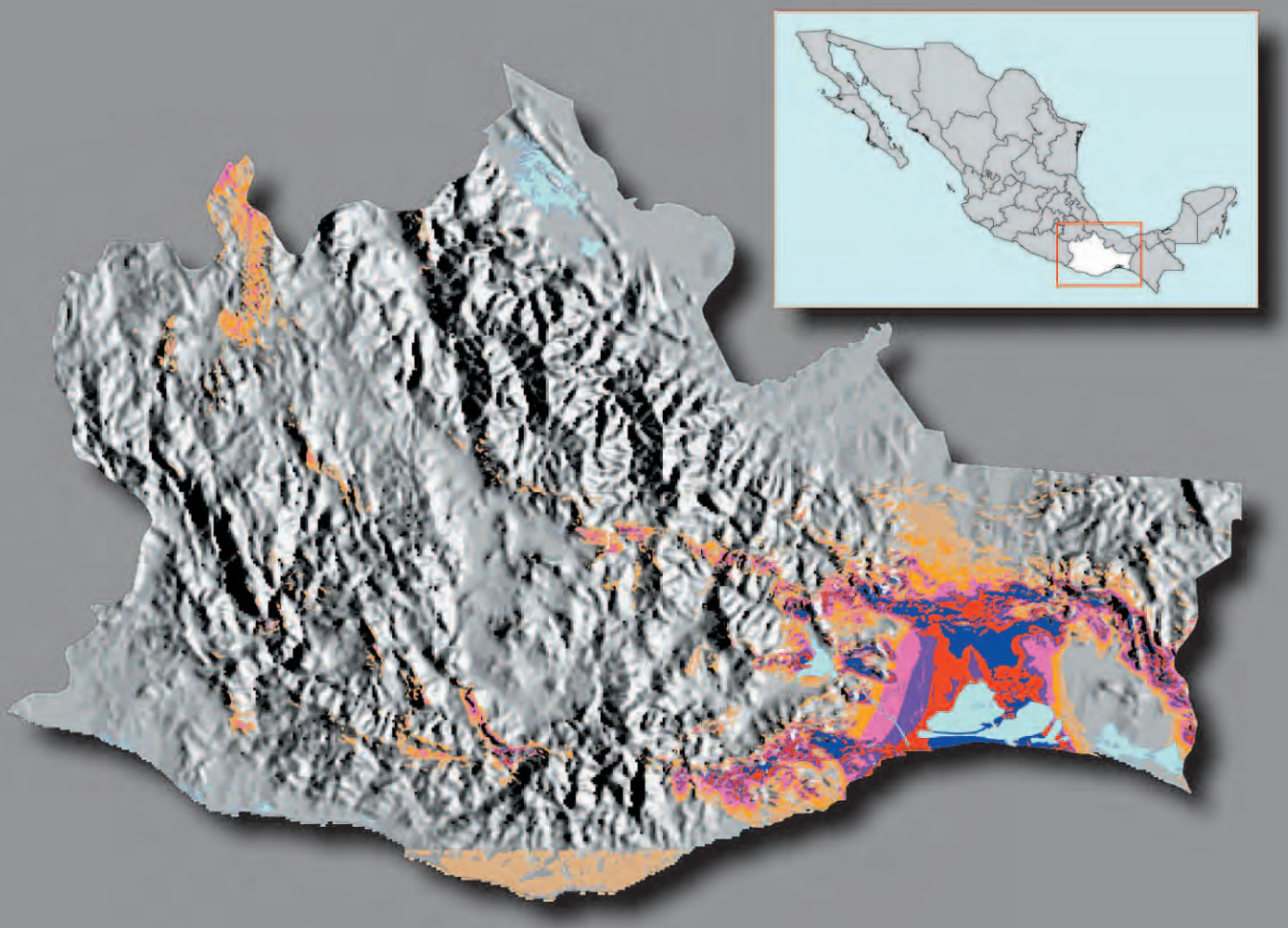
Wind Energy Resource Atlas of Oaxaca



D. Elliott, M. Schwartz, G. Scott, S. Haymes, D. Heimiller, R. George
National Renewable Energy Laboratory

August 2003 ◆ NREL/TP-500-34519

Wind Energy Resource Atlas of Oaxaca

D. Elliott
M. Schwartz
G. Scott
S. Haymes
D. Heimiller
R. George

Prepared under Task No. WF7C0310

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: reports@adonis.osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

Table of Contents

LIST OF TABLES ..... **IV**

LIST OF FIGURES ..... **V**

EXECUTIVE SUMMARY ..... **VI**

1.0 INTRODUCTION **1**

2.0 GEOGRAPHY AND CLIMATE OF OAXACA **3**

2.1 GEOGRAPHY 3
2.2 CLIMATE 3

3.0 FUNDAMENTALS OF WIND RESOURCE ESTIMATION **7**

3.1 INTRODUCTION 7
3.2 WIND SPEED AND DIRECTION 7
3.3 WIND SPEED FREQUENCY DISTRIBUTION 7
3.4 WEIBULL DISTRIBUTION FUNCTION 8
3.5 WIND POWER DENSITY 8
3.6 WIND SHEAR AND THE POWER LAW 9
3.7 SOURCES OF WIND DATA 10
3.7.1 Surface Observations 10
3.7.2 Upper-air Observations 10
3.7.3 Satellite Ocean Wind Measurements (SSMI) 11
3.7.4 Computer Model Climatic Data 11

4.0 WIND RESOURCE METHODOLOGY AND MAPPING SYSTEM **12**

4.1 INTRODUCTION 12
4.2 METHODOLOGY 12
4.2.1 Data Evaluation and Analysis 12
4.2.1.1 Initial Approach 12
4.2.1.2 Surface Data Evaluation 12
4.2.1.3 Upper-Air Data Evaluation 13
4.2.1.4 Goals of Data Evaluation 13
4.2.2 Wind Power Classifications 14
4.3 DESCRIPTION OF MAPPING SYSTEM 14
4.3.1 Input Data 14
4.3.2 Wind Power Calculations 15
4.3.3 Mapping Products 15
4.3.4 Limitations of Mapping Technique 17

5.0 WIND RESOURCE DATA FOR OAXACA **18**

5.1 INTRODUCTION 18
5.2 SURFACE DATA 18
5.2.1 DATSAV2 Data 18
5.2.2 National Water Commission Data 20
5.2.3 Validation Data from Wind Developers 21
5.3 UPPER-AIR DATA 21
5.3.1 Automated Data Processing Reports (ADP) Data 21
5.3.2 Computer Model-Derived Data Sets 21
5.3.2.1 Global Upper-Air Climatic Atlas (GUACA) 21
5.3.2.2 Reanalysis Data 22
5.3.2.3 Mesoscale Model Data 22
5.4 SATELLITE OCEAN WIND DATA 22

6.0 WIND RESOURCE CHARACTERISTICS OF OAXACA 23

6.1 INTRODUCTION 23
6.2 WIND POWER CLASSIFICATIONS 23
6.3 APPROACH 23
6.4 WIND RESOURCE DISTRIBUTION AND CHARACTERISTICS 24
6.4.1 Annual Wind Resource Distribution 24
6.4.2 Seasonal Wind Resource Distribution 26
6.4.3 Diurnal Wind Speed Distribution 27
6.4.4 Wind Direction Frequency Distribution 27
6.4.5 Confirmation of Wind Resource Estimates 28
6.5 REGIONAL SUMMARIES OF WIND RESOURCE 29
6.5.1 Eastern Oaxaca 29
6.5.2 Western Oaxaca 30

7.0 WIND ELECTRIC POTENTIAL 45

7.1 INTRODUCTION 45
7.2 WIND ELECTRIC POTENTIAL ESTIMATES 45

REFERENCES 47

APPENDIX A: DATSAV2 SURFACE METEOROLOGICAL STATIONS A-1

APPENDIX B: NATIONAL WATER COMMISSION MEASUREMENT SITES B-1

APPENDIX C: REANALYSIS UPPER AIR WIND DATA C-1

APPENDIX D: OCEAN SATELLITE WIND DATA D-1

List of Tables

TABLE 4.1. WIND POWER CLASSIFICATION 17
TABLE 5.1 VALIDATION DATA PROVIDERS 21
TABLE 6.1. WIND POWER CLASSIFICATION 23
TABLE 6.2. WIND RESOURCE COMPARISON 29
TABLE 7.1 OAXACA – WIND ELECTRIC POTENTIAL 46

List of Figures

FIGURE 2.1 OAXACA – POLITICAL BASE MAP. 4
FIGURE 2.2 OAXACA – ELEVATION MAP. 5
FIGURE 2.3 OAXACA – HILL-SHADED RELIEF MAP. 6
FIGURE 4.1 OAXACA – MODIS PERCENT TREE COVER MAP. 16
FIGURE 5.1 OAXACA – GTS SURFACE METEOROLOGICAL STATIONS. 19
FIGURE 5.2 OAXACA – DISAPPEARING WINDS AT HUATULCO (SPEED BY YEAR). 20
FIGURE 6.1 OAXACA – WIND RESOURCE MAP. 31
FIGURE 6.2 OAXACA – WIND RESOURCE MAP WITH ROADS AND TRANSMISSION. 32
FIGURE 6.3 OAXACA – WIND RESOURCE MAP WITH SHADED RELIEF. 33
FIGURE 6.4 SATELLITE OCEAN MONTHLY WIND DATA FOR THE OFFSHORE ISTHMUS REGION 34
FIGURE 6.5 ISTHMUS REGION – COMPARISON OF MEASUREMENT SITES AND OFFSHORE DATA 34
FIGURE 6.6 ISTHMUS OFFSHORE REGION – MONTHLY WIND POWER AND VARIABILITY 35
FIGURE 6.7 ISTHMUS OFFSHORE REGION – INTERANNUAL VARIABILITY OF WIND POWER 35
FIGURE 6.8 LOCATIONS OF MEASUREMENT DATA FOR MAP VALIDATION 36
FIGURE 6.9 EASTERN OAXACA – POLITICAL BASE MAP 37
FIGURE 6.10 EASTERN OAXACA – ELEVATION MAP 38
FIGURE 6.11 EASTERN OAXACA –WIND RESOURCE MAP 39
FIGURE 6.12 ISTHMUS REGION - WIND RESOURCE MAP WITH ROADS AND TRANSMISSION 40
FIGURE 6.13 ISTHMUS REGION - WIND RESOURCE MAP WITH SHADED RELIEF. 41
FIGURE 6.14 WESTERN OAXACA – POLITICAL BASE MAP 42
FIGURE 6.15 WESTERN OAXACA –ELEVATION MAP 43
FIGURE 6.16 WESTERN OAXACA – WIND RESOURCE MAP 44

Executive Summary

This wind energy resource atlas identifies the wind characteristics and distribution of the wind energy resource in the state of Oaxaca, located in the country of Mexico. The detailed wind resource maps and other information contained in the atlas facilitate the identification of prospective areas for use of wind energy technologies for utility-scale power generation, village power, and off-grid wind energy applications. The maps portray the wind resource with high-resolution grids of wind power density at 50 m above ground. The wind maps were created at the National Renewable Energy Laboratory (NREL) using a computerized wind mapping system that uses Geographic Information System (GIS) software.

NREL's advanced wind mapping methodology integrates terrain and climatic data sets, GIS technology, and analytical and computational techniques. The meteorological data sources include surface and upper-air data taken from measurement stations, ocean surface winds derived from satellite measurements, and model-derived estimates. Mesoscale model data from TrueWind Solutions (an NREL subcontractor) were used for initial estimates of the wind power in Oaxaca. The initial estimates in certain regions of Oaxaca were adjusted after NREL's extensive evaluation of the available data sets (including measurement data collected at prospective wind development sites). The major adjusted regions were enhanced or accelerated wind flow areas in some mountainous regions of Oaxaca, parts of the Isthmus of Tehuantepec region, and the south-central coastal area near Bahias de Huatulco and Puerto Escondido.

The wind-mapping results for Oaxaca show many areas that are estimated to have good-to-excellent wind resources (wind power Classes 4 to 7, with 7 being the highest). The best wind resource areas in Oaxaca are concentrated in the southeastern region of the state, primarily in the southern part of the Isthmus of Tehuantepec. The windy Isthmus region extends from the coast northward approximately 60 km and approximately 60 km to 80 km from east to west. Excellent wind resource (power Class 5 and above) is widespread in this Isthmus region. The highest resource (power Class 7) in the Isthmus occurs near the foothills (including La Mata and La Venta), ridges, and coast. Strong northerly winds (winds from the north) are frequent in the Isthmus region, particularly during the peak wind season from November through February. High-quality data from measurement sites in the Isthmus confirm the excellent wind resource potential in specific areas of the Isthmus, but additional data are needed to validate the map estimates in other areas of the Isthmus. Many ridges and elevated terrain areas adjacent to the Isthmus region (up to 100 km to the east and west of the Isthmus) are also estimated to have excellent wind resources, but many of these sites would be difficult to develop because of the rugged terrain and difficult access. Climatic data sets indicate that the ambient wind resource in and near the Isthmus significantly decreases at elevations above 1200 m to 1500 m, so it is likely that many of the higher elevations in this region have less wind resource than lower elevation sites in the Isthmus.

Some additional areas estimated to have good-to-excellent wind resource are located in specific areas of northwestern, central, and southern Oaxaca. In northwestern Oaxaca, notable areas are located primarily to the east and north of Huajuapan de Leon. In central Oaxaca, the most notable areas are located approximately 40-70 km east of the city of Oaxaca (near Mitla). In southern Oaxaca, some notable areas are located approximately 80-110 km south of the city of Oaxaca (near Miahuatlan). In all of these regions, the best areas are estimated to occur where terrain features channel and/or accelerate the northeast winds. The peak wind season is from October through February, when strong northeast winds are most prevalent.

NREL estimates that there are about 6600 km^2 of windy land with good-to-excellent wind resource potential in Oaxaca. The windy land represents slightly more than 7% of Oaxaca's total land area (91,500 km^2). Using a conservative assumption of 5 MW per km^2, this windy land could support approximately 33,000 MW of potential installed capacity. If only areas with the highest (Class 7) wind resource potential are considered, the estimated total windy land area is about 1200 km^2, and this land could potentially support about 6000 MW of installed capacity. Most of Oaxaca's windy land area is located in the Isthmus region. Although the Federal Electricity Commission of Mexico has conducted a general assessment of the transmission grid and accessibility, additional studies are required to accurately assess the wind electric potential, considering factors such as the existing transmission grid and accessibility.

Although the wind resource maps and other characteristic information provided by NREL will help identify prospective areas for wind energy applications, we strongly recommend that wind measurement programs be conducted to validate the resource estimates and to refine the wind maps and assessment methods.

1.0 Introduction

The United States Department of Energy (DOE) and the United States Agency for International Development (USAID) sponsored a project to help accelerate the widespread use of wind energy technologies in the Mexican state of Oaxaca through the development of a wind energy resource atlas for Oaxaca.

DOE's National Renewable Energy Laboratory (NREL) led the project in collaboration with USAID, the Oaxaca State Government's Department of Industrial and Commerce Development (SEDIC), Mexico's Secretary of Energy (SENER), the Electrical Research Institute of Mexico (IIE) and its Non-Conventional Energy Unit (GENC), and the Federal Electricity Commission of Mexico (CFE). The primary goals of the project were to develop detailed wind resource maps for all regions of Oaxaca and to produce a comprehensive wind resource atlas documenting the results.

This activity supports a broader collaboration between DOE and SENER to help the Mexican government to meet its goal of installing 1000 MW of renewable energy by 2006. The Oaxaca Government has also set a goal of installing 2000 renewable-based MW by 2015. This wind resource atlas is one example of the United States/Mexico collaboration and is an important element of the Mexican strategy to ensure that information and tools are available for defining specific renewable energy projects and accessing financial and developmental support. The goal in creating this wind atlas, along with other renewable resource assessments, is to ensure that the communities in Oaxaca ultimately receive the social and economic benefits of renewable energy.

