Wind Resource Assessment: San Nicolas Island, California

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FOREWORD

This joint Department of Energy (DOE) and National Renewable Energy Laboratory (NREL) report was prepared as an account of work for others funding contract, sponsored by the Department of Defense (DoD) Strategic Environmental Research and Development Program (SERDP) under DOE Contract # DE-AC02-83CH10093.

This report documents the wind resources on San Nicolas Island (SNI) from detailed field measurements collected for one year and coarse historical data collected over 32 years. This report will be used by DoD/ United States Navy (USN) Naval Facilities Engineering Service Center (NFESC) as input for additional economic and feasibility studies for a Wind-Diesel installation for SNI.

Timothy L. Olsen, Engineering Consultant, was contracted to provide data reduction analysis, research historical wind resource data, and assist with generation of this report.

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1.0 INTRODUCTION

This report presents an assessment of the local wind resource on San Nicolas Island(SNI), California. In section 2.0, SNI and its potential wind energy site are described, as well as the data collection and analysis procedures. Section 3.0 presents the wind resource data and its analysis results, including historical wind speed averages, current annual and monthly records, diurnal wind speeds, and annual wind roses. Conclusions about the SNI wind resource are presented in section 4.0.

2.0 BACKGROUND

2.1 San Nicolas Island

San Nicolas Island (SNI) is the site of the Navy Range Instrumentation Test Site which relies on an isolated diesel-powered grid for its energy needs. As shown in Figure 1, the island is located in the Pacific Ocean 85 miles southwest of Los Angeles, California and 65 miles south of the Naval Air Weapons Station (NAWS), Point Mugu, California. SNI is situated on the continental shelf at latitude N33°14' and longitude W119°27'. It is approximately 9 miles long and 3.6 miles wide and encompasses an area of 13,370 acres of land owned by the Navy in fee title [1].

The island, generally treeless, is relatively flat on top and drops sharply off on the south side with a more gradual slope to the ocean on the north side. The island's shoreline is formed by cliffs. The interior terrain is a rolling mesa, extensively eroded with little vegetation, mostly coarse grasses and few large shrubs. Its highest point is 907 feet high. The western end contains large shifting sand dunes, and the eastern end has a large sand spit extending eastward. Cliffs on the southern side of the island rise sharply from the sea to 700 feet within a mile of shore; cliffs on the northern side of the island rise to the mesa at 300-400 feet above sea level [1]. A topographic map of the island is shown in Figure 2.

The average mean monthly temperature on SNI is 15°C (59°F). In general, daily maximum temperatures vary from 16 to 21°C (60 to 70°F), and daily minimum temperatures vary from 9 to 14°C (48 to 58°F). The coolest month is usually January, and the warmest month is usually September. No freezing temperatures have been recorded on SNI, but temperatures over 38°C (100°F) have been recorded several times. Precipitation averages only 20.1 cm (7.91 inches) per year, and 86% of the rain falls from November through February. The relative humidity ranges from 57% to 100%.

Winds on San Nicolas are prevailingly northwest and are strong most of the year. The average wind speed is 7.2 m/s (14 knots) and seasonal variation is small. The windiest months, March through July, have wind speeds averaging 8.2 m/s (16 knots). The least windy months, August through February, have wind speeds averaging 6.2 m/s (12 knots)

Much of San Nicolas Island is used as the Navy Range Instrumentation Test Site. The island is equipped with facilities supporting metric radar, telemetry, Extended Area Test System, optics, communications, microwave, missile launching, drone launching, surveillance radar, and target control. The main support facilities include a runway, an air terminal, housing, a power plant, a fuel farm, a reverse osmosis water system, and a public works and transportation building [1].

Figure 1. San Nicolas Island location map
Source: San Nicholas Island Site Manual.

Figure 2. San Nicolas Island topographical map

2.2 Wind Energy Site Description

The wind energy site is located east-southeast of the center of the island, west of the airport, and along the island's crest, as shown in Figure 3. About 1.7 sq. km (0.7 sq. mi.) in area, the site is the west portion of the quadrant bounded by Harrington Road, Owens Road and Monroe Drive. The highest elevation, 818 feet, occurs along Harrington Road toward Owens Road, from which the terrain slopes down to the north and northeast to 550 feet near Monroe Drive.

