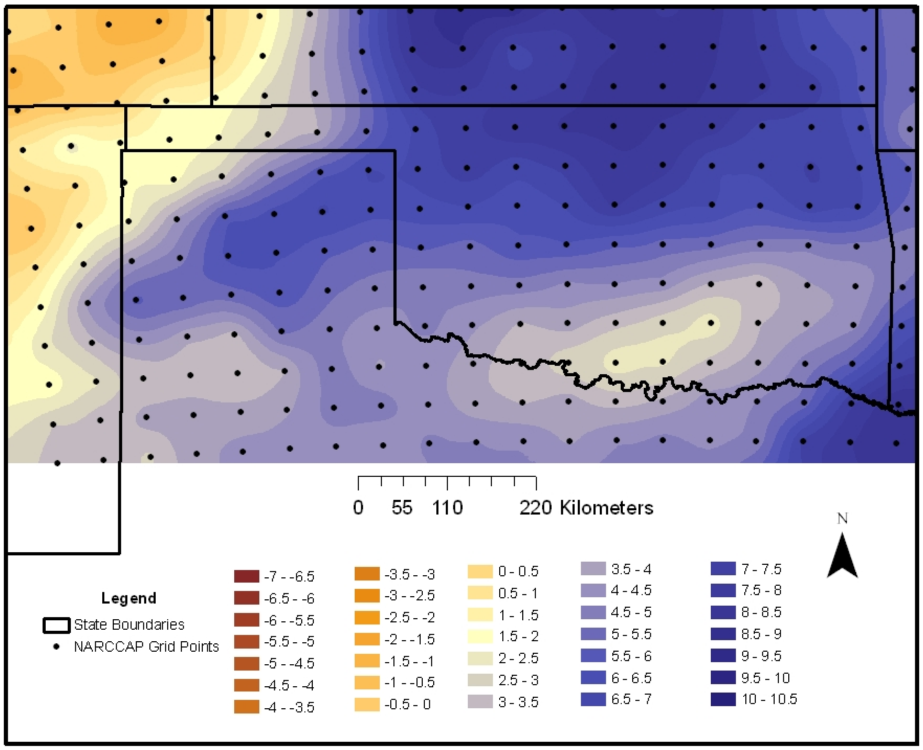


Figure 18: 2060-2069 percent change in averaged median Summer wind velocity simulations (ms^{-1}) at 10 m

The difference here is that it seems to be enhanced and perhaps pushed a little further south. To be consistent with the potential causes in the 2040-2049 decade, this could be from the movement of the mentioned pattern from that decade further south. For example, climatological patterns of dominating high-pressure systems shifting southwestward could explain this pattern, where baroclinicity would move further south along the clock-wise surface circulation associated with high-pressure systems in the northern hemisphere (high-pressure system bringing cooler temperatures from the north around its circulation). However, the sharp gradient along the Red River where high magnitude percent changes are next to locations with almost no change is harder to hypothesize.

Power Output and Percent Change

The results of this study show contradictory results compared to previous studies. According to Pryor et al. (2009), wind velocities are projected to decrease in the near future across southern portions of the Midwest, therefore potentially resulting in a decrease in power generated from the wind. However, other than minor decreases in Fall wind velocities resulting in minor decreases in electrical output in that season, this thesis shows increases in wind velocity resulting in increases in power generated from the wind over the majority of the temporal scale.

Power Generation Changes from Climate Change

The findings from this study are presented below. Refer to the ‘Power Derivations’ portion of Chapter III to review how the power generation changes were derived. First, the total gross power for the decade is shown in mega-watt hours (mWh), then by season for the 1990-1999 comparison decade. Following this is the total gross power for each future decade and by season. Then, the percent change in power generated is also shown by decade and by season for each decade based on a comparison to 1990-1999. The decadal totals reflect one constant percent change value applied to all wind velocities throughout the year; however, the seasonal values should be somewhat more accurate because there are four different percent change values being applied to the wind velocities throughout the year versus just once percentage applied to the whole year. For example, different seasons are windier than others, therefore if one season has a higher percent change that has higher winds it will yield different results compared to using one fixed percent change for the whole year.

Centennial Wind-farm shows increases in power generation for every season in every decade, except in the Fall season of the last two decades. See Table 6 below for electricity totals that represent the current decade (here the ‘1990-99 decade’ is defined as 1999 values times 10 for both farms).

	Centennial Wind-farm
	Decadal Gross Power Output 1999 (Used as decadal avg.) (mWh)
Total	**1,871,930**
Winter	446,084
Spring	612,360
Summer	424,913
Fall	388,574

Table 6: Power results for Centennial Wind-Farm for 1999 (x10)

Seen in Table 7 below, the largest percent increase in power generation is in the Summer for 2040-2049, in the Spring for 2050-2059, and in the Summer for 2060-2069. One conclusion to be drawn from this is that perhaps as time goes on and carbon emissions continue to increase exponentially (Figure 3), the transition seasons will become more extreme (low temperatures could get lower, windy seasons could get windier, etc.).

	Centennial Wind-farm	
	Decadal Gross Power Output 2040-2049 (mWh)	**% Change**
Total	**2,091,756**	**11.74**
Winter	452,490	1.44
Spring	728,151	18.91
Summer	508,848	19.75
Fall	402,268	3.52
	Decadal Gross Power Output 2050-2059 (mWh)	
Total	**1,994,232**	**6.53**
Winter	447,574	0.33
Spring	701,335	14.53
Summer	481,112	13.23
Fall	364,211	-6.27
	Decadal Gross Power Output 2060-2069 (mWh)	
Total	**2,046,492**	**9.33**
Winter	447,859	0.40
Spring	712,054	16.28
Summer	510,814	20.22
Fall	375,766	-3.30

Table 7: Power results for Centennial Wind-Farm for future decades

The WWEC wind-farm shows positive percent change and similar seasonal characteristics and higher generation values; however, it has less total percent change than Centennial Wind-farm. It appears that the seasonal wind velocity changes' force the WWEC wind velocities into a more efficient portion of the power curve, therefore generating more wind power with similar percent change patterns. This can be attributed to the wind climatology in that location. With respect to the seasonal characteristics, Spring and Summer by far show the biggest percent change from 1990-1999. See Tables 8 and 9 below. It is clear that in Oklahoma there are potentially great benefits to reap from a warming climate with respect to wind power generation.

	WWEC Wind-farm
	Decadal Gross Power Output 1999 (Used as decadal avg.) (mWh)
Total	**5,044,161**
Winter	1,212,052
Spring	1,390,705
Summer	1,237,841
Fall	1,203,563

Table 8: Power results for WWEC wind-farm for 1999 (x10)

	WWEC Wind-farm	
	Decadal Gross Power Output 2040-2049 (mWh)	**% Change**
Total	**5,325,627**	**5.58**
Winter	1,224,257	1.01
Spring	1,537,220	10.54
Summer	1,384,929	11.88
Fall	1,179,220	-2.02
	Decadal Gross Power Output 2050-2059 (mWh)	
Total	**5,275,866**	**4.59**
Winter	1,22,4819	1.05
Spring	1,536,485	10.48
Summer	1,365,021	10.27
Fall	1,149,541	-4.49
	Decadal Gross Power Output 2060-2069 (mWh)	
Total	**5,364,803**	**6.36**
Winter	1,227,644	1.29
Spring	1,561,284	12.27
Summer	1,406,503	13.63
Fall	1,169,371	-2.84

Table 9: Power results for WWEC wind-farm for future decades

If these simulations were to occur in the future, it appears the state of Oklahoma might be able to generate more power than it needs; therefore benefiting the economy further by having the capability to export power to other states.

Capacity Factor

In order to quantify how much electricity the power plant generates compared to the theoretical maximum electricity that could be generated, there is a value known as the capacity factor (Table 10 below). The capacity factor is “the ratio of the actual energy produced in a given period, to the hypothetical maximum possible, i.e. running full time at rated power” (RERL 2010) According to the Renewable Energy Research Laboratory at the University of Massachusetts:

> All power plants have capacity factors, and they vary depending on the resource, technology, and purpose. Typical wind power capacity factors are 20% to 40% (RERL 2010, 1).

With respect to Centennial Wind-Farm capacity factors, I hypothesize these values are low due to the fact that the power generation values were derived from the Buffalo Mesonet site. Although this Mesonet site is the closest location for wind observations, it is not physically representative of the wind regime at the Centennial Wind-Farm; the Mesonet site is at a lower elevation than the wind-farm which is located higher up on a bluff. Furthermore, it may be less of a bias than the physical differences explained above, but these capacity factors are also derived from extrapolated wind values which may influence the percentages as well.

Season	**Decade**	**Centennial C.F.**	**WWEC C.F.**
Total	1999 (Used as 1990-99)	0.18	0.48
Winter		0.17	0.46
Spring		0.23	0.53
Summer		0.16	0.47
Fall		0.15	0.46
Total	2040-2049	0.20	0.51
Winter		0.17	0.47
Spring		0.28	0.58
Summer		0.19	0.53
Fall		0.15	0.45
Total	2050-2059	0.19	0.50
Winter		0.17	0.47
Spring		0.27	0.58
Summer		0.18	0.52
Fall		0.14	0.44
Total	2060-2069	0.19	0.51
Winter		0.17	0.47
Spring		0.27	0.59
Summer		0.19	0.54
Fall		0.14	0.44

Table 10: Capacity Factors for each wind-farm through time

Capacity factors are important to wind power generation because they measure the turbines actual energy output over a period of time. Based on this description and information, the capacity factors for the GE 1.5 MW SLE commercial wind turbine stay the same in some cases, but mainly show increases for future decades. These values are impressive because the wind is not always blowing and, coupled with cut-out speeds, the turbine is producing a large amount of power.

Impacts on Oklahoma’s Wind Power Industry and Economy

It is clear that these results hint at potential positive impacts on Oklahoma’s wind power industry and economy. Since this study is not focused on the economic impacts of wind power in Oklahoma, the section will be kept to general implications. The goal of this study was to present the physical changes in wind power generation as a result of the effects of climate change. For a more in-depth focus on the economic impacts, perhaps the findings of this quantitative study should be applied to qualitative economic impact case-studies that have been completed.

One of the first major positives that these increases in wind power generation would have is on the Department of Energy’s ‘20% wind energy by 2030’ goal. According to the U.S. Department of Energy:

> The 20% Wind Scenario presented here offers potentially positive impacts in terms of greenhouse gas (GHG) reductions, water conservation, and energy security, as compared to the base case of no wind growth in this analysis… Wind power would be a critical part of a broad and near-term strategy to substantially reduce air pollution, water pollution, and global climate change associated with traditional generation technologies (US DoE 2008, 13).

The above quotation illustrates the importance and benefits of this goal and it was set with an understanding of current wind patterns and if Oklahoma’s winds do increase as modeled here, this goal would be more easily attained for Oklahoma.

It is well known that Oklahoma has some of the best *potential* for wind power generation in the world; however, there is a current lack of investment that has many impacts. In particular, the transmission line infrastructure across Oklahoma needs work in order to be able to take full advantage of this potential. The quotation from an article on Oklahoma wind power illustrates the transmission issue across the state:

> I think some of the other projects and priorities that have been put in place by this administration-in particular transmission, long term strategic transmission planning-will help us. The best wind resources tend to be fairly remote from the load centers, and there's a lot of government support from the highest levels to get the transmission infrastructure in place so that we can take advantage of the domestic resources that we have (Mettler 2010, 4).

First, the lack of investment exists for many reasons, but one of the main reasons is a lack of logistical means to get parts to rural areas that have the best wind. There is only one wind power manufacturer that has really tried to make use of all transport means possible to get parts into Oklahoma. DMI Industries makes use of the Arkansas River and the Port of Catoosa north of Tulsa to transport parts into the state. The results of this study that show a significant increase in power potential might catch the eyes of other companies and other investors.