NREL was responsible for obtaining meteorological data available from U.S. sources, such as the National Climatic Data Center (NCDC) and the National Center for Atmospheric Research (NCAR) that would be useful in the assessment. NREL was also responsible for data analysis, development of the final wind resource maps, and production of the final wind atlas. TrueWind Solutions (an NREL subcontractor) provided mesoscale model data for the initial wind resource estimates in Oaxaca. Some organizations assisted NREL by providing data from national Mexican government sources and from sources in Oaxaca. The Foundation for Wind Development in the Isthmus (Foundation) coordinated the identification of available data from various organizations that have measurement data in Oaxaca and the delivery of these data to NREL. Through this process, NREL obtained data from 20 wind measurement sites installed to assess the wind potential in different areas of the Isthmus of Tehuantepec region. CFE supplied the data for 10 of these sites. The Foundation also provided summaries of mean wind speeds from 126 meteorological stations operated by the National Water Commission of Mexico (NWC). However, the NWC data were of very limited use in the wind resource assessment because of the lack of detailed information on the measurement procedures and concerns with the quality of the data. In addition to supplying data from Oaxaca, the Foundation also assisted NREL in coordinating reviews of the preliminary wind resource maps and in organizing a workshop for presentation of the wind mapping results. GENC-IIE assisted NREL with the integration of important GIS data, such as major transmission lines and roads, for inclusion with the final wind resource maps.

The Wind Energy Resource Atlas of Oaxaca presents the wind resource analysis and mapping results for Oaxaca. An advanced automated wind mapping technique, developed at NREL with assistance from U.S. consultants, was used to generate the wind resource maps. This technique uses Geographic Information Systems (GIS) to produce high-resolution annual average wind resource maps. In addition to the wind resource maps, the atlas includes information on important wind characteristics, including seasonal and diurnal variability and wind direction frequency.

This atlas is the latest in a series of wind energy resource atlases and assessments produced by NREL. In addition to Oaxaca, NREL has applied its wind mapping system to produce wind resource assessments of the Dominican Republic (Elliott et al., 2001), the Philippines (Elliott et al., 2001), Mongolia (Elliott et al., 2001) and specific regions of Chile, China, Indonesia, Mexico, and the United States (Schwartz, 1999; Elliott et al., 1999). Many of NREL's international wind resource maps, and some produced by others, can be found on the Web at http://www.rsvp.nrel.gov/wind_resources.html.

The wind atlas of Oaxaca is divided into seven sections. Section 2.0 provides an overview of the geography and climate of Oaxaca. Section 3.0 contains a summary of the fundamentals of wind resource estimation. Section 4.0 describes the wind resource methodology and mapping system. Section 5.0 presents the wind resource data obtained and analyzed for the assessment. Section 6.0 describes the wind resource characteristics and mapping results for Oaxaca, and Section 7.0 contains an assessment of the wind electric potential in Oaxaca.

Appendices provide pertinent summaries of wind characteristics data from selected surface meteorological stations, upper-air data, and satellite ocean wind data.

2.0 Geography and Climate of Oaxaca

2.1 Geography

The state of Oaxaca is located in the southern part of Mexico. Its size is approximately 95,364 km^2, making it the fifth-largest state in Mexico. Oaxaca is bordered by the states of Puebla and Veracruz on the north, Guerrero on the west, Chiapas on the east, and by the Pacific Ocean on the south. It extends approximately 340 km from north to south and 500 km from east to west. Oaxaca is centered at approximately 96 degrees west longitude between 16 and 18 degrees north latitude.

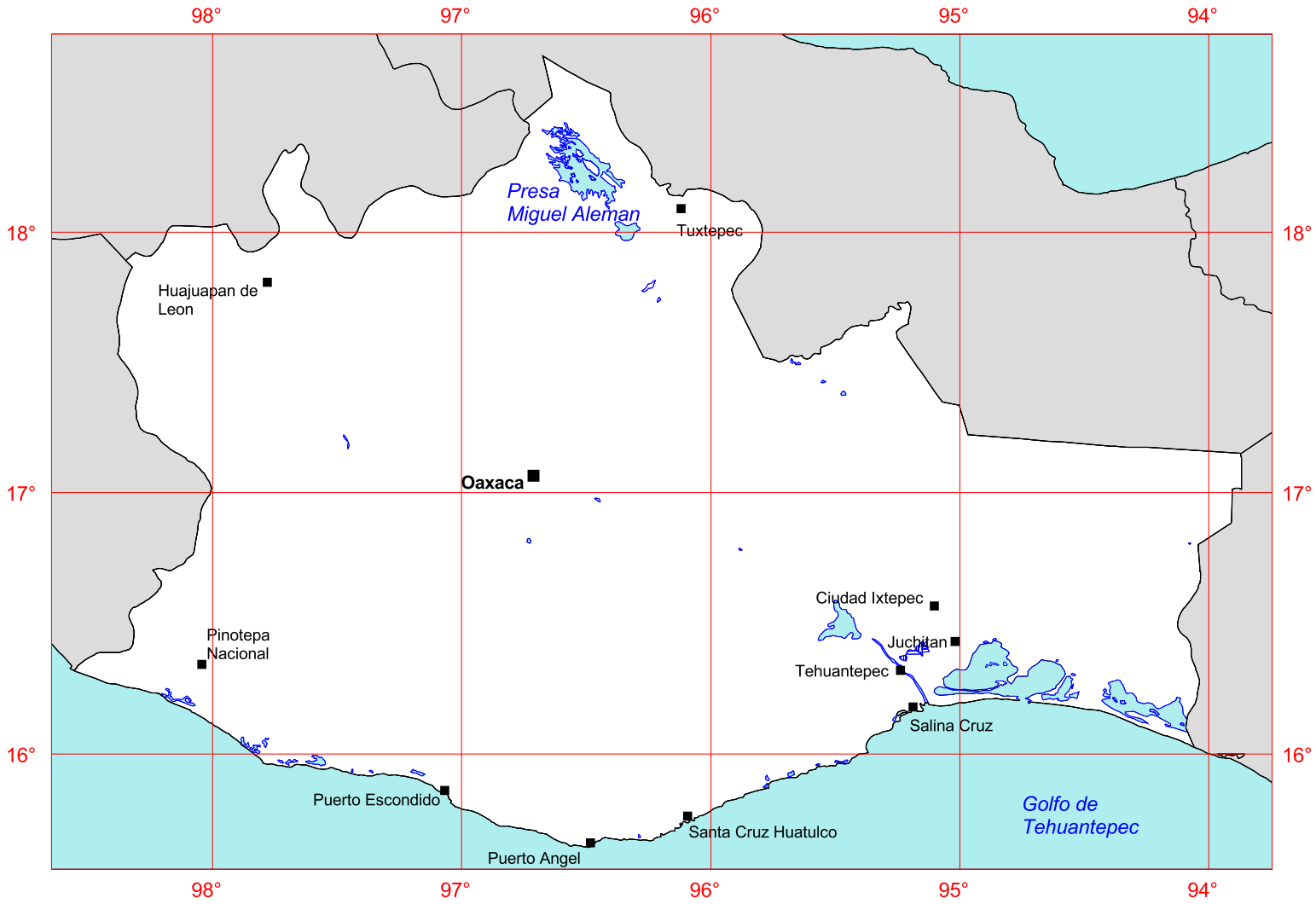
Figure 2.1 is a political map of Oaxaca that shows the major cities. The population of Oaxaca is around 3.4 million (2003). The capital of Oaxaca and largest city is Oaxaca de Juárez, with a population of approximately 260,000.

Oaxaca's terrain, shown in Figures 2.2 and 2.3, is varied and includes mountain ranges, broad plateaus, high valleys, and coastal plains. Much of Oaxaca is mountainous, with half the state higher than 1000 meters (m) above sea level. The northern part of Oaxaca is dominated by the Sierra de Oaxaca, with peaks exceeding 3,000 m, which trends northwest to southeast until ending in the Isthmus of Tehuantepec. The Sierra Madre del Sur, which also trends northwest to southeast, is south of the central valleys of Oaxaca and includes the highest point in Oaxaca, Cerro el Nacimiento at 3749 meters. The elevation of Oaxaca de Juárez is around 1,540 m. The eastern edge of Oaxaca is occupied by the Sierra Madre de Chiapas. A coastal plain characterizes the southern part of the state. There are several large lagoons in southeastern Oaxaca: Laguna Superior, Laguna Inferior, and Mar Muerto.

2.2 Climate

Oaxaca has a variety of climates, ranging from tropical along the coast to temperate in the interior. Oaxaca has distinct dry and rainy seasons. The rainy season generally lasts from April through October, although local climate variations can shorten or lengthen the season. The average annual rainfall is about 700 mm along the coast, 600 to 700 mm in the central valleys, and 2000 mm and greater in the mountains. The annual temperature along the coast ranges from 26 to 28 degree Celsius along the coast, 20 to 22 degrees Celsius in the central valleys, and 12 to 15 degrees Celsius in the mountains.

Oaxaca - Political Base Map



50 0 50 100 150 Kilometers

Legend

■ Town or ■ **Capital**

Lake or Lagoon

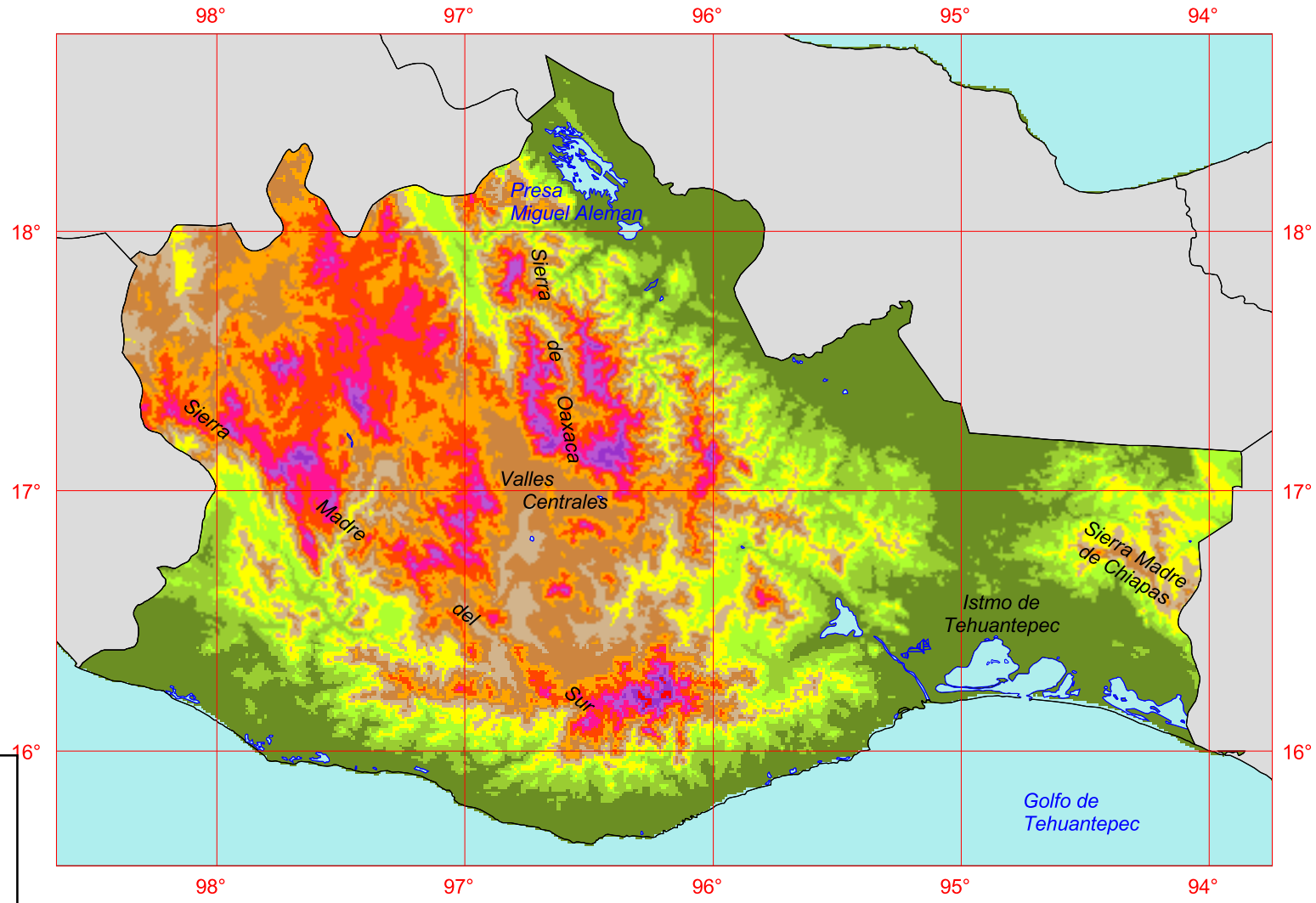
U.S. Agency for International Development

U.S. Department of Energy
National Renewable Energy Laboratory

JUL-2003 1.2.1

Figure 2-1

Oaxaca - Elevation Map



Elevation
Meters

3600
3300
3000
2700
2400
2100
1800
1500
1200
900
600
300
0

The elevation values are averaged over 1 km^2.

50 0 50 100 150 Kilometers

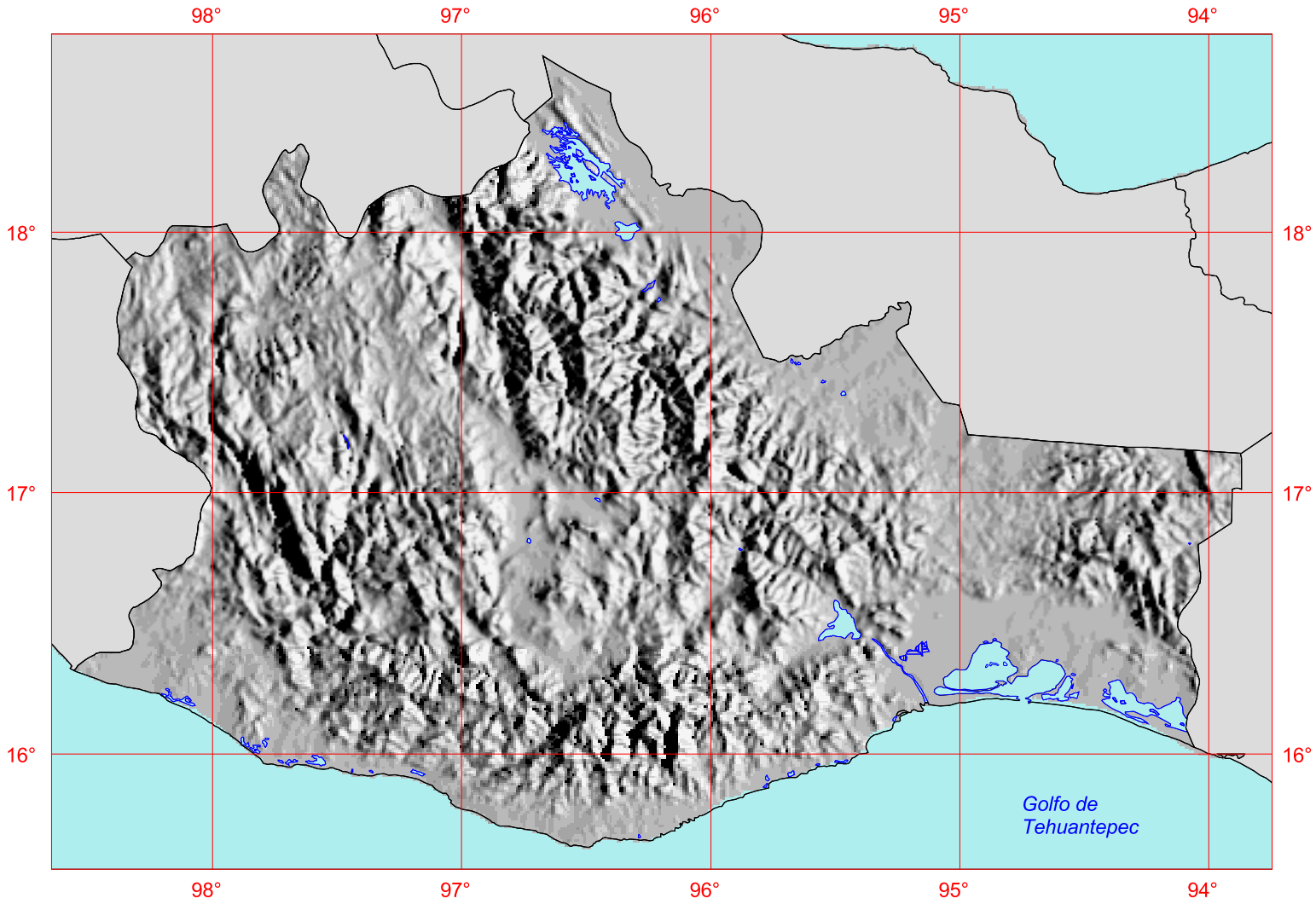
U.S. Agency for International Development

U.S. Department of Energy
National Renewable Energy Laboratory

GeoUL-2003 1.2.2

Figure 2-2

Oaxaca - Hillshaded Relief Map



50 0 50 100 150 Kilometers

U.S. Agency for International Development

U.S. Department of Energy
National Renewable Energy Laboratory

JUL-2003 1.2.3

Figure 2-3

3.0 Fundamentals of Wind Resource Estimation

3.1 Introduction

This section introduces the basic concepts of wind resource estimation and presents some of the data sources that can be used in an assessment study.