There are no trees or other wind obstructions on the site, just light vegetation including grasses and cacti. Parts of the site are very eroded and will require some fill and stabilization. Several low water tanks and buildings including the Power Plant Island Utilities are located upwind. The nearness of the power plant minimizes power line distances to the wind energy site.

This site has energetic winds year round. Although more optimal wind site locations may exist on the island, this particular site was selected so as not to interfere with radar, communications, and other naval operations, and to create minimum environmental and cultural impacts.

Figure 3. San Nicolas Island Naval Facilities and potential windfarm area
Source: San Nicholas Island Site Manual.

2.3 Wind Data Collection and Analysis

In July 1994, NREL entered into a cooperative agreement with NFESC to collect one full year of high quality wind energy resource data at SNI. We examined this data in detail, and reviewed historical summary data in order to describe long term behavior.

Instrumentation: The new data was collected through a full wind-energy meteorological sensor system including two anemometers, two wind vanes, a temperature probe, and a barometer. The sensors were mounted 30.5 m (100 ft) high atop Facility No. 186, the FIC Communications Tower. Details of the instrumentation are presented in Table 1.

Data collection: Data collection began 14 July 1994, and the full year used in this study ran from 1 August 1994 (0000 hours) to 1 August 1995 (0000 hours). All data was sampled at 1 Hz and then stored as 2-minute and 10-minute averages. The 10-minute average data was used for this report.

Data analysis: Daily records of the 10-minute average wind speed are plotted for the full year in Appendix A. The annual records use monthly data averages, and the monthly records use daily averages. An annual record is derived for air density using

$$\rho = p / (R * T)$$

where ρ is density, p is pressure, T is temperature, and $R = 0.286 \text{ kJ}/(\text{kg} * \text{K})$ for air. Then wind power density is derived using

$$P / A = 0.5 * \rho * V^3$$

where P is power, A is area, and V is wind speed. Using hourly average data, the diurnal wind speeds are created by computing an average for each hour of the day over all days in the period.

Wind direction data is difficult to present because the most common directions do not necessarily have the strongest winds. Therefore, this report includes three types of wind roses (in section 3.7): percent time at each direction, average wind speed at each direction, and time-weighted average wind speed at each direction.

Uncertainty Analysis: Measurement precision and accuracy are shown for each sensor and the data logger in Table 2. For air density and power density these values are derived from their corresponding source channels using the square root of the sum of the squares [2,3].

