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STANDARD PROCEDURES FOR METEOROLOGICAL MEASUREMENTS AT A POTENTIAL WIND TURBINE SITE

Prepared by:

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Standards Program
American Wind Energy Association
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Washington, DC 20001 USA
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FOREWORD

This foreword is included for informational purposes and is not part of *Standard Procedures for Meteorological Measurements at a Potential Wind Turbine Site, AWEA 8.1 - 1986.*

This standard is one in a series of standard documents being prepared by the American Wind Energy Association (AWEA) to facilitate uniform practices and communication in the technology of wind energy conversion. To continue to be of service to those organizations and individuals who use it, this document should not be static -- especially in view of the rapid evolution of wind energy technology. Suggestions for improvement will be welcomed by the Association. Address all correspondence to AWEA Standards Program, 122 C Street, NW, Fourth Floor, Washington, DC, 20001, USA.

AWEA 8.1 - 1986 was developed by the Siting Subcommittee of the AWEA Standards Program. The purpose of this subcommittee has been, and continues to be, to develop criteria for the design of wind energy conversion systems (WECS).

This document was prepared for submittal to the AWEA membership under the overall guidance of the AWEA Standards Coordinating Committee which was constituted as follows at the time of this submittal:

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1.0 Scope

This document provides procedures and methods for obtaining meteorological measurements at a site that has been proposed for wind energy use. Standards are provided for meteorological measurement systems and installation, operation, and calibration of equipment. Guidelines for sampling strategies, data processing and site evaluation practices are given in the appendices.

General wind turbine siting guidelines are not included here. References presenting this topic are given in "Applicable Documents".

This document does not cover standards for interpolating nearby data to the site, or for extrapolating short-term data into a long-term climatology. Numerical schemes for vertical extrapolation of data are also excluded. However, guidelines for obtaining the most representative measurements for the site and for recording these measurements during selected periods of the year to obtain annual estimates are given in Appendix C.

For the purposes of this document, wind energy utilization is defined as the use of single units or arrays of multiple units of wind turbines of any size greater than 1 kW for purposes of generating electricity. Although many of the guidelines in this document are applicable for all types of wind energy utilization, this document emphasizes procedures for commercial wind energy projects.

2.0 Applicable Documents

2.1 AWEA Terminology Standard AWEA 5.1 - 1985

2.2 Hiester, T. R. and W. T. Pennell, 1981. The Meteorological Aspects of Siting Large Wind Turbines. PNL-2522, Pacific Northwest Laboratory, Richland, Washington.

2.3 Wegley, H. L., et al. 1980. A Siting Handbook for Small Wind Energy Conversion Systems. PNL-2521 Rev. 1, Pacific Northwest Laboratory, Richland, Washington.

2.4 Pennell, W. T. 1983. Siting Guidelines for Utility Application of Wind Turbines. AP-2795, Research Project 1520-1. Electric Power Research Institute, Palo Alto, California.

3.0 Significance and Use

This document provides standard procedures for obtaining reliable, calibrated, and representative meteorological data from a site proposed for wind energy use. Adherence to this program will provide comparability of measurements among different sites and ensure that the data values are real and traceable to standards established by the National Bureau of Standards. The data base developed from this measurement program will enable the user to:

- Estimate energy production of wind systems over diurnal and monthly cycles from the installed equipment.
- Identify potential turbulence and/or site-specific wind characteristics wind turbines might encounter.
- Estimate on-peak, mid-peak, and off-peak energy production from the wind turbine site.

4.0 Description of Components of Wind Measurement Systems

4.1 Wind Sensors

Wind sensors measure the wind speed and direction. The most common type of sensors for measuring the horizontal wind speed component are cup or propeller anemometers. A wind vane is used to measure wind direction. Propeller anemometers also are used to measure the wind components in three orthogonal directions. These "uvw" anemometers can provide a measure of the vertical component of the wind.

4.1.1 Anemometer

A cup anemometer and wind vane could be independent sensors separated by a few feet, or the cup and vane could be mounted on the same vertical axis. When propellers and vanes are used, the propeller is attached to the vane. Because in this case the two sensors are not totally independent, structural or mechanical failure of the vane can cause erroneous wind speed data. Also, there may be errors introduced by the vane's response to wind direction, as opposed to cups that are essentially non-directional.