Wind resource assessment studies can be placed into three basic categories:

- Preliminary area identification
- Area wind resource evaluation
- Micrositing.

NREL's wind resource atlases are useful for the first two categories, but they do not contain the detailed information needed for micrositing studies. Details about micrositing and wind monitoring programs can be found in the *Wind Resource Assessment Handbook* (NREL/AWS Scientific, 1997).

3.2 Wind Speed and Direction

Wind speed is the simplest representation of the wind at a given point. Anemometers or other calibrated instruments measure wind speed. Wind speeds can be calculated as an average or expressed as an instantaneous value. Wind speed averaging intervals commonly used in resource assessment studies include 1 or 2 minutes (weather observations), 10-minute (the standard for wind energy monitoring programs), hourly, monthly, and yearly periods. It is important to know the measurement height for a given wind speed because of the variation of wind speed with height. It is also desirable to know the exposure of a particular location to the prevailing winds because nearby obstacles such as trees and buildings can reduce the apparent wind speed.

Wind direction is measured with a wind vane, usually located at the same height as the anemometer. Knowledge of the prevailing wind direction is important in assessing the available resource. Correct alignment of the wind vane to a reference direction is important to accurately measure the wind direction, but it is not always properly aligned. Wind direction observations at meteorological stations are often based on a 36-point compass (every 10 degrees). Some wind direction data are expressed in less precise 8-point (every 45 degrees), 12-point (every 30 degrees), or 16-point (every 22.5 degrees) intervals.

The wind direction distribution is often presented as a wind rose (a plot of frequency of occurrence by direction). Wind roses can also represent quantities such as the average speed or the percent of the available power for each direction.

3.3 Wind Speed Frequency Distribution

The wind speed frequency distribution characterizes the wind at a given location in two ways. First, the frequency distribution determines how often a given wind speed is observed at the location, and second, it identifies the range of wind speeds observed at that location. This

analysis is often accomplished by sorting the wind speed observations into 1-meter-per-second (m/s) bins and computing the percentage in each bin. The wind speed distribution is important because sites with identical average wind speeds but different distributions can result in substantially different available wind resource. These differences can be as great as a factor of two or three.

3.4 Weibull Distribution Function

The wind speed frequency distribution in many areas can be closely approximated by the Weibull Distribution Function. The Weibull Function is defined as:

$$f(V) = (k / c)(V / c)^{k-1} \exp(-V / c)^{k}$$

where:

- $f(V)$ = the Weibull probability density function, the probability of encountering a wind speed of V m/s;
- c = the Weibull scale factor, which is typically related to the average wind speed through the shape factor, expressed in m/s;
- k = the Weibull shape factor, which describes the distribution of the wind speeds.

Detailed explanations of the Weibull Distribution Function and its application are available in many texts, such as that by Rohatgi and Nelson (1994).

3.5 Wind Power Density

The wind resource at a site can be roughly described by the mean wind speed, but the wind power density provides a truer indication of a site's wind energy potential. Wind power density expresses the average wind power over one square meter (W/m^2). The power density is proportional to the sum of the cube of the instantaneous (or short-term average) wind speed and the air density. Due to this cubic term, two sites with the same average wind speed but different distributions can have very different wind power density values. The wind power density, in units of W/m^2, is computed by the following equation:

$$\mathbf{WPD} = \frac{\mathbf{1}}{\mathbf{2n}} \sum_{\mathbf{i=1}}^{\mathbf{n}} \rho \cdot \mathbf{v_i}^{\mathbf{3}}$$

where

- WPD = the wind power density in W/m^2;
- n = the number of records in the averaging interval;
- ρ = the air density (kg/m^3) at a particular observation time;
- v_i^3 = the cube of the wind speed (m/s) at the same observation time.

This equation should only be used for individual measurement records (hourly, 10-minute, etc.) and not for long-term average records such as a monthly or yearly value. Using this equation with long-term averages will underestimate the wind power density because long-term averages

will not include most of the higher-speed records that would more accurately calculate the wind power density.

The air density term (kg/m^3) is dependent on temperature and pressure and can vary by 10% to 15% seasonally. If the site pressure and temperature are known, the air density can be calculated using the following equation:

$$\rho = \frac{\mathbf{P}}{\mathbf{R} \cdot \mathbf{T}}$$

where

ρ = the air density in kg/m^3;
P = the air pressure (Pa or N/m^2);
R = the specific gas constant for air (287 J/kg·K);
T = the air temperature in degrees Kelvin (°C+273).

If site pressure is not available, air density can be estimated as a function of site elevation (z) and temperature (T) as follows:

$$\rho = \left(\frac{\mathbf{P_0}}{\mathbf{R} \cdot \mathbf{T}} \right) \varepsilon^{\left(\frac{-\mathbf{g} \cdot \mathbf{z}}{\mathbf{R} \cdot \mathbf{T}} \right)}$$

where

ρ = the air density in kg/m^3;
P_0 = the standard sea level atmospheric pressure (101,325 Pa), or the actual sea-level adjusted pressure reading from a local airport;
g = the gravitational constant (9.8 m/s^2);
z = the site elevation above sea level (m).

Substituting in the numerical values for P_0, R, and g, the resulting equation is:

$$\rho = \left(\frac{\mathbf{353.05}}{\mathbf{T}} \right) \varepsilon^{-0.034 \left(\frac{z}{T} \right)}$$

This air density equation can be substituted into the wind power density (WPD) equation for the determination of each instantaneous or multiple average values.

3.6 Wind Shear and the Power Law

The wind shear is a description of the change in horizontal wind speed with height. The magnitude of the wind shear is site-specific and dependent on wind direction, wind speed, and atmospheric stability. By determining the wind shear, one can extrapolate existing wind speed or wind power density data to other heights. The following form of the power law equation can be used to make these adjustments:

$$\mathbf{U = U_0 (z/z_0)^{\alpha}} \qquad \text{[Wind Speed]}$$

$$\mathbf{WPD = WPD_0 (z/z_0)^{3\alpha}} \qquad \text{[Wind Power Density]}$$

where

U = the unknown wind speed at height z above ground;
U_0 = the known speed at a reference height z_0;
WPD = the unknown wind power density at height z above ground;
WPD_0 = the known wind power density at a reference height z_0;
α = the power law exponent.

An exponent of 1/7 (or 0.143), which is representative of well-exposed areas with low surface roughness, is often used to extrapolate data to higher heights.

3.7 Sources of Wind Data

3.7.1 Surface Observations

Surface meteorological data are available from many sources. Most countries have a meteorological agency that collects data from a network of stations across the country. Other data may be available from regional agencies, scientific organizations, power utilities, and private companies.

For accurate wind resource estimation, wind speed and direction must be included, but temperature and pressure can also be helpful. A site's exposure, anemometer height, local topography, and site maintenance history are also quite useful.

Wind speeds at some sites are observed to decrease steadily over a period of years (the "disappearing winds" effect). This trend can be caused by new building construction near the site, tree growth near the site, or by lack of anemometer maintenance. Extra quality control procedures must be applied in analyzing data from sites with this wind speed trend.

3.7.2 Upper-Air Observations

Upper-air stations measure the meteorological properties of the atmosphere above the surface by launching balloons, usually between one and four times daily. Pilot balloons, which are un-instrumented balloons that are tracked through theodolites, comprise the simplest upper-air observations. Pilot balloons observations can only estimate wind speed and direction. Radiosonde (or rawinsonde) packages of instruments that relay atmospheric conditions to the base station by radio make more elaborate and accurate measurements. The instrumented packages measure temperature, pressure, and humidity data in addition to wind speed and direction.

3.7.3 Satellite Ocean Wind Measurements (SSMI)

The SSMI, which is part of the U.S. Defense Meteorological Satellite Program, provide 10-m ocean wind speed measurements. The data set provides much more uniform and detailed coverage of oceanic wind speeds than historical ship data. Comparisons of satellite-derived winds with ship observations along major shipping routes indicate consistent results. NREL currently has 15 years of SSMI data covering the period 1988 through 2002.

3.7.4 Computer Model Climatic Data

Computer weather prediction models can generate climatic data, including wind speed and direction. These computer models analyze meteorological data from many sources and generate sets of meteorological parameters at regular grid points. The large-scale model output covers the entire globe and usually includes meteorological data at the surface and for a number of levels above the surface. The horizontal distance between grid points for the large-scale data is often greater than 200 kilometers (km). Meteorological output from what is referred to as mesoscale computer models covers specified regions. The data grid points from the mesoscale model are much closer together than those from the large-scale data with the horizontal distance ranging from about 2 km to 20 km. Computer model data are valuable for assessment work in data-sparse regions of the world. The major drawback of depending entirely on computer model data is that output data at a particular grid point can be strongly influenced by input meteorological data that may not be representative of the climatic conditions in the study region. Good meteorological judgment is required when computer model data are used in assessment work.

.

4.0 Wind Resource Methodology and Mapping System

4.1 Introduction

This section describes the methodology used to analyze and evaluate the meteorological data used for this resource assessment and the mapping system used to generate the resource maps. Both components are crucial for the production of a wind resource atlas that is accurate enough to stimulate the development of wind energy in the study area.

NREL uses a GIS-based wind resource mapping technique to produce the maps presented in this atlas. This technique was also used in the production of wind atlases for the Philippines (Elliott et al., 2001), the Dominican Republic (Elliott et al., 2001), Mongolia (Elliott et al., 2001), and Southeast China (Elliott et al., 2002), and maps of specific regions of Chile, Indonesia, Mexico, and the United States (Schwartz, 1999; Elliott et al., 1999; Schwartz and Elliott, 2001; Elliott, 2002). NREL developed the mapping system with two primary goals in mind:

1) To produce a more consistent, detailed analysis of the wind resource, particularly in areas of complex terrain
2) To generate user-friendly, high-quality maps.

4.2 Methodology

4.2.1 Data Evaluation and Analysis

4.2.1.1 Initial Approach

The quality of the meteorological input depends on understanding the important wind characteristics in the study region such as the interannual, seasonal, and diurnal variability of the wind and the prevailing wind direction. NREL used innovative assessment methods on existing climatic data sets to develop a conceptual understanding of these key wind characteristics. These data sets, obtained from U.S. sources such as the National Climatic Data Center and National Center for Atmospheric Research, supplemented with data sets obtained from Oaxaca, are maintained at NREL as part of its global archive. The surface and upper-air (weather balloon) data used in this project usually had a long period of record (greater than 20 years). NREL's approach depends on the critical analysis of all the available (surface meteorological and upper-air) climatic data for Oaxaca and the surrounding areas. NREL used a comprehensive data-processing package to convert the data to statistical summaries of the wind characteristics for hundreds of surface stations and numerous upper-air locations. The summaries were used to highlight regional wind characteristics.

4.2.1.2 Surface Data Evaluation

Years of work at NREL revealed many problems with the available land-based surface wind data collected at meteorological stations in much of the world. Problems associated with observations taken at the meteorological stations include a lack of information on anemometer height, exposure, hardware, maintenance history, and observational procedures. These problems can cause the quality of observations to be extremely variable. In addition, many areas of the world

with good or excellent potential wind resource areas have very little or no meteorological station data to help assess the level of the available wind resource.

NREL took specific steps in its evaluation and analysis to overcome these problems. Site-specific products were screened for consistency and reasonableness. For example, the interannual wind speeds were evaluated to identify obvious trends in the data or periods of questionable data. Only representative data periods were selected for the assessment. The summarized products were also cross-referenced to select the sites that appeared to have the best exposure to the prevailing wind. These sites were used to develop an understanding of the wind characteristics of the study region.

4.2.1.3 Upper-Air Data Evaluation

Upper-air data can be useful in assessing the regional wind resource in several ways. First, upper-air data can be used to estimate the resource at low levels just above the surface. The low-level resource estimation is quite important in areas where surface data are sparse or not available. Second, upper-air data can be used to approximate vertical profiles of wind speed and power. The vertical profiles are used to extrapolate the quantity of wind resource to elevated terrain features and to identify low-level wind speed maximums that can enhance the wind resource at turbine hub-height.

NREL generated summaries of wind speed and wind power at specific pressure and height levels using upper-air data, as well as monthly and annual average vertical profiles of wind speed and power. One problem that continually occurs in the evaluation of upper-air data is that many of the locations where the balloons are launched are blocked from the ambient wind flow by high terrain. Using vertical profiles from the "blocked" locations can be misleading because the profiles only represent conditions at the upper-air station and will not apply throughout the region of interest. Therefore, NREL's analysis of the upper-air data uses vertical profiles that we judge to be representative of the ambient wind flow in a particular region.

4.2.1.4 Goals of Data Evaluation

The goal of a critical analysis and evaluation of surface and upper-air data is to develop a conceptual model of the physical mechanisms on a regional and local scale that influence the wind flow. When there is conflicting wind characteristic data in an analysis region, the preponderance of meteorological evidence from the region serves as the basis for the conceptual model. Several NREL papers (Elliott, 2002; Schwartz and Elliott, 1997; Elliott and Schwartz, 1998; Schwartz, 1999) describe the integration, analysis, and evaluation of meteorological data sets typically used for wind resource assessments.

The critical data analysis and the conceptual model are particularly important because a key component of NREL's wind mapping system requires that empirical adjustments be made to the wind power values before the final maps are produced. The conceptual understanding developed by the critical analysis of the available data guides the development of empirical relationships that are the basis of algorithms used to adjust the wind power. This empirical approach depends on an accurate ambient wind profile of the few hundred meters closest to the surface and being able to adjust it down to the surface layer. A prime advantage of this method is that NREL can produce reliable wind resource maps without having high-quality surface wind data for the study region.

