FullView®

WIND ASSESSMENT

Site Validation Analysis

PROJECT

Western Wind and Solar Integration Study
Tower 44003

FOR

National Renewable Energy Laboratory

DATE

January 20, 2009

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1 INTRODUCTION

3TIER has been retained by National Renewable Energy Laboratory (NREL) to assess the wind resource over the western region of the United States utilizing a numerical weather prediction (NWP) model. This report examines the quality of the NWP simulations used for that assessment at a single point within the study area. For this report, the observations were taken at Tower 44003 in Utah (latitude 39.2765, longitude -111.683).

The average observed wind speed (for all valid observational times) at 20 meters during the 9 months of the period of record (January, 2004 to September, 2004) is $3.98\ m/s$ with an hourly standard deviation of $2.76\ m/s$ at Tower 44003. This compares to a modeled $20m$ wind speed of $3.76\ m/s$ with a $2.16\ m/s$ standard deviation for these same times.

This report presents a comparison of the simulated winds with the observations at the reference tower. The focus of the verification is on the model's ability to reproduce the observed variability of the wind resource at daily and monthly time scales, while preserving the distribution of hourly wind speeds and the diurnal characteristics of the wind.

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2 MODEL SIMULATIONS BY 3TIER

The assessment of the wind resource across Western U.S. presented in this report is based on 9 months of simulated data (January, 2004 through September, 2004) using a regional nonhydrostatic primitive equation model of the atmosphere.

3TIER configured the NWP model using nested grids to simulate the wind resource over the Western U.S. region. Some details of the NWP configuration are shown below in Table 1. The extent of the coarsest grid was selected to capture the effect of synoptic weather events on the wind resource at the site, as well as to allow the model to develop regional, thermally-driven circulations. The increasingly fine 54km, 18km, 6km and 2km grids were selected to model the effect of local terrain and local scale atmospheric circulations. A map of the meteorological towers used to validate the model simulations is shown in Figure 1.

A detailed discussion of the model's ability to recreate the observed winds at Tower 44003 is contained in Section 3.

Parameter	Value
Mesoscale numerical weather prediction model	WRF
Horizontal resolution of valid study area	2km
Number of vertical levels	37
Elevation data base	3 second SRTM
Vegetation data base	30 second USGS
Soil classification	30 second USGS
Surface parameterization	Monin-Obukhov similarity model
Boundary layer parameterization	YSU model (MRF with entrainment)
Land surface scheme	5-layer soil diffusivity model

Table 1: Numerical weather prediction model configuration

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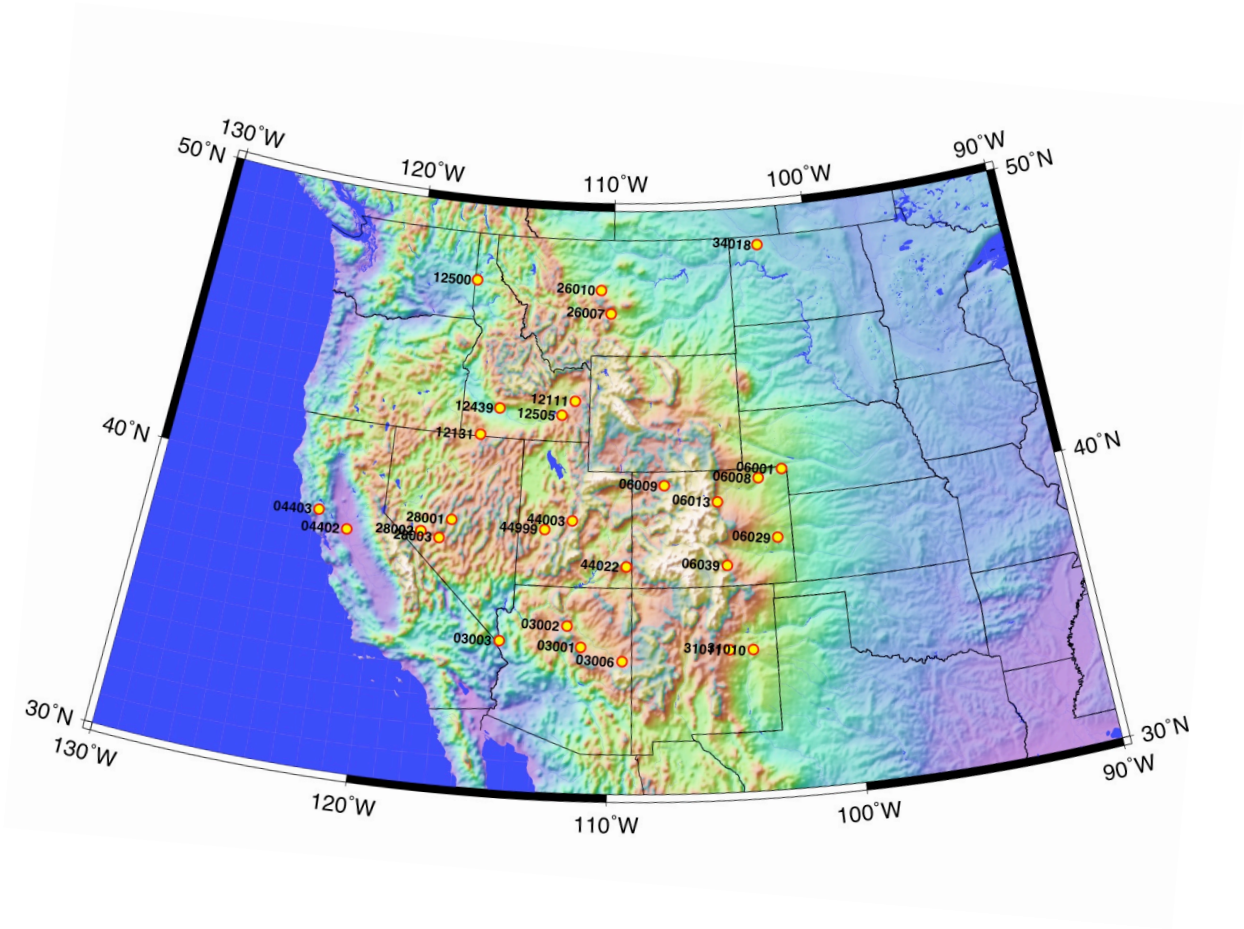

