Trends of Wind and Wind Power Over the Coterminous United States

Eric M. Holt
University of Nebraska-Lincoln, eric.holt@huskers.unl.edu

Follow this and additional works at: http://digitalcommons.unl.edu/geoscidiss

Part of the Atmospheric Sciences Commons, Climate Commons, Earth Sciences Commons, Environmental Sciences Commons, Meteorology Commons, and the Other Oceanography and Atmospheric Sciences and Meteorology Commons

http://digitalcommons.unl.edu/geoscidiss/22

This Article is brought to you for free and open access by the Earth and Atmospheric Sciences, Department of at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Dissertations & Theses in Earth and Atmospheric Sciences by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.
TRENDS OF WIND AND WIND POWER OVER THE COTERMINOUS UNITED STATES

By

Eric M. Holt

A THESIS

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Master of Science

Major: Earth and Atmospheric Sciences

Under the Supervision of Professor Jun Wang

Lincoln, Nebraska

March 2011
TRENDS OF HUB-HEIGHT WIND AND WIND POWER OVER THE COTERMINOUS UNITED STATES

Eric M. Holt, M.S.
University of Nebraska, 2011

Adviser: Jun Wang

The trends of wind and wind power at a typical wind turbine hub height (80 m) are analyzed using the North American Regional Reanalysis (NARR) dataset for 1979-2009. Based upon the wind speeds at NARR’s vertical layers right above and below the 80 m level, the wind speeds at 80 m are estimated using two methods assuming the wind profile respectively as linear and power-law distribution with respect to the altitude in the lower boundary layer. Furthermore, we calculate the following variables at 80 m that are needed for the estimation and interpretation of wind power: the air density, zonal wind ($u$), meridional wind ($v$), and total wind speed. It is found that the difference between using the power-law and linear interpolation for the derivation of the 80 m wind generally results in less than 20% difference in the estimate of annually-averaged wind power in the majority of U.S. Statistically significant and positive annual trends are found to be predominant over the contiguous United States with spring and winter being the two largest contributing seasons. Positive trends of surface wind speed (up to ~0.15 m s$^{-1}$ dec$^{-1}$) are generally smaller with less spread than those (up to ~0.25 m s$^{-1}$ dec$^{-1}$) to 80 m, reflecting stronger increases of wind speed at altitudes above the 80 m level. In the regional averages, trends are positive and linearly continuous during 1979-2009 for the West region, but for the East and Central regions, a larger positive trend is found for wind speed and wind power during 1991-2009. Large and positive trends of wind and wind power over the southeast region and
high mountain regions are primarily due to the increasing trend of the meridional wind, which
supports previous studies reporting the enhancement of subtropical (Bermuda) highs and the
(Mexican Gulf) low level jet in response to global warming. In contrast, large and positive trends
of wind and wind power over the northern states (bordering Canada) are primarily due to the
increasing trend of the zonal wind, again reflecting the previous reports of the poleward
expansion of the tropospheric zonal jet. The positive trend of wind power found in this study
supports recent studies using radiosonde and reanalysis data that showed a positive trend of wind
at the lower troposphere, but is inconsistent with previous ground-based reports. Further studies
are needed to resolve such inconsistencies and to explain the trend of wind in the context of
climate change.
# TABLE OF CONTENTS

1. Introduction ................................................................................................................................. 1

2. Data ............................................................................................................................................. 5

3. Methodology ................................................................................................................................. 6
   3.1 Method for Estimating Wind at 80 m ........................................................................................... 6
   3.2 Method for Computing the Wind Power Capacity ..................................................................... 11

4. Results and Analysis ...................................................................................................................... 12
   4.1 Impacts of the wind profile on estimates of annually-averaged power of wind ...................... 12
   4.2 Geographical Distribution of Trends of Wind and Wind power ............................................... 14
       4.2.1 Annual Analysis .................................................................................................................. 15
       4.2.2 Trends in Winter ................................................................................................................ 17
       4.2.3 Trends in Spring ............................................................................................................... 18
       4.2.4 Trends in Summer ............................................................................................................ 19
       4.2.5 Trends in Fall ................................................................................................................... 19
   4.3 Trends of Regionally averaged Annual Wind and Wind power from 1979-2009 ....................... 20
       4.3.1 East Regional Trend ....................................................................................................... 21
       4.3.2 Midwest Regional Trend ................................................................................................. 22
       4.3.3 West Regional Trend ...................................................................................................... 23

5. Possible Climate Drivers of Wind Trends .................................................................................. 24

6. Summary and Discussion ............................................................................................................. 25

Acknowledgements .......................................................................................................................... 28

References ......................................................................................................................................... 29

Tables ............................................................................................................................................... 33
Table 1. ............................................................................................................................................... 33

Figures .............................................................................................................................................. 35
TABLES AND FIGURES

TABLES
Table 1. ............................................................................................................................. 33
Table 2. ............................................................................................................................. 34

FIGURES
Figure 1. 80 m Wind, U.S. Wind Farm Locations and Regional Domains .................... 35
Figure 2. Verification Profiles ........................................................................................ 36
Figure 3. Wind Power Interpolation Methods, Average Alpha, Variance ..................... 37
Figure 4. 10 m Surface Trends ..................................................................................... 38
Figure 5. 30-yr Wind and Wind Power Trends ................................................................. 39
Figure 6. 30-yr Winter Seasonal Trends ........................................................................ 40
Figure 7. 30-yr Spring Seasonal Trends ........................................................................ 41
Figure 8. 30-yr Summer Seasonal Trends ...................................................................... 42
Figure 9. 30-yr Fall Seasonal Trends ............................................................................. 43
Figure 10. East Regional Trends ................................................................................... 44
Figure 11. Midwest Regional Trends ............................................................................ 45
Figure 12. West Regional Trends .................................................................................. 46
1. Introduction

Currently, fossil fuels provide almost 80% of world energy supply [Intergovernmental Panel on Climate Change (IPCC), 2007]. In an effort to reduce the greenhouse gases emitted from burning of fossil fuels, the last two decades have seen a rapid growth in harvesting wind power, an important form of renewable energy. Between 1996 and 2010, global installed wind power capacity increased nearly from 1,280 MW to 35,802 MW [Global Wind Energy Council (GWEC), 2011]. Considering the global wind speed averages over land and water, total wind power that could be possibly generated at locations with a mean annual wind speed \( \geq 6.9 \text{ m s}^{-1} \) at the common wind turbine height of 80 m above the surface is \( \sim 72 \text{ TW} \) for the year 2000 [Archer and Jacobson, 2005].

China, which overtook the United States as the world’s largest CO\(_2\) emitter in 2006 [Netherlands Environmental Assessment Agency (NEAA), 2007], is also the 2\(^{nd}\) in the world in power generating capacity (792.5 GW), behind the United States (1032 GW) [McElroy et al., 2009]. In the United States, wind power generating capacity has grown by an average of 29% per annum from 2003-2007 [AWEA, 2009].