4.2.2 Wind Power Classifications

The values on the wind resource maps in the atlas are based on the wind power density, not wind speed. Wind power density is a better indicator of the available resource because it incorporates the combined effects of the wind speed frequency distribution, the dependence of the wind power on air density, and the cube of the wind speed. Seven wind power classifications, based on ranges of wind power density, were used for the Oaxaca maps. Each of the classifications was qualitatively defined for utility-scale applications (poor to excellent). In general, locations with an annual average wind resource greater than 400 W/m^2 or approximately 7 m/s at 50 m above ground are the most suitable for utility-scale applications. Rural or village power applications can be viable at locations with lower levels of wind resource. In Oaxaca, such applications may be viable with wind resources greater than 200 W/m^2, or approximately 5.5 m/s at 50 m above ground.

4.3 Description of Mapping System

NREL's mapping system uses GIS mapping software. The main GIS software, ArcInfo®, is a powerful and complex package that features a large number of routines for scientific analysis. None of the ArcInfo® analysis routines are specifically designed for wind resource assessment work; therefore, NREL's mapping technique requires extensive programming in ArcInfo® to create combinations of scientific routines that mimic direct wind resource assessment methods. For more information about GIS and wind energy research at NREL, see Heimiller and Haymes (2001).

The mapping system is divided into three main components: the input data, the wind power adjustments, and the output section that produces the final wind resource map. These components are described below.

4.3.1 Input Data

The two primary model inputs are digital terrain data and meteorological data. The elevation information consists of digital elevation model (DEM) terrain data that divide the analysis region into individual grid cells, each having its own unique elevation value. The U.S. Geological Survey's Earth Resource Observing Satellite Data Center produced updated DEMs for most of the world from previously classified U.S. Department of Defense data and other sources. The data sets have a resolution of 1 km^2 and are available for large parts of the world. This represents a significant improvement in elevation data used by the mapping system. The model previously relied on 1:1,000,000-scale maps and 305 m (1,000 ft) elevation contours. The final resource maps use a 400 m by 400 m grid.

The meteorological inputs to the mapping system come in two phases. The first phase provides wind power data for each grid cell obtained via output from a mesoscale numerical model. The second phase, following the data screening process, provides the appropriate vertical profiles of wind power density and wind power roses that express the percentage of total potential power from the wind by direction. The vertical profiles are broken down into 100-m intervals centered every 100 m above sea level. The wind power rose is used to determine the degree of exposure of a particular grid cell to the power-producing winds. These inputs and the original wind power grid are incorporated as Arc/Info® compatible files and used in the power adjustment algorithms.

4.3.2 Wind Power Calculations

The wind power calculation methodology is presented in Section 3.5. TrueWind Solutions (TWS), a U.S. company in Albany, New York, provided to NREL the initial wind power density values for each grid cell in Oaxaca. TWS used its proprietary MesoMap system (Brower et al., 2001) to calculate the wind power density values. The MesoMap system consists of the MASS (a mesoscale model) and WindMap (a mass-conserving wind flow model).

The MASS model simulated weather conditions over Oaxaca and the surrounding regions for 366 days randomly selected from a 15-year period. The random sampling was stratified so that each month and season was represented equally. Each simulation generates wind and other meteorological variables throughout the model domain for a particular day and stores the information at hourly intervals. The simulations use a variety of meteorological and geophysical data. MASS uses climatic data to establish the initial conditions for each simulation as well as lateral boundary conditions for the model. The model determines the evolution of atmospheric conditions within the study region during each simulation.

The main geophysical inputs into MASS are elevation, land cover, and soil moisture. The new Moderate Resolution Imaging Spectroradiometer (MODIS) data developed by the U.S. National Aeronautics and Space Administration, which include land cover and a percent tree cover data set, were used in the MASS simulations. The MODIS data have several advantages over the data set previously used for land cover: The imagery used in the classification is from recent years (2000 and 2001), the data have a horizontal resolution of 500 m (compared to 1000 m), and the MODIS sensor system includes seven bands that were specifically designed to capture land cover information. The MODIS percent tree cover data correlated well with a separate land cover data set provided by USAID for the isthmus area of Oaxaca, and based on this correlation, the percent tree cover data were used for all of Oaxaca. The MASS translated the percent tree cover into the important surface parameter of surface roughness. Figure 4.1 is a map of the MODIS percent tree cover data for Oaxaca.

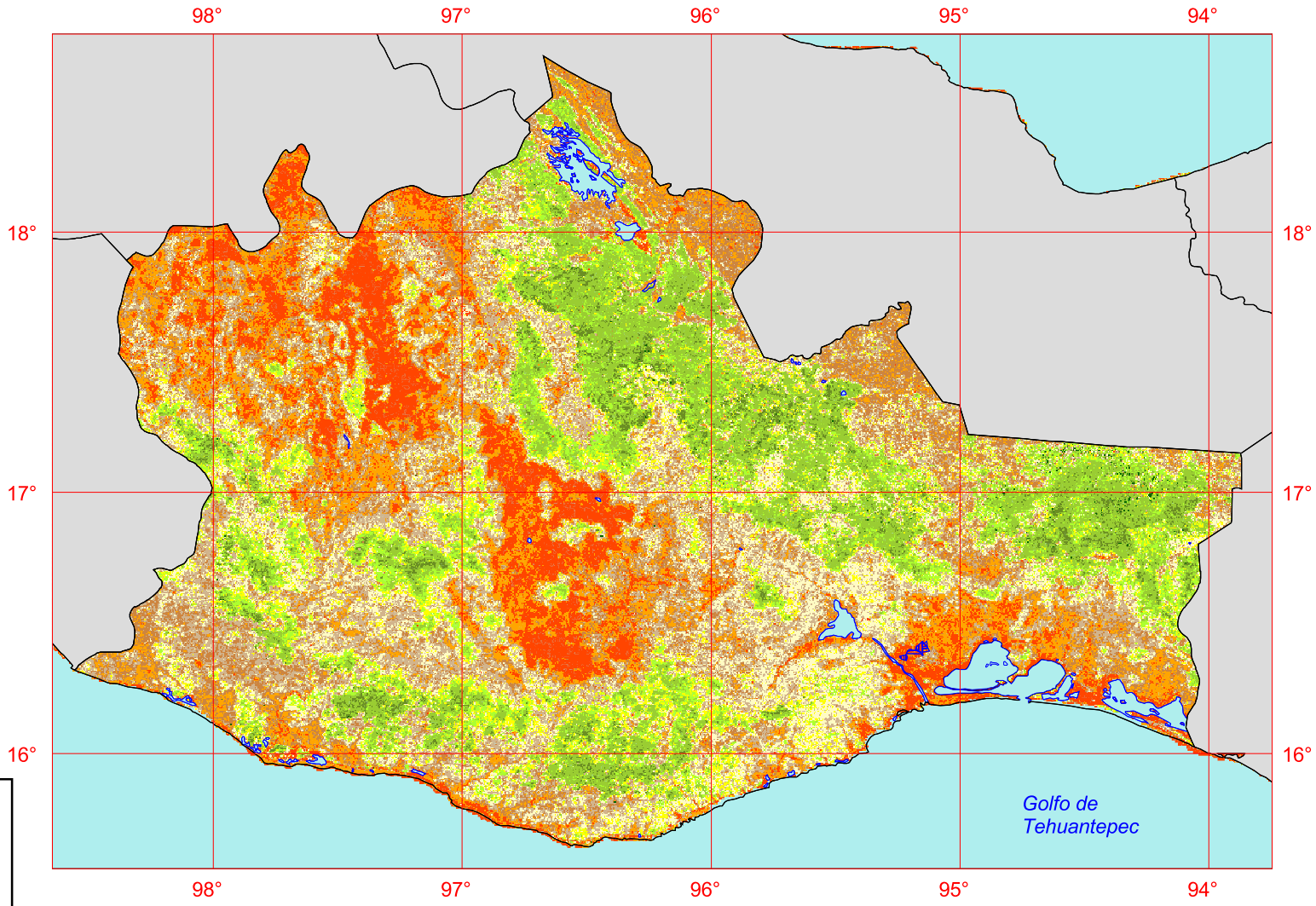
The MASS was run with a horizontal resolution of 2 km. After all the simulations were completed, the results were processed into summary data files that were input into the WindMap model. WindMap then calculated the wind power density down to the final 400 m by 400 m grid cell resolution.

The wind power adjustment modules in NREL's wind mapping system use different routines depending on the results of NREL's data evaluation. Power adjustment modules can be activated to account for blocking of the ambient flow by terrain; the relative elevation of particular regions; acceleration and enhanced wind flow areas; proximity to lakes, oceans, or other large water bodies; or any combination of the above. The power adjustment routines use general topographical descriptions classified as either complex terrain (hills and ridges), complex terrain with large flat areas present, or areas designated as flat. The adjustment to the initial wind power density depends on which routines are activated during the final mapping run.

4.3.3 Mapping Products

The primary output of the mapping system is a color-coded wind power map in units of W/m^2 and equivalent mean wind speed for each individual grid cell. The wind power classification scheme for the Oaxaca maps is presented in Table 4-1. In this atlas, the 50-m height above ground level (agl) was chosen as a compromise hub height for large utility-scale wind turbines that may range between 30 m and 80 m.

Oaxaca - MODIS Percent Tree Cover



MODIS
Percent Tree Cover

100
90
80
70
60
50
40
30
20
10
0

The percent land tree cover is from the Moderate Resolution Imaging Spectroradiometer (MODIS) data with a resolution of 500 m.

50 0 50 100 150 Kilometers

U.S. Agency for International Development

U.S. Department of Energy
National Renewable Energy Laboratory

JUL-2003 1.4.1

Figure 4-1

The wind power is shown only for those grid cells that meet certain slope requirements. A grid cell is excluded if the slope of the terrain is too steep. The slope of the terrain in a grid cell must be less than or equal to 20% to be included in the wind power calculations. The wind resource values are estimates based on the surface roughness for each grid cell derived from the MASS model output.

Table 4.1. Wind Power Classification

Class	Resource Potential (Utility Scale)	Wind Power Density (W/m^2) @ 50 m agl	Wind Speed [(a)] (m/s) @ 50 m agl
1	Poor	0 – 200	0.0 – 5.3
2	Marginal	200 – 300	5.3 – 6.1
3	Moderate	300 – 400	6.1 – 6.7
4	Good	400 – 500	6.7 – 7.3
5	Excellent	500 – 600	7.3 – 7.7
6	Excellent	600 – 800	7.7 – 8.5
7	Excellent	> 800	> 8.5

[(a)] Mean wind speed is estimated assuming a sea level elevation and a Weibull distribution of wind speeds with a shape factor (k) of 1.8. The actual mean wind speed may differ from these estimated values by as much as 20%, depending on the actual wind speed distribution (or Weibull k value) and elevation above sea level.

The mapping system output uses software to produce the proper map projection for the study region, and to label the map with useful information such as a legend, latitude and longitude lines, locations of meteorological and other wind measurement stations, important cities, and a distance scale. The DEM data can also be used to create a color-coded elevation map, a hill-shaded relief map, and a map of the elevation contours. When combined with the wind power maps, these products provide the user with a three-dimensional image of the distribution of the wind power in the analysis region.

4.3.4 Limitations of Mapping Technique

The mapping technique has several limitations, the first of which is the resolution of the DEM data. Significant terrain variations can occur within the DEM's 1 km^2 area; thus, the wind resource estimate for a particular grid cell may not apply to all areas within the cell. A second potential problem lies with the extrapolation of the conceptual model of the wind flow to the analysis region. Many complexities in the wind flow make this an inexact methodology. The complexities include the structure of low-level jets and their interaction with the boundary layer; localized circulations, such as land-sea breezes and mountain-valley flows; and channeling effects in areas of steeply sloping terrain. Finally, the power estimates are based on each grid cell's surface roughness based on the MASS output. Because the geophysical input to MASS is not 100% accurate, errors in the surface roughness estimate can occur and consequently, the estimates of wind resource for particular locations.

5.0 Wind Resource Data for Oaxaca

5.1 Introduction

An accurate wind resource assessment depends on the quantity and quality of the input data. NREL reviews many sources of wind data and previous wind assessments as part of its overall evaluation. Several global data sets maintained at NREL, including surface and upper-air observations spanning many years of record, were used in this assessment. Because the quality of data in any particular data set can vary, and high-quality data can be quite sparse in many regions of the world, multiple data sets are used. Each data set plays an integral role in the overall assessment. In this section, we summarize the data sets used to prepare the wind resource mapping activity for the State of Oaxaca, Mexico. All data sets were analyzed and evaluated in accordance with the procedures outlined in Section 4.0.

5.2 Surface Data

High-quality surface wind data from well-exposed locations can provide the best indication of the magnitude and distribution of the wind resource in the region. Studies by NREL and others in many different regions of the world have found that the quality of surface wind data from meteorological stations varies and is often unreliable for wind resource assessment purposes.

The following sections present a summary of the surface data sets obtained and examined in the assessment.

5.2.1 DATSAV2 Data

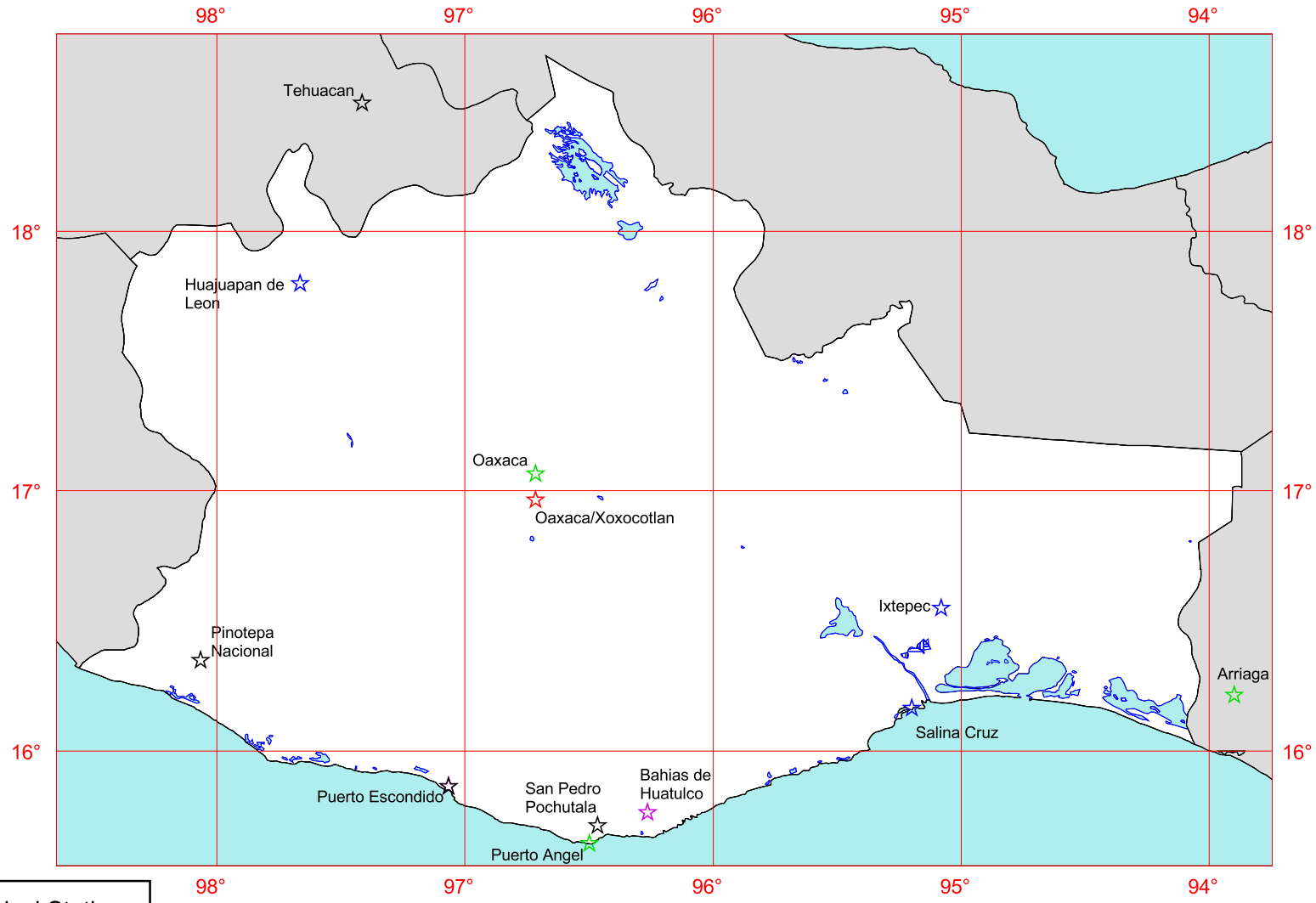
The DATSAV2 global climatic database obtained from the NCDC contains the surface weather observations, transmitted via the Global Telecommunications System (GTS), from first-order meteorological stations throughout the world. Meteorological parameters such as wind speed, wind direction, temperature, pressure, and altimeter setting are used to create statistical summaries of wind characteristics. A unique six-digit number based on the World Meteorological Organization (WMO) numbering system identifies each station in the DATSAV2 data set.