**Figure 4: Meteorological Instrumentation,
San Nicolas Island**

Manufacturer	Tag No	Description	Model	Serial	NREL QA Code Calibration Date	Cost \$	San Nicolas Island, CA. SNI Site #1
AIR							Returned to NREL 7/14/94 Ed
AIR	n/a	Intellisensor II 800-1060 mb Barometer	AB-2A	4E0029	Factory - 05/20/94	\$695	SNI Tower Base ENC 16/18
Campbell Scientific	02104C	Data Acquisition & Control System [MET]	CR-10	08178	Factory, 4/22/94	\$1,090	SNI Tower Base ENC 16/18
Campbell Scientific	n/a	CR10KD Bracket Kit	6226	0000	NCR	\$16	SNI Tower Base ENC 16/18
Campbell Scientific	n/a	SM-716 Mounting Bracket	6234	0000	NCR	\$18	SNI Tower Base ENC 16/18
Campbell Scientific	n/a	Temperature Probe w/ 9 ft lead	107-U	0000	NCR	\$40	SNI 3m Base Temp Shield
Campbell Scientific	n/a	Solar Radiation Shield for 107-U	41301	0000	NCR	\$95	SNI 3m Base Temp Shield
Campbell Scientific	n/a	CR10 Wiring Panel	8032	1984	NCR	\$210	SNI Tower Base ENC 16/18
Campbell Scientific	n/a	12 v Power Supply / w/charger	PS12LA	0000	NCR	\$250	SNI Tower Base ENC 16/18
Campbell Scientific	n/a	SOLAREX 10 Watt Solar Panel w/ mount	MSX 10	JP93L21000083	NCR	\$250	SNI Tower Base w/ ENC 16/18
Campbell Scientific	02200C	CR10KD Keyboard / Display	CR-10 KO	3853	NCR	\$275	SNI Tower Base ENC 16/18
Campbell Scientific	n/a	Enclosure 16" x 18"	ENC 16/18	0000	NCR	\$300	SNI Tower Base ENC 16/18
Campbell Scientific	n/a	Telephone Modem	DC112	6612	NCR	\$315	SNI Tower Base ENC 16/18
Campbell Scientific	01529C	Storage Module "1" Extended Temp Range	SM-716	1379	NCR	\$750	SNI Tower Base ENC 16/18
Campbell Scientific	01682C	Storage Module "2" Extended Temp Range	SM-716	1772	NCR	\$750	Module # 2 left w/ S.Miller NFESC
Campbell Scientific	n/a	9-Pin Peripheral to RS-232 Interface	SC-532	4776	NCR	\$180	NFESC -- Scott Miller Computer
Campbell Scientific	n/a	External Power Cable	PS12	#6186/ LT#512410	NCR		SNI Tower Base ENC 16/18
		Max vol = 30v, Isc = 0.65 A		0000			
		100 ft Wind Sensor System "A"	WS-201 J			\$1,400	
Met One Instruments	n/a	Wind Direction Sensor, W/D "A"	SD-201	488	Factory 6/1/94		SNI Tower Mast / Boom Assy
Met One Instruments	n/a	Wind Direction Vane Assembly	V-201	N/A	NCR		SNI Tower Mast / Boom Assy
Met One Instruments	n/a	Wind Speed Sensor, W/S "A"	SS-201	N3315	Factory 6/1/94		SNI Tower Mast / Boom Assy
Met One Instruments	n/a	Match w/ Cup	C-201	N3315	NCR		SNI Tower Mast / Boom Assy
Met One Instruments	n/a	Wired Crossarm (with connectors)	CA-201	N/A	NCR		SNI Tower Mast / Boom Assy
Met One Instruments	n/a	Junction Box	JB-201-A	N/A	NCR		SNI Tower Mast / Boom Assy
		100 ft Wind Sensor System "B"	WS-201 J			\$1,400	
Met One Instruments	n/a	Wind Direction Sensor, W/D "B"	SD-201	489	Factory 6/1/94		SNI Tower Mast / Boom Assy
Met One Instruments	n/a	Wind Direction Sensor, W/D "B" Replacement	SD-201	MetOne	Factory 10/1/94	\$500	Sensor shipped to S.Miller NFESC
Met One Instruments	n/a	Wind Direction Vane Assembly	V-201	N/A	NCR		SNI Tower Mast / Boom Assy
Met One Instruments	n/a	Wind Speed Sensor, W/S "B"	SS-201	N3316	Factory 6/1/94		SNI Tower Mast / Boom Assy
Met One Instruments	n/a	Match w/ Cup	C-201	N3316	NCR		SNI Tower Mast / Boom Assy
Met One Instruments	n/a	Wired Crossarm (with connectors)	CA-201	N/A	NCR		SNI Tower Mast / Boom Assy
Met One Instruments	n/a	Junction Box	JB-201-A	N/A	NCR		SNI Tower Mast / Boom Assy
Met One Instruments	n/a	8 Ft. Retractable Instrument Boom Arm	SPEC	n/a	NCR	\$550	SNI Tower Mast / Boom Assy
w/ NWTC	n/a	10 Ft. Retractable Mast Assy.	Keller	SPEC	NCR	\$500	SNI Tower Mast / Boom Assy
					TOTAL \$	\$9,584	SNI Tower Mast / Boom Assy