Figure 1: Meteorological towers used to validate the Western Wind and Solar Integration Study simulations are shown as yellow dots.

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3 VALIDATION OF MODEL RESULTS AT TOWER 44003

3.1 Observational Data

Approximately 9 months of data (January, 2004 to September, 2004) from a $20m$ meteorological tower (Tower 44003) at Western U.S. were used in this analysis. This tower will be referred to as the reference tower throughout this report. The data at $20m$ were used to assess the quality of the model simulations at $20m$.

The observed and modeled wind speeds shown in this section represent the mean of all times during the month for which a valid wind speed observation was available. Therefore they should not be interpreted as estimates of the true wind speeds at the site, but rather a verification of the model's ability to reproduce the available observed wind speeds. Any month or hour missing greater than 50% of the available observations is omitted from the following figures, tables, and statistics.

It should be noted that meteorological observations provided to 3TIER are not allowed to influence the raw model simulations.

3.2 Model validation statistics

Table 2 presents some basic statistical measures of the model performance relative to the measured winds at the reference tower during the observational period. For reference, the correlation (r) of the reference tower data to itself is perfect and hence the explained variance (r^2) value is 1.0.

Comparison	Value
Correlation of monthly-mean simulated wind speed to observed	0.88
RMS error of monthly-mean simulated wind speed	0.45 m/s
Correlation of daily-mean simulated wind speed to observed	0.72
RMS error of daily-mean simulated wind speed	1.22 m/s

Table 2: Correlation (r) and root mean square (RMS) error statistics of modeled wind speeds.

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3.3 Monthly-mean wind speed

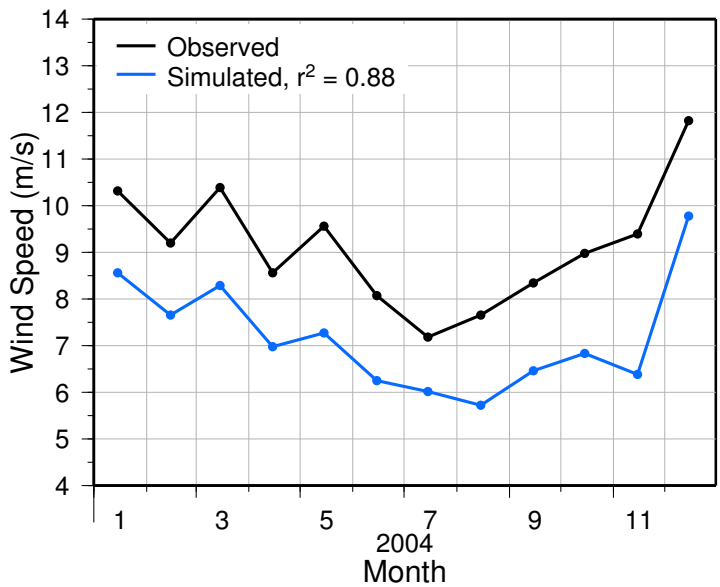

Figure 2: A comparison of the observed and simulated monthly-mean $20m$ wind speed at Tower 44003. Explained variance (r^2) value of each data source relative to the monthly reference tower wind speeds are shown in the legend. Months missing greater than 50% of the available observations are not plotted. Tabular formatted data are available in Table 3 (p. 12).

