Climatology of Surface Wind Speeds Using a Regional Climate Model

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ABSTRACT

Long-term changes in global climate have implications for surface wind speeds. Research has shown significant trends in wind speeds at various locations across the contiguous United States. In this study we test the hypothesis that there are statistically significant trends in mean monthly wind speeds and mean 3-hourly wind speeds over the period 1979-2004 in a simulation by a regional climate model. Analyses included examining both the model and observed monthly mean wind speeds over time and comparing the means and trends of two data sets. The model tended to overpredict the winds, especially in the Winter months. The infrequent underestimates typically occurred during the Summer months. Months from each season were then analyzed for trends in wind speed at six US locations. The model and observed monthly mean values were tested for significant differences and results indicated model data are significantly different from observations. Mean diurnal cycles for the cities revealed the model overpredicts wind speeds in the early morning hours which may be related to the boundary layer physics of the model. Due to its biases and misrepresentation of surface flow at night, the model does not accurately simulate the climatology of surface wind speeds nor a changing climate.

1. Introduction

Studies of surface wind speed conducted over the past thirty years contain useful information on methods for analysis of data, significant trends in wind speeds across the contiguous United States, and application of wind speeds to wind energy.

Zhang and Zheng (2003) studied how well PBL parameterizations being used in numerical models reproduce surface wind speed in relation to surface temperature. They found both surface wind speeds and surface temperature are sensitive to PBL parameterizations. However, the PBL schemes underestimated wind speed during the day and overestimate wind speeds at night. Well-simulated diurnal cycles of temperature did not necessarily reproduce the same caliber of wind speeds. The wind speeds were almost always too low and phase errors were prominent.

Takle et al. (1978) studied characteristics of wind speed and reported a significant increase in mean wind speed westward across Iowa over the time period of 1966-1975 varying 5ms^{-1} or less. Variations over Des Moines, Sioux City, and Burlington showed approximately the same order of increase as a study by Justus et al. (1976). In particular, plots revealed maximum wind speeds in the Great Lakes region, a slight minimum over hilly terrain in Wisconsin, a subtle increase in speeds across eastern Iowa, Missouri, and Minnesota, and distinct increases in speed over South Dakota, Nebraska, western Iowa, and eastern Kansas.

Pryor et al. (2007) studied observed wind speeds for the period 1973-2005. They found the highest wind speeds and energy density extend in a path between Texas and Montana/North Dakota. The 90th percentile of wind speeds for most stations had declining values. The significant declines are mostly grouped in the midwestern and eastern US. The highest winds were observed during Winter in the eastern part of the country and during Spring in the Western. New instrument integration in the 1990's did not result in significant changes in the 90th and 50th percentile wind speeds over the time period and suggest wind speed trends may be linked to climate variability.

In the past, analyzing wind speed trends was difficult due to calm winds and zero values in the data. Takle and Brown (1977) developed a method using a Weibull density function that more accurately represents wind speed data by accounting for zero wind speeds. Researchers have found accurate methods for analyses, significant trends in observed wind speeds, and diurnal relationships between temperature and wind speeds. An important addition to this research is to analyze wind speed output from a regional climate model by examining trends and comparing them to observed trends.

The objectives of this study are to test if there are statistically significant trends in mean monthly wind speeds and mean 3-hourly wind speeds over the period 1979-2004 in a simulation by a regional climate model. Pryor et al. (2007) suggest a general decline in surface wind speeds for a similar time period and it is hypothesized the model data at six locations will also show trends. I hypothesized the model trends would be weaker than the observed, but would have the same trend direction (positive or negative).

2. Data sets

a. MM5

The primary data set used for this study was surface wind speed output from the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5) which simulates regional-scale atmospheric circulation. This version of the model uses the KF2 convective parametrization (Kain et al. 2004), the planetary boundary layer scheme (Hong and Pan 1996), and has 51km grid spacing. In particular, the data set contains simulated wind speeds over North America 1 Jan 1979 to 30 November 2004 at a standardized height of 10 m (based on a log-scale relationship with the lowest model level). Only grid points over the contiguous United States were used in this analyses.

b. Observed data

The standard for evaluating the accuracy of simulated winds were the quality-controlled observed wind speeds at several stations in the US obtained from the National Climatic Data Center (NCDC) records in a daily format. Hourly observations were obtained from the Computational and Information Systems Laboratory (CISL) archive.

3. Data processing

Three main programs were written and used to average data:

- A Fortran program to read daily wind speed observations, sum and average over each month, and output mean monthly wind speeds.
- A Fortran program to read hourly wind speed observations, average eight three-hourly wind speeds for each day over each month, and output monthly three-hourly averages.
- A Fortran program to read MM5 data files containing the u and v components of the wind, combine corresponding files to calculate the total wind, calculate and output monthly means and monthly three-hourly means.