Also, going back to national-scale impacts, there are tremendous transmission-line deficiencies with respect to moving the power and implementing it in the grid after it has been generated. Transmission lines are expensive, but are the only way to get power generated from rural windy areas into the grid. With a large enough transmission capacity in place, the wind power generated in Oklahoma could be sent to other states where the wind climate is less conducive to wind power generation so that they can enjoy renewable energy as well. Results from this study might make investing more attractive and desirable to not only invest in new transmission-line projects, but create Oklahoma jobs as well.

Even though this study does not focus on all the economic impacts of wind power generation, it has clearly outlines some interesting implications. With a potential increase in wind velocities and therefore wind power generation in the future, there is at least the same, if not bigger, potential for the creation of many jobs through wind-farm construction, operation and maintenance, and transmission-line construction. This increase in jobs might directly impact Oklahoma’s economy in many positive ways.

CHAPTER V

CONCLUSION

The goal of this study was to attempt to quantify the potential changes that climate change might have on Oklahoma's wind climate in the future. Furthermore, these results were used to calculate potential changes in future wind power generation. It was hypothesized that climate change would have an important effect on Oklahoma's wind power generation. Before the study was initiated, it was not clear if the results would show increases, decreases, or negligible change. The results of this study support the hypothesis that there could be significant changes in wind power generation in the future resulting from climate change in Oklahoma. For all future decades studied, there was a gross increase in power generated from the wind. The findings are important because the results of the modeled simulations suggest that winds might increase in areas where there are favorable winds already and because this is the first study to find increases in wind patterns with respect to climate change and future energy outlooks. The few studies mentioned in the literature review found negative trends in wind velocities (Pryor et al. 2009).

Limitations of Study

When a study such as this one is carried out, many assumptions must be made and many things must be simplified. There is always a gap between theory and reality because reality simply cannot be replicated in controlled studies. The predictions in this study are based on climatological, atmospheric dynamic and thermodynamic theory as applied by the NARCCAP models. This section of this chapter will identify the main limitations of this study.

First it is important to understand the NARCCAP data is model output, which may or may not be correct. For the purposes of this study, the output was assumed to be valid and representative of what will actually occur. Next, with respect to the characteristics of the vertical structure of the atmosphere, the simple power law equation (Equation 2) was used to extrapolate wind from 10 meters up to an 80-meter turbine height. The shear coefficient alpha of .143 was used to assume a statically stable atmosphere. This was thought to be a reasonable approximation, but speed sheer with height is not constant in reality. Third, when calculating power generated from the wind, it is ideal to use infinitesimal time interval wind observations to be as accurate as possible. This study made use of 5-minute observations because of the absence of better data in Oklahoma. Fourth, with respect to the Mesonet data, the 5-minute yearly wind observations for 1999 from each Mesonet station were assumed as the wind climate for the whole decade from 1990-1999, on which all percent changes are based (See Appendix B). The last main limitation of this study has to do with the efficiency of the power generated. This study refers to the power as ‘total-gross power’ which does not account for inefficiencies such as loss of power during transport (line loss) to the grid and/or mechanical failure.

Future Research

There are many more avenues of future research on this subject that could be pursued and just a few are suggested here. The findings of the current study could be refined by addressing some of the limitations above and could be extended in several ways. Future research on this subject could attempt to compare the NARCCAP and other model output to reanalysis data to see how well the past simulations represent real observations. This would enable the accuracy of the results of such a study to be better assessed. Also, an attempt to quantify the vertical structure of the atmosphere with respect to wind-shear characteristics by using wind profiler data would increase confidence in the vertical extrapolation process.

Extending studies such as this one might be important to perform a detailed economic analysis of what these types of energy increases might have on local, state, and national economies using economic models such as the National Renewable Energy Laboratory's Job and Economic Development Impact model. Furthermore, it would be interesting to see the NARCCAP output applied to other wind-farms in the study domain as well as the output in other geographical domains to see what sort of results might occur with respect to geographical location.

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APPPENDICES

Appendix A

V_1	C_1	C_2	C_3	C_4
0	0	0.363543	0	-0.363543
1	0	-1.817717	1.09063	0.727087
2	0	6.907326	-4.362522	-2.544805
3	0	3.188412	16.359457	9.45213
4	29	-5.660975	25.924694	51.736282
5	101	4.455491	8.941768	86.602745
6	201	-2.16099	22.308239	117.852753
7	339	9.188473	15.825269	155.986252
8	520	-9.592901	43.390686	215.202209
9	769	-12.816865	14.611981	273.204895
10	1044	11.860363	-23.838614	263.978241
11	1296	-59.624588	11.742476	251.882111
12	1500	70.637993	-167.131287	96.493294
13	1500	-18.927393	44.782692	-25.855299
14	1500	5.071579	-11.999486	6.927907
15	1500	-1.358926	3.215252	-1.856327
16	1500	0.364123	-0.861524	0.497401
17	1500	-0.097566	0.230845	-0.133278
18	1500	0.026143	-0.061855	0.035712
19	1500	-0.007005	0.016574	-0.009569
20	1500	0.001877	-0.004441	0.002564
21	1500	-0.000503	0.00119	-0.000687
22	1500	0.000135	-0.000319	0.000184
23	1500	-0.000035	0.000085	-0.00005
24	1500	0.000007	-0.000021	0.000014