While wind is often considered a sustainable power source, recent studies have indicated a declining trend of surface wind speed. In Australia [Roderick et al., 2007], China [Xu et al., 2006a, 2006b], Europe [Pirazzoli and Tomasin, 2003], and North America [Klink, 1999; Tuller, 2004], the decline of near-surface wind speeds was apparent over the last 50 years (Table 1). The analysis of the North American Regional Reanalysis dataset (NARR) and observation stations over the Gulf of St. Lawrence in eastern Canada indicated a 0.05 m s\(^{-1}\)a\(^{-1}\) decrease of wind speed over the inland and
offshore areas [Hundecha et al., 2008]. In China, a decrease in wind speed was found in 1960-2000 in the Yangtze River Basin [Xu et al., 2006a]. Continental scale studies in Australia found statistically significant average negative trends of 0.009 m s\(^{-1}\) a\(^{-1}\) from 1975 to 2006 [McVicar et al., 2008]. Vautard et al. [2010] found in Europe, Central Asia, Eastern Asia and in North America that statistically significant annual mean surface wind speed has decreased on average at a rate of 0.09, 0.16, 0.12 and 0.07 m s\(^{-1}\) dec\(^{-1}\), respectively (or 2.9%, 5.9%, 4.2% and 1.8% per decade) [Vautard et al., 2010]. Along the eastern seaboard of the United States and upper Midwest, it was found that the 50\(^{th}\) percentile average of 10 m wind speeds declined at magnitude for 118 of 157 Automatic Surface Observation System (ASOS) stations analyzed for 1973-2005, while 90\(^{th}\) percentile 10 m wind speeds declined at 105 of 157 ASOS stations [Pryor et al., 2007]. Pryor et al. [2009], based upon surface observations, showed a 0.84 ± 0.32 m s\(^{-1}\) decrease of 90\(^{th}\) percentile winds of over the United States from 1973-2005. While the declining trend reported by previous studies often is statistically significant, they are generally small (< 0.1 m s\(^{-1}\)a\(^{-1}\)) and thus unlikely to reduce the sustainability of wind energy, at least in the lifespan of a typical wind power plant (presumably 20-30 years) [Pryor and Barthelmie, 2011].

The converse results reporting positive trend of wind speed, although only a few, do exist. In Europe, Pryor and Barthelmie, [2003] found that annual mean wind speeds at 850 hPa increased during 1953-1999. Recently, Vautard et al., [2010] further found from radiosonde observations that at higher altitudes (above ~950hPa), trends of wind speed become more positive with respect to the altitude.
The change in the global climate is assumed to be a key factor affecting the trend of wind speed, with a notion that the changes are partly affected by the atmospheric dynamics at the synoptic or global scale [Pryor and Barthelmie, 2009]. The specific mechanisms causing the observed global decline of wind speed, however, are currently unknown; future projections of the trend of wind speed are inconsistent and sometimes of the opposite sign among climate models [Pryor et al., 2009; Pryor and Barthelmie, 2011]. At regional scale, Tuller [2004] found that a decrease of up to 0.017 m s$^{-1}$ a$^{-1}$ for 3 stations in western Canada correlates (not statistically significant) with the negative phases of the Pacific North American index and the Pacific Decadal Oscillation Index. In the Midwest region of the United States, wind speed and power trends have been linked to positive and negative phases of the Atlantic Oscillation (AO) and the North Atlantic Oscillation (NAO) [Klink et al., 2003; Klink, 2007]. Klink et al. [2003] further noted that the El Nino - Southern Oscillation (ENSO) (characterized from sea-surface temperature (SST) anomalies in the central Pacific Ocean) describes 6%-15% of the variance in wind speed residuals in 1995-2003 (assuming a 5-month lag in the analysis).

It is worth noting, however, that previous studies generally focused on the use of site-specific tower observations with limited use of model data, with few recent exceptions. While the ground-based observation data are expected to have a higher accuracy than the modeled data, their spatial coverage is often limited is some areas due to a lower number of surface observations sites. This limitation makes it difficult to correlate surface observations with any possible synoptic-scale mechanisms of the declining trend. Another limitation involves inconsistent altitudes at which wind speeds were measured (Table 1). Furthermore, it was found that tree growth around surface
stations can explain between 25% - 60% of the observed wind trend decrease from 1979-2008 [Vautard et al., 2010], exemplifying the limitations associated with surface stations. The use of model-based data would allow the resolution of boundary layer winds over a broad area in a manner that is amenable to and self-consistent with the physics of that model. Only a few studies, however, have used the meteorological re-analysis data (an optimal estimate of atmospheric state based upon observations and models) for studying wind power trends [Pryor et al., 2007; McVicar et al., 2008; Pryor et al., 2009; Li et al., 2010]. McVicar et al. [2008] revealed that the wind at 10 m from the NCEP-NCAR reanalysis and ECMWF 40 Years Reanalysis are 1.85-2.25 m s⁻¹ larger than the observed wind speed at a low height of 2 m. It should be noted that the 2.5° × 2.5° spatial resolution of the NCEP-NCAR reanalysis is ~30 times coarser than the spatial resolution (32 km × 32 km) of the North American Regional Reanalysis (NARR) data that are used in this study. This high horizontal resolution of NARR, coupled with its vertical resolution of 25 hPa below 700 hPa makes the NARR dataset uniquely suited for studying the climatology and trend of wind power at the regional-continental scales. As shown by Pryor et al. [2009], NARR 10 m wind data was analyzed from 1979-2006, finding that winds were declining over much of the western United States using the 0 Z time average (data averaged using only at 0Z), while trends were found to be positive at 12 Z (data averaged only at 12 Z). Li et al., [2010], who used NARR to investigate wind power resources over the U.S. Great Lakes region, found increasing winds over the entire region from 1979-2008.
This study uses the NARR dataset for discerning the trends of wind and wind power at each NARR grid box, assuming 5 MW km\(^{-2}\) or 2000 2.5 MW turbines per grid box (32 km × 32 km). Available wind power resources in the contiguous United States have undergone serious consideration for advancement in the last decade [Foltz et al., 2007], with the potential of accommodating up to 16 times the current U.S demand for electricity [Lu et al., 2009]. This advancement is already apparent by the commercial development of wind power in the Midwest and the remaining U.S. shown in Figure 1.

The specific objectives of this study are to: (1) design a method to estimate wind speed at the 80 m height level (typical height of a wind turbine) from NARR data; and (2) determine changes in spatial location, intensity and seasonal variability of the wind power for harvest in the continental U.S.

2. Data

The primary dataset used for this analysis is the North American Regional Reanalysis (NARR) dataset that is archived at the National Climatic Data Center (NCDC). The NARR data are derived from the NCEP-DOE Global Reanalysis, the NCEP regional Eta model and its data assimilation system, and a version of the Noah Land-Surface Model [Mesinger et al., 2006]. The dataset has 45 vertical layers with a horizontal grid spacing of approximately 32 km × 32 km over the continent of North America. NARR has a vertical grid spacing of 25 hPa (~200 m) from 1000 hPa to 700 hPa, which is more ideal than other reanalysis datasets, however interpolation is still needed. This dataset spans from 1979 to present, every 3 hours (0-21 Z) with real-time
assimilation using the Regional Climate Data Assimilation System, or R-CDAS [Ebisuzaki, et al., 2004]. The temporal granularity of the data used for this study is every 6 hours, from 0 Z to 18 Z. Extensive tests to assess the impact of assimilating these atmospheric components with surface temperature found that the 10 m winds and 2 m temperatures in the NARR dataset are improved compared to the NCEP-NCAR global reanalysis dataset [Mesinger et al., 2006].

3. Methodology

3.1 Method for Estimating Wind at 80 m

As outlined in Table 1, the data that denote the decline of wind speed were taken from observation towers at variable heights. For this study, however, winds at the 80 m level are the focus, due to its representation of the typical industrial turbine height in the range of 60-100 m [Ray et al., 2006]. Here, we derive the 80 m winds every 6 hours (0, 6, 12, 18 UTC) from 10 m through 500 hPa from 1979-2009. NARR’s fine vertical resolution in the boundary layer allows us to use the hydrostatic equation to directly find two altitudes (pressure levels) that are 25 hPa (~200m) apart that bracket the 80 m height level above the surface. If the pressure at the lowest vertical level bracketing the turbine is larger than the surface pressure (indicating that surface is above the bottom NARR level), the level at 10 m will be used as the bottom level. Winds at 30 m are available in NARR, however, due to a systematic error within NARR, these winds are either wrong, or near zero over areas at and near sea-level. The wind speed at 80 m can then be derived through interpolation by using the wind speed in these two levels (right above and below 80 m). We argue that extrapolation and/or interpolation of the wind at turbine height is
usually necessary because neither measured nor modeled wind profile data are common at the 80 m level [Peterson and Hennessey, 1978; also Table 1].