Particular locations were analyzed based on the study by Pryor et al. (2007). The following locations showed significant negative trends in the 90th and 50th percentiles: (1) Caribou, ME,

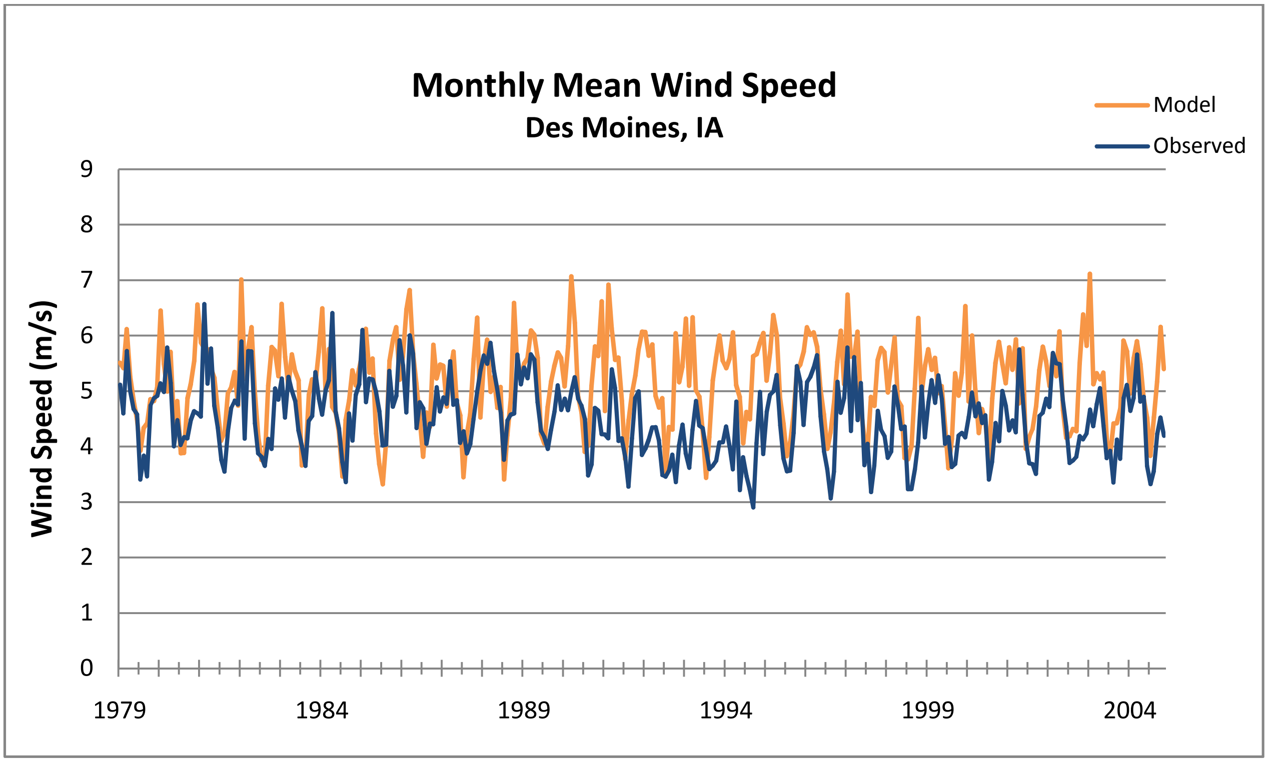

FIG 1. Surface wind speeds averaged for every month over the study period plotted against month of the year for Des Moines, Iowa.