**Figure 5: Sensor Accuracy and Precision,
San Nicolas Island**

Manufacturer	Tag No	Description	Model	Serial	Factory Calib. Date	Precision (EU)	Precision (% FS)	Accuracy (+/- EU)	Accuracy (+/- % FS)	Range	Engr. Units
Campbell Scientific	02104C	CR-10 Analog Channels 1 thru 8	CR-10	08178	4/22/94	333E-6	0.013		0.05	2.5 vdc	vdc
Campbell Scientific	02104C	CR-10 Pulse Channel 1 - 2	CR-10	08178	4/22/94	8-bit	0.390	8-bit		2000	Hz
Met One Instruments	n/a	Wind Speed Sensor, W/S "A"	SS-201	N3315	6/1/94		0.390	0.500	2.00	0 - 90	m/s
Met One Instruments	n/a	Wind Direction Sensor, W/D "A"	SD-201	488	6/1/94		0.013	3.600	1.00	0 - 360	deg.
Met One Instruments	n/a	Wind Speed Sensor, W/S "B"	SS-201	N3316	6/1/94		0.390	0.500	2.00	0 - 90	m/s
Met One Instruments	n/a	Wind Direction Sensor, W/D "B"	SD-201	489	6/1/94		0.013	3.600	1.00	0 - 360	deg.
Campbell Scientific	n/a	Temperature Probe w/ 9 ft lead	107-U	0000	6/1/94	0.100	0.140	0.100	0.14	-36 to +53	deg C
AIR	n/a	Barometer 800-1060 mb	AB-2A	4E0029	6/1/94	0.0635	0.024	0.500	0.19	800-1060	hPa
Calculated	n/a	Air Density				0.001	0.142	0.002	0.24	0.86 - 1.56	kg/m ³
Calculated	n/a	Power Density				3.920	0.690	19.700	3.47	0-569	W/m ²

3.0 WIND RESOURCE

3.1 Historical Data

The wind resource at most sites varies from year to year and, in fact, it can vary widely. For this reason, it is prudent to review some long-term data at the nearest site available. Therefore, this section begins with a review of 32 years of wind speed data (1947-1978) at the SNI station number 93116, compiled by Pacific Northwest Laboratories and managed by the National Climatic Data Center [4]. Newer data is not yet available.

The anemometer locations changed several times for this collection of historical wind data, and therefore had different sensors, mountings, heights, exposures, and possibly drifting calibrations. The heights varied from 4.6 m to 19.8 m, so each year's data was adjusted to this study's measurement height (30.5 m) using the $1/7$ power law.

Readings generally were made 12-18 times a day – more often in the daytime -- thereby raising the possibility of skewing the averages with non-uniform intervals. Some bias toward lower wind speed measurements might be expected if more readings occurred in daytime, if unknown obstructions were present, or if old anemometers began to bind. Since these factors are not tractable, no attempt is made to account for them. The results of the historical wind speed data follow in Figure 4.

Figure 4: SNI Historical Wind Speeds

Interannual Variability in The Wind Resource: It is important to realize that a single year of good wind data does not guarantee the same energy production each year. Examination of historical data will help to quantify the interannual variability. The 32 year average wind speed at SNI is 6.1 m/s (11.8 knots) based on annual averages of hourly data, and the average of the annual standard deviations is 3.8 m/s (7.4 knots). But the standard deviation of the annual averages is 0.6 m/s, (1.2 knots) giving a variability of $0.6 / 6.1 = 0.10$, or 10%. Despite our low confidence in the average wind speed, this variability implies that the annual average wind speed will fall within +/- 30% (3 standard deviations) 99% of the time, assuming these values are normally distributed. This can seriously affect energy production, as power is proportional to wind speed cubed. As an example, a 10% change in wind speed will cause about a 30% change in power; a 30% change in wind speed can alter power by a factor of three.

3.2 Current Data Statistics

Statistical analysis of the full year of NREL 10-minute data yields the results which follow in Table 3, and a full wind-speed distribution is presented in Figure 5.

Table 3: Summary of Current SNI Meteorological Data

Channel	Units	Average	Standard Deviation	Minimum	Maximum
Wind Speed	m/s	7.2	4.8	0.0	28.5
Wind Speed	knots	14.0	9.3	0.0	55.4
Ambient Temperature	°C	14.5	3.9	6.4	33.4
Ambient Pressure	mbar	983	4.6	965	997
Air Density	kg/m ³	1.20	0.02	1.14	1.22
Power Density	W/m ²	473	759	2.3	4010

Figure 5: SNI Wind Speed Frequency Distribution

3.3 Annual Meteorological Records

Annual records using monthly averages have been plotted for wind speed, ambient temperature, ambient pressure, air density, and power density. These plots appear in Figures 6-10. The source data was derived from NREL testing on SNI at 30.5 m (100 ft) on Facility No. 186 for the period 1 August 1994 through 31 July 1995. Wind speeds reached their highest monthly average (10.3 m/s, 20 knots) in April and lowest (4.5 m/s, 8.7 knots) in February, with near average levels the rest of the year. Temperature and pressure cycled gently with more warmth and lower pressure in the summer, causing slightly lower summer densities. Power density looks like an exaggeration of wind speed, as expected from its cubic relationship.