Specifically, we first find the model pressure level that is closest to and above the surface. This level is called \( P_1 \). We then estimate the geometric thickness from the surface to \( P_1 \) using the hydrostatic equation:

\[
\Delta h_1 = \frac{\Delta P}{\rho g} = \frac{P_{\text{sf}e} - P_1}{\rho g}
\]  
(Eq. 1)

where \( \Delta P \) is a difference in pressure (in Pa), \( P_{\text{sf}e} \) is surface pressure, \( \rho \) is air density (in g m\(^{-3}\)), and \( g \) denotes the gravitational constant (9.8 m s\(^{-2}\)). It should be noted that \( \rho \) varies with elevation and moisture content in the air, as well as temperature (at a specified pressure). Such variability is taken into account in our calculations (see details for estimating air density in section 3.2).

If the thickness \( \Delta h_1 \) is larger than 80 m, then the wind speeds respectively at 10 m and at the pressure level \( P_1 \) will be used in the interpolation to estimate the wind speed at 80 m; otherwise, we will compute the thickness (\( \Delta h_2 \)) between \( P_1 \) and the pressure level right above \( P_1 \) (hereafter \( P_2 \)). Because the vertical grid point spacing of NARR is equal to or larger than 25 hPa, \( \Delta h_2 \) term is usually larger than 80 m, which makes \( P_2 \) as the model pressure level right above the altitude of 80 m from the surface. Hence, in cases where \( \Delta h_1 \) is less than 80 m (which can be true depending on surface pressure), we will use the wind speed between \( P_1 \) and \( P_2 \) for the interpolation at 80 m.

With the method above, we can identify the two closest model levels that bracket the 80 m height, and infer the height of both levels above the surface (hereafter \( Z_{a80} \) and \( Z_{a80} \)). We then take the winds at these two levels to estimate the wind at 80 m. This
estimation requires the assumption of the variation of wind with height (e.g., a wind profile). We derive the wind at 80 m by applying a commonly used (power-law) profile \cite{Robeson_and_Shein_1997, Elliot_etal_1986, Arya_1988, Archer_and_Jacobson_2003} to the winds between $Z_{b80}$ and $Z_{a80}$:

$$V_{b80} = V_{80} \times \left( \frac{Z_{b80}}{80} \right)^\alpha$$

(Eq. 2)

$$V_{a80} = V_{80} \times \left( \frac{Z_{a80}}{80} \right)^\alpha$$

(Eq. 3)

From which we can derive

$$\alpha = \frac{\ln \frac{V_{b80}}{V_{a80}}}{\ln \frac{Z_{b80}}{Z_{a80}}}$$

(Eq. 4)

and

$$V_{80} = V_{b80} \left( \frac{80}{Z_{b80}} \right)^\alpha$$

(Eq. 5)

Based upon equations 4 and 5, we can obtain the 80 m wind from the wind speed at $Z_{b80}$ and $Z_{a80}$, respectively. Use of the power-law profile is of course empirical \cite{Arya_1988}; but given that the boundary layer process is generally parameterized in the regional or global meteorological models, it has been widely used in the literature to estimate wind speed at a different altitude within the boundary layer \cite{Robeson_and_Shein_1997, Elliot_etal_1986, Arya_1988} and is shown to have good accuracy \cite{Archer_and_Jacobson_2003}. The exponent $\alpha$ is generally around 0.1-0.3, depending on atmospheric stability and surface roughness length \cite{Arya_2001}. It is fixed as 1/7 in the development of Wind Resource Map at the National Resource Energy Lab (NREL) as well as in a recent model-based assessment of future wind energy trend \cite{Pryor_and_Barthelmie_2011}.
After the total wind speed at 80 m is calculated, the next step is to estimate the \( u \) and \( v \) component at 80 m (hereafter \( u_{80} \) and \( v_{80} \), respectively). We simply derive the 80 m wind direction based upon the wind direction (\( \gamma \)) at two different levels below and above 80 m:

\[
\gamma_{b80} = \tan^{-1}\left( \frac{v_{b80}}{u_{b80}} \right) \quad \text{(Eq. 6)}
\]

\[
\gamma_{a80} = \tan^{-1}\left( \frac{v_{a80}}{u_{a80}} \right) \quad \text{(Eq. 7)}
\]

The wind direction at 80 m (\( \gamma_{80} \)), under the assumption that wind direction varies linearly as a function of altitude, is estimated from the wind directions at \( L_{b80} \) and \( L_{a80} \):

\[
\gamma_{80} = \gamma_{b80} + (\gamma_{a80} - \gamma_{b80}) \left( \frac{80 - Z_{b80}}{Z_{a80} - Z_{b80}} \right) \quad \text{(Eq. 8)}
\]

In equations 6 and 7, the mathematical solutions for \( \gamma_{b80} \) and \( \gamma_{a80} \) in a computer code (such as written in Interactive Data Language in this study) are both in the range from \(-\pi/2\) to \(\pi/2\). Note however, in the numerical models, the wind direction usually is defined as counterclockwise relative to the east (to ensure the westerly wind as a positive value), and should be in the range from 0 to \(2\pi\). Hence, we adjusted \( \gamma_{a80} \) and \( \gamma_{b80} \) in the above equation by adding \( \pi \) when \( u \) (\( v \)) at that level is negative (greater than zero), and by adding \( 2\pi \) whenever \( v \) at that level is negative. In other words, we are choosing the smallest angle from the two possible angular differences. Furthermore, because the absolute change of wind direction within NARR vertical resolution (25 hPa or 120 m) should rarely exceed \( \pi \), \( \gamma_{80} \) deduced from equation 8 should be adjusted whenever the absolute difference between \( \gamma_{b80} \) and \( \gamma_{a80} \) is larger than \( \pi \); such adjustment is to add (subtract) \( \pi \) if \( \gamma_{80} \) from equation 8 is smaller (larger) than \( \pi \). Certainly, if the
absolute difference between $\gamma_{b80}$ and $\gamma_{d80}$ is no larger than $\pi$, no adjustment needs to be made for $\gamma_{b80}$ computed from equation 8. After wind direction at 80 m is correctly computed, $u$ and $v$ components at 80 m are estimated as:

$$u_{80} = V_{80} \cos(\gamma_{80})$$  \hspace{1cm} (Eq. 9)

$$v_{80} = V_{80} \sin(\gamma_{80})$$  \hspace{1cm} (Eq. 10)

However, while widely used, the power-law equation is only empirical and lacks theoretical basis. To further use the fine vertical resolution of NARR data, we also estimate the 80 m wind speed through linear interpolation, similar to Li et al., [2010]. The purpose here is not to assess which method is more accurate, but rather to see if a different method can significantly vary the estimated trend and total amount of the wind power capacity. That difference will also allow us to have a first estimate of uncertainty in our calculation of wind power. The wind components are then individually linearly interpolated to 80 m from the nearest two pressure levels found in the technique described above. Using a linear interpolation method allows for an alternative assessment of wind power at the 80 m height level.