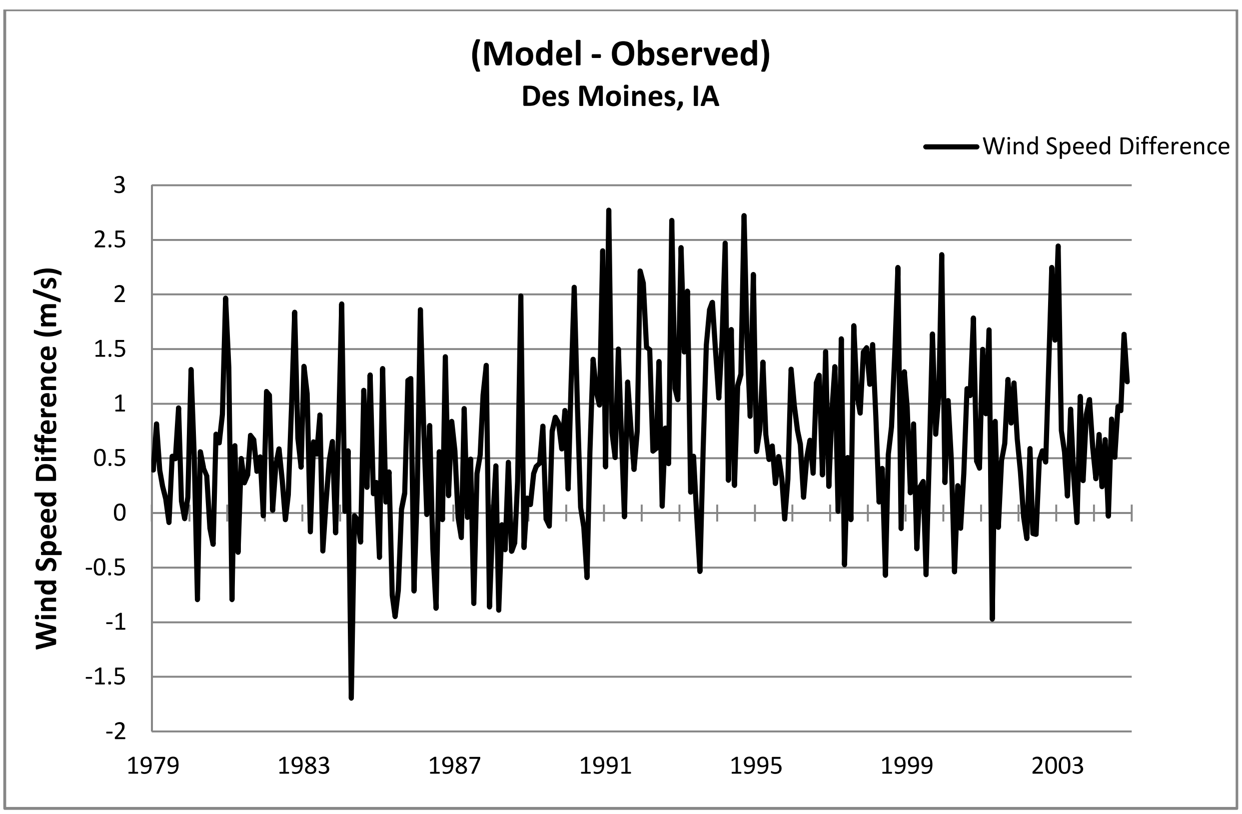

FIG 2. Model monthly mean wind speed minus observed monthly mean wind speeds plotted against month of the year for Des Moines, Iowa.

(2) Fort Worth, TX, and (3) Des Moines, IA. Cities showing large positive trends were (4) Indianapolis, IN, (5) Peoria, IL, and (6) Jacksonville, FL.

4. Analyses

a. Monthly means

Before assessing wind speed trends over the data record, I compared the model wind speeds with the observations. Monthly means were calculated to determine trends over the twenty-five year data record. Figure 1 illustrates data for the Des Moines, IA monthly mean wind speed over the period for both model and observed values. The model closely resembled the observed wind speeds at this location with similar seasonal variations and overall progression of speeds from the beginning to the end of the period.

A noticeable difference between the two data sets occurred between the years 1990-1995 where the model wind speed was about 1.5 m/s higher on average than the actual wind speeds (Fig. 2). The overall values of the model data were consistently higher than the observed winds. During 1979-1988 the model overestimated the wind speeds for most of the months with infrequent underestimates. The speeds were overestimated up to +2 m/s (maximum error in December 1980) and underestimated up to -1.7 m/s (maximum error in April 1984). The 10-year mean wind speed was 5.09 m/s (compared to the observed data mean of 4.72 m/s). Between 1989-2004 the model typically overestimated speeds and at higher values than the 10 years previous. The overestimated maximum speed was +2.8 m/s in February 1991. The underestimated maximum was only -.97 m/s in April 2001. For the rest of this section on monthly mean wind speeds, "error" refers to the difference between the model and observed values for each month:

$$M(month) - O(month) = Error \qquad (1)$$

where *M(month)* is the model mean monthly wind speed, *O(month)* is the observed mean monthly wind speed, and "month" is the month of the entire period ((25 years x 12 months)+11 months in 2004 = 311 months total). Similarly, the "mean error" was calculated by

$$\frac{\sum_{i=1}^{311} error(i)}{total\ number\ of\ months} \qquad (2)$$

where *i* is the month of the period and *total number of months* is 311.

Table 1 lists the most extreme overestimated and underestimated wind speed months from Figure 2 for the first period (1979-1988) and the count with which they had extreme error (Table 1). "Extreme error" was calculated from data distribution and for this analyses is considered error above the 90th quantile of wind speed difference (model minus observed) or error below the 10th quantile of wind speed difference.

Table 1. Months between 1979 and 1988 with extreme overestimates and underestimates for Des Moines

Month	Extreme overestimates count	Extreme underestimates count
January	4	1
February	2	1
March	-	2
April	-	2
May	-	1
June	-	1
July	-	4
October	4	-
November	1	-
December	1	2

*Extreme error for the case of an underestimate for this period is any speed at least -.35 m/s below observed speeds (10% quantile of error). Likewise, any speed overestimated by at least 1.26 m/s is considered extreme error on the positive side (90% quantile of error). Months omitted did not have "extreme" errors in the model data.

January and October were the most frequent months with the highest overestimates while July had the most frequent and largest underestimates by the model. Similarly, the same analyses can be done for the second period 1989-2004 (Table 2).

Table 2. Months between 1989 and 2004 with extreme overestimates and underestimates for Des Moines

Month	Extreme overestimates count	Extreme underestimates count
January	3	-
February	1	-
March	3	1
April	-	3
May	-	2
June	-	5
July	-	6
September	1	-
October	4	-
November	2	1
December	4	-

*Extreme error for the case of an underestimate for this period is any speed at least -.06 m/s below observed speeds (10% quantile of error). Likewise, any speed overestimated by at least 1.72 m/s is considered extreme error on the positive side (90% quantile of error).

For the second period, the following months had the largest overestimates: January, March, October, and December. The months with the largest underestimates were April, June, and July.

The entire period (1979-2004) mimicked the same pattern each period had individually. In the Fall and Winter months, wind speeds typically were overestimated while in the Spring and Summer months winds typically were underestimated.

Plots of single months were then examined to test the statistical significance of the seasonal variation found in the mean monthly model wind speeds. January mean wind speeds were consistently higher in the model data, except during 1985 and 1988 when the model results matched the observations. A linear fit to the January monthly means 1979-2004 showed decreases in both model and observations. A similar analysis for October revealed the model had higher values than observed every year except in 1995 (Fig. 3). Trend analysis showed the modeled values increasing and the observations decreasing over the period.