Ten stations in Oaxaca are included in the DATSAV2 data set. Of these, 8 stations have sufficient meteorological data to use in this analysis. These station data were supplemented by DATSAV2 data from two stations in other states near the border of Oaxaca: Arriaga in Chiapas and Tehuacan in Puebla. Figure 5.1 shows the locations and number of observations for these stations.

The number of observations at the individual sites for each year and from year to year are highly variable. The stations in Oaxaca typically recorded data every 3 hours or in some cases, 3 times a day.

The processed data records for each of these stations contained monthly and annual averages of wind speed and wind power. Table A.1 (Appendix A) provides location data and wind speed summaries for these stations. Graphical summaries for selected stations are also shown in Appendix A. These data are useful for evaluating the interannual and monthly variability, the

Oaxaca - GTS Surface Meteorological Stations



Meteorological Stations
Total Observations

- ☆ 80,000 to 130,000
- ☆ 40,000 to 80,000
- ☆ 20,000 to 40,000
- ☆ 5,000 to 20,000
- ☆ 500 to 5,000

Total Stations = 12

The Global Telecommunication System (GTS) surface meteorological stations are part of NREL's global database.

50 0 50 100 150 Kilometers

U.S. Agency for International Development

U.S. Department of Energy
National Renewable Energy Laboratory

JUL-2003 1.5.1

Figure 5-1

diurnal distribution of wind speed and wind power, and the joint frequency of wind speed and direction.

The quality of these wind data is largely unknown because of the lack of information on equipment maintenance and exposure to the wind. Some of the stations had obvious trends or abrupt changes in the historical wind speeds recorded on an interannual basis. Figure 5.2 shows an example of the "disappearing wind syndrome," as evidenced by the downward trend in the historical wind speeds at the Huatulco airport station. New construction, growth of trees around the meteorological station, or degradation of the measurement equipment may have caused the decrease in wind speeds. Large reductions in wind speeds correspond to even greater percentage reductions in the wind power density. For these reasons, the long-term historical average for many stations is not a reliable indicator of the wind resource, particularly where obvious trends or abrupt changes are evident in the historical wind speeds.

5.2.2 National Water Commission Data

Annual average wind speeds for 121 meteorological stations were obtained from the National Water Commission (Comisión Nacional del Agua) of Mexico. Stations, their locations, and their average wind speeds are listed in Table B.1. Locations of some stations were not given or could not be precisely determined. Monthly average wind speeds were also provided for many of the stations, and these are listed in Table B.2 for stations with annual average wind speeds of 4 m/s or greater.

The quality of these wind data is largely unknown because of the lack of information on measurement equipment, exposure to the wind, and observation methods. Any presence of buildings and trees around the meteorological station or degradation of the measurement equipment may have a huge effect on the wind speeds recorded at these stations. For these reasons, the average wind speeds reported for these stations are not necessarily a reliable indicator of the wind resource in the area. An evaluation of these data is described in Section 6.

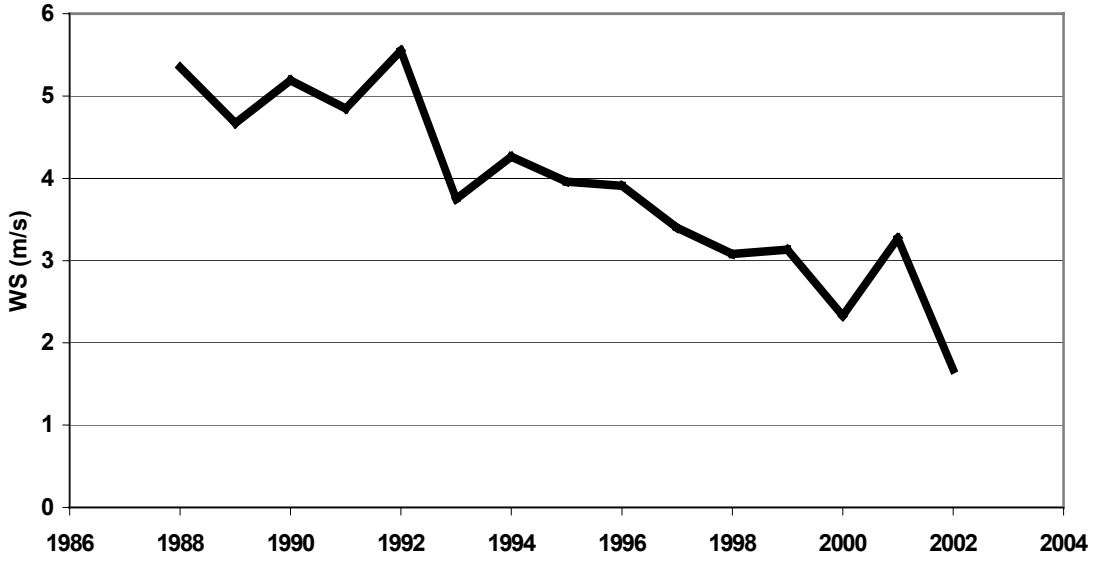


Figure 5.2 Oaxaca – Disappearing Winds at Huatulco (speed by year).

5.2.3 Validation Data from Wind Developers

Wind data for validating the preliminary wind resource maps were provided by various developers and utilities. These data were collected at 20 sites on measurement towers that ranged from 30 m to 60 m high. All the sites were located in the Isthmus region. Some data sets included time series data (hourly or 10-minute observations) of wind speed and direction, which were processed to examine the wind resource characteristics. The characteristics included monthly average wind speed and power, average wind speed and power by hour of the day, frequency and speed by wind direction, and frequency of wind speed and percent of power by wind speed. Some data consisted of monthly average wind speeds, and other data consisted of annual and seasonal average wind speeds and wind power densities. Due to confidentiality agreements, we are not able to show the actual wind resource at the sites or provide the exact locations of the sites. Table 5.1 shows a list of the data providers and the number of stations for which data were provided. These data were used to confirm the wind resource estimates on the maps as described in Section 6.

Table 5.1 Validation Data Providers

Data Provider	Number of Sites	Time Series	Summaries
CFE	10	1	9
De Proe	3	3	
Clipper Windpower/Fuerza Eólica	5	5	
Gamesa	2		2

5.3 Upper-Air Data

The upper-air data, consisting of profiles of wind speed and wind direction, are an important meteorological input parameter for the wind-mapping model. Upper-air data also provide an estimate of the wind resource just above the surface-layer and contribute to the understanding of the vertical distribution of the wind resource. This is useful in estimating the winds on elevated terrain features and the wind resource at exposed locations without reliable surface wind observations.

NREL's in-house data sets include both observational and computer-model-derived upper-air information. The following upper-air data sets were employed for the assessment.

5.3.1 Automated Data Processing (ADP) Data

There were no representative upper-air observing stations in the region of interest.

5.3.2 Computer-Model-Derived Data Sets

5.3.2.1 Global Upper-Air Climatic Atlas (GUACA)

The GUACA data set contains computer-model-derived monthly means and standard deviations of climatic elements for 15 atmospheric levels (surface and 14 pressure levels) at grid points

every 2.5° throughout the world. GUACA was developed using analyses produced at the European Centre for Medium Range Weather Forecasts. NREL's data, obtained from the NCDC, cover the period from 1980 to 1991. This data set is used to supplement the ADP information in areas where upper-air data are scarce. The levels of interest for this study include surface, 850 mb, 700 mb, and 500 mb.

The GUACA data were used to generate wind roses of the prevailing wind directions and to estimate the wind speeds at 850 mb and 700 mb for the analysis of the wind resource. Trends in wind speed and direction from across the GUACA grid helped to describe the large-scale wind patterns across the assessment region.

5.3.2.2 Reanalysis Data

The U.S. National Centers for Environmental Prediction, in collaboration with NCAR, produced a reanalysis data set. This is a 40-year record of global analyses of atmospheric parameters. This project used a global weather prediction computer model to create worldwide data sets of wind, temperature, and other variables on a global 208-km resolution grid. Reanalysis incorporates all available rawinsonde and pilot balloon data, as well as observations from surface, ship, aircraft, satellites, and other data sources. Reanalysis data over Oaxaca were produced four times a day.

5.3.2.3 Mesoscale Model Data

TrueWind Solutions of Albany, New York, provided NREL with wind speed and wind power data for Oaxaca at a 400 m by 400 m horizontal resolution at levels from 30 m to 500 m above ground as well as surface roughness and elevation data from its proprietary MesoMap system. This data set was used as an initial estimate for the distribution of the wind resource (power) in Oaxaca.

5.4 Satellite Ocean Wind Data

Because Oaxaca is bordered on the south by the Pacific Ocean, measurements and estimates of ocean winds can aid the wind resource assessment studies. The satellite SSMI data set contains estimates of 10-m ocean wind speeds. These data also provide an excellent overview of the ambient wind conditions in the ocean areas off the southern coast of Oaxaca. Maps and graphs of ocean satellite data for Oaxaca are presented in Appendix D.

6.0 Wind Resource Characteristics of Oaxaca

6.1 Introduction

This section presents an overview of the wind mapping results and wind power density estimates for Oaxaca. The classification scheme for wind power density used in the atlas is applicable for utility-scale applications.

6.2 Wind Power Classifications

Table 6.1 shows the wind power classifications for utility-scale applications in Oaxaca. Wind resource areas of Class 4 and higher are considered suitable for utility-scale wind power development. Rural or off-grid applications require less wind resource for a project to be viable. For these types of applications, Class 2 and higher resources may be sufficient for viable wind power development.

Table 6.1. Wind Power Classification

Class	Resource Potential (Utility Scale)	Wind Power Density (W/m^2) @ 50 m agl	Wind Speed [(a)] (m/s) @ 50 m agl
1	Poor	0 – 200	0.0 – 5.3
2	Marginal	200 – 300	5.3 – 6.1
3	Moderate	300 – 400	6.1 – 6.7
4	Good	400 – 500	6.7 – 7.3
5	Excellent	500 – 600	7.3 – 7.7
6	Excellent	600 – 800	7.7 – 8.5
7	Excellent	> 800	> 8.5

[(a)] Mean wind speed is estimated assuming a sea level elevation and a Weibull distribution of wind speeds with a shape factor (k) of 1.8. The actual mean wind speed may differ from these estimated values by as much as 20%, depending on the actual wind speed distribution (or Weibull k value) and elevation above sea level.

6.3 Approach

The mapping methodology used in this project was described in Section 4.0. The mesoscale model data from TrueWind Solutions were used as the initial estimate of the wind power in Oaxaca. Adjustments to the initial power estimates in certain regions were made after NREL's evaluation of the available meteorological data. The data from the measurement towers in the Isthmus region were quite valuable in evaluating the initial estimates for this region. The primary adjusted regions were some areas in some mountainous regions of Oaxaca, specific areas of northwestern Oaxaca, parts of the Isthmus region, and selected coastal areas. Adjustments in the mountainous regions included areas in the Sierra Madre de Chiapas, Sierra de Oaxaca, and Sierra Madre del Sur. Because no obvious high-quality measurement stations were available in the windier areas of the mountainous regions as estimated by the mesoscale model, adjustments to the initial power estimates for these areas were based primarily on NREL's analysis and interpretation of climatic data, particularly the Reanalysis upper-air data. In coastal regions, adjustments were based on an analysis of meteorological station data and satellite ocean data.

6.4 Wind Resource Distribution and Characteristics

6.4.1 Annual Wind Resource Distribution

Figures 6.1 to 6.3 show the wind resource maps of Oaxaca. Figure 6.1 is the basic wind resource map, which shows the wind power estimates and the major cities and water bodies. In this figure, one can clearly see the wind resource values of specific areas, without being obscured by other information. Figure 6.2 shows the major transmission lines and roads, in addition to the wind resource. Wind resource areas located near major transmission lines and roads are usually more suitable for potential wind energy development (for utility-scale applications) than in remote locations. Figure 6.3 shows the wind resource in combination with the hill-shaded relief. This figure is useful in that it allows one to easily relate the wind resource to the major terrain features in Oaxaca. Very dark or bright areas on the hill-shaded relief are typically areas of steeply sloped terrain. These steep areas are generally not suitable for wind energy development, because of turbulent wind conditions often associated with the steep slopes. (As previously noted in Section 4.3.3, the wind resource values are not calculated for steep areas with greater than a 20% slope.)

Oaxaca is influenced by three predominant wind flows: a northeast to north wind from October through February, a west wind from March through May, and an east to northeast trade wind from June through September.

The strongest of the wind flows is the northeast to north wind, and because episodes of this strong flow do occur in March and April, this wind flow is the most predominant in Oaxaca. The origin of this northerly flow is the pressure gradient between the higher pressure in the Gulf of Mexico and the lower pressure in the Pacific Ocean. This wind flow is typically more northerly near the surface and becomes more northeasterly at heights of a few hundred meters above the surface, according to the Reanalysis upper-air data. In the Isthmus of Tehuantepec region, where the wind is strongly channeled by the topography, the direction of the wind may remain more northerly with increasing elevation. The strong free-air winds, greater than 10 m/s in eastern Oaxaca during this season, can extend from just a few hundred meters above sea level to about 1200 m above sea level. Therefore, locations fully exposed to these strong free-air winds, such as locations in the channeled Isthmus region and on ridges and exposed terrain where these winds are channeled or enhanced, can have Class 6 or Class 7 annual wind resource. In western Oaxaca, the free-air winds are 8 m/s to 10 m/s in this season and extend to higher elevations of 2000 m to 2400 m above sea level. Therefore, exposed areas of western Oaxaca where these winds are channeled or enhanced can have Class 4 and higher annual wind resource.

Winds are generally weaker during the prevailing west wind flows of April through May and the east to northeast trade wind flows from June through September. During these months, the peak free-air winds average about 6 m/s to 7 m/s. The summer trade wind flow extends to 1500 m in eastern Oaxaca. Although the summer trade winds are substantially lower than the fall-winter winds, areas that channel or enhance the northeast summer winds can have good wind resource during this season. Examples of these areas are La Mata and La Venta, which have good wind resource during the summer months. Vertical profiles of wind speed from the Reanalysis data set show the differences between the three prevalent wind flow regimes and across Oaxaca (Appendix C).

The wind maps show many areas that are estimated to have good-to-excellent wind resources (Class 4 and higher). The best wind resource areas in Oaxaca are concentrated in the southeastern region of the state, primarily in the southern part of the Isthmus of Tehuantepec. The windy Isthmus region extends from the coast northward approximately 60 km, and approximately 60 km to 80 km from east to west. Excellent wind resource (power Class 5 and above) is widespread in this Isthmus region. The highest resource (Class 7) in the Isthmus occurs near the foothills (including La Mata, La Venta, and La Ventosa), ridges, and coast. Strong northerly winds are frequent in the Isthmus region, particularly during the peak wind season from November through February. High-quality data from measurement sites in the Isthmus confirm the excellent wind resource potential in specific areas of the Isthmus, such as La Mata, La Venta, and La Ventosa near the foothills and coastal locations. However, additional data are needed to validate the map estimates in other areas of the Isthmus.