Figure 2 represents sample wind profiles at two different locations to illustrate the accountability for the varying topography (and hence surface pressure) in our methods of using power-law and linear interpolation to estimate winds at 80 m. In Figure 2a, the surface pressure is 1014 hPa, and our method is able to find the model pressure level right above 80 m, which is 1000 hPa. In Figure 2b where the surface pressure is 992 hPa, our method is able to correctly find the pressure level right above 80 m as 975 hPa. Hence, depending on local terrain/pressure variations, either the surface pressure or a
pressure level within NARR is used as the base interpolation level. Both Figure 2a and 2b indicate that the location and magnitude of the calculated $u$, $v$, and total wind speed (from the power-law or linear interpolation) at the 80 m above the surface are consistent with the NARR wind profile.

3.2 Method for Computing the Wind Power Capacity

After $u_{80}$, $v_{80}$, and $V_{80}$ (total wind speed at 80 m) are estimated using the power law and the linear methods described in section 3.1, wind power ($P$ in unit of watts) can be calculated using the following equation, as in Hennessey, [1977]:

$$P = \frac{1}{2} A \rho V_{80}^3$$

(Eq. 11)

where $A$ is the windswept area of a turbine (assuming its radius of 20 m), and $\rho$ the air density that includes the contribution from both dry air and moist air. In previous studies, $\rho$ was often assumed as constant with respect to space and time [Pryor and Barthelmie, 2011; Archer and Jacobson, 2003]. However, $\rho$ can vary significantly with topography and temperature, and is likely to have an increasing trend as a warmer atmosphere (due to greenhouse effect) can hold more water vapor. We estimate the air density $\rho$ by first deriving the water vapor pressure ($e$) from the NARR specific humidity ($q$) and pressure ($p$):

$$e = \frac{pq}{\varepsilon}$$

(Eq. 12)

where $\varepsilon = 0.622$ (ratio of the molar masses of water vapor and dry air). The water vapor density ($\rho_v$) is then computed with the ideal gas law:
\[ \rho_v = \frac{e}{R_v T} \]  
(Eq. 13)

where \( R_v \) is the specific gas constant of water vapor (461.5 J kg\(^{-1}\) K\(^{-1}\)), and \( T \) is temperature. Likewise, the dry air density (\( \rho_d \)) is determined by subtracting \( e \) from the level pressure, and using 286.9 J kg\(^{-1}\) K\(^{-1}\) as the specific gas constant for dry air:

\[ \rho_d = \frac{p - e}{R_d T} \]  
(Eq. 14)

After \( \rho_v \) and \( \rho_d \) are calculated, the total density of the air is their sum (\( \rho_0 = \rho_v + \rho_d \)), and is then linearly interpolated to 80 m and applied in equation 11 to estimate \( P \). Monthly-averaged wind power is calculated as:

\[ P_{AVG} = \frac{\sum_{i=1}^{n} (A \rho V_{80}^3)_i}{n} \]  
(Eq. 15)

where subscript \( i \) is the index for different times (4 times per day), \( A \) is the turbine area (assuming with a radius of 10 m), and \( n \) is the number of times of having valid modeled data within a month. For each grid point, the averaging scheme (equation 15) computes the sum of 80 m wind and power at each time step (or every 6 hrs), and then obtains the monthly average (\( P_{AVG} \)).

4. Results and Analysis

4.1 Impacts of the wind profile on estimates of annually-averaged power of wind

To estimate the annually-averaged power of wind (AE) in 1979-2009, the following two steps are taken: (i) calculate the monthly-averaged wind power (as described above),
and (ii) for each year, sum 12 monthly-averaged power of wind and then average them to obtain the averaged power of wind per annum.

The monthly-averaged power of wind is calculated using our temporal averaging method (section 3.3) and two different estimates of 80 m winds (respectively assuming power-law and linear wind profile, section 3.2). As a result, two sets of data for the monthly-averaged power of wind are made: (a) using our averaging method (equation 15) and the 80 m wind estimated assuming the power-law profile, hereafter $P_{PLAVG}$ and (b) using our averaging method but for the 80 m wind estimated from the linear-interpolation, hereafter $P_{LP AVG}$.

Figure 3a shows the geographical distribution of $P_{PLAVG}$. Higher values of power (~350 kW a$^{-1}$) are evident over parts of the Dakotas, Minnesota, Iowa and Nebraska, with lower values ranging from approximately 75-225 kW a$^{-1}$ over the coastal regions. Higher values of wind power generally indicate the regions with the most potential for commercial development, which has been the case, as shown in Figure 1. Even though offshore developments are currently being pursued, our domain is restricted to the coterminous United States due to this established commercial development.

Figure 3b shows the geographical distribution of the relative change (in %) using our averaging method (equation 15) but for different estimates of wind speed, e.g., $(P_{PLAVG} - P_{LP AVG}) / P_{PLAVG} \times 100$. This indicates the difference in the estimate of power using a different interpolation method for deriving the 80 m wind speed. Here, the maximum differences occur in the intermountain west, which can be upwards of 40-50% (Fig. 3b). Smaller differences (<20%) are found in areas with minimal topographical features. The
conclusion is that $P_{\text{PLAVG}}$ is systematically larger than $P_{\text{LPAVG}}$ (Fig 3b). The exponent $\alpha$ values over the majority of the U.S. are in the range of 0.16-0.20, and thus are consistent with the 0.17 ($1/7$) value used by the National Resource Energy Lab (NREL) as well as in [Pryor and Barthelmie, 2011]. In this regard, we argue that our method of using wind speeds at two vertically adjacent layers to invert (recover) power exponent $\alpha$ has its unique advantage (over the past methods) because the surface roughness and atmospheric stability have been considered in the NARR’s boundary layer scheme to regulate the winds near above the surface [Mellor and Yamada, 1974; Janjic, 1994]. While these advantages should be best illustrated using daily or weekly data, it is still partially reflected in the climatology (Fig. 3c) where larger $\alpha$ values are found in the U.S. intermountain west, Midwest, Appalachia, and parts of Louisiana. Since it is not reasonable to assume large surface roughness values over parts of the southeast and Midwest, this may give an indication of stability in these regions. Of course, additional studies would be required to learn exactly why alpha values vary in different regions.

Figure 3d represents the variance of the wind, showing higher variances over areas with more positive trends, such as the high plains, southern plains, the Columbia River valley, and northern Wisconsin/Upper Michigan Peninsula (illustrated in Figures 4-9). This makes sense, given that the variance represents the spread about the mean value.

4.2 Geographical Distribution of Trends of Wind and Wind power

The trends of wind and wind power (at each grid point) from 1979 to 2009 are investigated using linear regression. Only the linear trends at 95% or higher significance level are shown, using a two-tailed T test for each grid point. Generally, since the
planetary boundary layer is often described via power law wind profile [Peterson and Hennessey, 1977], the trend analysis for 80 m U & V wind components, total 80 m wind, and 80 m wind power, regardless of annual or seasonal averages of wind and wind power, are calculated solely based upon the monthly averages assuming the power-law profile. The seasonal division is as follows: Winter (December-January-February), Spring (March-April-May), Summer (June-July-August), and Fall (September-October-November), as described through the course of a year (Winter-Fall).