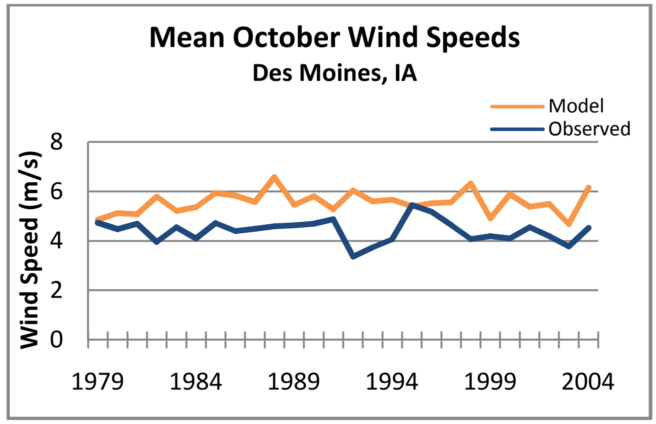

FIG. 3. Mean October wind speeds in Des Moines, Iowa.

The model and observations showed negative trends in April with a fairly small mean error between the model and observed values. Similar to October, trend analysis for the July data showed an increase in the model and decrease in the observations (Fig. 4). Model values for July had the smallest standard deviation and mean error of the four months analyzed for Des Moines.

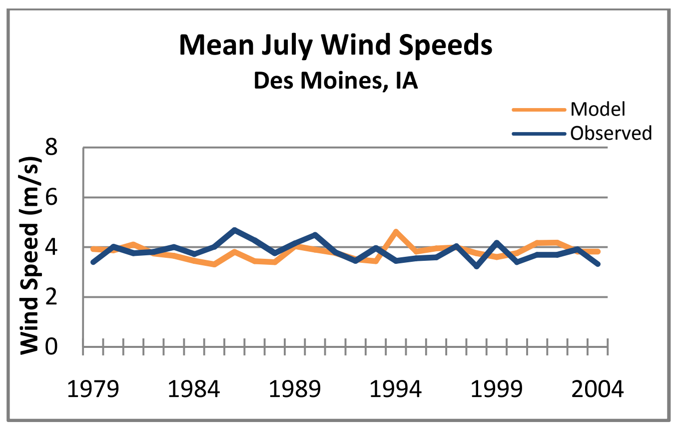

FIG. 4. Mean July wind speeds in Des Moines, Iowa.

Table 3. Statistics of mean monthly wind speeds by month for Des Moines, Iowa

Month	Slope of linear fit (model)	Slope of linear fit (obs.)	Standard dev. of error	Mean error
January	-.023 m/s	-.033 m/s	.767 m/s	+0.91 m/s
October	+.007 m/s	-.009 m/s	.679 m/s	+1.14 m/s
April	-.015 m/s	-.017 m/s	.654 m/s	+0.24 m/s
July	.+009 m/s	-.014 m/s	.504 m/s	-0.02 m/s

The model was much less accurate in Caribou, ME where there was a large negative trend in the observations (Fig. 5). A linear fit to the model monthly mean wind speeds over the period revealed zero trend, while the observations showed a -0.084 m/s decrease per year. The model overpredicted winds in all months except April 1982. The maximum error occurred in November, December, January , and February where many modeled wind speeds were above the 90th percentile of error. The model mean error was +2.28 m/s.

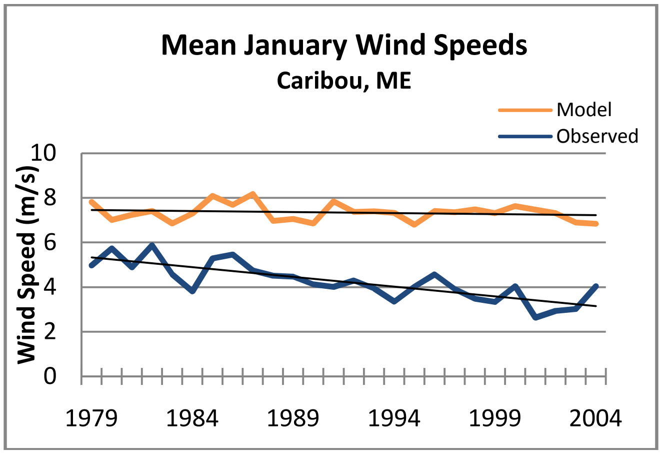

FIG. 5. Mean January wind speeds in Caribou, ME with linear fits.

For Indianapolis, IN the model overestimated winds above the 90th percentile of error in August, September, and October and underestimated winds below the 10th percentile of error January through April (not shown). The mean model error for the entire period is +0.612 m/s.

Wind data from Fort Worth, TX differed from those of other stations analyzed in that the standard deviation of error was much higher (large overestimates and underestimates). There was a higher count of months in the 90th and 10th percentiles compared to the other locations. The majority of the July wind speeds in the Fort Worth data set were extremely underestimated. December, January, and February were the most common months overestimated (not shown). The mean error for the period was +0.703 m/s.

Peoria, IL showed a similar pattern to Des Moines with a distinct error variation between the first and second halves of the period. Between 1979 and April 1991 the mean error was +0.962 m/s whereas May 1991 through November 2004 the mean error was +1.468 m/s (not shown).

Wind speeds in Jacksonville, FL were persistently overestimated by the model. Every monthly average was higher than the observed average. The mean error was +2.305 m/s (not shown). The grid spacing of the model may have this particular gridpoint partially representing the ocean. This would cause wind speeds to be higher due to less friction over water.