Many ridges and elevated terrain areas adjacent to the Isthmus region (up to 100 km to the east and west of the Isthmus) are also estimated to have excellent wind resource, but many of these sites would be difficult to develop because of the rugged terrain and difficult access. Climatic data sets indicate that the ambient wind resource in and near the Isthmus significantly decreases at elevations above 1200 m to 1500 m, so it is likely that many of the higher elevations in this region have less wind resource than lower elevation sites in the Isthmus. The Sierra Madre de Chiapas has many areas estimated to have good-to-excellent resource, but the wind resource will be reduced considerably at the highest elevations, especially those above 1500 m. The best elevated resource areas are generally the lower ridges and particularly the spur ridges that are 500 m to 1000 m in elevation. For example, the spur ridges located north and northeast of Santo Domingo are estimated to have Class 7 resource. Similarly, the ridges located to the northwest and southwest of Ixtapec are shown to have excellent wind resources. The elevation of these ridges, which form the extreme southeastern extension of the Sierra de Oaxaca, is generally less than 1500 m, with most of the ridges ranging from 500 m to 1000 m in elevation. Finally, many areas of excellent wind resource are estimated for the ridges located to the west of Salina Cruz and southwest of Tehuantepec. These ridges form the extreme eastern extension of the Sierra Madre del Sur. Areas of good-to-excellent resource are estimated to occur along the ridges for up to 80 km west of Salina Cruz; however, the most concentrated area of Class 7 resource is located about 20 km to 30 km west of Salina Cruz.

Some other regions of Oaxaca estimated to have good-to-excellent wind resource are located in specific areas of northwestern, central, and southern Oaxaca. In all of these regions, the best areas are estimated to occur where the terrain features channel and/or accelerate northeast winds. The peak wind season is from October through February, when the northeast winds are strongest and most prevalent. In northwestern Oaxaca, notable high resource areas are located to the east and north of Huajuapan de Leon. The most concentrated area of Class 4 and Class 5 resource is an area of plains and hills in the vicinity of Santiago Chazumba, approximately 50 km north of Huajuapan de Leon. This area appears to be part of a broad pass that channels and accelerates the northeast winds. Elevations in the pass area range between about 1800 m and 2200 m. Within 30 km to the east and west of this pass, elevations drop to 1200 m or less. In central Oaxaca, the most notable areas are located approximately 40-70 km east of the city of Oaxaca (near Mitla). Here, the northeast winds appear to accelerate over the relatively low ridges to the north and east of Mitla as they are diverted around the southern end of high mountains in the Sierra de Oaxaca. In southern Oaxaca, high resource areas are located approximately 80-110 km south of Oaxaca City near the town of Miahuatlan. The northeast winds appear to accelerate over the relatively low ridges to the south and west of Miahuatlan as they are diverted around the western end of high mountains in the Sierra Madre del Sur.

6.4.2 Seasonal Wind Resource Distribution

The exact seasonal distribution of the wind resource for a particular site in Oaxaca depends on elevation, its location, and its exposure to the prevalent and strongest wind flows. Throughout most of Oaxaca, places that are well exposed to north and northeast winds will have a maximum resource during October through March. As discussed previously, almost all places with good-to-excellent wind resource in Oaxaca have good exposure to these winds and have maximum wind resource during this period. These places include the windy Isthmus areas and specific ridges and other areas of Oaxaca where the northeast winds are channeled or enhanced.

The best long-term data set for characterizing the seasonal distribution of the free-air wind flow over Oaxaca is the Reanalysis data, which is shown in Appendix C for five areas of Oaxaca. As evident in the plots of the Reanalysis data, the highest average free-air wind speeds in the lowest 600 m above ground occur from October through March with the strongest and most prevalent winds from the northeast to north during these months.

In the windy Isthmus region, the best long-term data set for characterizing the seasonal distribution of surface winds is the satellite ocean wind data. Figure 6.4 shows the seasonal distribution of monthly mean wind speed and power density, based on data measured from 1988 through 2002, for an offshore area located about 50 km south of Santa Maria del Mar. The months of October through March have the highest average wind power, with values exceeding 600 W/m^2 at 10-m height. Peak wind power months are December, January, and February, when values exceed 1200 W/m^2. The low season for wind power is April through September, with lowest values occurring in May and June. However, even during the low wind months, the resource is reasonably good.

NREL selected four inland measurement sites that had several years of data to assess how well the offshore data may represent the seasonal patterns at windy locations in the Isthmus. Figure 6.5 shows a comparison of the onshore and offshore ratios of the normalized wind speeds (seasonal/annual). Monthly values were not available for the onshore sites, so only the seasonal average could be presented. The results indicate that the seasonal wind resource distribution for windy onshore sites in the Isthmus can be well characterized by the offshore data.

Figure 6.6 shows why individual months from a single year may not be reliable in characterizing the monthly or seasonal distribution of the wind resource. For each month, the triangles show the wind power values of 15 individual months. The wind power for an individual month may deviate considerably from the 15-year average wind power for that month. The wind power for an individual year may also deviate significantly from the long-term average wind power. Figure 6.7 indicates that the wind power of individual years may deviate as much as 20% from the long-term average. We believe that for the Isthmus region, these offshore data could be used to identify anomalous wind resource years and help adjust or interpret the data from individual years or short-term periods of site measurement data.

In coastal areas of south-central Oaxaca, the maximum wind resource occurs from March through May when strong sea breeze winds blow during the afternoon hours. The predominant wind direction is from the south (all year), with the strongest winds occuring during March, April, and May. Places that are exposed to these strong southerly winds (such as the Bahias de Huatulco airport from 1989 to 1991) are estimated to have Class 4 resource during these months and Class 2 resource on an annual average basis. Available data indicate that the sea breeze winds are

significantly weaker along the southwest coastal areas, and the seasonal distribution of wind resource is less pronounced.

6.4.3 Diurnal Wind Speed Distribution

The diurnal wind speed distribution (or wind speed versus time of day) is influenced by site elevation, topography, and direct exposure to the predominant wind flows. The distribution at the low wind resource sites in the interior lowlands of Oaxaca typically features a maximum wind speed during the afternoon and a minimum speed during the night. Largest diurnal variations and the highest afternoon wind speeds occur during the spring months of March and April at most locations.

Very large diurnal variations occur in the south-central coastal areas, as evident by the wind data from the Bahias de Huatulco airport (Appendix A). Strong southerly sea breeze winds result in wind speeds that average from 6.0 m/s to 7.5 m/s between noon and 5 pm local standard time. These afternoon sea breeze winds are strongest from March through May, averaging 7.5 m/s to 8.5 m/s, and weakest from June to October when they average 5.0 m/s to 6.5 m/s. The winds become very light and are frequently calm during most of the night and early morning hours. Consequently, even though the afternoon wind resource is good-to-excellent (Classes 4-6 annual average), the overall wind resource is only Class 2 because of the very low wind speeds during the night and early morning hours. Further west along the coast, the sea breeze appears significantly weaker, as evident by the data from Puerto Escondino. A land breeze occurs during the early morning hours at Puerto Escondino, but it appears to only average between 4 and 5 m/s.

The diurnal pattern at the higher wind resource sites in the windy Isthmus region is relatively flat. The amplitude is only around 1 m/s at Class 7 locations, with the maximum resource generally from late morning to afternoon. However, during the windiest months (November through February), the wind resource is sometimes slightly greater at night than during the day. Slightly larger diurnal amplitudes and daytime maximums are typical in lower wind resource months from April through September. At Isthmus locations with reduced resource, such as the Salina Cruz meteorological station, larger diurnal amplitudes of 2 m/s to 3 m/s occur because stability effects reduce the nighttime wind speeds.

Unfortunately, high-quality wind measurement data were not available from exposed ridge crest locations or from areas of western and central Oaxaca estimated to have good-to-excellent wind resource. In general, exposed ridge crest locations frequently have nighttime maximums of wind speed and a minimum near noon.

6.4.4 Wind Direction Frequency Distribution

The prevailing wind directions are strongly influenced by the topography, elevation, and direct exposure to the predominant wind flows. In windy areas at low elevations of the Isthmus region, the prevailing strong winds are from the north throughout the year. At elevated locations that are exposed to the ambient free-air winds, such as ridge crest sites of 500 m to 1000 m above sea level, the prevailing strong winds are from the northeast. During March through May, west winds are as frequent as the northeast winds but not as strong. Estimates of the wind direction frequency distribution for elevated terrain features are based on upper-air data from Reanalysis, as there was no measurement data available from elevated terrain sites.

In coastal areas of central and western Oaxaca, the land and sea breeze wind flows prevail in most areas. During the day, prevailing wind directions are generally from the south or southwest (sea breeze winds). At night, prevailing wind directions are from a northerly component (northeast to northwest). Topography features and coastline orientation influence the strength and exact directions of the sea and land breeze flows.

In basins and valleys of central and western Oaxaca, prevailing wind directions are strongly influenced by the local topography and atmospheric stability conditions. The areas generally have low wind resource, and winds are frequently light and variable, particularly at night when calm conditions are frequent in many areas. At exposed areas with good wind resource, such as passes and ridges, prevailing winds are usually from the northeast.

6.4.5 Confirmation of Wind Resource Estimates

We compared the wind resource estimates on the maps to actual measurements at 10 locations in the Isthmus regions where the CFE and other organizations had recently collected data on towers that ranged from 30 m to 60 m high. We chose these 10 locations because the data collected at these sites appeared to be of sufficiently high quality to allow a reasonable comparison between the mapped and measured values. Although data were available from 20 locations, many of the locations that were not used had inadequate data due to short periods of data collection or considerable periods of missing data. Some of the sites used had only about one year of measurement data, not sufficient to resolve questions of year-to-year variability. These factors made the conclusions of the study somewhat tenuous but still useful. The results of this study are summarized in Table 6.2.

The estimated wind resource was within one power class, or about 20%, of the annual wind power at all 10 locations. Figure 6.8 shows the three areas of the Isthmus where the measurement sites were located. The wind resource measured at these locations ranged from high Class 6 to high Class 7. As evident from the map, these areas are largely estimated to have Class 7, with some Class 6 in area 1 (including Juchitan). The Class 7+ resource in the coastal region, including the Santa Maria del Mar area, is also confirmed by the satellite ocean wind data. These data indicate that the Class 7+ resource extends well offshore to at least 50 km south of Santa Maria del Mar.

Although the National Water Commission (NWC) provided summaries of mean wind speed data from approximately 120 stations, NREL's analysis of these data indicated that these data were generally not reliable for use in the wind resource assessment. For example, eight NWC stations are located in the windy region of the Isthmus estimated to have Class 4 and higher resource. However, the measured wind speeds at the NWC stations were quite low, even in areas estimated to have excellent wind resource. Local obstructions (such as buildings and trees) around these stations are a likely cause of the low wind speeds. Only one of the eight stations reported a mean annual wind speed greater than 4 m/s (Santa Maria del Mar, which reported a mean speed of 5 m/s). The mean annual wind speeds at the other seven stations ranged from only 2.2 m/s to 3.7 m/s. The station at Juchitan had the lowest mean annual wind speed, just 2.2 m/s. This Juchitan data would indicate only Class 1 resource (poor), an area estimated to have Class 6 (excellent) on the wind map. Most of the reported anemometer heights were about 7 m above ground, but no information was provided on the exposure of the anemometers with respect to the nearby surroundings, such as buildings, trees, or other obstructions to the wind flow. At this anemometer

height (7 m), exposed sites in good wind resource areas would generally have a mean wind speed of at least 5 m/s. Previous studies by NREL, particularly for Mexico (Schwartz and Elliott, 1995), have shown that measured wind speeds at anemometers located in towns and cities are often substantially lower than those measured at nearby airport locations. Local obstructions such as buildings and trees will considerably reduce the measured wind speeds, especially at low measurement heights of only 5 m to 10 m (typical for meteorological stations).

Table 6.2. Wind Resource Comparison

Station Name	Wind Power Class	
	Measured	Map
La Venta A	7+	7+
La Venta B	7+	7+
Santo Domingo	7	7
La Mata	7+	7+
La Ventosa A	7	7
La Ventosa B	7	7
La Ventosa C	7-	6-7
Juchitan A	6+	6-7
Juchitan B	6+	6-7
Santa Maria del Mar	7+	7+

In summary, we believe that the annual wind power estimates shown on the map are within 20% of the measured values at more than 80% of the sites used in this study. This degree of accuracy is comparable to NREL's other mapping projects and atlases, so we are confident the maps in this atlas reflect the distribution of the resource in Oaxaca.

6.5 Regional Summaries of Wind Resource

Oaxaca is divided into two regions for this atlas, plus an enlargement of the southeast Isthmus area. The Western Oaxaca region extends from the western border to about 96° west longitude. The Eastern Oaxaca region covers the area from about 96° east to the eastern border of the state. Some overlap occurs between the two regional maps. The southeast enlargement is centered over the Isthmus area.

6.5.1 Eastern Oaxaca

Eastern Oaxaca exhibits a wide range of terrain features and elevations. There are low elevation plains along most of the northern border, much of the southern coast, and the Isthmus of Tehuantepec. In other areas of this region, the terrain is quite hilly and mountainous. Elevations exceed 3000 m on some of the higher mountains of the Sierra Madre del Sur and Sierra de Oaxaca located in the western part of this region. In the eastern part of the region, closer to the Isthmus area, the mountains are lower with highest elevations generally between about 1500 m and 2200 m. The mountains include the Sierra de Chiapas to the east of the Isthmus and the eastern fringes of the Sierra Madre del Sur and the Sierra de Oaxaca to the west of the Isthmus.

The most dominant feature of eastern Oaxaca, from a wind perspective, is the relatively wide Isthmus area that splits these mountain chains. The Isthmus is a channel for very strong northerly winds caused by strong surface pressure gradients from higher pressure over the Gulf of Mexico and lower pressure over the Pacific Ocean. Figures 6.9 through 6.11 show the political features, elevation features, and potential wind resource of this region.

The most concentrated areas of good-to-excellent resource in this region are located in the southern part of the Isthmus of Tehuantepec. Figures 6.12 and 6.13 are enlargements of the wind resource maps, centered over the Isthmus area. Figure 6.12 shows the locations of major cities, roads, and transmission lines. Figure 6.13 is a hill-shaded relief map of the area. The windy Isthmus region extends from the coast northward approximately 60 km, and approximately 60 km to 80 km from east to west. Excellent wind resource (power Class 5 and above) is widespread in this Isthmus region. The highest resource (Class 7) occurs near the foothills (including La Mata, La Venta, and La Ventosa), ridges, and coast.