4.2.1 Annual Analysis

Previous studies using near-surface (10 m) wind speeds have generally found slight declines in wind trends [Pryor et al., 2007; Vautard et al., 2010], citing the increase of surface roughness (due to tree growth and urban development) as a major source of surface station observation bias [Vautard et al., 2010]. However, our findings indicate an opposite trend; the trend of surface wind and wind power trends in many places are positive but less than 4 kW dec$^{-1}$ for wind power (Fig. 4a) and less than 0.15 m s$^{-1}$ dec$^{-1}$ for total wind (Fig. 4b) over the majority of the continental U.S. from 1979-2009. Trends up to 8 kW dec$^{-1}$ for wind power and 0.3 m s$^{-1}$ dec$^{-1}$ for total wind are found in parts of the central plains and upper Midwest. However, negative trends of total wind speed up to -0.5 m s$^{-1}$ dec$^{-1}$ (Fig. 4b) are evident over parts of Virginia and the Carolinas, while -4 kW a$^{-1}$ (Fig. 4a) are evident over much of the Carolinas, Georgia, west Texas, Arizona and the high plains of Colorado. Previous studies using near-surface (10 m) wind speeds have generally found slight declines in wind trends [Pryor et al., 2007; Vautard et al., 2010], citing the increase of surface roughness (due to tree growth
and urban development) as a major source of artificial biases in surface observations

[Vautard et al., 2010; DeGaetano, 1998]. Specifically, general decreases of up
to 0.5 m s⁻¹ dec⁻¹ at the surface are found with rawinsonde data over much of the
coterminous United States from 1979-2008, while trends calculated with the ECMWF
ERA-interim reanalysis are generally negligible over the majority of the coterminous
U.S. [Vautard et al., 2010]. Vautard et al., [2010] points to deficiencies and/or missing
key processes in the models such as land-use changes as factors for the lack of wind
trends being resolved.

Trends of 80-m wind and wind power (Figure 5) are more positive than their
counterparts at the surface. Since topography generates mechanical turbulence and shear
in mountainous regions, surface wind and wind power trends are more representative of
those at 80 m, which explains the relatively smaller differences between Fig 5b, and Fig
4b over the mountain regions. In other words, the overall geographic signal is the same at
the surface and 80 m but the trend has a higher mean value at 80 m compared to the
surface. Conversely, over flatter regions such as the Great Plains, 80 m winds are more
influenced by winds higher in the boundary layer and the free atmosphere, explaining
some of the large differences in trends at the surface and 80 m. Wind power at 80 m (Fig
5a.) show increases of up to 35 kW dec⁻¹ for low-topographic areas, with little (if any
statistically) discernable areas of declining trends. The region containing the more
positive trends is the Midwest, from North Dakota to Texas, and from eastern Colorado
and New Mexico to West Virginia. Consequently, as wind power is a function of the
wind speed cubed (eq. 10), 80 m wind speed (Fig. 5b) illustrate similar positive trends,
with values up to 0.25 m s⁻¹ dec⁻¹. While it is difficult to discern the performance of
NARR in areas of extreme topography, there are grid boxes in parts of Colorado, Utah and Nevada (Fig. 5a & Fig. 5b) that contain anomalous positive trends as compared to negligible trends in the immediate surrounding grid boxes.

The positive trend of $u$ and $v$ wind components at 80 m over the United States (Fig. 5c & Fig. 5d) show comparable results with the trends of wind power (Fig. 5a) and total wind (Fig. 5b). However, we calculate the trend based on the component’s absolute value (i.e., trends are strictly calculated from the absolute magnitude of the components, not the sign of the components), and since the wind direction changes substantially, trends of $u$ and $v$ wind components are not necessarily reflected in the trends of wind speed and wind power. Trends of $u$ and $v$ components can be useful when analyzing the trends’ relationship with the direction and magnitude of the wind on a synoptic scale, which is part of the future work of this project.

4.2.2 Trends in Winter

Using the monthly averaged data, we examine the seasonal trends of wind and wind power to examine any common positive trends between the annually and seasonally averaged data. Positive trends (~0.24 m s$^{-1}$ dec$^{-1}$) of winter $u$ component wind at 80 m in 1979-2009 (Fig. 6c) are found over portions the mid-Mississippi River valley and the Ohio River valley. This signal is also shown in the $v$ component (Fig. 6d), as well as the 80 m wind speed (Fig. 6b) and wind power (Fig. 6a). Other widespread areas of positive trend with greater spatial variability (in Figures 6a and 6b) extend from the Ohio River valley into Mississippi and Alabama, northern Wisconsin/Upper Michigan Peninsula, as well as in parts of Oregon and the Columbia River valley, with values ranging from 0.20-
0.40 m s$^{-1}$ dec$^{-1}$ (10-30 kW dec$^{-1}$) for total 80-m wind (Fig. 6b) (80 m wind power, Fig. 6a). These patterns are recognizable in the total 80 m trend of wind speed (Fig. 5b) and wind power (Fig. 5a) as well. Insignificant trend values are apparent over parts of the upper Midwest, specifically over parts of Iowa, Nebraska and Minnesota (Figures 6a, 6b, and 6d), and are also vaguely apparent in Figure 5c.

4.2.3 Trends in Spring

During the spring, positive trends with significant spatial variability up to 0.25 m s$^{-1}$ dec$^{-1}$ and 30 kW dec$^{-1}$, respectively for total 80 m winds (Fig. 7b) and 80 m wind power (Fig. 7a) are found for the vast majority of the Midwest, from Texas to the Canadian border. This is in contrast to winter, in which the spatial extent of the positive trends was not as widespread. Although the most positive trends of wind power are centered in the Great Plains region, they are less positive toward the west and southeast. The consistent southwest-northeast swath of increased 80 m wind and wind power trend over the Ohio River valley found during the winter is more vague, but still apparent in the spring. This swath is also comparable to the annually averaged 80 m wind (Fig. 5b) and wind power (Fig. 5a). However, a relatively consistent area of positive 80 m wind trend (approximately 0.35 m s$^{-1}$dec$^{-1}$) is evident in both winter (Fig. 6b) and spring (Fig 7b) over the state of Arkansas, as well as the high plains region. Another recurring feature in the analysis includes consistent increasing trends over southern parts of Arizona and the Columbia River valley of Washington and Oregon (as mentioned hereinabove) evident in Figures 5-9, meaning that both monthly averaging and annual averaging are showing these features. The magnitude of the trends during the spring season are generally higher
than the annually averaged trends, however the spatial distribution of these magnitudes are very similar.

4.2.4 Trends in Summer

The highly positive trends of 80 m wind in Spring (0.35-0.42 m s\(^{-1}\) dec\(^{-1}\), Fig. 7b) and wind power (>25-30 kW dec\(^{-1}\), Fig. 7a) decreased during the summer season. Compared to spring, significantly less positive trends during the summer are evident for portions of the Midwest, eastern Arkansas, and southern Mississippi/Alabama. In these regions, total 80 m wind trends (Fig. 8b) are very comparable to that of the annually-averaged trends (Fig 5b). Annually-averaged 80-m wind power (Fig 5a) also shows comparable positive trends (~30 kW dec\(^{-1}\)) over parts of the upper Midwest, such as the Dakotas, Minnesota and northern Wisconsin. Larger/significant trends of \(u\) and \(v\) wind components (Fig. 8c and Fig. 8d) are concentrated over parts of the upper Midwest, Texas, and the High Plains region. Trends of the \(v\) wind component are more positive over parts of the Southeast and the Ohio River valley compared to the \(u\) components over these same regions.

4.2.5 Trends in Fall

During the fall, there is evidence of a decrease in the spatial extent of the positive trends as compared with the annually averaged wind and wind power (Figures 5a and 5b), with less significant trends over western Illinois, and parts of Oklahoma and Texas (Figures 9a and 9b). As compared to the summer analysis, this spatial extent is increased. Also compared to the summer analysis, the \(u\) wind component trends (Fig. 9c) between 0.12-0.18 m s\(^{-1}\) dec\(^{-1}\) are more apparent over portions of the upper Midwest. Similar
results are found for the $v$ wind component trends (Fig. 9d) over this area, as well as portions of Arkansas, Alabama and Georgia.