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3.4 Wind speed distribution

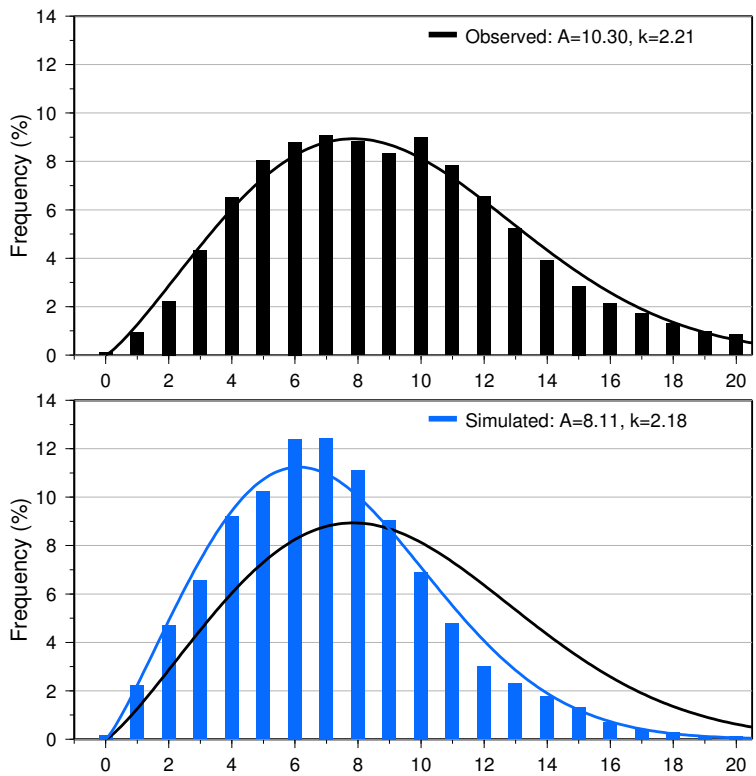

Figure 3: A comparison of the observed and simulated hourly wind speed distributions at $20m$ at Tower 44003 during the period of record, using $1\,m/s$ bins. ($0\,m/s$ bin contains only values ≤ 0.5) Fitted Weibull distributions are also displayed with the scale(A) and shape(k) parameters listed in the legend. Simulated data in tabular format are available in Tables 6 (p. 15).

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3.5 Wind direction distribution

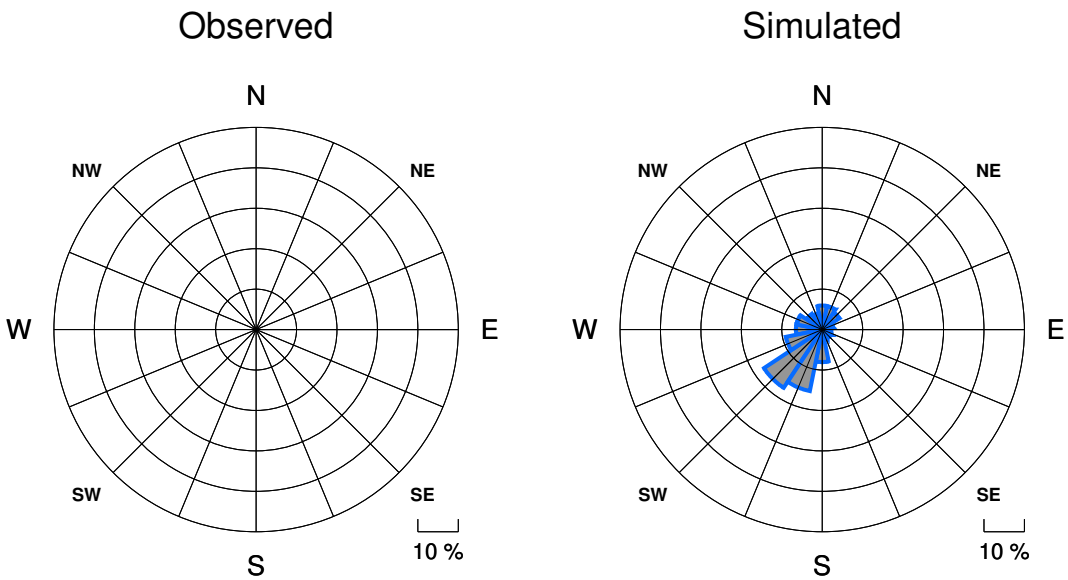

Figure 4: Wind roses at Tower 44003 for simulated model output for the period of January, 2004 to September, 2004. No valid observations are available for comparison. Directional bins are 22.5° wide, and the radial contour interval is 10%. Tabular formatted data, including mean wind speed values and Weibull parameters for each wind direction sector, are available in Table 7 (p. 16).