Table A.1 – Cubic Spline Coefficients

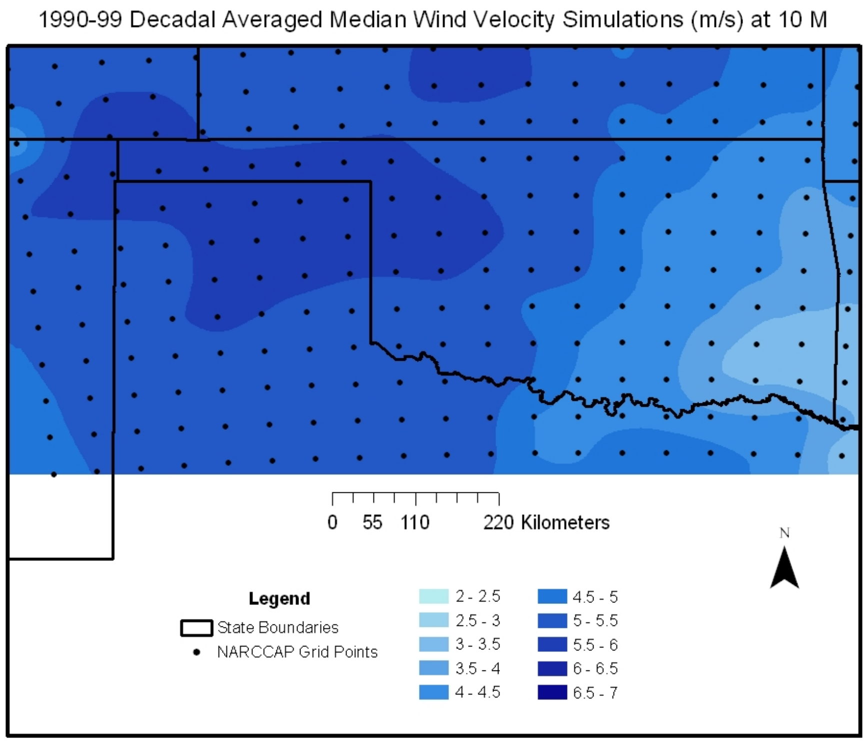

1990-99 Decadal Averaged Median Wind Velocity Simulations (m/s) at 10 M

Figure A.1

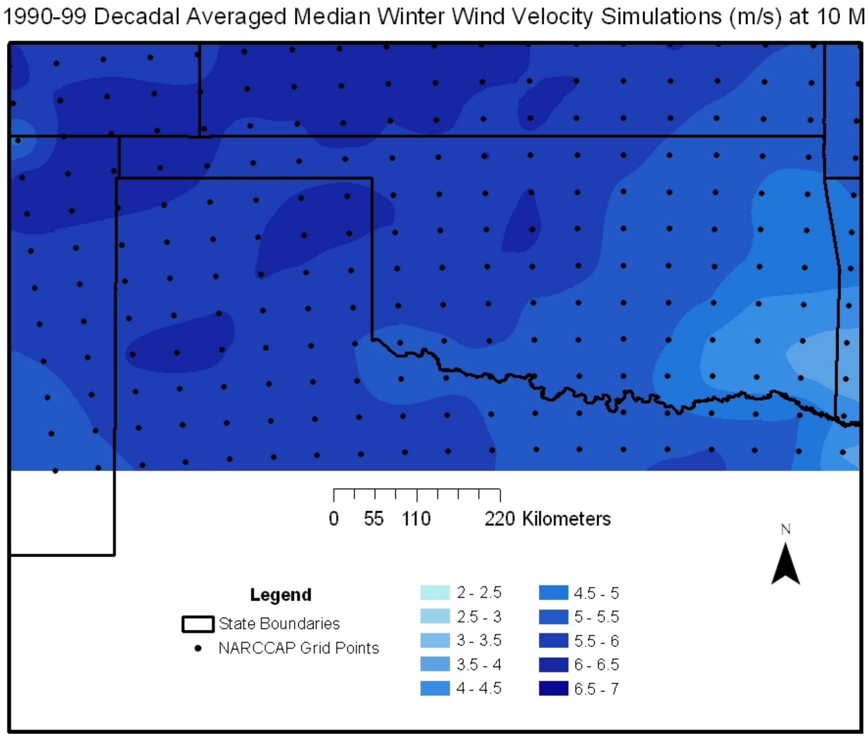

1990-99 Decadal Averaged Median Winter Wind Velocity Simulations (m/s) at 10 M

Figure A.2

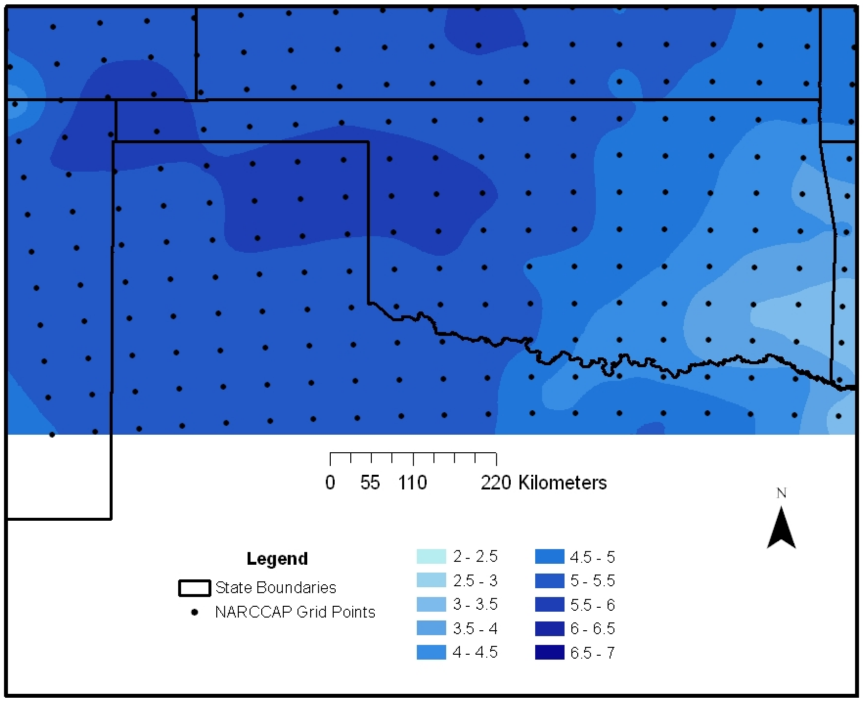

1990-99 Decadal Averaged Median Spring Wind Velocity Simulations (m/s) at 10 M

Figure A.3

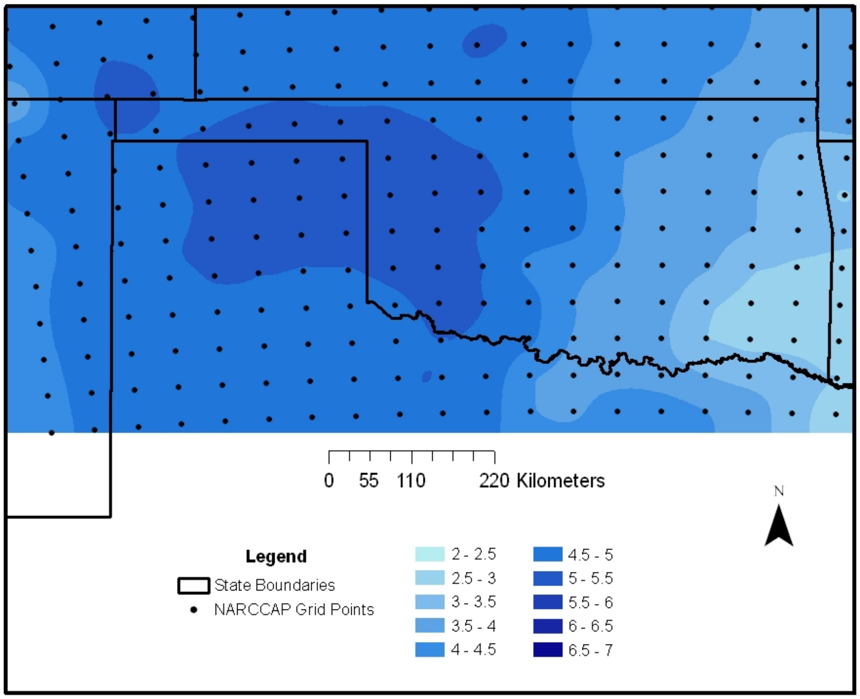

1990-99 Decadal Averaged Median Summer Wind Velocity Simulations (m/s) at 10 M

Figure A.4

1990-99 Decadal Averaged Median Fall Wind Velocity Simulations (m/s) at 10 M

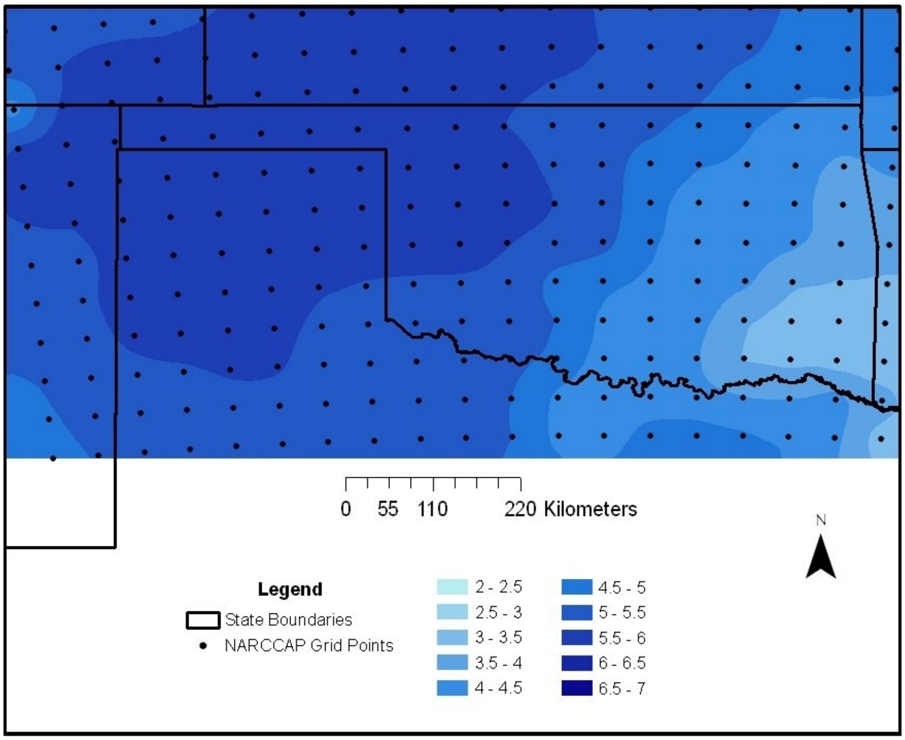


Figure A.5

2040-49 Decadal Percent Change in Averaged Median Wind Velocity Simulations (m/s) at 10 M

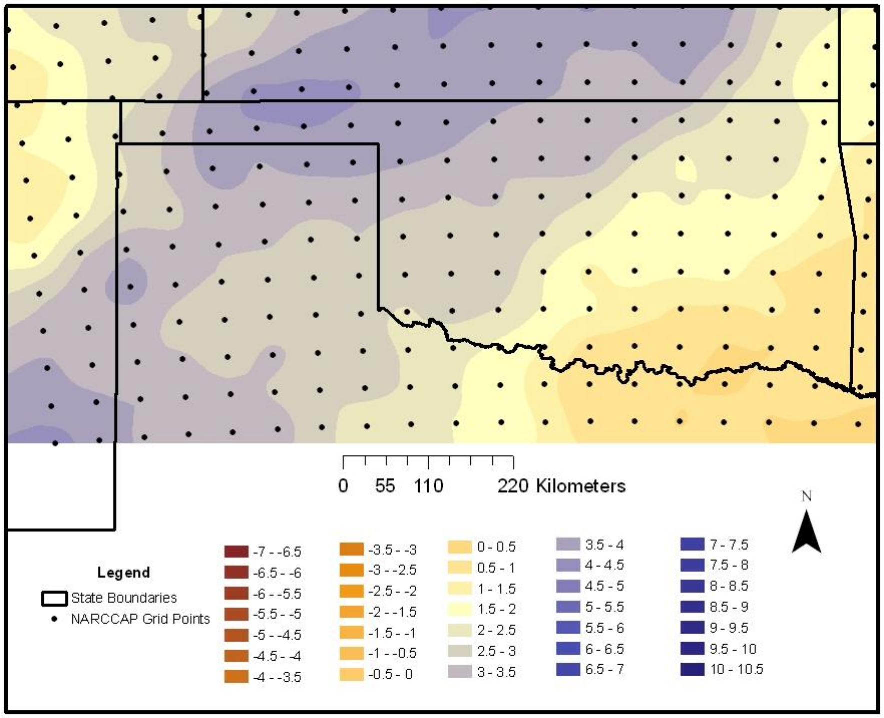


Figure A.6

2040-49 Decadal Percent Change in Averaged Median Winter Wind Velocity Simulations (m/s) at 10 M

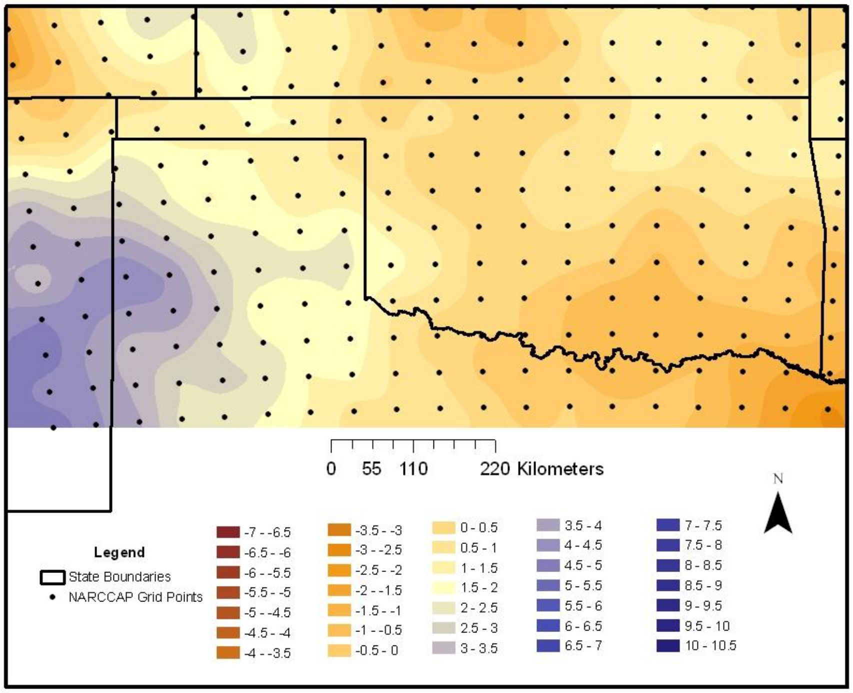


Figure A.7

2040-49 Decadal Percent Change in Averaged Median Spring Wind Velocity Simulations (m/s) at 10 M

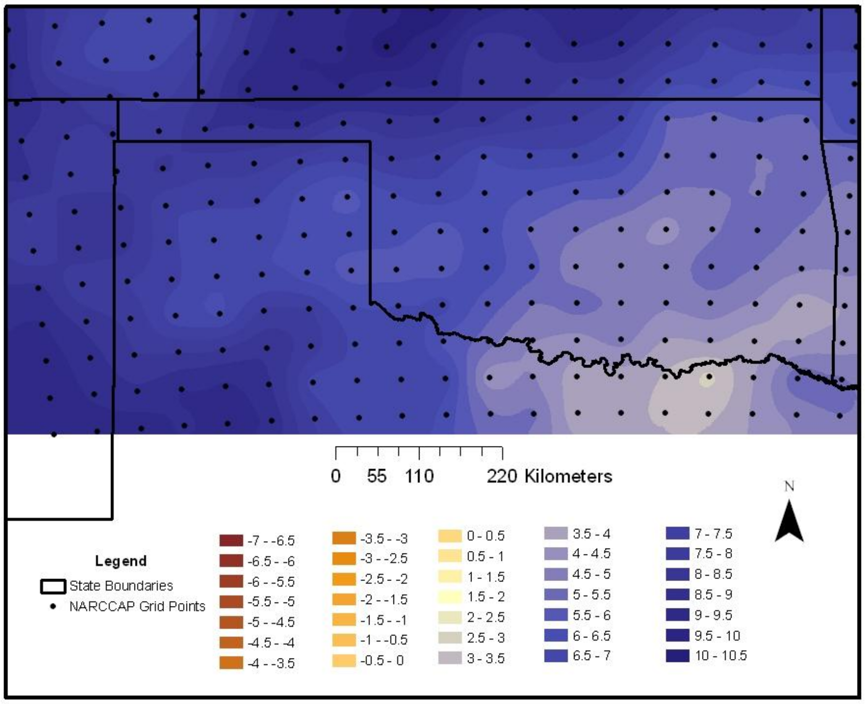


Figure A.8

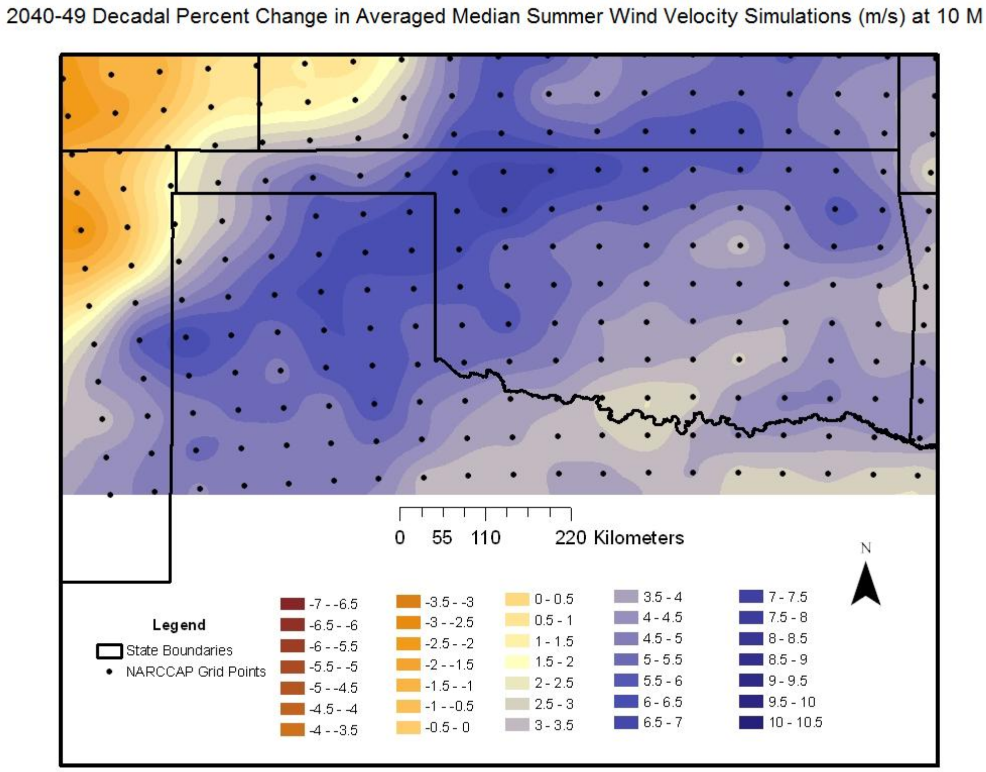

2040-49 Decadal Percent Change in Averaged Median Summer Wind Velocity Simulations (m/s) at 10 M