Overall, we have shown that the spring and winter seasons have the largest influence on the annually averaged trends, while the summer season has the lowest. However, the summer season significantly influences the annual $u$ and $v$ component trends over the Midwest and parts of the High Plains, with the $u$ component trends generally larger than the $v$ component trends. The fall season also influences the annually averaged trends, but only significantly over the Dakotas and Minnesota. The majority of the Great Plains states contain very significant trends year round, while parts of the mountain west contain no significant trends year round. The region with the most consistent positive trends for all variables and seasons is the High Plains region of eastern New Mexico, Colorado and Wyoming, in which the $v$ component trend is the primary contributor. This region contains the most consistent wind power source. If past trends are an indication of future trends, this area should be recommended as a prime area for future commercial wind power development.

4.3 Trends of Regionally averaged Annual Wind and Wind power from 1979-2009

After investigating the total and seasonal trends for every grid point over the continental United States, trends in regional averages are analyzed. Three regions were selected on state boundaries near major topographic features (i.e., east region was determined by states east of the Appalachians, the west region was determined by states west of the front range of the Rocky Mountains, while the Midwest region was
determined by states in between the Rocky Mountains and the Appalachian Mountains). Grid points for three U.S. regions (Fig. 1) are averaged for \( u \) & \( v \) components, 80 m total wind, and 80 m wind power calculated from the power law (eq. 5) as well as the linear interpolation (not included). All trends are again calculated using a two-sided t-test at a 95% significance level. Two separate trend lines are calculated for 1979-2009 and 1990-2009. The first trend line is calculated for the entirety of the dataset. We noticed that there was a visible increase in the average annual wind magnitudes from about 1990-2009. Specifically, the period from 1991-2000 is observed to be lower than normal, while greater than normal values from 2001-2009 are evident. This observation is very similar to the inter-annual variability analysis performed by Li et al., [2010]. The cause of this difference could stem from either a change in the observations that was assimilated into the NARR dataset, or stem from an actual occurrence. Therefore, a second trend line from 1990-2009 is also calculated based on this observed increase. All regional trend statistics are summarized in Table 2.

4.3.1 East Regional Trend

Within the majority of the trend analyses, the trends are positive from 1979-2009, but trends are also observed in our analysis to become more positive from 1990-2009. \( u \) & \( v \) component trends (Fig. 10c and 10d) are indicative of this. Results from the East regional 80 m total wind (Fig. 10b) also indicate a more positive regression from 1990-2009 (\( R = 0.76; p = 0.00016 \)) compared to 1979-2009 (\( R = 0.60; P = 0.00041 \)). The slope for Fig. 10b indicates an increase of 0.009 m s\(^{-1}\) over the 30 year span, with a similar magnitude (albeit negative) found over Australia in McVicar et al., [2008]. The spring
season seems to have more influence on the positive trends of 80 m wind and wind power over the East region (Fig. 7a & 7b), while trends of annually-averaged power of 80 m wind are generally 4-10 kW dec^{-1} over the region (Fig. 5a). Trends are mainly insignificant over the New England area, also found in Figure 5. The statistics from the analysis of $u$ component wind (Fig. 10c) are significant as well, indicating $R = 0.61$ in 1979-2009 and $R = 0.69$ in 1990-2009. However, trends remain more positive during 1990-2009 than 1979-2009. The analysis of $v$ component of wind (Fig. 10d) illustrates similar results as the $u$ wind component, but with slightly lower correlation from 1979-2009.

4.3.2 Midwest Regional Trend

The Midwest region shows slightly more positive trends for the $u$ component of wind (Fig. 11c), while trends for the $v$ component of wind (Fig. 11d) are higher than that of the East region (Fig. 10d, Table 2), showing comparable regression values but more statistically significant from 1990-2009. Total wind trends at 80 m (Fig. 11b) show very similar results with the East region (Fig. 10b) indicating a 0.67 (0.81) regression value with $P = 0.00006$ ($P = 0.00006$) from 1979-2009 (1990-2009). Both regions exemplify a similar range in trend values, with a visible spike in total wind from 2002-2009, the catalyst for the more positive trends from 1990-2009. Similar results between the regions also appear in the 80 m wind power (Fig 11a) with $R = 0.60$ and $P = 0.00036$ ($R = 0.80$ and $P = 0.00006$) from 1979-2009 (1990-2009), with again a visible spike in wind power from 2002-2009. Compared to the seasonally averaged analysis, the Midwest region sees
more positive trends during the spring, while maintaining that status over the 1979-2009 temporal span for the annually averaged analysis (Figure 5).

4.3.3 West Regional Trend

Trends from the West region of our analysis exhibit consistent characteristics with the East and Midwest, however the region exhibits lower values of all four variables. The trends for $u$ component of wind (Fig. 12c) show a very positive trend ($R = 0.69; P = 0.00006$) from 1979-2009, and $R = 0.60; P = 0.000645$ from 1990-2009, while trends are slightly less positive for the $v$ component of wind. 80 m total wind trends (Fig. 12b) are more positive than the East and Midwest from 1979-2009 ($R = 0.76; P = 0.00001$), but less robust from 1990-2009 ($R = 0.72; P = 0.00056$). While it is difficult to ascertain the cause of this disparity, it is possible to cite major terrain variation as a possible reason given the region. Similar regression values between the temporal spans are also present with 80 m wind power (Fig. 12a, Table 2). For all variables examined, p-values and regression values are very consistent from 1979-2009 (Table 2). Trends over the west region are more positive during the winter season for 80 m wind speed and wind power (Figure 6a & 6b) when compared to the seasonal analysis.

In short summary, all 3 regions indicate positive trends for all the analyzed variables including $u$, $v$, total wind, and power. However, it is shown that the East and Midwest regions both contain very similar values of wind and power, while the West region is noticeably lower. Stronger winds, combined with relatively uniform topography and lower densities of population and urban centers, make the Midwestern United States a relatively appealing place for the development of wind power plants in the U.S.
5. Possible Climate Drivers of Wind Trends

On the basis of the trend results presented herein, we conclude that significant positive trends in the mean wind speed and power are evident over much of the coterminous United States. The \( u \) and \( v \) wind component trends can be used as a foundation for a more intricate analysis of the climatic drivers of these trends, which is part of the future work of this project. However, our analysis of the trend of \( u \) and \( v \), which has not been conducted in the past research, are intriguing enough to hypothesize that the wind trends found here are linked to such past reported climate changes as strengthening of the low level jet, subtropical highs and zonal winds. Even though most of the studies presented hereafter are above 80 m and the boundary layer, major changes in wind processes that occur in the free atmosphere will have some influence on the processes in the boundary layer. Based upon climate model simulations, Kushner et al. [2001] showed that within a warming climate, the upper-level zonal wind and eddy kinetic energy is likely to increase in response to the thermal wind balance from tropospheric warming and stratospheric cooling [Lorenz and DeWeaver, 2007]. Furthermore, Lu et al., [2008] showed in their modeling studies that in response to global warming, the mid–low-level subtropical air temperature gradient decreases, and the zonal mean midlatitude westerlies and tropospheric zonal jet shift poleward, and the subtropical highs move poleward. Their proposed mechanisms further support Lorenz and DeWeaver [2007] in suggesting that the change in the height of the tropopause may also be responsible for the poleward shifts in the tropospheric jets and synoptic-scale storm tracks, leaving much of the Great Plains susceptible to intensified subtropical (Bermuda)
highs, favoring more frequent southerly low level jet formation [Song et al., 2005]. In fact, it has been shown using NARR that the core low level jet over the Great Plains has strengthened/expanded by 38% from 1979-2003 [Weaver and Nigam, 2008]. These modeling-based studies and analysis all support and can also explain our major findings:

(a) the trend of $v$ (and to some extent the trend of $u$) is distinct over the southeast (Arkansas, Texas, Oklahoma and Louisiana, Fig. 6) during winter and spring seasons, possibly because of the poleward shift of subtropical (Bermuda) high and strengthening of low level jet emanating from Gulf of Mexico; (b) the trend of $u$ (not $v$) is distinct in the northern states bordering Canada in all seasons, possibly because of the poleward shift and strengthening (expansion) of the tropospheric mid-latitude zonal jets (although an increase in upper level winds cannot be assumed to be directly associated with an increase in low-level winds); (c) the trend of $v$ and total wind is large over the high plains and could be attributed to an increase in midlatitude cyclone intensity [Lambert, 1995; McCabe et al., 2001], specifically cyclones that develop off of the lee side of the Rocky Mountains. For the future, IPCC simulations all report continued warming, so it is likely that wind trends will continue to be positive; however, different global model simulations may not produce a consistent result [Pryor and Barthalmie, 2011] and downscaling techniques are needed to study the trend at regional scale [Pryor et al., 2005].