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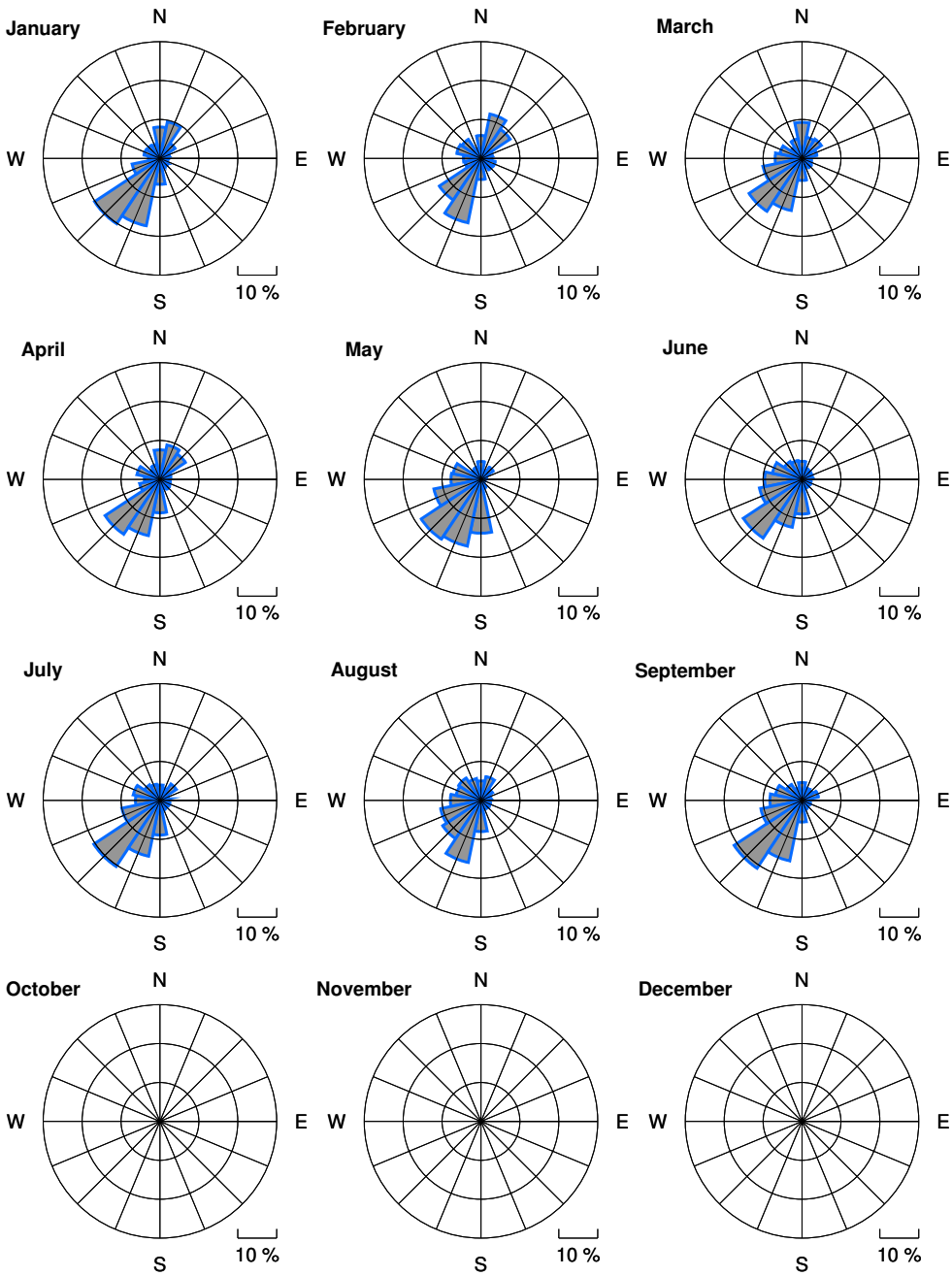

Figure 5: Wind rose of simulated wind direction at Tower 44003 for each month. Directional bins are 22.5° wide, and the radial contour interval is 0.1, i.e. 10%.