The rotation of anemometers is used to generate a signal that is proportional to wind speed. In most cases, the signal is electrical, although some anemometers produce mechanical signals. These signals may be continuous or intermittent. Continuous signals permit the wind speed to be determined at any instant. Intermittent signals can only be used to determine the average wind speed during a specific interval, depending on sampling rate.

Note: An example of a continuous signal would be the output of a small DC generator. If an anemometer is connected to a DC generator, the output of the generator can be displayed using a voltmeter or ammeter. The needle of the voltmeter will rise and fall with each wind gust, and the average wind speed is reflected by the average position of the needle. An example of an intermittent signal would be a flashing light. An anemometer can be connected to the light switch so that the number of light flashes over a predetermined time period equals the average wind speed. No information would be available on the speed during gusts during that period. Other methods of obtaining intermittent signals include use of reed switches or photocell light-choppers.

4.1.2 Wind Vanes

Wind vanes produce continuous signals; however, there are two types of signals. One type relates the signals to discrete direction sectors (i. e., north, northwest, etc.). As long as the wind continues within the sector, the signal remains constant even though there may be small direction fluctuations. The other type relates the signal to the instantaneous wind direction.

4.2 Signal Conditioners

Signal conditioners can supply power to sensors when required, and receive the signal from the sensor and convert it to a form that can be used by a recorder or display. Signal conditioning equipment is often included in the recorder or display equipment.

4.3 Displays

4.3.1 Dials

The information is read directly by needles or pointers.

4.3.2 Digital Displays

Information is presented directly by numerals and letters.

4.4 Recorders

4.4.1 Electromechanical Counters

Electromechanical counters record only the total amount of wind passing the sensor over a specified time interval. To estimate wind speed for electromechanical counters, it is necessary to determine elapsed time and divide the total amount of wind passing the sensor by the elapsed time. For example:

Average wind speed (mph) = miles of wind passage/elapsed time (hours)

4.4.2 Electronic Storage Data Loggers

In their simplest form, electronic data loggers can combine a number of accumulated signals, each with certain wind data. At the end of the observation period, the contents of the accumulators can provide a variety of statistics on wind, such as wind speed frequency distributions or sequential wind speed averages representative of predetermined time intervals. More complex data loggers may be used to record wind speed by direction and/or time of day. Data loggers that perform electronic calculations using the input signals and then record the results of the calculations are called "smart" data loggers.

4.4.3 Chart Recorders

In a chart recorder, the signal from the sensor moves a pen or other marking device back and forth across a piece of paper, which is typically moving at speeds between 2 and 15 centimeters (1 and 6 inches) per hour. The trace is a continuous wind record in which time of occurrence is determined by position along the chart.

4.4.4 Magnetic Tape or Solid State Recorders

Recorders can be used to record time sequential raw data or to record data that have been processed by the data logger. In the second case, a large part of the data analysis may be completed before recording. This preprocessing reduces the amount of data stored on the tapes, but may limit the flexibility of further data analysis, because the raw "time sequential" data have been lost. On the other hand, if the system only records the raw data, the sampling frequency must be high enough to ensure that sufficient samples are recorded for statistical analysis.

4.5 Wind Measurement Data Systems

Wind measurement data systems are defined on the basis of data storage capability as shown in Table 1.

Class I Systems: These systems do not have any data storage capability. If data are to be collected, an observer must monitor the system and manually record the data.

Class II Systems: These systems characterize the wind with a single number. Wind-run odometers are examples of these systems. Other instruments in this class record available energy in the wind (proportional to the sum of the cubes of instantaneous wind speed samples) or extractable energy (assuming a wind turbine's cut-in, rated, and cutout wind speeds are known). The time between readings of these instruments must be known to use the results.

Class III Systems: These systems store data in a sequential or accumulated form that retains information about the individual wind observations, including date and time. As a result, Class III systems record, store, and accumulate more data than the other systems. The data from these systems can be summarized in more than one form for analysis. As long as the recorded data are not lost, flexibility in analysis is retained, even after data collection is completed. Data collected by these systems can be used even if the details of data analysis were not determined before the data collection.

These systems are suitable for many wind turbine siting applications and provide more information on wind characteristics than Class II systems. Class III systems are particularly useful if diurnal load matching is important, because the data can be organized by time of day. Many of these systems are designed for unattended operation in remote locations and contain their own power sources.