Table 4 compares the standard deviations, means, and trends of both model and observed wind speeds for the 6 locations in four different months (Table 4). The standard deviation is representative of seasonal variation. The mean represents the average wind speeds for the total period or particular months of the period. T-testing was used to look at the difference between the model and observed values:

$$t = \frac{\overline{x_1} - \overline{x_2}}{\sqrt{\frac{var1}{n1} + \frac{var2}{n2}}} \qquad (3)$$

where x_1 is the observed monthly mean, x_2 is the model mean, *var*1 is the observed variance, *var*2 is the model variance, *n*1 is the total number of months used for the observed mean, and *n*2 is the total number of months used for the model mean. A significant difference is a less than 5% probability that the values are related. Caribou, Jacksonville, and Peoria all had significant differences between model and observed monthly means for all four study months. Des Moines had significant differences in January and October. Fort Worth had significant differences in January, April, and October. Indianapolis had significant differences in July and October. Each of the locations showed at least 2 of the 4 study months had significant differences between observed and model monthly mean wind speeds (Table 4).

The trends for each of the locations are summarized in Table 5. Overall, the model trends were much smaller than the actual observed trends. The observed trend for Caribou was the largest negative trend of the 6 cities, however, the model showed very small negative trends in January and April. During July and October the model actually showed a positive trend in Caribou. The model simulated the Des Moines trend well in the four separate months, but had large error in the overall trend. Although Peoria had a similar wind speed pattern as Des Moines over the period, the model showed small negative trends in January and April with a positive trend during October.

Table 4. Analysis of Mean Wind Speeds for Observations and Model

	Total mean	Monthly means				Monthly standard deviations			
	Months (all years)	Jan	Apr	Jul	Oct	Jan	Apr	Jul	Oct
Observations (m/s)									
Caribou	4.041	4.234	4.428	3.591	3.980	0.839	0.812	0.891	0.689
Des Moines	4.503	4.857	5.201	3.826	4.414	0.615	0.466	0.359	0.453
Fort Worth	4.294	4.250	4.890	4.132	4.003	0.385	0.348	0.559	0.389
Indianapolis	4.235	4.828	4.972	3.396	3.983	0.436	0.466	0.309	0.379
Jacksonville	3.082	3.276	3.332	2.736	2.955	0.333	0.353	0.364	0.425
Peoria	3.991	4.519	4.773	3.132	3.589	0.627	0.516	0.406	0.487
Model Results (m/s)									
Caribou	6.325	**7.337**	**6.454**	**5.487**	**6.300**	0.375	0.418	0.331	0.344
Des Moines	5.140	**5.762**	5.440	3.809	**5.558**	0.682	0.517	0.291	0.451
Fort Worth	4.997	**6.551**	**5.834**	2.905	**4.949**	0.746	0.816	0.232	0.479
Indianapolis	4.847	5.075	5.144	**3.952**	**5.226**	0.567	0.358	0.278	0.509
Jacksonville	5.387	**6.138**	**5.535**	**4.286**	**5.605**	0.606	0.377	0.351	0.622
Peoria	5.218	**5.630**	**5.603**	**4.052**	**5.691**	0.613	0.400	0.292	0.497

Values in bold are significantly different from observed values.

Table 5. Analysis of Historical Wind Speed Trends in Observations and Model Data

	Trends of monthly wind speed				
Observations (ms^{-1}/year)	Total trend (all years)	January	April	July	October
Caribou	-2.177	-2.175	-1.850	-2.600	-1.825
Des Moines	-0.311	-0.825	-0.425	-0.350	-0.225
Fort Worth	-0.311	-0.025	-0.100	+0.025	-0.450
Indianapolis	+0.290	+0.225	+0.500	+0.300	+0.150
Jacksonville	-0.250	-0.475	-0.100	-0.100	-0.425
Peoria	-0.933	-1.150	-0.825	-0.725	-0.975
Model Results (ms^{-1}/year)					
Caribou	-0.025	-0.225	-0.075	+0.150	+0.125
Des Moines	+0.003	-0.575	-0.375	+0.225	+0.175
Fort Worth	-0.125	-0.650	-0.950	+0.075	-0.010
Indianapolis	+0.125	-0.350	-0.175	+0.100	+0.525
Jacksonville	+0.010	+0.100	+0.150	-0.350	+0.925
Peoria	+0.009	-0.425	-0.275	0.000	+0.400

The model had the largest total trend error for Des Moines, Peoria, and Caribou (the model underestimated the trends by about two orders of magnitude). The model underestimated the Jacksonville wind speed trend by about one order of magnitude. The Fort Worth and Indianapolis trends had the least overall error.

b. Diurnal means

Hourly wind speeds for the period were averaged to produce mean 00 UTC, 03 UTC, 06 UTC, 09 UTC, 12 UTC, 15 UTC, 18 UTC, and 21 UTC values for each month. The observations for these analyses span 1980 through 1996, and the model results span 1979-2004. Figure 6 compares model results with observations of 3-hourly wind speeds during April for Des Moines, Caribou, Indianapolis, Fort Worth, Peoria, and Jacksonville, respectively. The April diurnal cycle of the model had the most error between 9 UTC and 12 UTC for all of the locations except Caribou.
Caribou does not have the traditional wind speed minimum overnight because of its coastal location where most error occurred between 00 UTC and 03 UTC. For the rest of the cities, the overnight wind speed minimum is due to a very stable planetary boundary layer near the surface. Wind speeds subsequently increase during the