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3.6 Diurnal variability of wind speed

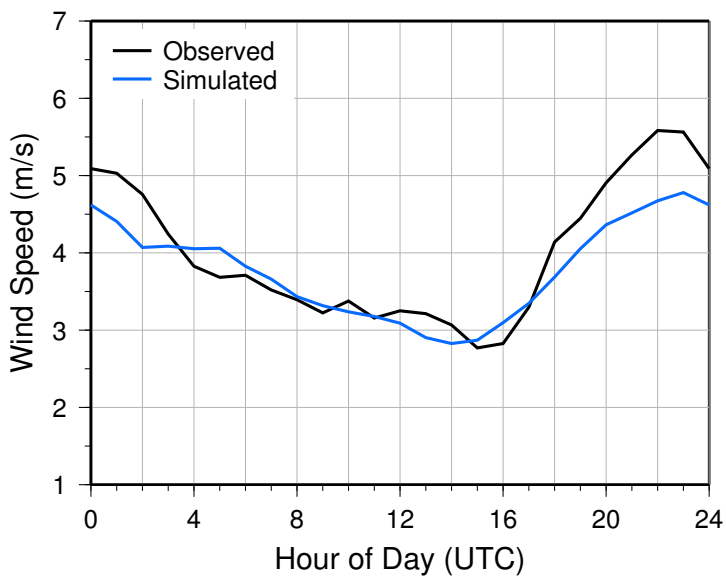

Figure 6: A comparison of the diurnal cycle of observed and simulated $20m$ wind speed at Tower 44003. Data are averaged over the period of record (January, 2004–September, 2004). Hours missing greater than 50% of the available observations are not plotted. Tabular formatted data are available in Tables 4 and 5 (p. 13 and 14).

Time Zone	UTC Offset	24-hour Time				
Hawaii	−10:00	14:00 Sun	20:00 Sun	02:00 Mon	08:00 Mon	13:00 Mon
US Pacific	−08:00	16:00 Sun	22:00 Sun	04:00 Mon	10:00 Mon	15:00 Mon
US Eastern	−05:00	19:00 Sun	01:00 Mon	07:00 Mon	13:00 Mon	18:00 Mon
Brazil Eastern	−03:00	21:00 Sun	03:00 Mon	09:00 Mon	15:00 Mon	20:00 Mon
UTC/GMT	**±00:00**	**00:00 Mon**	**06:00 Mon**	**12:00 Mon**	**18:00 Mon**	**23:00 Mon**
Central European	+01:00	01:00 Mon	07:00 Mon	13:00 Mon	19:00 Mon	00:00 Tues
India	+05:30	05:30 Mon	11:30 Mon	17:30 Mon	23:30 Mon	04:30 Tues
China	+08:00	08:00 Mon	14:00 Mon	20:00 Mon	02:00 Tues	07:00 Tues
Australia Eastern	+10:00	10:00 Mon	16:00 Mon	22:00 Mon	04:00 Tues	09:00 Tues

All times in this report are in Coordinated Universal Standard Time (UTC), also known as Greenwich Mean Time (GMT). This table can be used to convert from UTC to Local Standard Time for the time zones listed above. To change to Daylight Savings Time, add +1 hour. For example, at 00:00 UTC on Monday, the local standard time in the US Eastern time zone is 19:00 on Sunday.