The summary and analysis of data from Class III systems require the handling of large quantities of data. These systems generally require more attention to maintain the same levels of data recovery as Class I and II systems. However, because of the continuous nature of the data record obtained from these systems, software programs can be designed to obtain summaries of wind statistics over any time period desired. Many Class III systems have internal programs that summarize the data in various ways before recording them.

TABLE 1

DESCRIPTION OF THREE MAJOR CLASSES OF WIND MEASUREMENT SYSTEMS

Class	Storage Capability	Recording Medium	Primary Application	Comments
I	None	Manual records by observer	Real time, instantaneous data	Lowest cost,but human factor could introduce bias error
II	Single register	Counter or Electronic	Weekly, monthly averages	Minimum system for average speed or annual energy output
III	Multiple register, processed and sequential	Magnetic tape/ solid state/ strip chart	Summarized bin data, detailed statistical data analysis	Raw data retained for further processing;some internal processing;data storage dependent on sophistication of processing and logging systems.

5.0 Minimum Requirements for Standard Site Measurement Procedures

5.1 Data Use

Illustrations of different measurement strategies that can be used for various machine evaluations are shown in Appendix A.

5.2 Minimum Data Requirements

Data shall cover the wind speed range from 0 to 45 m/s (0 to 100 mph). In the wind speed range of 4.5 to 20 m/s (10 to 45 mph), resolution of the data shall be at a minimum of 0.5 m/s (1 mph). Data shall be recorded on a continuous basis for at least one year, even if wind turbines are installed before that period. During that year, a valid data recovery goal of at least 90% shall be established.

For the purposes of this document, "valid data" are measured data that are representative of the unknown quantities within the calibration tolerances of the instrumentation used and that would be confirmed by redundant measurements.

5.3 Maximum Wind Measurement System Inaccuracy

The wind measurement system consists of two primary subsystems: The physical subsystem (anemometer and wind vane sensors) and the electronic subsystem (signal conditioning, recording devices, and all cabling and connectors). The overall maximum wind speed system inaccuracy shall be +-2% of the true wind speed. The maximum wind direction system inaccuracy shall be +-5 degrees. These system inaccuracies shall apply over the temperature range specified by the manufacturer.

5.3.1 Physical Subsystem Measurement Inaccuracy

Under steady airflow conditions in a wind tunnel the physical subsystem contribution to the maximum wind speed inaccuracy shall be +-2% of the true wind speed for the range of 4.5 to 27 m/s (10 to 60 mph).

Note: Under normal use in the atmosphere, the inaccuracy of cup and propeller anemometers has not been documented, but may be greater than wind tunnel inaccuracies due to unsteady wind effects.

The physical subsystem contribution to the maximum wind direction inaccuracy shall be +-5 degrees of the true wind direction for the range of 4.5 to 27 m/s (10 to 60 mph) over the active part of the sensor. The sensors shall have a "dead band" (in which no measurement is possible) of less than 10 degrees.

5.3.2 Electronic Subsystem Measurement Uncertainty

The electronic subsystem contribution to the inaccuracy of wind speed and wind direction measurements shall be negligible for the range of 4.5 to 27 m/s (10 to 60 mph).

Note: Should the electronic subsystem measurement inaccuracy be significant, the total system measurement inaccuracy shall still be less than +-2% for wind speed and +-5 degrees for wind direction.

5.4 System Reliability

In assessing system reliability, data losses can result from malfunctions of sensors, processors, and data recorders. As a result, the data collection program shall incorporate the quality assurance procedures specified in Section 7 of this document.

Missing data records shall be clearly marked. Data processing procedures shall be established that ensure that missing data are not factored into statistical averages.

Note: In some cases, missing data gaps need to be filled so that a complete data set is available. Procedures for filling missing data are beyond the scope of this document.

6.0 Installation of Measurement Systems

6.1 Wind Energy Site Characteristics

Before selecting a site for wind energy measurements, and ultimately for wind energy use, consideration shall be given to local topography and obstructions, and preferred locations that may experience wind enhancement. References are given in the Applicable Documents section that provide detailed guidance on the siting of wind turbines incorporating these considerations.