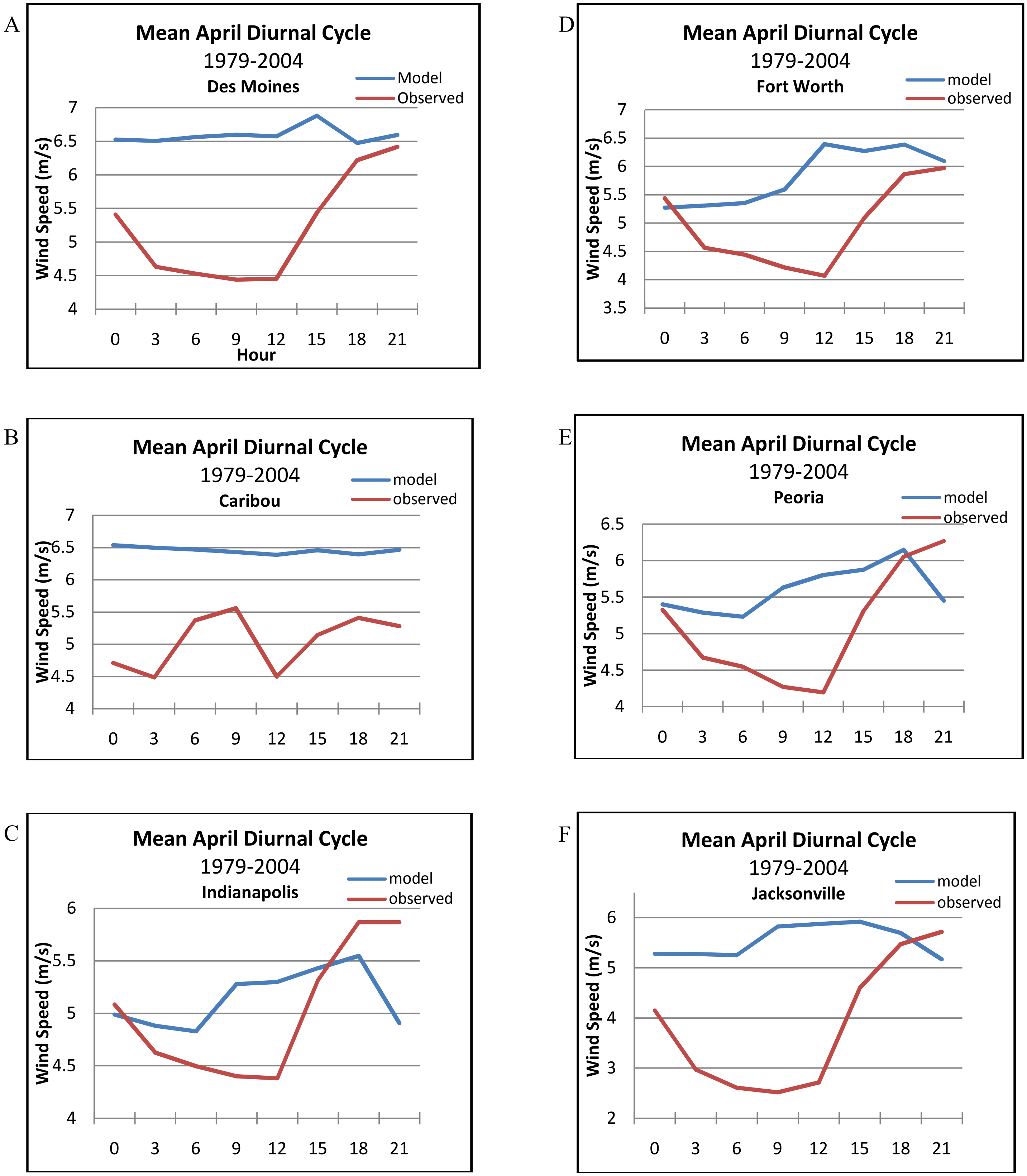

FIG. 6. The mean April diurnal cycles averaged over the entire period for A. Des Moines, IA. B. Caribou, ME. C. Indianapolis, IN. D. Fort Worth, TX. E. Peoria, IL. F. Jacksonville, FL.

day when heating causes vertical transport of momentum and leading to an unstable PBL.

The simulated diurnal cycle for Des Moines and Caribou had an almost zero trend. The diurnal cycles simulated for Indianapolis, Peoria, and Jacksonville had opposite trends to the actual diurnal cycle between 6 UTC and 12 UTC. Peoria and Jacksonville model wind speeds also had opposite trends to the actual diurnal cycles between 18 UTC and 21 UTC (early afternoon). Fort Worth had inaccurate model diurnal trends between 0-9 UTC, 12-15 UTC, and 18-21 UTC. The high wind speeds show the model is not decoupling the surface flow from upper level flow overnight.

Time history plots were also analyzed for each of the locations. As nighttime temperatures are rising due to climate change, it is hypothesized the nocturnal surface layer will be less stably stratified and winds should be stronger in the last half of the period. Figures 7 and 8 are plots of the 00 UTC, 03 UTC, 06 UTC, and 09 UTC wind speeds for Des Moines during April and October. The hypothesis is correct for the model values in April. The average nighttime wind speed between 1979-1988 was 6.42 m/s. The average nighttime wind speed between 1989-2004 was 6.63 m/s (a 0.21 m/s increase). The actual wind speed seemed to be decreasing over time, however, the 1997-2004 data was not plotted and a complete trend cannot be analyzed. The model data for all of the nighttime hours showed identical trends. The observations showed the 00 UTC with the highest winds speeds which declined through 09 UTC (Fig. 7).