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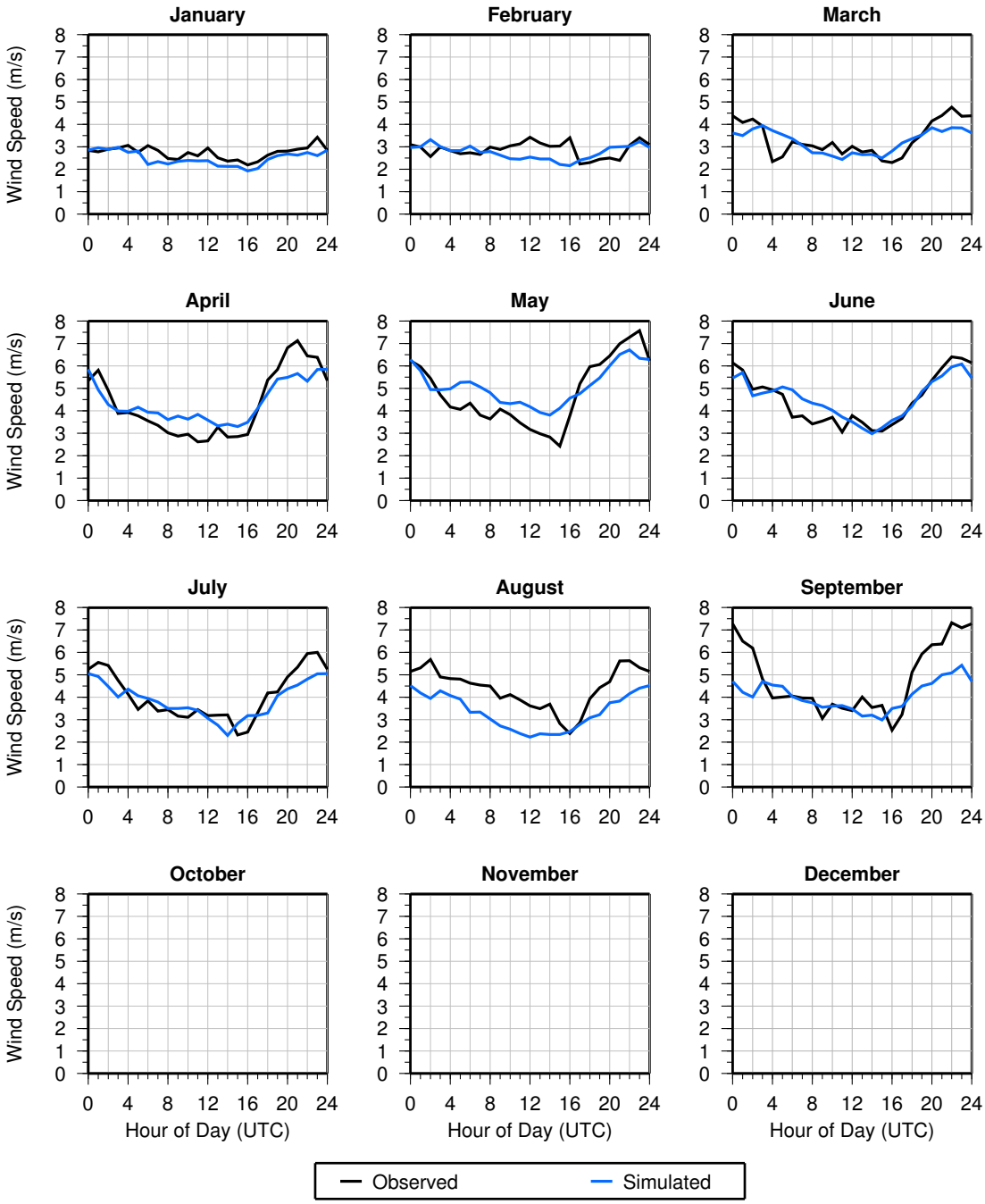

Figure 7: A comparison of the diurnal cycle of observed and simulated $20m$ wind speed for each month at Tower 44003. Hours missing greater than 50% of the available observations are not plotted. Tabular formatted data are available in Tables 4 and 5 (p. 13 and 14).

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3.7 Tabular data

Month	Observed	Simulated	Bias	Availability(%)
01/2004	2.75	2.49	-0.25	86.7
02/2004	2.88	2.73	-0.14	92.8
03/2004	3.33	3.25	-0.09	97.2
04/2004	4.31	4.34	0.03	97.1
05/2004	4.78	5.09	0.31	99.2
06/2004	4.45	4.54	0.09	98.3
07/2004	4.07	3.85	-0.22	98.3
08/2004	4.38	3.31	-1.06	99.1
09/2004	4.73	4.08	-0.66	87.6
All	3.98	3.76	-0.22	95.1

Table 3: Monthly-mean $20m$ wind speeds (m/s) at Tower 44003. Time series graph of data is available in Figure 2 (p. 6).

Observed = mean of all available wind speed observations
Simulated = mean of simulated model output for times with observations
Bias = Simulated − Observed