6.2 Representativeness of Measurement System Locations

Measurements shall be taken as close to the intended turbine location as possible and at the anticipated hub height (or, for a vertical-axis machine, the equator height) of the rotor. At a minimum, the anemometer shall be at a height of at least 33 feet (10 meters).

To ensure representativeness of the planned wind turbine site, anemometers installed for site evaluation purposes shall be in exposures similar to the turbines. For example, if turbines are to be sited along a ridge crest, the anemometer shall be installed on the same crest. Use of isolated hills for anemometers, when the turbines are subsequently installed in lower terrain, often leads to unrepresentative measurements. Measurements shall be taken in an open area, free of heavy vegetation and structures. If sensors must be located near an obstruction, the location shall be a horizontal distance at least ten times the height of the obstruction.

Rooftop locations shall not be used for wind measurement systems unless the generator will also be on top of the roof at nearly the same height as the anemometer.

For large machine installations, or for multiple installations, or for complex terrain areas, more than one measurement location and/or level may be necessary. Due to the change of wind speed with height that normally occurs in the atmosphere, and the fluctuation of the magnitude of this change with time, anemometer heights must be at the turbine hub or equator height to avoid the introduction of uncertainties in the representativeness of the measurements due to this phenomenon. Multiple levels of measurements are beneficial when the exact hub height of the turbine is not known, or if the turbine height must be optimized.

6.3 Installation and Calibration of Wind Measuring Systems

6.3.1 Inspecting the Equipment

Before they are installed, measurement systems shall be given a functional check and calibration.

Signal conditioning and recording/display equipment shall be checked by putting simulated signals corresponding to sensor outputs for known wind speeds or directions into the signal conditioning equipment and comparing the recording/display equipment's outputs to the known speeds or directions. The check shall be performed for signals representing zero, as well as three or four additional wind speeds (e. g., 10, 20, and 30 mph), and four wind directions (0, 90, 180, and 270 degrees).

Note: When appropriate, torque watch values can be used to measure the starting speed of a sensor for comparison with manufacturers' specifications, if available. A torque watch is a device that is used to measure the amount of drag of the rotating shaft of the anemometer.

The chart speed of strip chart recorders shall be verified to be within manufacturer's specifications by running the recorder a minimum of one hour, and then measuring the amount of chart travel.

6.3.2 Installation

To avoid the effect of towers and cross-arms on sensors, the sensors shall be mounted on a mast above their support. Wind sensors shall be placed at a distance at least three structure diameters from lattice-type towers and at least six structure diameters from solid towers. Sensors shall be oriented into the prevailing wind direction.

The supporting structure shall be designed to withstand the wind loading expected for the site (structural standards for this loading are available from tower manufacturers). The structure shall be free of vibration and motion induced by the wind. The structure shall include lightning protection equipment to protect the sensors and data logging equipment. The structure shall be adequately secured against vandalism, unauthorized tower climbing, and other hazards. All necessary warning signs and ownership tags shall be clearly visible. If the supporting structure is 60 meters (200 feet) or higher, or is near an airport, proper FAA permits shall be obtained, and the tower shall be lighted according to regulations.

The anemometer and wind vane shall be aligned to assure that the appropriate axes are vertical (cup anemometers) and/or horizontal (propeller anemometers and wind vanes).

The wind vane shall be aligned by one of the following methods: 1) Drive a surveyor-type stake into the ground about 60 meters (200 feet) from the sensor toward true north and visibly align the "north" mark on the sensor to the stake; 2) Identify an existing landmark at the true north or other known direction position from the sensor and align according to 1); or 3) Use a compass to align the "north" mark to magnetic north then adjust the sensor's alignment for magnetic deviation. Before installation, sensor north shall be aligned with the supporting cross arm, since the cross arm is easier to line up with the reference point.

6.4 Operating the Equipment for Site Evaluation

A sampling strategy for site evaluation for a wind turbine or wind turbine array shall be designed to incorporate information on the turbulence characteristics of the site, fluctuations in winds that affect turbine operating strategies, the diurnal and seasonal variability, and the interannual variability of the winds. Examples of data analysis and reporting procedures may be found in Appendix A.