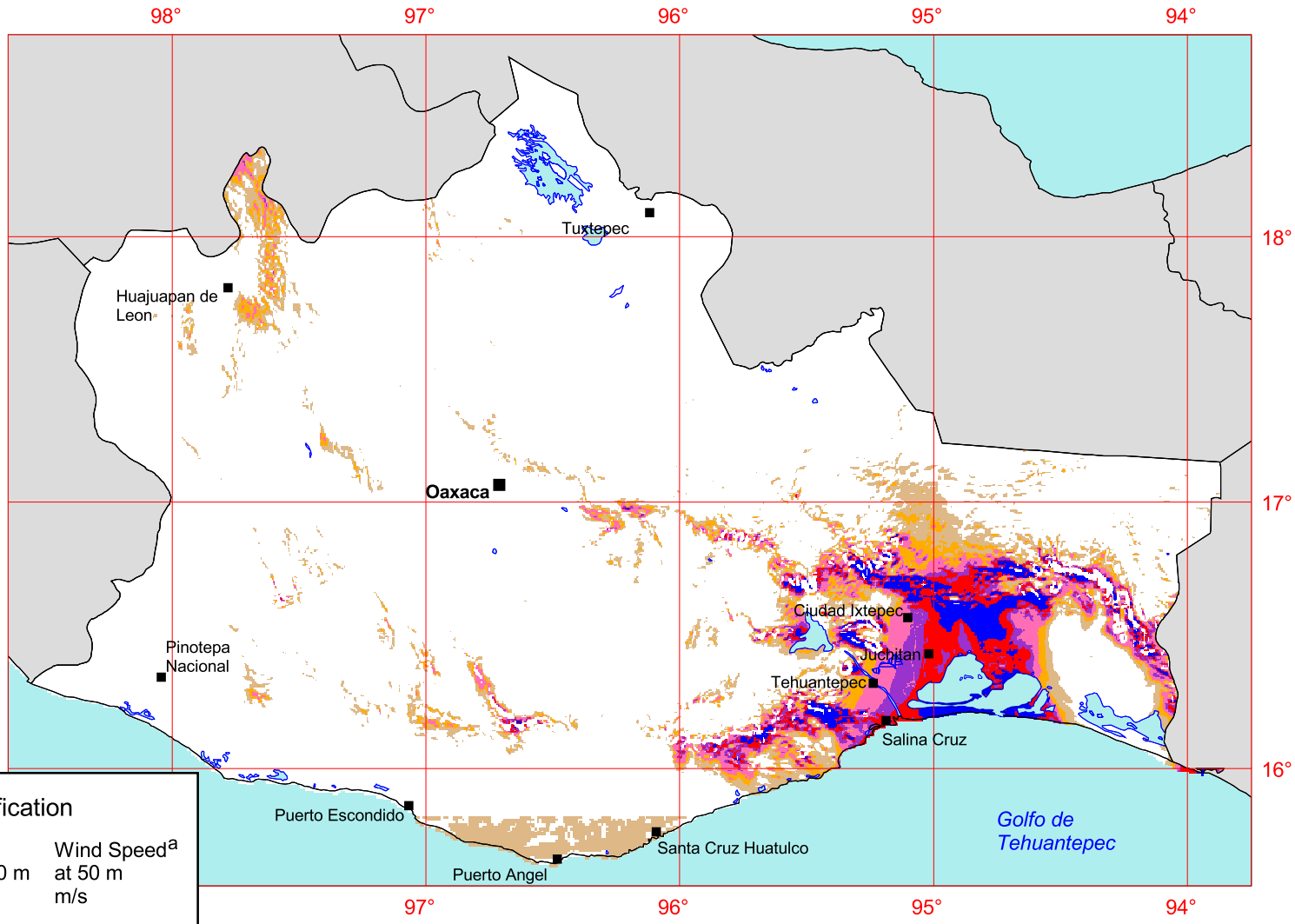
Many ridges and elevated terrain areas adjacent to the Isthmus region (up to 100 km to the east and west of the Isthmus) are also estimated to have excellent wind resource, but many of these sites would be difficult to develop because of the rugged terrain and difficult access. The elevated areas with the best resource are generally the lower ridges and particularly the spur ridges that are 500 m to 1000 m in elevation. For example, the spur ridges located north and northeast of Santo Domingo are estimated to have Class 7 resource. Similarly, the ridges located to the northwest and southwest of Ixtapec and to the west of Salina Cruz are estimated to have excellent wind resource.

6.5.2 Western Oaxaca

Western Oaxaca also consists of a wide range of terrain features and elevations. Most of western Oaxaca consists of hilly or mountainous terrain with some high elevation basins and valleys. Elevations exceed 3000 m on some of the higher mountains of the Sierra Madre del Sur and Sierra de Oaxaca. Many of the basins and valleys range in elevation from 1200 m to 2000m. Low-elevation plains and valleys occur along much of the southern coastal area and near the northern border with the State of Veracruz. Figures 6.14 through 6.16 show the political features, elevation features, and potential wind resource of this region.

Specific areas estimated to have good-to-excellent wind resource are located in northwestern, eastern, and southern parts of this region. The best areas are estimated to occur where terrain features channel and/or accelerate northeast winds. In northwestern Oaxaca, notable high resource areas are located to the east and north of Huajuapan de Leon. The most concentrated area of Class 4 and Class 5 resource is an area of plains and hills in the vicinity of Santiago Chazumba, approximately 50 km north of Huajuapan de Leon. This area appears to be part of a broad pass that channels and accelerates the northeast winds. In central Oaxaca, the most notable areas are located approximately 40-70 km east of the city of Oaxaca (near Mitla). Here, the northeast winds appear to accelerate over the relatively low ridges to the north and east of Mitla as they are diverted around the southern end of high mountains in the Sierra de Oaxaca. In southern Oaxaca, high resource areas are located approximately 80-110 km south of Oaxaca City near the town of Miahuatlan. The northeast winds appear to accelerate over the relatively low ridges to the south and west of Miahuatlan as they are diverted around the western end of high mountains in the Sierra Madre del Sur.

Oaxaca - Wind Resource Map



Secretaría de Energía (SENER)

Gobierno del Estado de Oaxaca, Secretaria de Desarrollo Industrial y Comercial (SEDIC)

Comision Federal de Electricidad

Instituto de Investigaciones Electricas

Comision Nacional del Agua (CONAGUA)

Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m²	Wind Speed[a] at 50 m m/s
1	Poor	0 - 200	0 - 5.3
2	Marginal	200 - 300	5.3 - 6.1
3	Moderate	300 - 400	6.1 - 6.7
4	Good	400 - 500	6.7 - 7.3
5	Excellent	500 - 600	7.3 - 7.7
6		600 - 800	7.7 - 8.5
7		> 800	> 8.5

[a] Wind speeds are based on a Weibull k value of 1.8

This map was produced by NREL with technical assistance from TrueWind Solutions and with funding from the U.S. Agency for International Development.

Legend

■ Town or ■ **Capital**

50 0 50 100 150 Kilometers

U.S. Agency for International Development

U.S. Department of Energy
National Renewable Energy Laboratory

JUL-2003 1.6.1

Figure 6-1

Oaxaca - Wind Resource Map

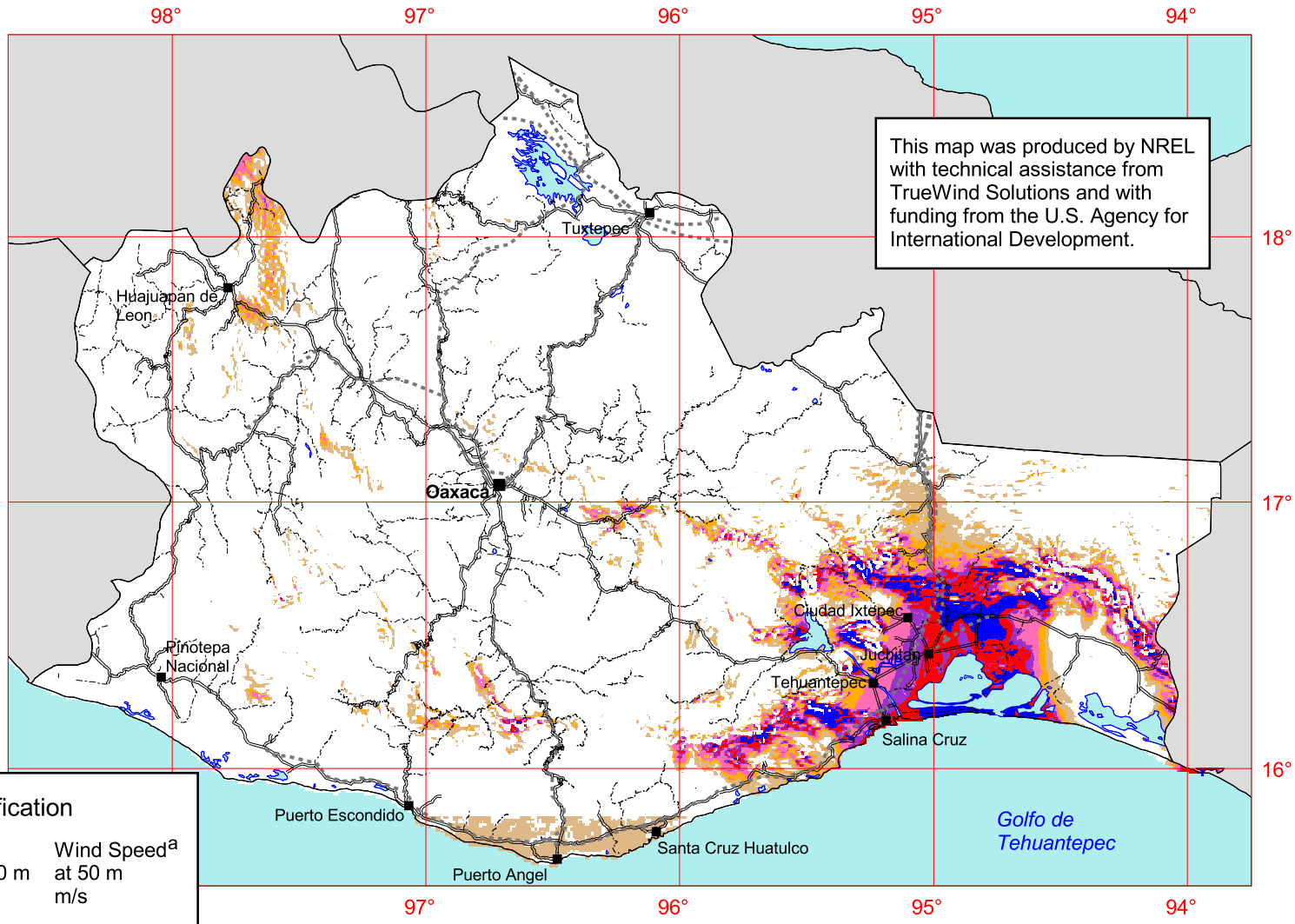
Secretaría de Energía (SENER)

Gobierno del Estado de Oaxaca, Secretaria de Desarrollo Industrial y Comercial (SEDIC)

Comision Federal de Electricidad

Instituto de Investigaciones Electricas

Comision Nacional del Agua (CONAGUA)



This map was produced by NREL with technical assistance from TrueWind Solutions and with funding from the U.S. Agency for International Development.

Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m²	Wind Speed[a] at 50 m m/s
1	Poor	0 - 200	0 - 5.3
2	Marginal	200 - 300	5.3 - 6.1
3	Moderate	300 - 400	6.1 - 6.7
4	Good	400 - 500	6.7 - 7.3
5	Excellent	500 - 600	7.3 - 7.7
6		600 - 800	7.7 - 8.5
7		> 800	> 8.5

[a] Wind speeds are based on a Weibull k value of 1.8

Legend

- Town or **Capital**
- Transmission Line
- **Paved Road**
- Unpaved Road

50 0 50 100 150 Kilometers

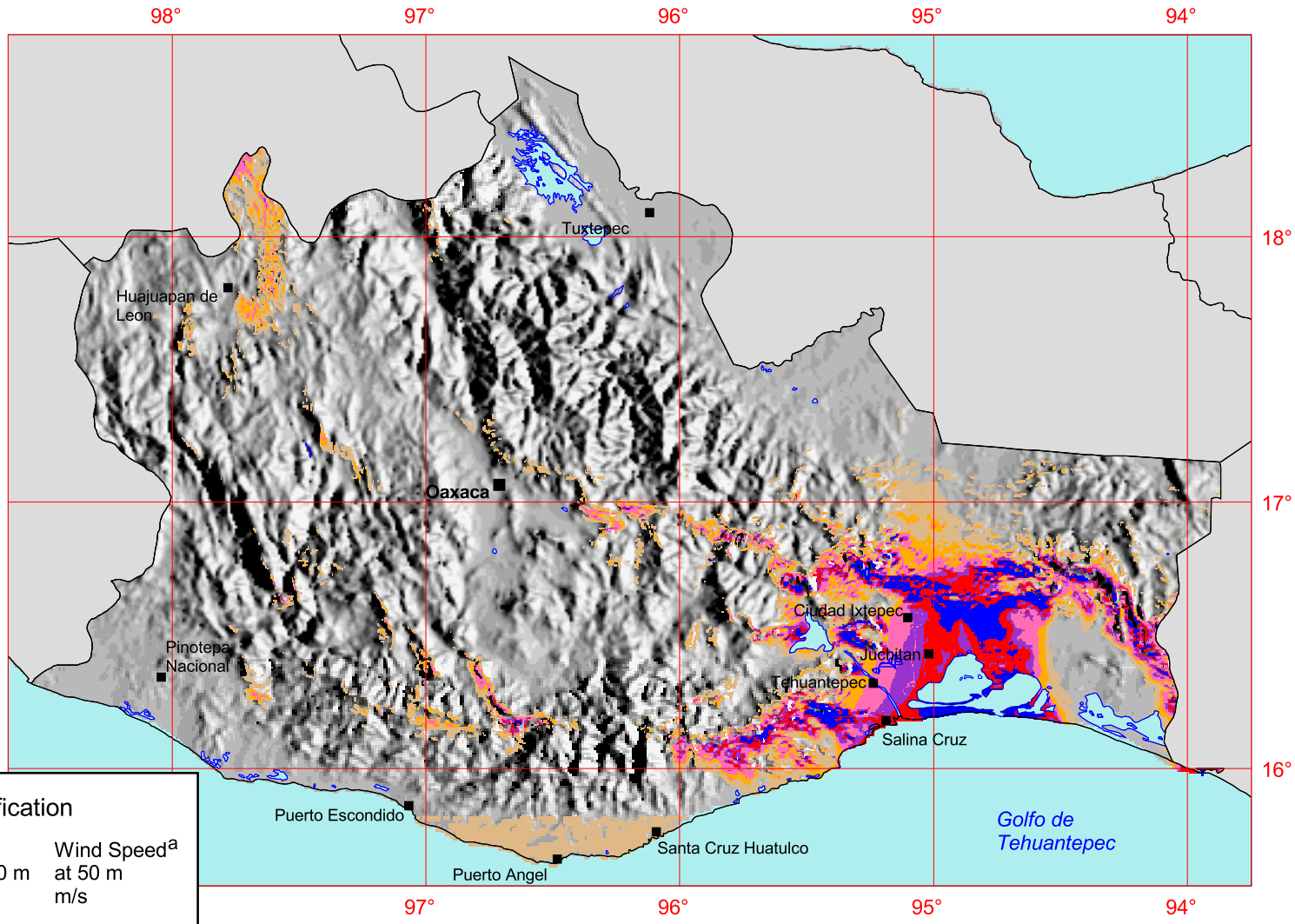
U.S. Agency for International Development

U.S. Department of Energy
National Renewable Energy Laboratory

JUL-2003 1.6.2

Figure 6-2

Oaxaca - Wind Resource Map



Secretaría de Energía (SENER)

Gobierno del Estado de Oaxaca, Secretaria de Desarrollo Industrial y Comercial (SEDIC)

Comision Federal de Electricidad

Instituto de Investigaciones Electricas

Comision Nacional del Agua (CONAGUA)

Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m²	Wind Speed[a] at 50 m m/s
1	Poor	0 - 200	0 - 5.3
2	Marginal	200 - 300	5.3 - 6.1
3	Moderate	300 - 400	6.1 - 6.7
4	Good	400 - 500	6.7 - 7.3
5	Excellent	500 - 600	7.3 - 7.7
6		600 - 800	7.7 - 8.5
7		> 800	> 8.5

[a] Wind speeds are based on a Weibull k value of 1.8

This map was produced by NREL with technical assistance from TrueWind Solutions and with funding from the U.S. Agency for International Development.