Figure A.9

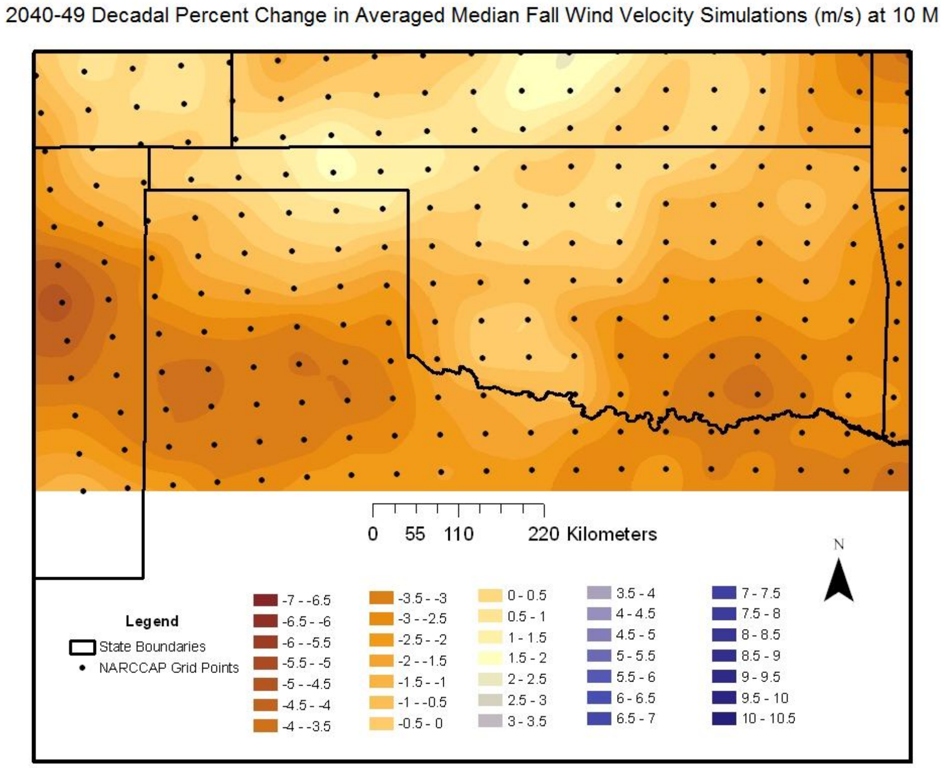
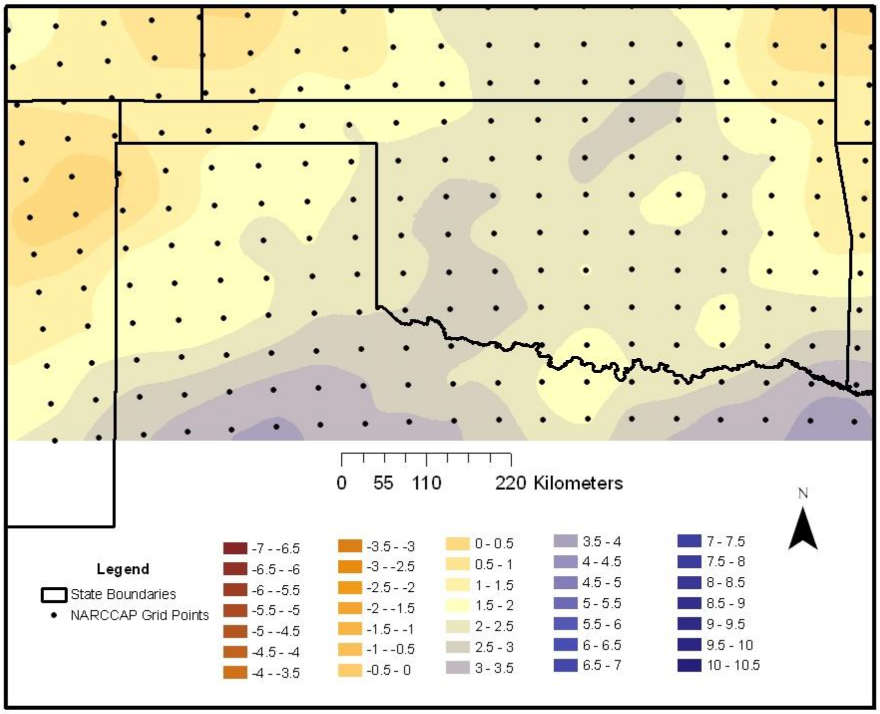
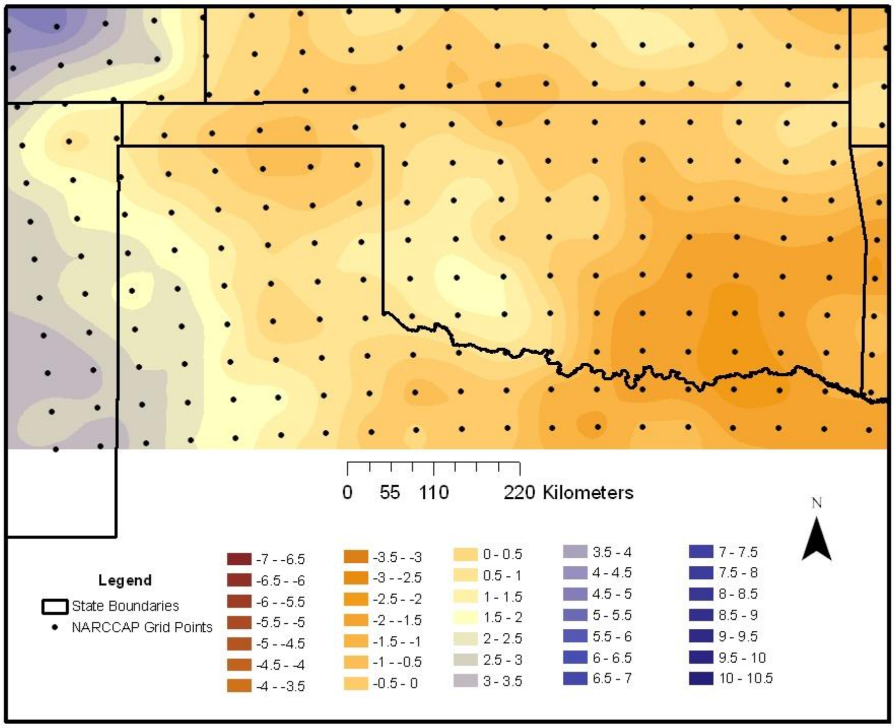

2040-49 Decadal Percent Change in Averaged Median Fall Wind Velocity Simulations (m/s) at 10 M

Figure A.10



2050-59 Decadal Percent Change in Averaged Median Wind Velocity Simulations (m/s) at 10 M

Figure A.11



2050-59 Decadal Percent Change in Averaged Median Winter Wind Velocity Simulations (m/s) at 10 M