A similar plot for mean October nighttime wind speeds in Des Moines showed the model data slightly decreasing between the first and second halves of the period. The observed data had a pronounced decrease in the 16-year period. Between 1979-1988 the average model nighttime wind speed is lower than the observed, but this trend reversed in the second half of the period with the observations being lower than the simulated winds. The 09 UTC model wind speed had the highest overall winds compared to the other nighttime hours whereas the observations again showed 00 UTC with the highest winds (not shown). Simulated nighttime wind speeds in the other five locations also had 09 UTC wind speeds the highest over the other hours. Des Moines, Jacksonville, and Caribou have positive trends while Peoria, Indianapolis, and Fort Worth have negative trends in the nighttime model data (not shown).

It can be expected that if climate change affects the diurnal cycle, that it should be more pronounced in Winter than Summer. Figure 8 compares the diurnal cycles of July and December for Peoria. Both the July and December model wind speeds at 00 UTC, 06 UTC, 12 UTC, and 18 UTC had small positive trends over the period. The December trend

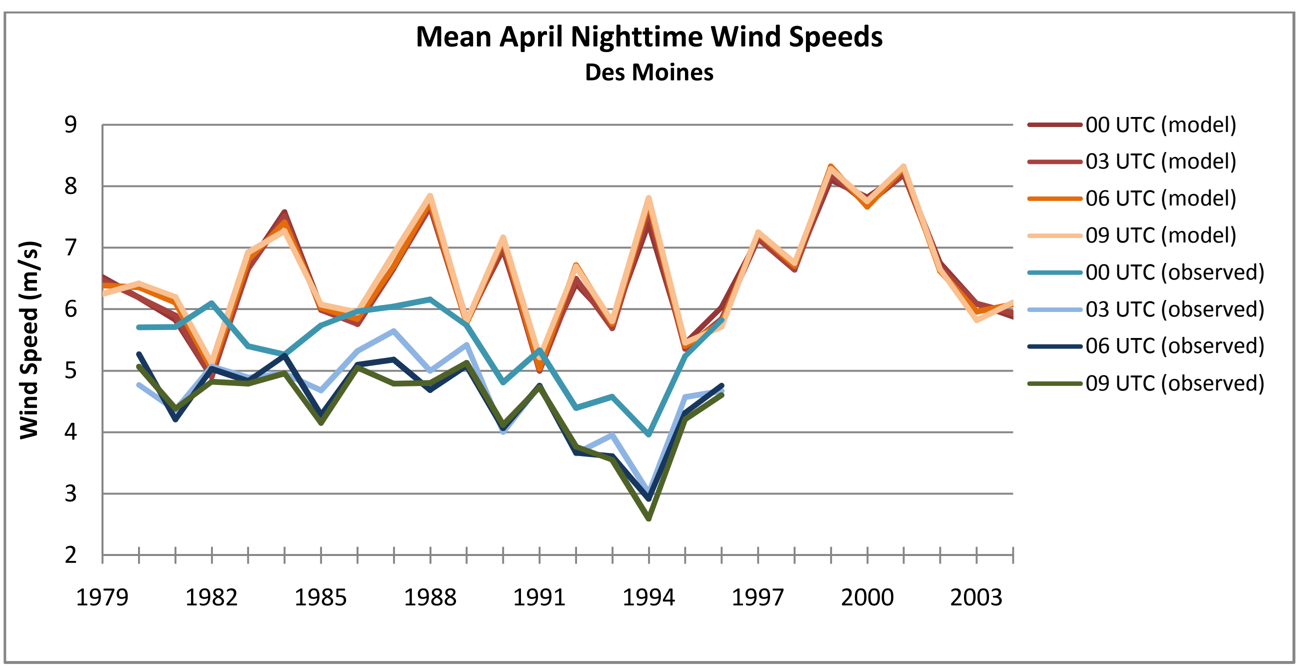

FIG. 7. The nighttime wind speeds for Des Moines plotted 1979-2004 for model data and 1980-1996 observed data.