Monthly records using daily average wind speeds are shown in Appendix B for each month from August 1994 through July 1995. Daily records based on 10-minute average wind speeds appear in Appendix A, as mentioned earlier.

Figure 6: Annual Wind Speed Record

Figure 7: Annual Temperature Record

Figure 8: Annual Pressure Record

Figure 9: Annual Density Record

Figure 10: Annual Power Density Record

3.4 Annual Average Diurnal Wind Speed

Although the diurnal (or daily cycle) wind speeds may vary widely from day to day, certain trends exist at most sites. These trends can be elucidated by averaging many daily cycles together. This is done by averaging the wind speeds for each hour of the day over the averaging period, in this case one year. For example, all wind speeds for 0000 to 0100 hours each day are averaged and labeled 0100, all wind speeds for 0100 to 0200 hours are averaged and labeled 0200, and so on. The annual average diurnal wind speed, as shown in Figure 11, is based on the NREL test data at 30.5 m (100 ft) on SNI Facility No. 186 from 1 August 1994 through 31 July 1995. The diurnal wind speed pattern shows a single cycle with a 6.1 m/s (12 knots) average low at 1100 hours and an 8.6 m/s (17 knots) high at 2000 hours.

The same techniques used to calculate annual average diurnal wind speed distribution were used to calculate monthly averages, using NREL/SNI data. The monthly average diurnal wind speeds appear in Appendix C.

Figure 11: Annual Average Diurnal Wind Speed

3.5 Prevailing Wind Direction

In this report “wind direction” refers to the source -- the direction from which the wind blows. Wind direction data is difficult to summarize because of the need to show both the duration of winds at different directions and the average wind speed at different directions, and these may not correlate well. As mentioned earlier, this data is presented three ways: percent time at each direction in Figure 12, average wind speed at each direction in Figure 13 a and b, and time-weighted average wind speed at each direction in Figure 14 a and b. The time-weighted averages will sound relatively low, since this calculation assigns a wind speed of zero for time not at the given direction. However, the sum of these values equals the annual average wind speed (from all directions). The percent-time and time-weighted-average plots both show the primary wind direction out of the northwest to north by northwest, with occasional wind from the west and southwest. (Note: Figures 13a and 14a have the units m/s; figures 13b and 14b are in knots.)

Figure 12: Wind Rose: Percent Time

True Source Direction, 1 Aug 1994 – 31 Jul 1995
 San Nicolas Island, 30.5 m (100 ft), FIC Tower

Figure 13a: Wind Rose: Average Wind Speed (m/s)

True Source Direction, 1 Aug 1994 – 31 Jul 1995
 San Nicolas Island, 30.5 m (100 ft), FIC Tower

Figure 13b: Wind Rose: Average Wind Speed (knots)

True Source Direction, 1 Aug 1994 – 31 Jul 1995
 San Nicolas Island, 30.5 m (100 ft), FIC Tower

Figure 14a: Wind Rose: Time Weighted Average Wind Speed (m/s)

True Source Direction, 1 Aug 1994 – 31 Jul 1995
 San Nicolas Island, 30.5 m (100 ft), FIC Tower

Figure 14b: Wind Rose: Time Weighted Average Wind Speed (knots)

4.0 CONCLUSION

The predominantly northwest direction of the wind would favor that end of the island for wind generation, but facility operations confine any potential windfarm to the central region which was tested for this study. San Nicolas Island has an excellent wind resource at that central site, with an annual average wind speed of 7.2 m/s (14.0 knots) as measured by NREL at 30.5 m (100 ft) at Facility No. 186 during the year ending July 31, 1995. The 32-year historical data set shows an average wind speed of 6.1 m/s (11.8 knots), with a standard deviation on the annual averages of 0.6 m/s (1.2 knots). This also would indicate a good site, with annual averages falling between 4.3 m/s (8.4 knots) and 7.9 m/s (15.3 knots). Although the historical data carries a statistical advantage in its duration, the NREL data had much higher quality control.