6. Summary and Discussion

This study has provided a statistical assessment of the linear trends of wind and wind power at a common hub height of 80 m using the NARR gridded dataset. Linear trend of total winds and wind power in 1979-2009 in each NARR model grid box over
the contiguous United States are analyzed. One emphasis of this work focuses on the estimate of \( u \) and \( v \) components of wind at 80 m, so that the trend of wind speed at 80 m can be better interpreted in the context of the reported changes of various synoptic systems (i.e., low level jet over the Great Plains, tropospheric zonal jet, subtropical high, etc.). Critical to our estimation of wind at 80 m is to locate the two altitudes that are directly below and above 80 m and have the available wind data from NARR. This is done through the use of hydrostatic equation through a power law and linear interpolation, while accounting for terrain and air density variations.

Over the majority of U.S., it was found that high wind power values are evident over the central U.S., particularly the upper Midwest, representing the regions with the largest wind resources and the most potential for commercial development; but other factors such as transmission line proximity and government policies also play a important role in the commercial development of wind entities. Trends are found to be generally positive from 1979-2009, for all wind variables studied. However, the trends at the surface are relatively small, and in some regions negative. In contrast, trends at 80 m are mostly positive with large values in the Southeast, the Great Plains, the intermountain west, and northern states bordering Canada. Our results contrasts with previous works finding negative trends at the surface using observation stations (while citing significant biases), but is consistent with positive trends higher in the boundary layer found in the past studies [Li et al., 2010; Pryor et al., 2009; Vautard et al., 2010].

Seasonal analyses show that spring and winter are the two seasons that contribute the most to the increasing trend of annually-averaged wind power, while summer
contributes the least. The positive trend of $v$ exists over the southeast in all seasons and has distinct large values in spring and winter, which may reflect the strengthening of the subtropical Bermuda high in response to global warming [Lorenz and DeWeaver, 2007]. Furthermore, the strong positive trend of $v$ is also found in all seasons in the intermountain west, suggesting role of the strengthening low level jet over the southern plains and gulf states. [Lorenz and DeWeaver, 2007]. In contrast, the large positive trend of $u$ is found in all seasons over the northern border Canada, which can be interpreted as the result of strengthening of tropospheric zonal jets [Lu et al., 2008]. Further modeling studies are needed to evaluate our proposed link between the wind trend and climate change, while more observational-based analysis are required to validate our trend analysis and to resolve differences among different studies. It is also difficult to illustrate the link between the increasing upper-level winds and low-level winds, since this relationship cannot be assumed. It is unlikely to see an increase of upper-level winds and a decrease of lower-level winds (without outside influences), however, an additional study would be required to confirm such a notion. It has been shown that winds calculated via the power law interpolation have a systematically higher average than winds calculated with the linear interpolation, with increased disparity over the Rocky Mountains. We offer no reason as to why this occurs over the Rockies without further examination of local scale wind trends over mountainous terrain. Another caveat of this work involves the interpretation of alpha as it varies across the U.S. While there are higher values of alpha over extreme topography, other areas with higher values include
the Midwest and the southeastern U.S. This cannot be directly explained without additional research explaining the sensitivities of alpha.

**Acknowledgements**

First and foremost, I would like to thank my adviser Dr. Jun Wang for his support, help, and advice throughout my 2.5 years here at the University of Nebraska-Lincoln. I am very grateful for his patience and faith in my learning, and my success will forever be in debt to his efforts. Within the University of Nebraska-Lincoln, I would like to thank my committee: Dr. Clinton Rowe and Dr. Adam Houston for their support, our department chair: Dr. David Watkins for his advice and support and our secretaries: Tina Gray, Wendi Fletcher for their logistical support. I would like to thank Dr. Mark Anderson, Dr. Song Feng, Dave Peterson, George Limpert, Richard Xu, and Michael Veres for their technical support. I would like to thank the Department of Earth and Atmospheric Science for funding my T/A position, allowing me to perform this work. I would also like to thank my parents Mike and June Holt for their continuous moral support over the years.
References


http://rredc.nrel.gov/wind/pubs/atlas/


GWEC (2011), Global Wind Statistics 2010,


Pryor, S. C., R. J. Barthelmie, and E. S. Riley (2007), Historical evolution of wind climates in the USA, J. Phys. Conf. Ser., 75, 012065


# Tables

**Table 1.** Summary of previous works showing the declining trend of near-surface wind speed.

<table>
<thead>
<tr>
<th>Location</th>
<th>Time Span</th>
<th>Number of Sites</th>
<th>Trend (ms(^{-1})a(^{-1}))</th>
<th>Height(^1) (m)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>1975-2006</td>
<td>163</td>
<td>-0.009</td>
<td>station data: 2</td>
<td>McVicar et al., 2008</td>
</tr>
<tr>
<td>Australia</td>
<td>1975-2004</td>
<td>41</td>
<td>-0.01</td>
<td>2</td>
<td>Roderick, et al., 2007</td>
</tr>
<tr>
<td>United States</td>
<td>1960-1990</td>
<td>176</td>
<td>-0.004</td>
<td>6-21</td>
<td>Klink, 1999</td>
</tr>
<tr>
<td>United States</td>
<td>1973-2005(^3)</td>
<td>193</td>
<td>-0.026</td>
<td>10</td>
<td>Pryor et al., 2009</td>
</tr>
<tr>
<td>China</td>
<td>1960-2000</td>
<td>150</td>
<td>-0.008</td>
<td>10</td>
<td>Xu et al., 2006a</td>
</tr>
<tr>
<td>China</td>
<td>1969-2000</td>
<td>305</td>
<td>-0.2</td>
<td>10</td>
<td>Xu et al., 2006b</td>
</tr>
<tr>
<td>Loess Plateau, China</td>
<td>1980-2000</td>
<td>52</td>
<td>-0.01</td>
<td>10</td>
<td>McVicar et al., 2005</td>
</tr>
<tr>
<td>Italy</td>
<td>1955-1996</td>
<td>17</td>
<td>-0.013</td>
<td>Unavailable</td>
<td>Pirazzoli and Thomasin, 2003</td>
</tr>
<tr>
<td>Canada</td>
<td>1979-2004</td>
<td>13</td>
<td>Variable</td>
<td>10</td>
<td>Hundecha et al., 2008</td>
</tr>
<tr>
<td>Canada</td>
<td>1950-1995(^2)</td>
<td>4</td>
<td>-0.017</td>
<td>3-92</td>
<td>Tuller, 2004</td>
</tr>
</tbody>
</table>

\(^1\)The altitude at which the wind speed is measured or analyzed.