Figure A.12

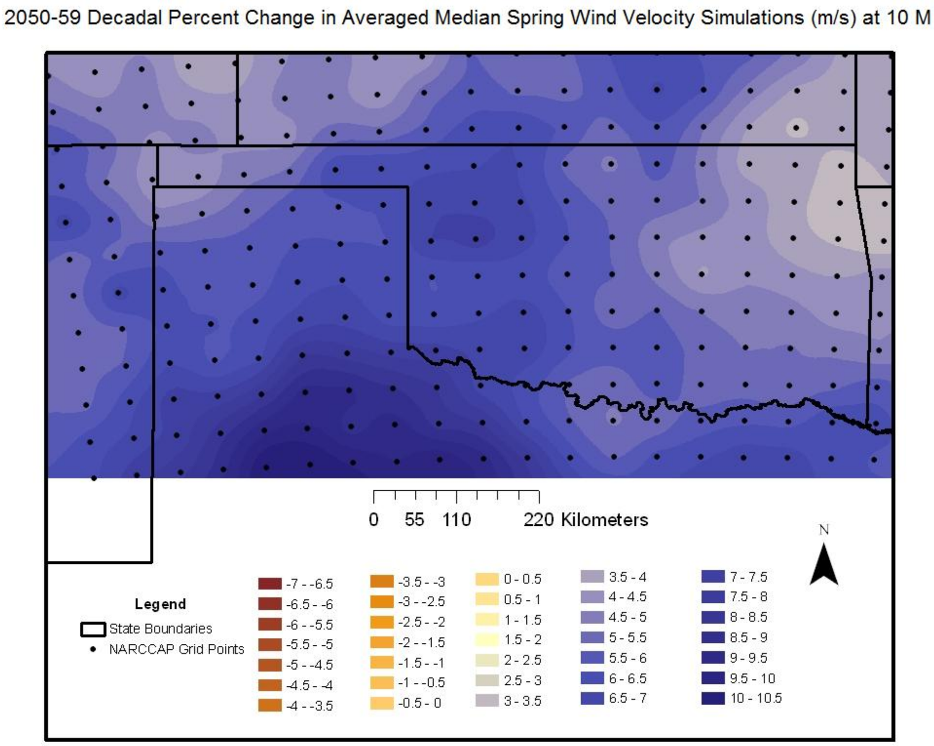


Figure A.13

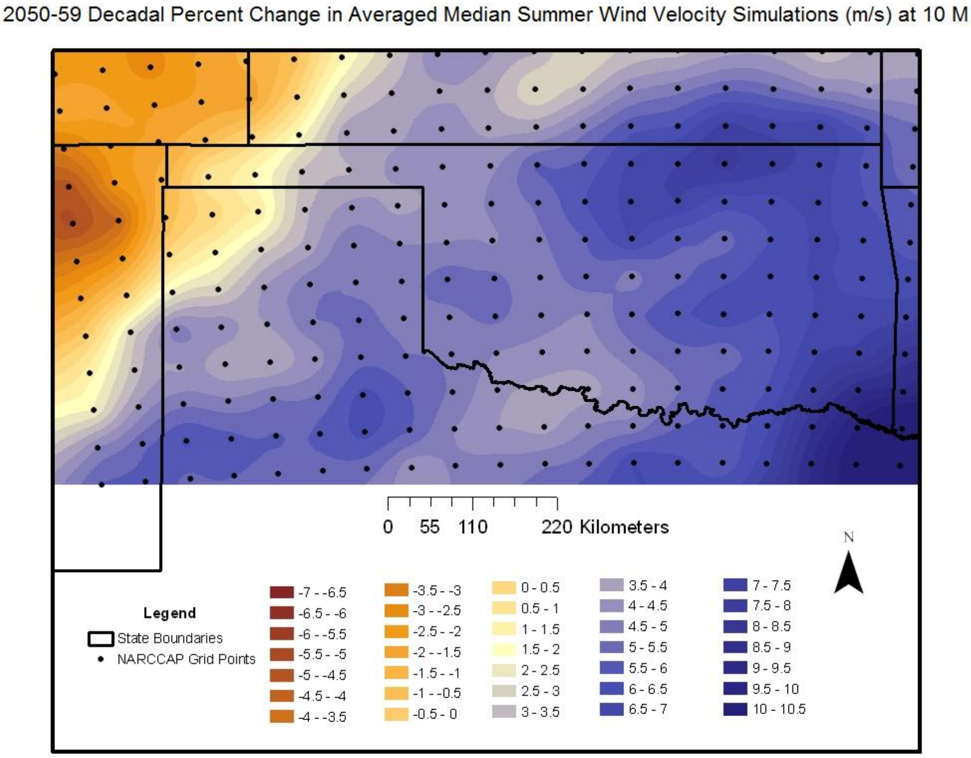


Figure A.14

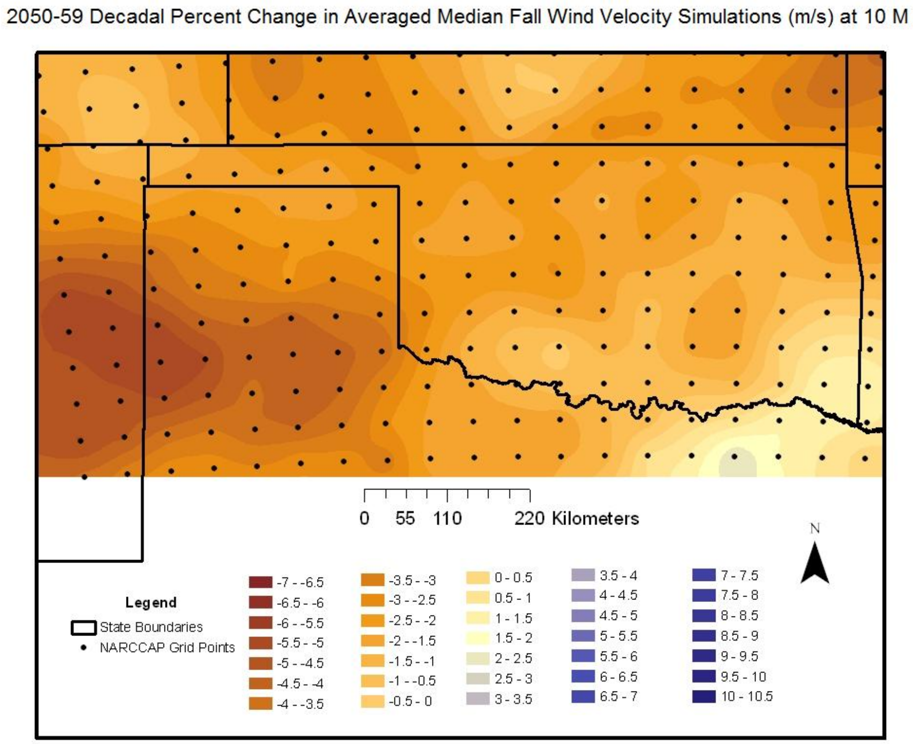

2050-59 Decadal Percent Change in Averaged Median Fall Wind Velocity Simulations (m/s) at 10 M

Figure A.15

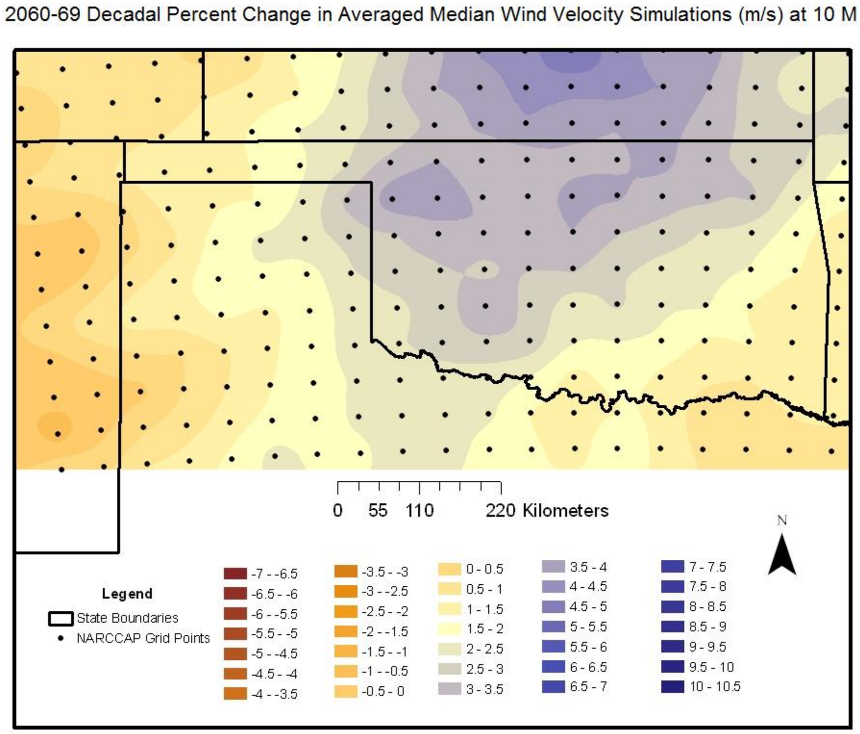
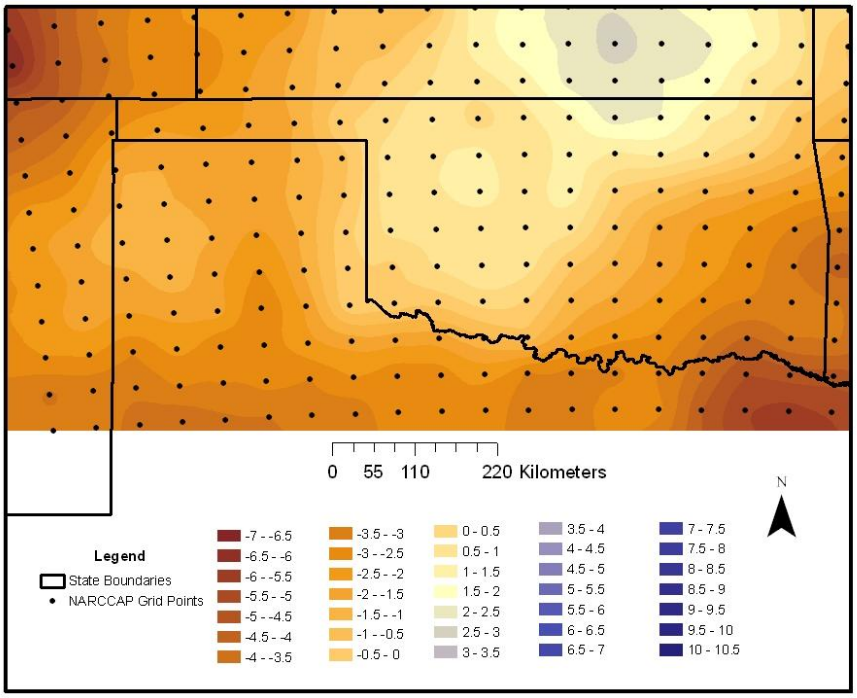
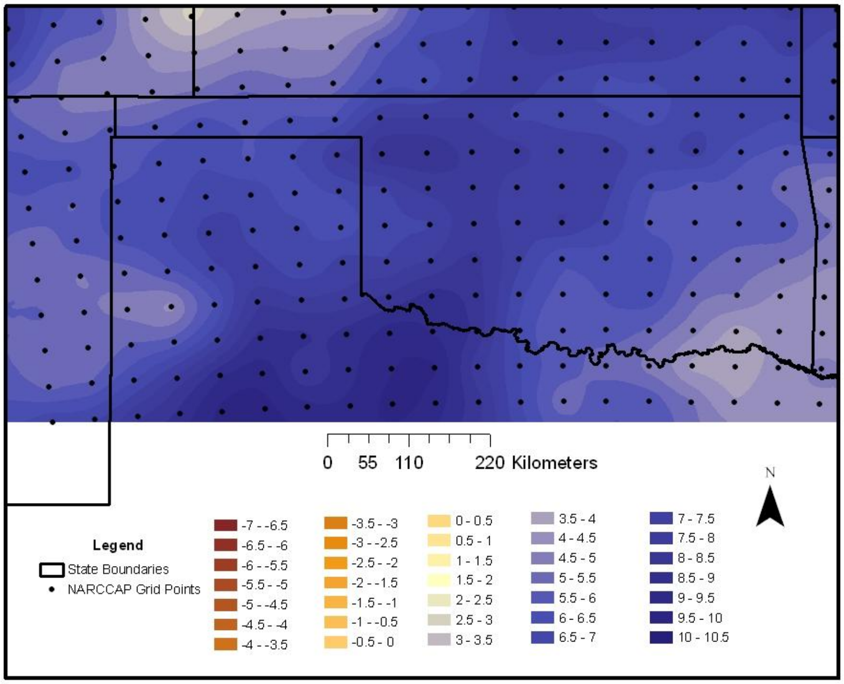

2060-69 Decadal Percent Change in Averaged Median Wind Velocity Simulations (m/s) at 10 M

Figure A.16



2060-69 Decadal Percent Change in Averaged Median Winter Wind Velocity Simulations (m/s) at 10 M

Figure A.17



2060-69 Decadal Percent Change in Averaged Median Spring Wind Velocity Simulations (m/s) at 10 M

Figure A.18

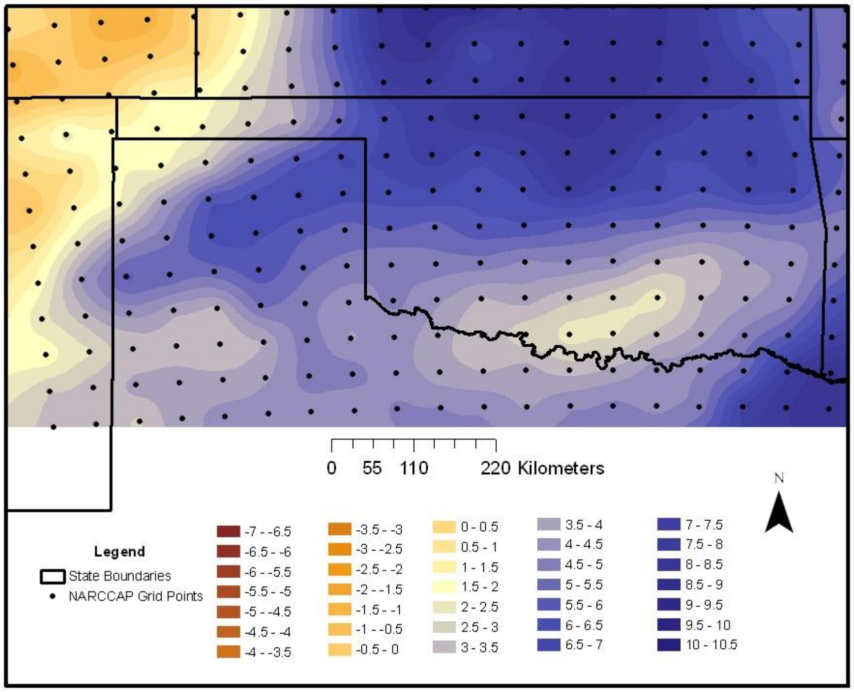

2060-69 Decadal Percent Change in Averaged Median Summer Wind Velocity Simulations (m/s) at 10 M