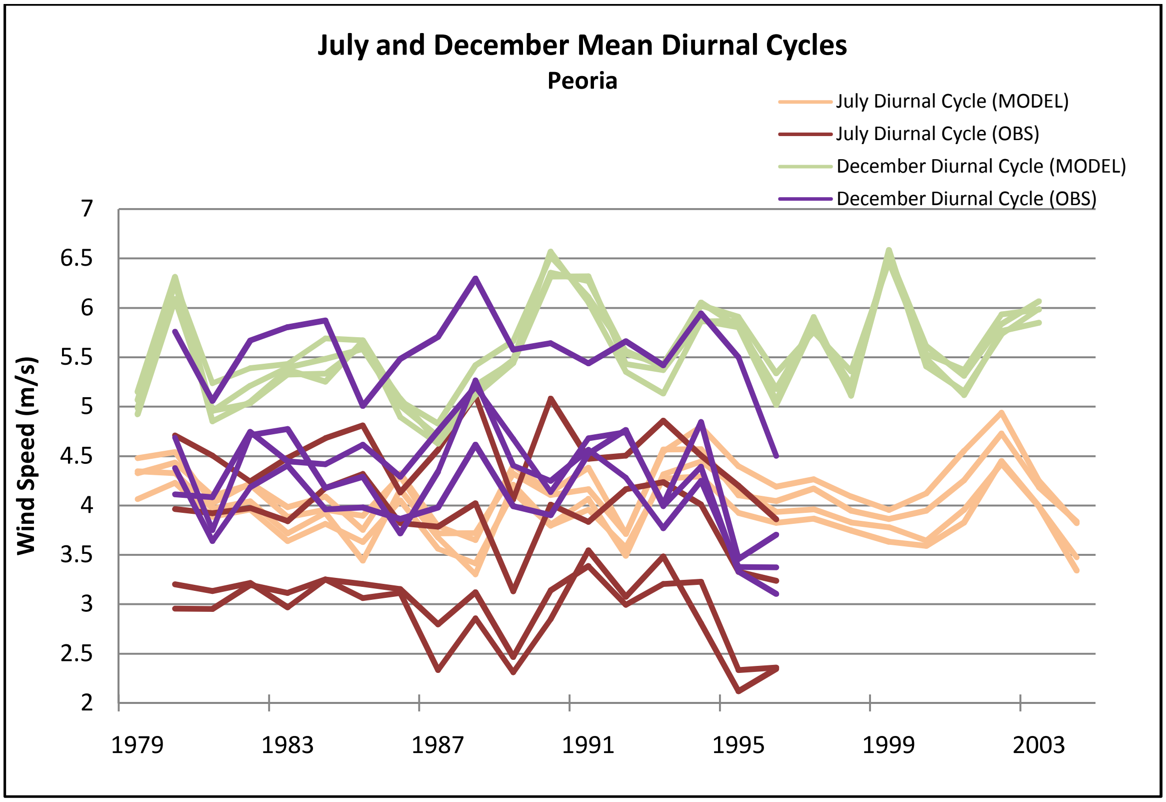

FIG. 8. Wind speeds at 00 UTC, 06 UTC, 12 UTC, and 18 UTC for July and December (model and observations) for Peoria, IL. The 6-hourly data are plotted together (one color) to represent the total variation over the course of a day. Lines of the same color that are far apart represent large variations while lines of the same color close together represent small variations.

over the first 12 years had a slightly higher standard deviation than the last 13 years (0.505 m/s and 0.415 m/s, respectively). For July the opposite was true where the first half of the period had a smaller standard deviation than the second half.

The January diurnal cycle had a small mean monthly variation (00 UTC to 18 UTC had low variation within a month). July had a comparatively larger variation in the diurnal cycle for each month. Table 6 summarizes the variances of the July and December data for Peoria.

The July wind speed variance (from the *total* mean over 3-hourly data) for every hour except 00 UTC is lower in the first 12 years as compared to the last 13 years. This suggests wind speeds are becoming more variable with time. The 06 UTC wind speeds vary the most with respect to the total mean in both subsets of years.

During the first 12 years, the December wind speeds at 06 UTC, 12 UTC, and 18 UTC were less variable than July wind speeds. However, the 00 UTC variance was higher in December. December wind speeds were overall more variable in the first 12 years as compared to the last 13 years. Looking at the change in diurnal cycles, the mean variance at 00 UTC in July decreased 0.002 m/s between the first and second periods. The mean variance at 18 UTC in July increased 0.027 m/s during the period

Table 6. Analysis of mean monthly diurnal cycles between first and second halves of the period for Peoria

Variance of 6-hourly means from total mean (all hours) between 1979-1990[1]				
Model (m/s)	00UTC	06 UTC	12 UTC	18 UTC
July	0.005	0.026	0.010	0.012
December	0.013	0.003	0.008	0.000
Variance of 6-hourly means from total mean (all hours) between 1991-2004				
Model (m/s)	00 UTC	06 UTC	12 UTC	18 UTC
July	0.003	0.041	0.019	0.039
December	0.001	0.006	0.003	0.003
Difference in variance between first and second halves of the period[2]				
Model (m/s)	00 UTC	06 UTC	12 UTC	18 UTC
July	-0.002	+0.015	+0.009	+0.027
December	-0.012	+0.003	-0.005	+0.003

[1] Total mean is the average of all 3-hourly data over a subset of years. [2]Difference in variance is the mean variance during first 12 years minus mean variance during last 13 years.

(relative to the total means for each subset of years). The Winter results showed 00 UTC variance decreased 0.012 m/s between the two periods while 18 UTC variance increased 0.003 m/s. This implies the July diurnal cycle was more effected by climate change. The actual results were not analyzed since the data is only through 1996 and not representative enough of the latter period.

5. Conclusions

Understanding bias of a regional climate model is important if the output is used for assessment of climate change. The focus of this study was to test if mean monthly wind speeds and mean 3-hourly wind speeds simulated by a regional climate model showed significant trends at particular locations based on the study by Pryor et al. (2007).

Results of the analyses indicated mean monthly wind speeds were on average overestimated by the model especially in the Fall and Winter months. It can be concluded the model has a bias towards overestimating surface wind speeds. Surface friction may be underestimated in the model or the surface layer scheme is actually more representative of the atmosphere above 10 m.

Similarly, diurnal analyses showed model wind speeds were too high at most hours. The wind speed minimum apparent in the observations was weak in the model data. The model results for April and October showed little to no trend while the observations had a sharp increase in wind speed in the morning. The inaccuracy of the diurnal cycle may be caused by mesoscale or local-scale pressure gradients that are not resolved. The PBL scheme and height of the lowest model level also affect the diurnal cycle.

Due to its biases, misrepresentation of surface flow at night, and coarse grid spacing, the model does not accurately simulate the climatology of surface wind speeds and changing climate. The hypothesis that the model trends would be weaker than the observed proved true, but the direction of the trend was not always correct. The results found in this study argue against the hypothesis that surface wind speeds simulated by a regional climate model show significant trends between 1979-2004. The model should include a more representative surface layer in order to fully assess significant trends and the climatology of surface wind speeds.

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