\(^2\)Years are approximate; each station has a different period of record.

\(^3\)Period of record includes 1979-2000.

\(^4\)Small amount of data was corrected to 10 m.
Table 2. Summary of the statistics of the regional trend analysis.

<p>| | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>U</td>
<td>V</td>
<td>Total</td>
<td>Power</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>R</td>
<td>P-Value</td>
<td>R</td>
<td>P-Value</td>
<td>R</td>
<td>P-Value</td>
<td>R</td>
</tr>
<tr>
<td><strong>East</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1979-2009</td>
<td>0.61</td>
<td>0.00026</td>
<td>0.52</td>
<td>0.00300</td>
<td>0.6</td>
<td>0.00041</td>
<td>0.49</td>
</tr>
<tr>
<td>1990-2009</td>
<td>0.69</td>
<td>0.00106</td>
<td>0.72</td>
<td>0.00051</td>
<td>0.76</td>
<td>0.00016</td>
<td>0.74</td>
</tr>
<tr>
<td><strong>Midwest</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1979-2009</td>
<td>0.70</td>
<td>0.00006</td>
<td>0.60</td>
<td>0.00036</td>
<td>0.67</td>
<td>0.00006</td>
<td>0.6</td>
</tr>
<tr>
<td>1990-2009</td>
<td>0.73</td>
<td>0.00041</td>
<td>0.81</td>
<td>0.00006</td>
<td>0.81</td>
<td>0.00006</td>
<td>0.8</td>
</tr>
<tr>
<td><strong>West</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1979-2009</td>
<td>0.69</td>
<td>0.00006</td>
<td>0.75</td>
<td>0.00001</td>
<td>0.76</td>
<td>0.00001</td>
<td>0.73</td>
</tr>
<tr>
<td>1990-2009</td>
<td>0.60</td>
<td>0.00645</td>
<td>0.71</td>
<td>0.00066</td>
<td>0.72</td>
<td>0.00056</td>
<td>0.69</td>
</tr>
</tbody>
</table>
Figure 1. Mean of annually-averaged 80-m wind speeds in 1979-2009. The 80 m wind speeds are estimated assuming the wind profile in the boundary layer as the power-law distribution (equation 5 in the text), and their annual averages are based upon the averaging method one (equation 15 in the text). Triangles represent the location of all U.S. wind farms (as of December 31, 2009), with size proportionate to the farm’s power capacity in kW. Also shown in the figure are the regions of West, Midwest, and East over the contiguous U.S., as defined in this study for the regional analysis of wind power.
Fig 2. Sample wind profile for NARR level winds and interpolated 80 m winds on 1 January 1979 0Z at (35.13N, -98.10W). Shown are NARR pressure levels and surface pressure (in hPa) on the right axis and the corresponding estimated height above the surface (in m) on the left axis. (b) Same as (a) but for the location of (31.98N, -111.05W) to illustrate the accountability for the varying topography (and hence surface pressure) in our methods of estimating 80 m wind (see section 3 for details).
Fig 3. (a) Geographical distribution of the mean of annual averages of wind power (kW) in 1979-2009 hereafter $P_{PLAVG}$. (b) relative change (in %) of (a) $P_{PLAVG}$ but different 80 m wind speed calculated with the linear interpolation (eq. 6), eg., $\frac{(P_{PLAVG}-P_{LPAVG})}{P_{PLAVG}} \times 100$; (c) same as (a) but for mean of annual averages of $\alpha$, the exponent used in the power-law equation for deriving wind at 80 m and computed based upon equation 4 in the text; (d) same as (c) but for the statistical variance of the 80 m wind.
Fig. 4. (a) Geographical distribution of linear trends (in kW/dec) of annually-averaged power of surface wind in 1979-2009. (b) Same as (a) but for trend (in m s\(^{-1}\)/dec\(^{-1}\)) of surface wind speed. Shaded are regions where the trends are at the 95% significance level or higher. Areas in white color indicate the regions that either are covered by a water surface or have insignificant trends.
Fig. 5. (a) Geographical distribution of linear trends (in kW dec⁻¹) of annually-averaged power of winds at 80 m in 1979-2009; (b) Same as (a) but for the trend (in m s⁻¹ dec⁻¹) of total wind speed at 80 m. (c) and (d) are the same as (a) but for trends (in m s⁻¹ dec⁻¹) of the U and V wind components, respectively. The absolute values of the U and V wind components are used in the trend calculation. Shaded are regions where the trends are at the 95% significance level or higher. Areas in white color indicate the regions that either are covered by a water surface or have insignificant trends.
Fig 6. (a) 1979-2009 Winter seasonal (December, January, February) linear trends of 80 m wind power; (b) Same as (a) but for the trend (in m s⁻¹ dec⁻¹) of total wind speed at 80 m. (c) and (d) are the same as (a) but for trends (in m s⁻¹ dec⁻¹) of the U and V wind components, respectively. The absolute values of the U and V wind components are used in the trend calculation. Shaded regions indicate trends at the 95% significance level or higher. Areas in white indicate regions that are either a water surface or have insignificant trends.
Fig 7. (a) Geographical distribution of the linear trends of Spring (March, April, May) seasonally-averaged power of winds at 80 m; (b) Same as (a) but for the trend (in m s$^{-1}$ dec$^{-1}$) of total wind speed at 80 m. (c) and (d) are the same as (a) but for trends (in m s$^{-1}$ dec$^{-1}$) of the U and V wind components, respectively. The absolute values of the U and V wind components are used in the trend calculation. Shaded are regions where the trends are at the 95% significance level or higher. Areas in white color indicate the regions that either are covered by a water surface or have insignificant trends.
Fig 8. (a) Geographical distribution of the linear trends of Summer ((June, July, August)) seasonally-averaged power of winds at 80 m; (b) Same as (a) but for the trend (in m s$^{-1}$ dec$^{-1}$) of total wind speed at 80 m. (c) and (d) are the same as (a) but for trends (in m s$^{-1}$ dec$^{-1}$) of the U and V wind components, respectively. The absolute values of the U and V wind components are used in the trend calculation. Shaded are regions where the trends are at the 95% significance level or higher. Areas in white color indicate the regions that either are covered by a water surface or have insignificant trends.
Fig 9. (a) Geographical distribution of the linear trends of Fall (September, October, November) seasonally-averaged power of winds at 80 m; (b) Same as (a) but for the trend (in m s$^{-1}$ dec$^{-1}$) of total wind speed at 80 m. (c) and (d) are the same as (a) but for trends (in m s$^{-1}$ dec$^{-1}$) of the U and V wind components, respectively. The absolute values of the U and V wind components are used in the trend calculation. Shaded are regions where the trends are at the 95% significance level or higher. Areas in white color indicate the regions that either are covered by a water surface or have insignificant trends.
Fig. 10. (a) 1979-2009 time series of the power of annually-averaged wind at 80 m in the U.S. East region (Fig. 1). The wind power is calculated with the wind estimated assuming the wind profile as power law distribution (eq. 5 in text). (b), (c) and (d) are the same as (a), but for total wind speed at 80 m, U wind component and V wind component, respectively. In (a)-(d), the solid lines in red and blue show the best linear fits of the variation of variables (y-axis) with time (x-axis) for 1979-2009 and 1990-2009, respectively. The statistics for the linear fit, including the correlation coefficient (R), number of data samples (N), the equation of the fit, and the statistical significance (P) are also shown correspondingly in red and blue color, respectively.
Fig. 11. Same as Fig. 10 but for the U.S. Midwest region (Fig. 1).
Fig. 12. Same as Fig. 10 but for the U.S. West region (Fig. 1).