7.0 Standard Operating Procedures

The successful completion of a field monitoring program depends on the adherence to a set of Standard Operating Procedures. These procedures define all necessary steps to perform system calibrations, document site visits, identify and correct system problems, and provide for proper record keeping of all the steps involved from collecting data to summarizing the results with the assurance that the results are accurate and traceable to known standards. The Standard Operating Procedures shall include, at a minimum, procedures for the following activities.

7.1 Site Visits

At a minimum, the following steps shall be taken during each routine site visit:

- Record the date and time.
- Visually inspect the sensors, and document (and correct, if possible) any irregularities.
- Visually inspect the sensor support, including guy wire tensions, trueness of the support in the vertical, and condition of grounding system. Correct as needed.
- Check the power source or batteries. Replace batteries on a scheduled or as needed basis and document changes.
- Check the recorder or data logger operation according to manufacturer's specifications.
- Where appropriate, check "0" and "full scale" spans on signal conditioning equipment, and adjust where necessary. Document "as arrived" and "as left" conditions.
- Annotate the recording medium to identify the in formation recorded, the date and time that data recording started, and the time that it was completed.
- Document any actions taken during emergency or routine visits. The person performing the site visit shall be identified in the log each time.

7.2 Record Keeping Procedures

A record shall be kept for descriptions of the status of the instrument system. This record shall include the manufacturer and model number, and serial numbers of all pieces of equipment. References to the equipment shall always include the serial number.

7.2.1 Site Inspections

Each site inspection shall be documented in the record. This documentation shall include the pertinent features of the inspection procedures listed in Section 7.1. Where corrective action was required, this shall be noted in the record, and the date of the action shall be documented if different from the date of the inspection.

7.2.2 Instrument Inspection

The record shall contain a complete history of the instruments used in a measurement program from the time the instruments are received until the program is completed. Initial entries shall describe the instruments, the pre- installation inspection and calibration, the measurement site, the installation, and any recalibrations. Sufficient information shall be contained so that the measurement program could be reconstructed at a later date.

All records shall be initialed by the person making the entry. The initials shall be correlated to individuals.

7.3 Sensor Calibrations

Sensor calibrations shall be done with equipment traceable to National Bureau of Standards. Calibration reports shall be factored into any post-processing of data.

7.3.1 Field Calibrations

Instruments and recorders that can be field calibrated shall be calibrated to manufacturers' specifications at least twice a year. This calibration shall consist of an electronics check of the signal conditioning and recording equipment.

Note: Adequate steps shall be taken to assure that the bearings and DC generators have not deteriorated to the point of affecting the sensor calibration. Consequently, the Standard Operating Procedures shall include provisions for checking and replacing the sensors at appropriate intervals..

7.3.2 Laboratory Calibrations

Sensors shall be removed and tested in the laboratory on a regularly scheduled interval. Sensors shall be refurbished with new bearings and/or other parts as needed. Sensors shall be recalibrated by appropriate measures to ensure that the equipment is operating within the manufacturer's specifications.

Appendix A

EXAMPLES OF DATA ANALYSIS AND REPORTING PROCEDURES

A.1 Data Analysis

A wide range of sampling strategies and data processing procedures is available depending on the kind of recording equipment used in the collection program. Data logger sampling frequencies and averaging times are partially determined by the wind turbine application and utility purchase rate structure. As a result, advance planning should be done to determine the most appropriate and useful strategy.

For Class III systems, data should be sampled approximately once every one to three seconds, averaged over a period not to exceed one hour, and then stored in bins to obtain a variety of information. Also included in this sampling strategy should be a calculation of turbulence over the averaging period, as defined in AWEA's Terminology Standard. A Class III system should record the following information:

- The mean wind speed and direction.
- Turbulence data.

Software may be required to produce the type of information listed for Class III systems. For most Class III systems currently available, this type of sampling strategy should allow for approximately one month of data collection before the recording medium needs to be refreshed or replaced from the system. From this basic sampling and recording strategy, summarized output of Class III systems should be as follows:

- Mean wind speed for each recording period not to exceed one hour.
- A wind speed frequency histogram in 1 m/s (2 mph) speed intervals.
- A joint distribution of wind speed and direction in 2 m/s (5 mph) speed intervals and 22.5-degree direction intervals.
- A joint distribution of wind speed versus time of day in 2 m/s (5 mph) speed intervals and time intervals not to exceed 3 hours.
- A joint distribution of wind direction versus time of day in 22.5-degree intervals and 3-hour time intervals.
- Information about turbulence.
- Maximum peak gust and sustained (based on averaging interval) wind speeds.