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Observations

Hour of Day (UTC)	Jan	Feb	Mar	Apr	May	Jun	Jly	Aug	Sep	Oct	Nov	Dec	Avg
0	2.84	3.10	4.39	5.34	6.24	6.14	5.25	5.15	7.28	--	--	--	5.09
1	2.78	3.00	4.09	5.81	5.97	5.83	5.56	5.32	6.51	--	--	--	5.03
2	2.89	2.56	4.23	4.91	5.45	4.96	5.42	5.68	6.20	--	--	--	4.76
3	2.95	2.99	3.93	3.89	4.71	5.06	4.76	4.91	4.82	--	--	--	4.24
4	3.06	2.84	2.34	3.93	4.17	4.94	4.14	4.83	3.97	--	--	--	3.83
5	2.76	2.69	2.55	3.78	4.06	4.74	3.46	4.81	4.02	--	--	--	3.68
6	3.06	2.74	3.22	3.56	4.35	3.71	3.84	4.64	4.06	--	--	--	3.71
7	2.85	2.66	3.11	3.35	3.81	3.78	3.39	4.55	3.97	--	--	--	3.52
8	2.48	3.00	3.04	3.02	3.64	3.42	3.45	4.51	3.96	--	--	--	3.39
9	2.44	2.88	2.87	2.87	4.08	3.54	3.16	3.96	3.05	--	--	--	3.22
10	2.74	3.05	3.20	2.96	3.84	3.72	3.11	4.12	3.69	--	--	--	3.38
11	2.59	3.12	2.68	2.62	3.47	3.06	3.45	3.88	3.51	--	--	--	3.16
12	2.95	3.43	3.03	2.66	3.17	3.79	3.18	3.62	3.41	--	--	--	3.25
13	2.52	3.18	2.77	3.27	2.98	3.49	3.21	3.49	4.01	--	--	--	3.21
14	2.36	3.02	2.84	2.83	2.83	3.12	3.21	3.70	3.55	--	--	--	3.07
15	2.42	3.03	2.37	2.86	2.43	3.09	2.32	2.84	3.64	--	--	--	2.77
16	2.19	3.41	2.30	2.95	3.78	3.39	2.45	2.38	2.53	--	--	--	2.83
17	2.33	2.23	2.50	4.06	5.21	3.66	3.31	2.87	3.24	--	--	--	3.30
18	2.63	2.30	3.18	5.37	5.98	4.34	4.19	3.94	5.12	--	--	--	4.14
19	2.80	2.45	3.55	5.84	6.07	4.71	4.24	4.43	5.93	--	--	--	4.45
20	2.81	2.50	4.15	6.82	6.45	5.36	4.91	4.70	6.34	--	--	--	4.91
21	2.89	2.39	4.40	7.13	6.99	5.92	5.34	5.63	6.37	--	--	--	5.27
22	2.94	3.07	4.77	6.46	7.28	6.41	5.95	5.63	7.33	--	--	--	5.58
23	3.43	3.41	4.36	6.39	7.58	6.35	6.01	5.33	7.10	--	--	--	5.56
Avg	2.75	2.88	3.33	4.31	4.78	4.45	4.07	4.38	4.73	--	--	--	3.98

m/s
2 3 4 5 6 7 8
Wind Speed

Table 4: Hourly-mean values of observed $20m$ wind speed at Tower 44003. Hours missing greater than 50% of the available observations are not plotted. Time series graphs are available in Figures 6 and 7 (p. 10 and 11).

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Simulated

Hour of Day (UTC)	Jan	Feb	Mar	Apr	May	Jun	Jly	Aug	Sep	Oct	Nov	Dec	Avg
0	2.86	2.97	3.62	5.86	6.29	5.46	5.05	4.53	4.71	--	--	--	4.62
1	2.96	3.00	3.50	4.94	5.79	5.70	4.92	4.19	4.22	--	--	--	4.41
2	2.89	3.33	3.80	4.28	4.95	4.67	4.49	3.95	4.02	--	--	--	4.07
3	2.98	3.01	3.95	3.99	4.94	4.79	4.02	4.29	4.71	--	--	--	4.09
4	2.76	2.84	3.72	3.99	4.98	4.89	4.36	4.08	4.55	--	--	--	4.05
5	2.81	2.83	3.55	4.17	5.27	5.07	4.07	3.91	4.50	--	--	--	4.06
6	2.22	3.03	3.36	3.94	5.29	4.94	3.95	3.34	4.03	--	--	--	3.83
7	2.34	2.76	3.06	3.91	5.07	4.54	3.79	3.34	3.86	--	--	--	3.66
8	2.23	2.79	2.74	3.61	4.81	4.34	3.51	3.04	3.76	--	--	--	3.43
9	2.35	2.63	2.72	3.77	4.38	4.23	3.51	2.72	3.56	--	--	--	3.32
10	2.40	2.47	2.59	3.63	4.32	4.03	3.53	2.58	3.61	--	--	--	3.24
11	2.37	2.45	2.43	3.84	4.38	3.72	3.42	2.38	3.63	--	--	--	3.18
12	2.39	2.55	2.74	3.58	4.18	3.52	3.06	2.23	3.48	--	--	--	3.09
13	2.14	2.46	2.65	3.34	3.93	3.23	2.76	2.37	3.16	--	--	--	2.90
14	2.13	2.46	2.67	3.40	3.81	2.98	2.30	2.34	3.21	--	--	--	2.83
15	2.13	2.21	2.50	3.30	4.12	3.24	2.83	2.34	2.99	--	--	--	2.87
16	1.93	2.16	2.81	3.49	4.57	3.57	3.18	2.47	3.51	--	--	--	3.10
17	2.04	2.41	3.17	4.11	4.77	3.78	3.19	2.79	3.60	--	--	--	3.35
18	2.44	2.51	3.37	4.78	5.13	4.21	3.30	3.09	4.14	--	--	--	3.69
19	2.61	2.69	3.53	5.42	5.47	4.86	4.08	3.22	4.51	--	--	--	4.05
20	2.69	2.98	3.86	5.50	6.02	5.30	4.37	3.76	4.62	--	--	--	4.36
21	2.63	3.00	3.68	5.66	6.51	5.55	4.55	3.83	5.01	--	--	--	4.52
22	2.74	3.02	3.85	5.33	6.72	5.96	4.82	4.16	5.08	--	--	--	4.67
23	2.61	3.24	3.85	5.84	6.34	6.09	5.05	4.41	5.42	--	--	--	4.78
Avg	2.49	2.73	3.25	4.34	5.09	4.54	3.85	3.31	4.08	--	--	--	3.76

m/s
1 2 3 4 5 6 7
Wind Speed

Table 5: Hourly-mean values of simulated $20m$ wind speed at Tower 44003. Hours missing greater than 50% of the available observations are not plotted. All model values are computed only for times with valid observations. Time series plots are available in Figures 6 and 7 (p. 10 and 11).