The annual wind speed pattern varied from a low of 4.5 m/s (8.7 knots) in February to a high of 10.3 m/s (20 knots) in April, based on one month averages. The diurnal cycle swung from 6.1 m/s (12 knots) at 1100 hours to 8.6 m/s (17 knots) at 2000 hours. The mild effect of these cycles imply a fairly steady wind resource, which is favorable for supplemental wind energy. However, short term wind speed variations are significant, as indicated by the standard deviation of 4.8 m/s (9.3 knots) and extremes of 0 m/s (0 knots) and 28.5 m/s (55.4 knots). Such variations could place significant demands on a hybrid wind/diesel energy system design.

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APPENDIX A: Daily Wind Speed Records

SNI - 18 SEP 1994

SNI - 19 SEP 1994

SNI - 20 SEP 1994

SNI - 21 SEP 1994

SNI - 22 SEP 1994

SNI - 23 SEP 1994

SNI - 5 DEC 1994

SNI - 6 DEC 1994

SNI - 7 DEC 1994

SNI - 8 DEC 1994

SNI - 9 DEC 1994

SNI - 10 DEC 1994

SNI - 22 APR 1995

SNI - 23 APR 1995

SNI - 24 APR 1995

SNI - 25 APR 1995

SNI - 26 APR 1995

SNI - 27 APR 1995

SNI - 4 MAY 1995

SNI - 5 MAY 1995

SNI - 6 MAY 1995

SNI - 7 MAY 1995

SNI - 8 MAY 1995

SNI - 9 MAY 1995

SNI - 16 MAY 1995

SNI - 17 MAY 1995

SNI - 18 MAY 1995

SNI - 19 MAY 1995

SNI - 20 MAY 1995

SNI - 21 MAY 1995

SNI - 15 JUL 1995

SNI - 16 JUL 1995

SNI - 17 JUL 1995

SNI - 18 JUL 1995

SNI - 19 JUL 1995

SNI - 20 JUL 1995

SNI - 27 JUL 1995

SNI - 28 JUL 1995

SNI - 29 JUL 1995

SNI - 30 JUL 1995

SNI - 31 JUL 1995

SNI - 1 AUG 1995

Repeat Figures for Days with Wind Speed Over 20 m/s

San Nicolas Island - 28 AUG 1994

San Nicolas Island - 29 AUG 1994

San Nicolas Island - 2 SEP 1994

San Nicolas Island - 9 SEP 1994

San Nicolas Island - 10 SEP 1994

San Nicolas Island - 12 OCT 1994

San Nicolas Island - 13 OCT 1994

San Nicolas Island - 15 OCT 1994

San Nicolas Island - 16 NOV 1994

San Nicolas Island - 4 JAN 1995

San Nicolas Island - 8 APR 1995

San Nicolas Island - 9 APR 1995

San Nicolas Island - 18 APR 1995

San Nicolas Island - 19 APR 1995

San Nicolas Island - 20 APR 1995

San Nicolas Island - 11 JUL 1995

San Nicolas Island - 12 JUL 1995

San Nicolas Island - 28 JUL 1995

APPENDIX B: Monthly Wind Speed Records

Figure B1: Wind Speed Record, August 1994

Figure B2: Wind Speed Record, September 1994

Figure B3: Wind Speed Record, October 1994

Figure B4: Wind Speed Record, November 1994

Figure B5: Wind Speed Record, December 1994

Figure B6: Wind Speed Record, January 1995

Figure B7: Wind Speed Record, February 1995

Figure B8: Wind Speed Record, March 1995

Figure B9: Wind Speed Record, April 1995

Figure B10: Wind Speed Record, May 1995

Figure B11: Wind Speed Record, June 1995

Figure B12: Wind Speed Record, July 1995

APPENDIX C: Monthly Average Diurnal Wind Speeds

Figure C1: Diurnal Wind Speed, August 1994

Figure C2: Diurnal Wind Speed, September 1994

Figure C3: Diurnal Wind Speed, October 1994

Figure C4: Diurnal Wind Speed, November 1994

Figure C5: Diurnal Wind Speed, December 1994

Figure C6: Diurnal Wind Speed, January 1995

Figure C7: Diurnal Wind Speed, February 1995

Figure C8: Diurnal Wind Speed, March 1995

Figure C9: Diurnal Wind Speed, April 1995

Figure C10: Diurnal Wind Speed, May 1995

Figure C11: Diurnal Wind Speed, June 1995

Figure C12: Diurnal Wind Speed, July 1995

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