A.2 Data Reporting Formats

Table A-1 summarizes information that should be reported on a routine (preferably monthly) basis for the various classes of data measurement systems.

TABLE A-1

ROUTINE (PREFERABLY MONTHLY) REPORTING RECOMMENDATIONS FOR VARIOUS CLASSES OF INSTRUMENTATION SYSTEMS

	Class I	Class II	Class III
Monthly/annual mean wind speed		X	X
Wind speed frequency distribution and cumulative frequency distribution			X
Wind direction frequency distribution			X
Mean speed/direction by time of day			X (not more than 1/4 day increments)
Vertical shear of speed by direction and time of day*			X
Turbulence			X
Maximum gusts		X	X

* Requires at least two levels of instrumentation on tower

Appendix B

EXAMPLE PROCEDURES FOR ENHANCING DATA REPRESENTATIVENESS AT A SITE

B.1 Extrapolating On-Site Data to Long-Term Statistics

It is obviously impractical to sample at a proposed wind turbine site long enough to obtain information on interannual variability, and perhaps even seasonal variability. Wind measurement strategies, based on the known statistical characteristics of high-wind sites, have been developed, and are recommended here to obtain information on the likely long-term variability of a site.

For a single season or year of measurements at the wind turbine site, the long-term wind speed for the corresponding season, or the long-term annual wind speed for a single year of measurements, will be within +-10% of the single season or year observation with about 90% confidence (References 1, 2, and 3).

When a nearby long-term reference station is available, and the diurnal and seasonal wind patterns at the reference station and measurement station are similar, the short-term site data can be adjusted to the climatological station using the following relationship:

If a number of different sites in a wind turbine array are to be monitored, an intermittent measurement strategy can be used at each site to maximize instrument usage (Reference 3).. Based on results quoted in (3) it is recommended that at least two to three months of intermittent measurements be made at each location for a period of at least three years. This will provide a data set that will give at least the same, if not higher, confidence of the long-term estimate at all sites than one year of continuous measurements at each site.

B.2 Special Measurements for Site Evaluation

B.2.1 Turbulence Measurements

For site evaluation for large wind turbines or wind turbine arrays, special turbulence measurements may be desirable to determine more precisely the types of loads wind machines might experience at the site. It is recommended that a special measurement program using high quality, sensitive wind sensors and sophisticated data loggers be undertaken for short periods of time. Detailed descriptions of these programs is beyond the scope of this document.

B.2.2 Kite Anemometer Measurements

Kite anemometers can be used in the site evaluation process to obtain information on the spatial representativeness of the measurement station(s) installed at the site. For these studies, it is recommended that kite anemometer studies be made at different times on each of 2 to 3 days per month, three to four times per year. The studies should involve at least two kites, which are first flown together to obtain a relative comparison on the readout of each. Then one kite is flown continuously, close to the measurement station and at the same height as the anemometer of the measurement station, while the other is flown at the same height at several pre-determined locations around the site. These locations should be representative of the locations where wind turbines would be installed. At each location, at least three 10-minute measurement periods are recommended, with a 3- to 5-minute break between each period. During each measurement period, readings approximately every 15 seconds should be taken. At the conclusion of the measurements, all values within each 10-minute measurement period should be averaged and compared with the "control" kite anemometer.

A kite anemometer can also be used to estimate the vertical variation of the wind speed at the measurement station, and at any location within the site. These measurements should also be done for several hours on 2 to 3 days per month, 3 to 4 months per year, using the same sampling strategy as before. A "control" kite at the measurement station is recommended for this practice as well.

References for Appendix B

1. Corotis, R. B., et al., 1977: "Variance Analysis of Wind Characteristics for Energy Conversion." Journal of Applied Meteorology 16:1149-1157.

2. Justus, C. G., et. al., 1979: "Interannual and Month-to-Month Variations of Wind Speed." Journal of Applied Meteorology 18:913-920.

3. Ramsdell, J. V., et. al., 1980. Measurement Strategies for Estimating Long-Term Average Wind Speeds. PNL-3448, Pacific Northwest Laboratory, Richland, Washington.