Figure A.19

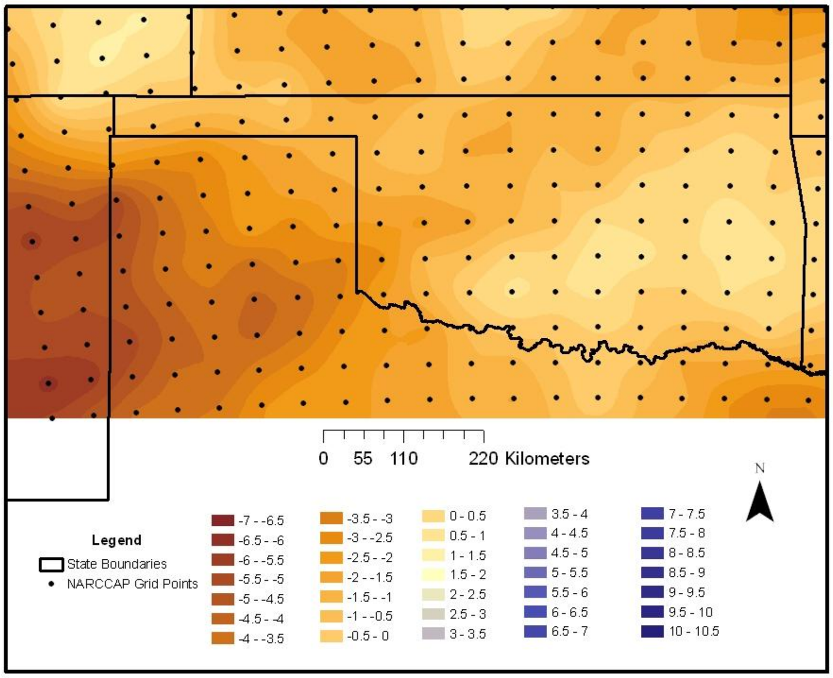

2060-69 Decadal Percent Change in Averaged Median Fall Wind Velocity Simulations (m/s) at 10 M

Figure A.20

Appendix B

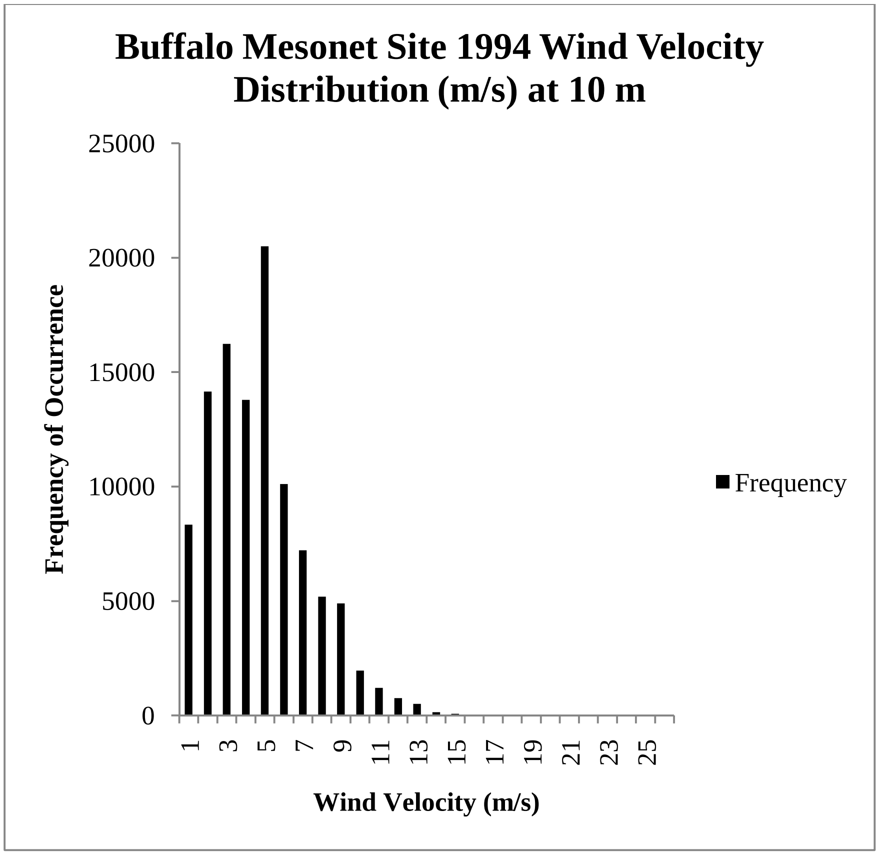


Figure B.1

Descriptive Statistics for Buffalo 1994 Wind Velocity Distribution	
Mean	4.17
Median	4.02
Standard Deviation	2.57
Kurtosis	75.54
Skewness	-1.07

Table B.1

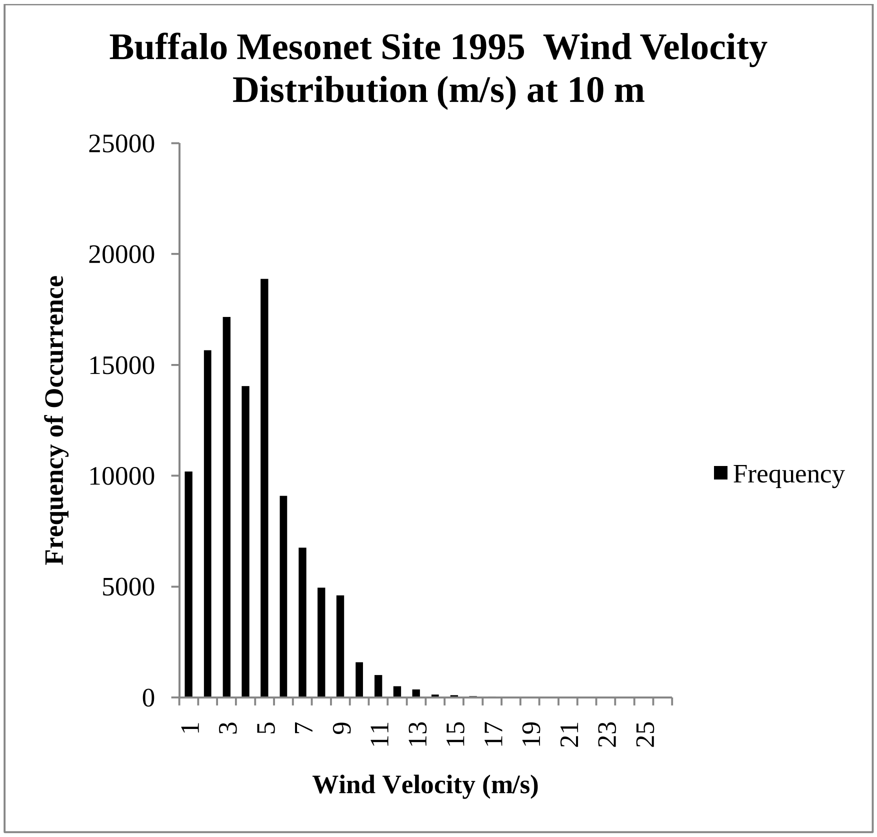


Figure B.2

Descriptive Statistics for Buffalo 1995 Wind Velocity Distribution	
Mean	3.89
Median	3.57
Standard Deviation	5.93
Kurtosis	4747.43
Skewness	-62.46

Table B.2

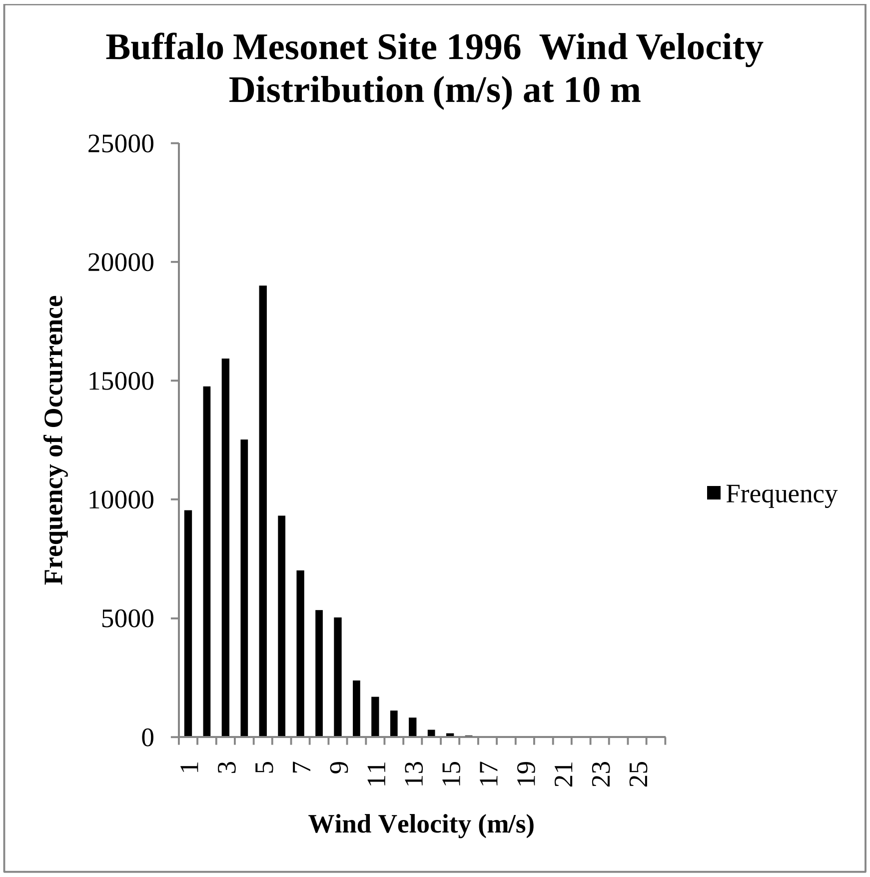


Figure B.3

Descriptive Statistics for Buffalo 1996 Wind Velocity Distribution	
Mean	4.03
Median	3.57
Standard Deviation	10.57
Kurtosis	1687.74
Skewness	-39.67

Table B.3

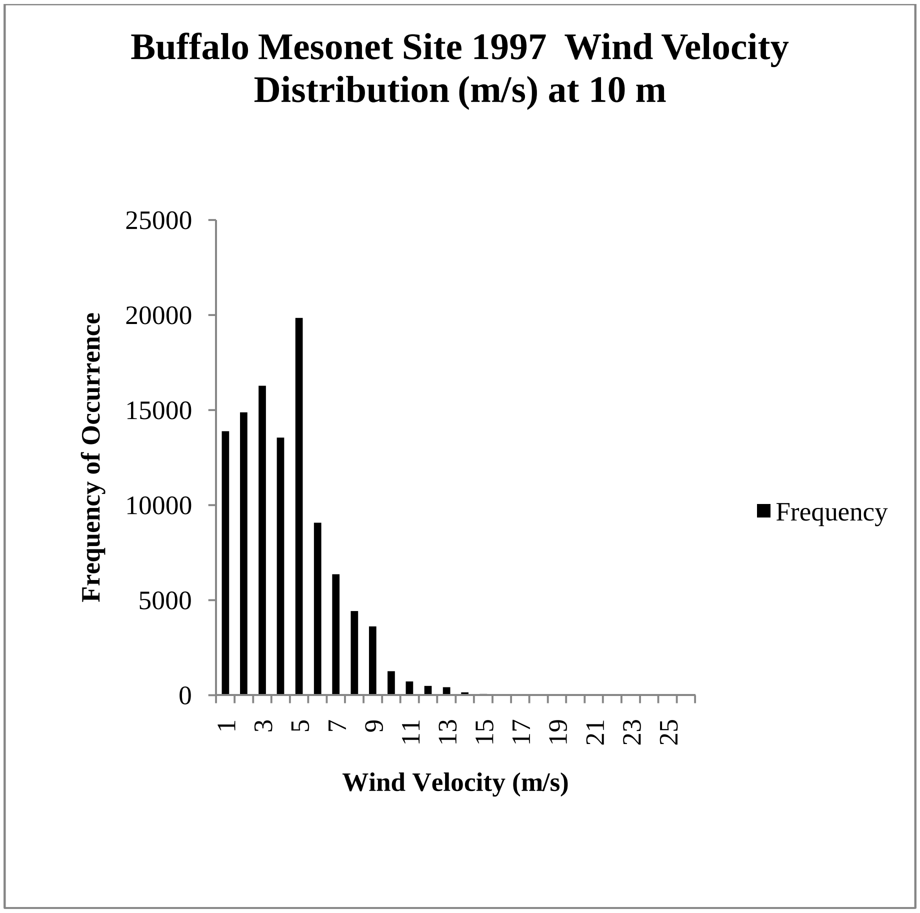


Figure B.4

Descriptive Statistics for Buffalo 1997 Wind Velocity Distribution	
Mean	3.66
Median	3.57
Standard Deviation	6.68
Kurtosis	3904.78
Skewness	-57.99