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Wind Speed (m/s)	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	All
0 - 0.5	0.05	0.11	0.08	0.02	0.05	0.02	0.06	0.06	0.08	0.06	0.14	0.06	0.08	0.10	0.10	0.06	1.13
0.5 - 1.5	0.93	0.72	0.56	0.48	0.51	0.67	0.42	0.45	0.80	1.20	1.53	1.01	0.81	0.75	0.88	0.91	12.62
1.5 - 2.5	1.65	1.55	1.13	0.89	0.48	0.78	0.67	0.54	0.86	2.13	2.78	1.37	0.99	1.45	1.12	0.86	19.27
2.5 - 3.5	1.05	1.20	1.52	0.74	0.38	0.43	0.50	0.35	0.66	2.29	3.31	1.76	1.05	1.31	0.81	0.88	18.23
3.5 - 4.5	0.69	1.10	1.01	0.34	0.19	0.10	0.40	0.26	0.77	2.52	3.42	1.44	1.44	1.12	0.78	0.66	16.22
4.5 - 5.5	0.66	0.61	0.46	0.19	0.13	0.18	0.16	0.21	1.07	2.27	2.32	0.88	0.97	0.99	0.43	0.34	11.86
5.5 - 6.5	0.42	0.26	0.30	0.08	0.10	0.05	0.05	0.13	1.65	2.17	1.60	0.72	0.74	0.45	0.27	0.13	9.09
6.5 - 7.5	0.24	0.24	0.02	0.03	0.02	0.06	0.02	0.08	1.20	1.25	0.96	0.66	0.16	0.21	0.10	0.16	5.39
7.5 - 8.5	0.14	0.02	0.00	0.00	0.00	0.02	0.02	0.05	0.67	0.96	0.66	0.48	0.10	0.02	0.06	0.06	3.24
8.5 - 9.5	0.11	0.08	0.00	0.00	0.00	0.00	0.00	0.02	0.19	0.40	0.29	0.40	0.11	0.03	0.02	0.00	1.65
9.5 - 10.5	0.02	0.00	0.00	0.00	0.00	0.02	0.03	0.03	0.06	0.16	0.13	0.22	0.02	0.02	0.02	0.02	0.74
10.5 - 11.5	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00	0.03	0.06	0.06	0.11	0.02	0.00	0.02	0.00	0.34
11.5 - 12.5	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.03	0.03	0.03	0.02	0.02	0.00	0.00	0.14
12.5 - 13.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.00	0.00	0.00	0.00	0.03
13.5 - 14.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.02
14.5 - 15.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.02
15.5 - 16.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.02
16.5 - 17.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17.5 - 18.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18.5 - 19.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19.5 - 20.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 6: Distribution of simulated $20m$ wind speed by direction at Tower 44003. All model values are computed only for times with valid observations. Histogram of data is available in Figure 3 (p. 7).

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Sector	Mean Speed(m/s)	Weibull Scale(A)	Weibull Shape(k)	Frequency(%)
N	3.31	3.72	1.75	5.94
NNE	3.22	3.63	1.95	5.88
NE	3.08	3.48	2.32	5.08
ENE	2.71	3.06	2.15	2.76
E	2.55	2.86	1.79	1.85
ESE	2.49	2.79	1.66	2.32
SE	2.96	3.29	1.57	2.36
SSE	3.12	3.47	1.60	2.17
S	4.90	5.53	2.21	8.04
SSW	4.48	5.06	2.12	15.50
SW	4.02	4.54	1.99	17.27
WSW	4.35	4.88	1.74	9.17
W	3.73	4.21	2.00	6.50
WNW	3.36	3.79	2.00	6.46
NW	3.05	3.43	1.75	4.60
NNW	2.96	3.33	1.77	4.07
ALL	3.76	4.23	1.83	100.0

Table 7: Simulated $20m$ mean wind speed, Weibull parameters, and frequency at Tower 44003. All model values are computed only for times with valid observations; blank values correspond to times with less than 10 data points. Wind rose of data is available in Figure 4 (p. 8).

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