Table B.4

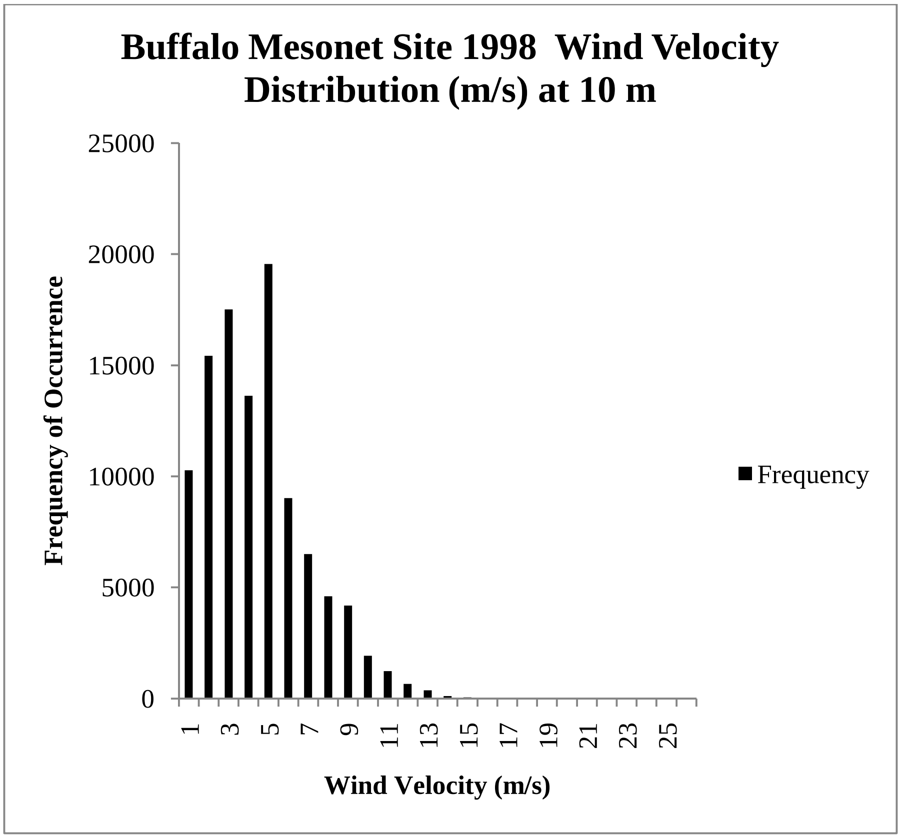


Figure B.5

Descriptive Statistics for Buffalo 1998 Wind Velocity Distribution	
Mean	3.46
Standard Error	0.04
Median	3.57
Standard Deviation	15.09
Kurtosis	860.15
Skewness	-28.95

Table B.5

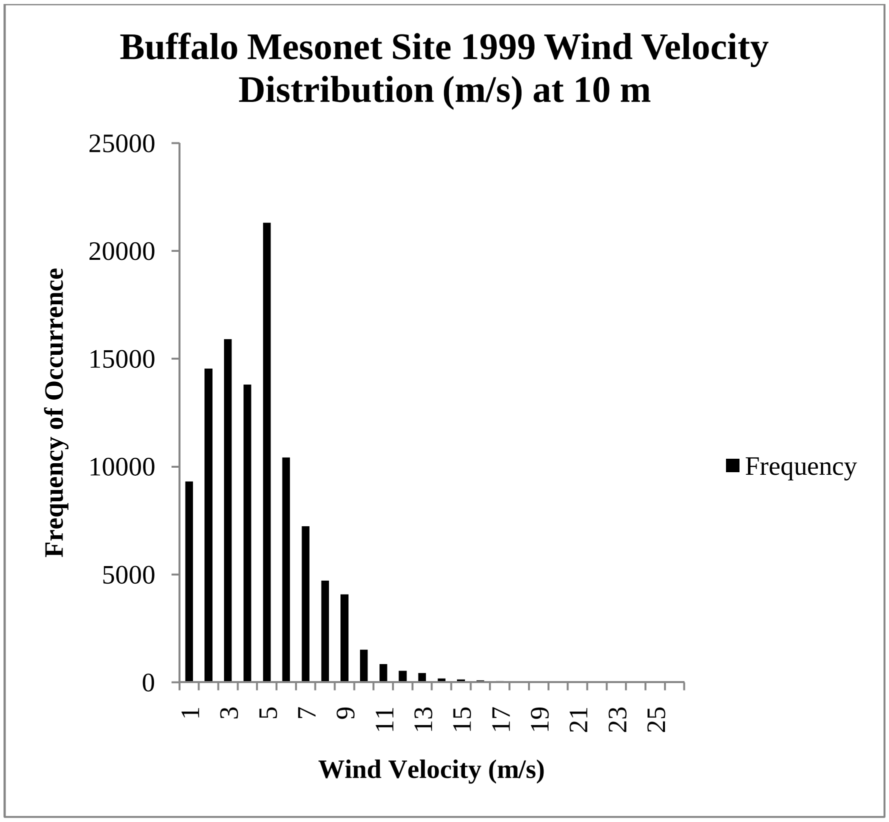


Figure B.6

Descriptive Statistics for Buffalo 1999 Wind Velocity Distribution	
Mean	3.713
Median	3.57
Standard Deviation	12.66
Kurtosis	1211.27
Skewness	-34.15

Table B.6

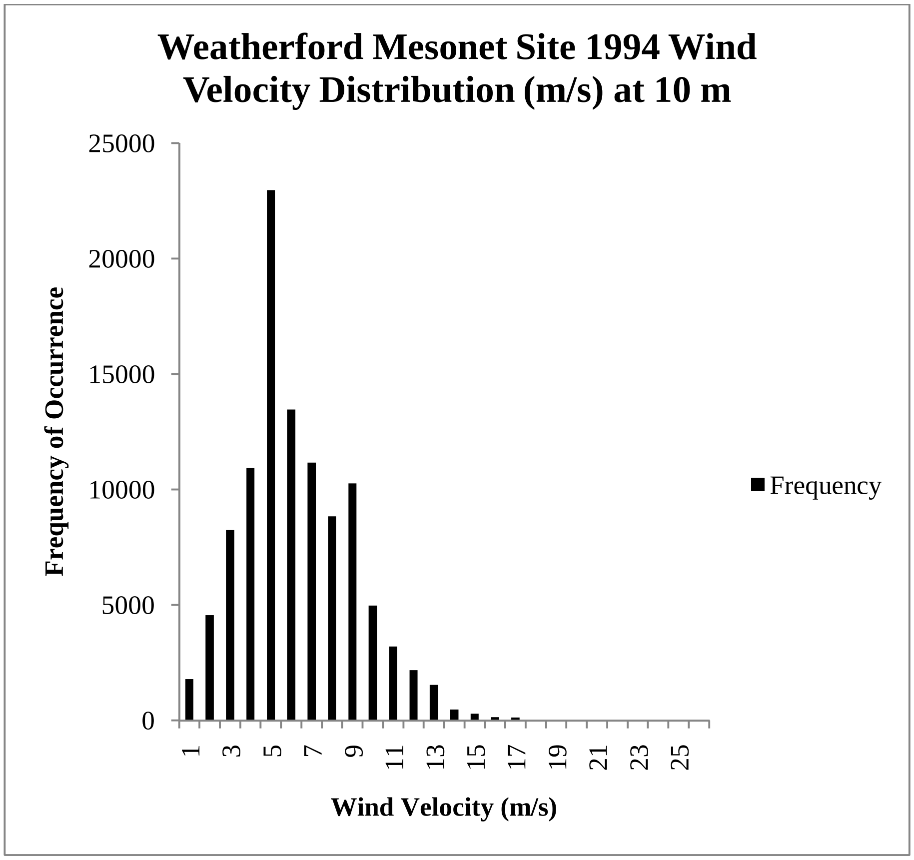


Figure B.7

Descriptive Statistics for Weatherford 1994 Wind Velocity Distribution	
Mean	5.74
Median	5.36
Standard Deviation	3.62
Kurtosis	363.78
Skewness	-12.29

Table B.7

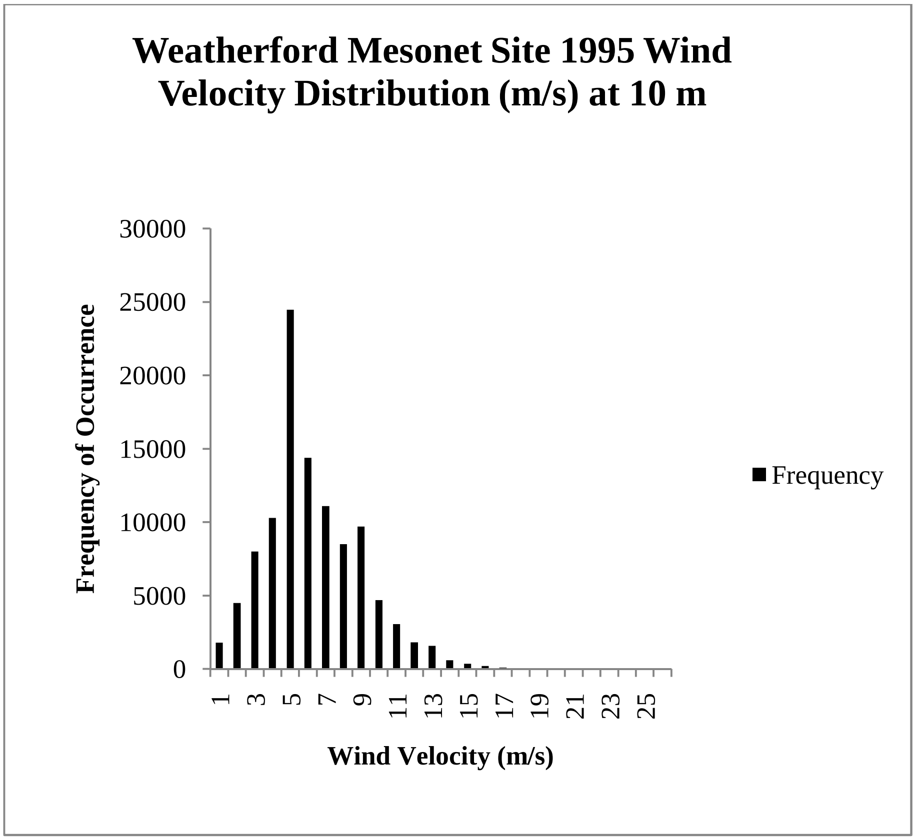


Figure B.8

Descriptive Statistics for Weatherford 1995 Wind Velocity Distribution	
Mean	5.71
Median	5.36
Standard Deviation	5.53
Kurtosis	5072.83
Skewness	-62.07

Table B.8

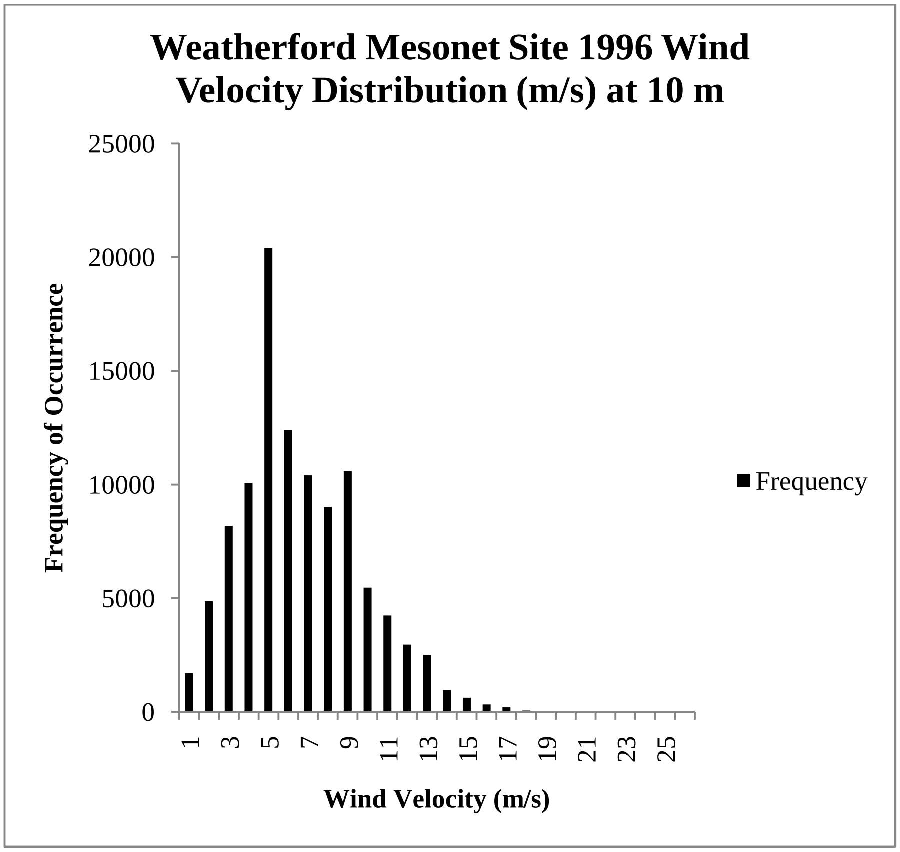


Figure B.9

Descriptive Statistics for Weatherford 1996 Wind Velocity Distribution	
Mean	6.04
Median	5.81
Standard Deviation	6.65
Kurtosis	3659.41
Skewness	-53.78

Table B.9

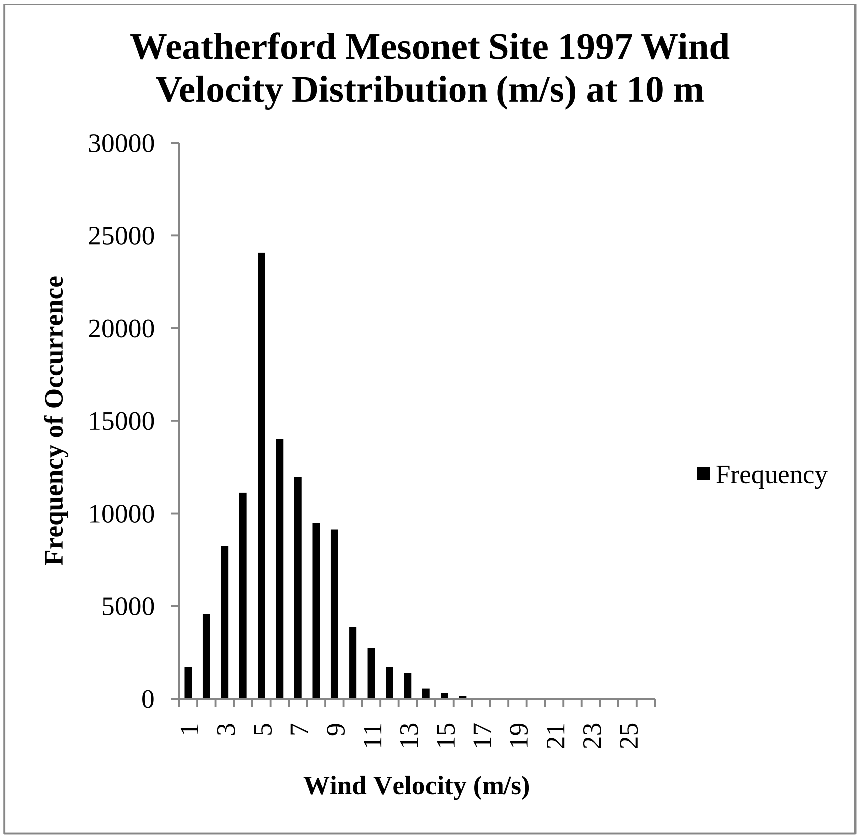


Figure B.10

Descriptive Statistics for Weatherford 1997 Wind Velocity Distribution	
Mean	5.60
Median	5.36
Standard Deviation	6.16
Kurtosis	4392.04
Skewness	-59.89

Table B.10

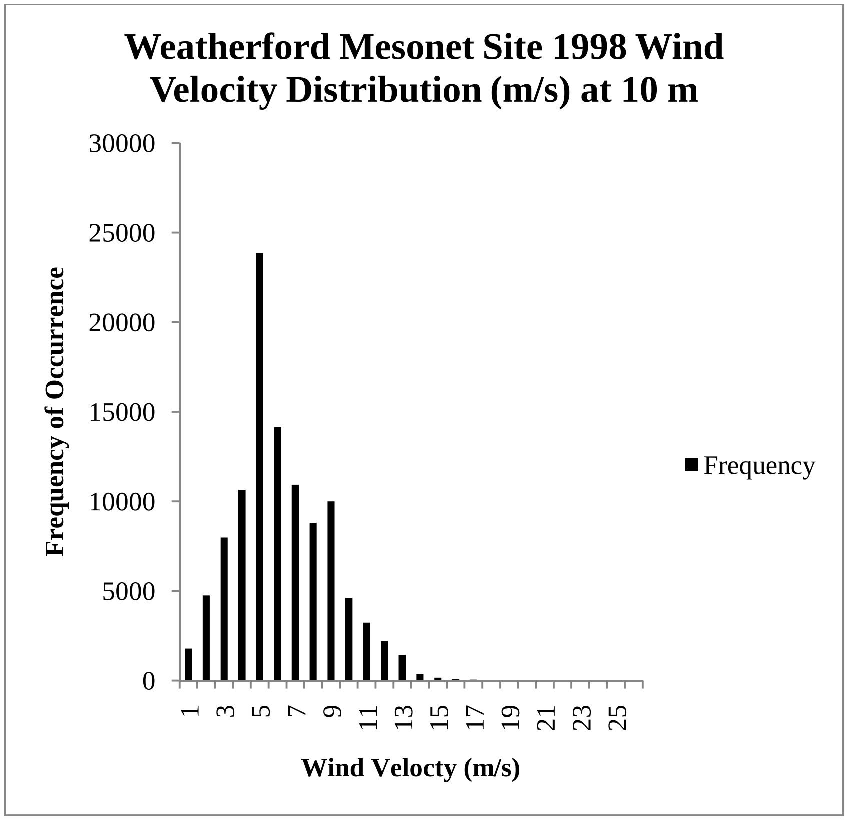


Figure B.11

Descriptive Statistics for Weatherford 1998 Wind Velocity Distribution	
Mean	5.54
Median	5.36
Standard Deviation	9.82
Kurtosis	1957.52
Skewness	-42.59

Table B.11

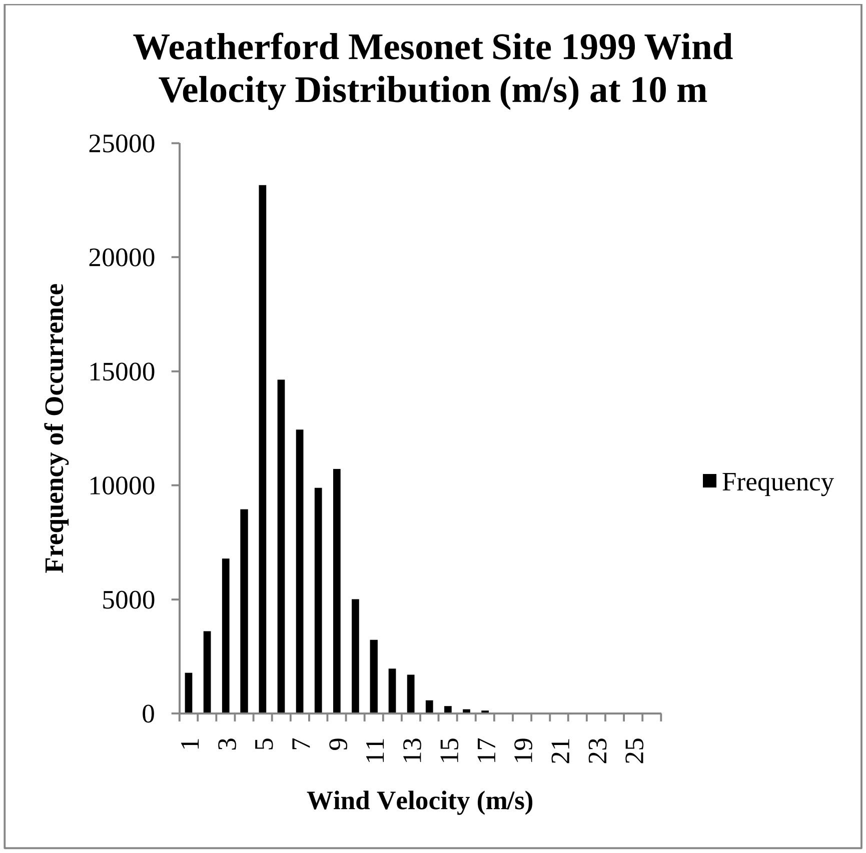


Figure B.12

Descriptive Statistics for Weatherford 1999 Wind Velocity Distribution	
Mean	4.96
Median	5.81
Standard Deviation	21.71
Kurtosis	421.66
Skewness	-20.42

Table B.12

VITA

James Mack Dryden, Jr.

Candidate for the Degree of

Master of Science

Thesis: POTENTIAL CLIMATE CHANGE IMPACTS ON OKLAHOMA'S WIND RESOURCE: A FOCUS ON FUTURE ENERGY OUTPUT

Major Field: Geography

Biographical:

Education:

Completed the requirements for the Master of Science in Geography at Oklahoma State University, Stillwater, Oklahoma in May 2011

Completed the requirements for the Bachelor of Science in Meteorology at University of Oklahoma, Norman in 2008.

Experience:

Graduate Research Assistant, Oklahoma State University, Department of Geography; January 2009 – December 2010

GIS Intern, Chesapeake Energy; January 2010 –August 2010

Project Meteorologist, Seeding Operations and Atmospheric Research; May 2008 – December 2008

Professional Memberships:

Phi Kappa Phi Honor Society

Name: James Mack Dryden, Jr. Date of Degree: May, 2011

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: POTENTIAL CLIMATE CHANGE IMPACTS ON OKLAHOMA'S WIND RESOURCE: A FOCUS ON FUTURE ENERGY OUTPUT

Pages in Study: 92 Candidate for the Degree of Master of Science

Major Field: Geography

Scope and Method of Study:

The current study focused on the potential climate change effects on wind resources in Oklahoma. This was a quantitative study that involved Global Climate Model output, Oklahoma Mesonet data, and electric power-curve characteristics for a commercial wind turbine. The analyses were done in Microsoft Excel and Geographical Information Systems. Essentially, the goal of the study was to examine how human-caused climate change might increase or decrease wind speeds, therefore affecting energy output, in the future.

Findings and Conclusions:

The findings of the current study include increasing wind speeds for every season, except for fall, from 2039 through 2070. Furthermore, electricity generated from these wind velocities increased at Centennial Wind-farm and Weatherford Wind Energy Center wind-farm over the same time period. The findings of this study could have a significant impact on Oklahoma's wind power industry.

ADVISER'S APPROVAL: Dr. Stephen Stadler