Legend

■ Town or ■ **Capital**

50 0 50 100 150 Kilometers

U.S. Agency for International Development

U.S. Department of Energy
National Renewable Energy Laboratory

JUL-2003 1.6.3

Figure 6-3

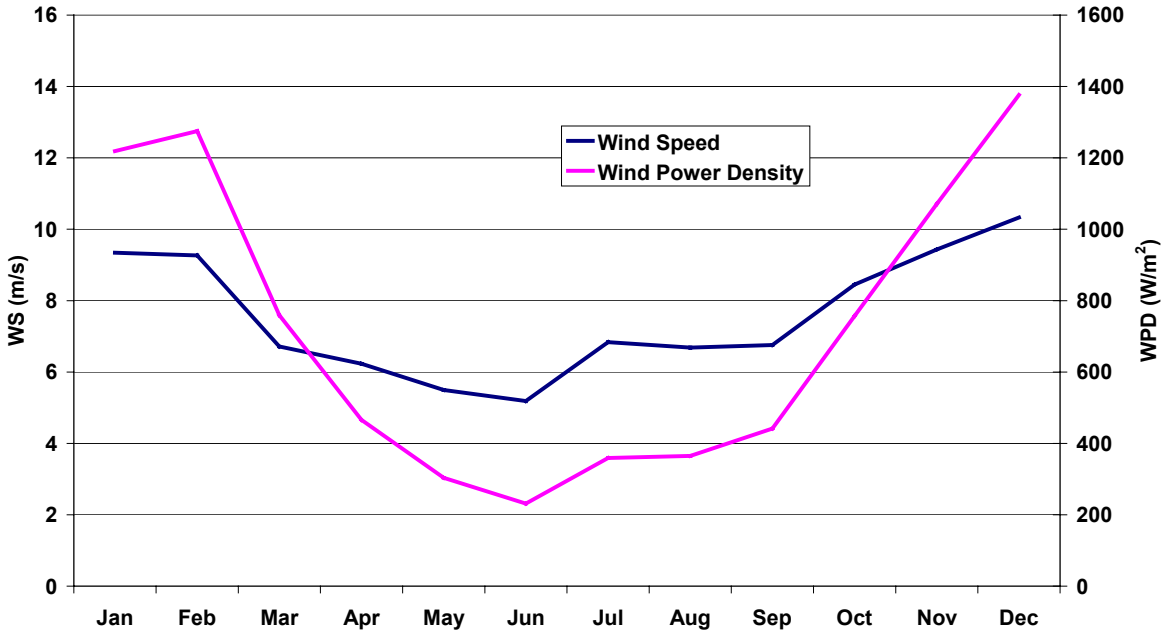


Figure 6.4 Satellite Ocean Monthly Wind Data for the Offshore Isthmus Region.

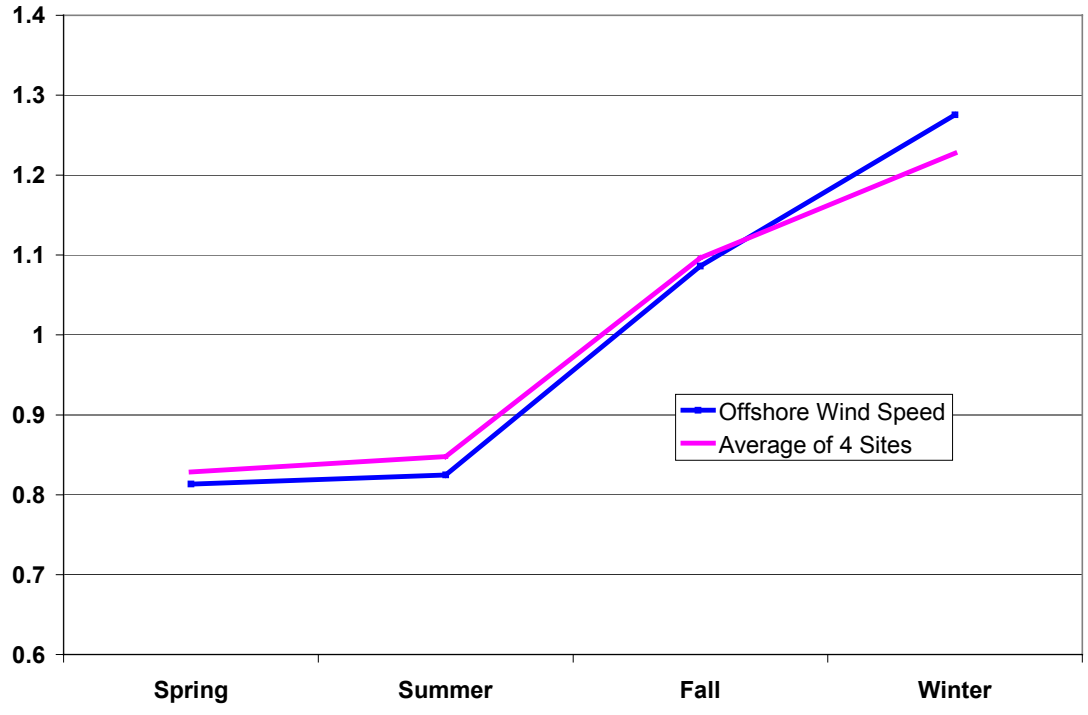


Figure 6.5 Isthmus Region – Comparison of Measurement Sites and Offshore Data.

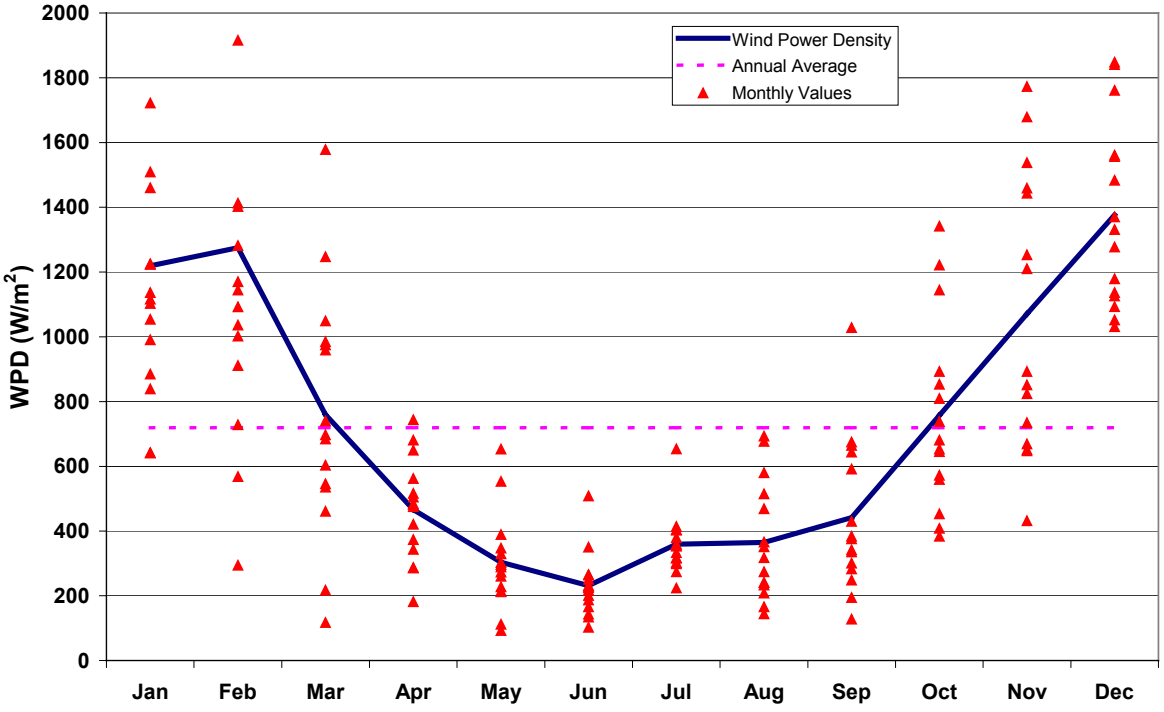


Figure 6.6 Isthmus Offshore Region – Monthly Wind Power and Variability.

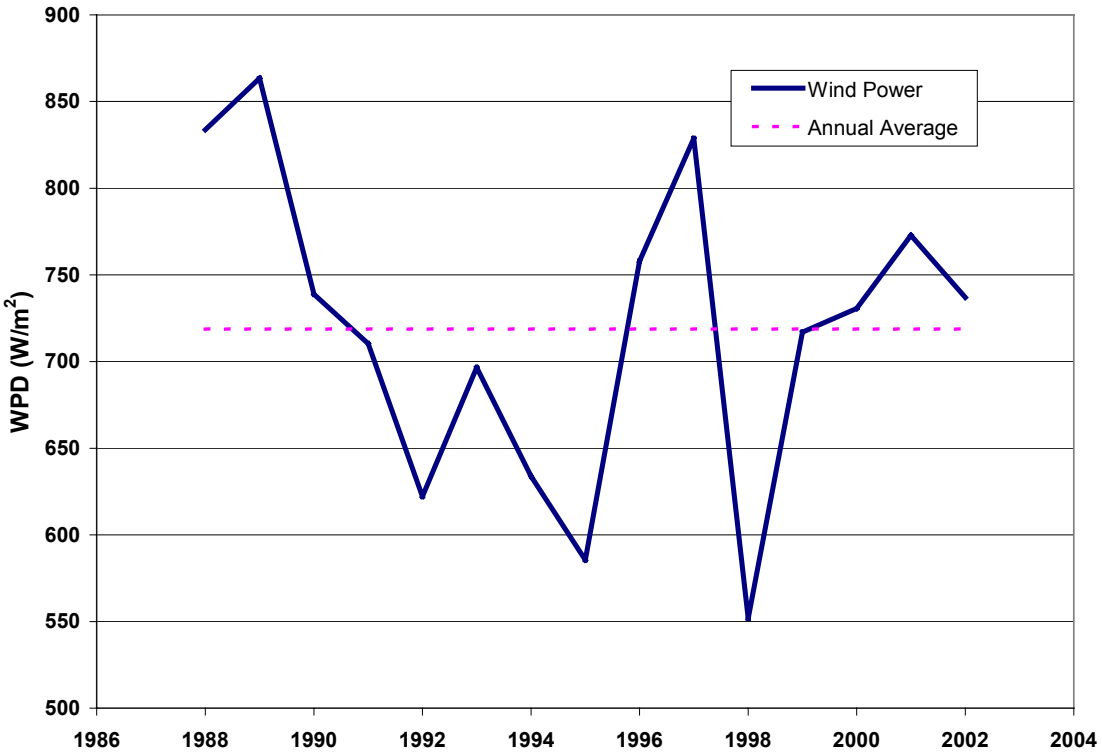
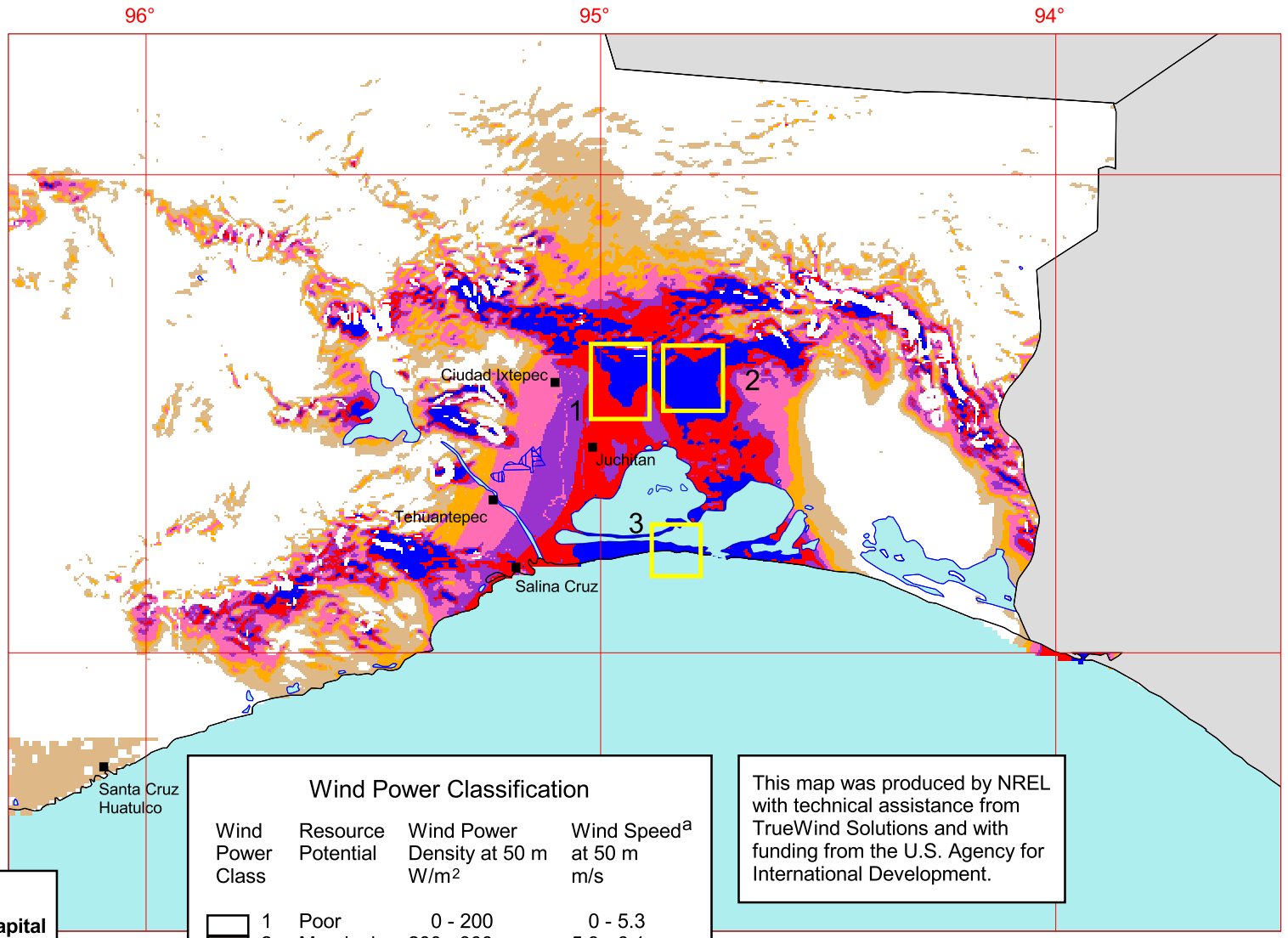


Figure 6.7 Isthmus Offshore Region – Interannual Variability of Wind Power.

Locations of Measurement Data for Map Validation



Secretaría de Energía (SENER)

Gobierno del Estado de Oaxaca, Secretaria de Desarrollo Industrial y Comercial (SEDIC)

Comision Federal de Electricidad

Instituto de Investigaciones Electricas

Comision Nacional del Agua (CONAGUA)

Legend

- Town or **Capital**
- Transmission Line

Measurement Site Locations

1. La Mata - Juchitan
2. La Venta - Santo Domingo
3. Santa Maria del Mar

Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m²	Wind Speed[a] at 50 m m/s
1	Poor	0 - 200	0 - 5.3
2	Marginal	200 - 300	5.3 - 6.1
3	Moderate	300 - 400	6.1 - 6.7
4	Good	400 - 500	6.7 - 7.3
5	Excellent	500 - 600	7.3 - 7.7
6		600 - 800	7.7 - 8.5
7		> 800	> 8.5

[a] Wind speeds are based on a Weibull k value of 1.8

This map was produced by NREL with technical assistance from TrueWind Solutions and with funding from the U.S. Agency for International Development.

20 0 20 40 60 80 Kilometers

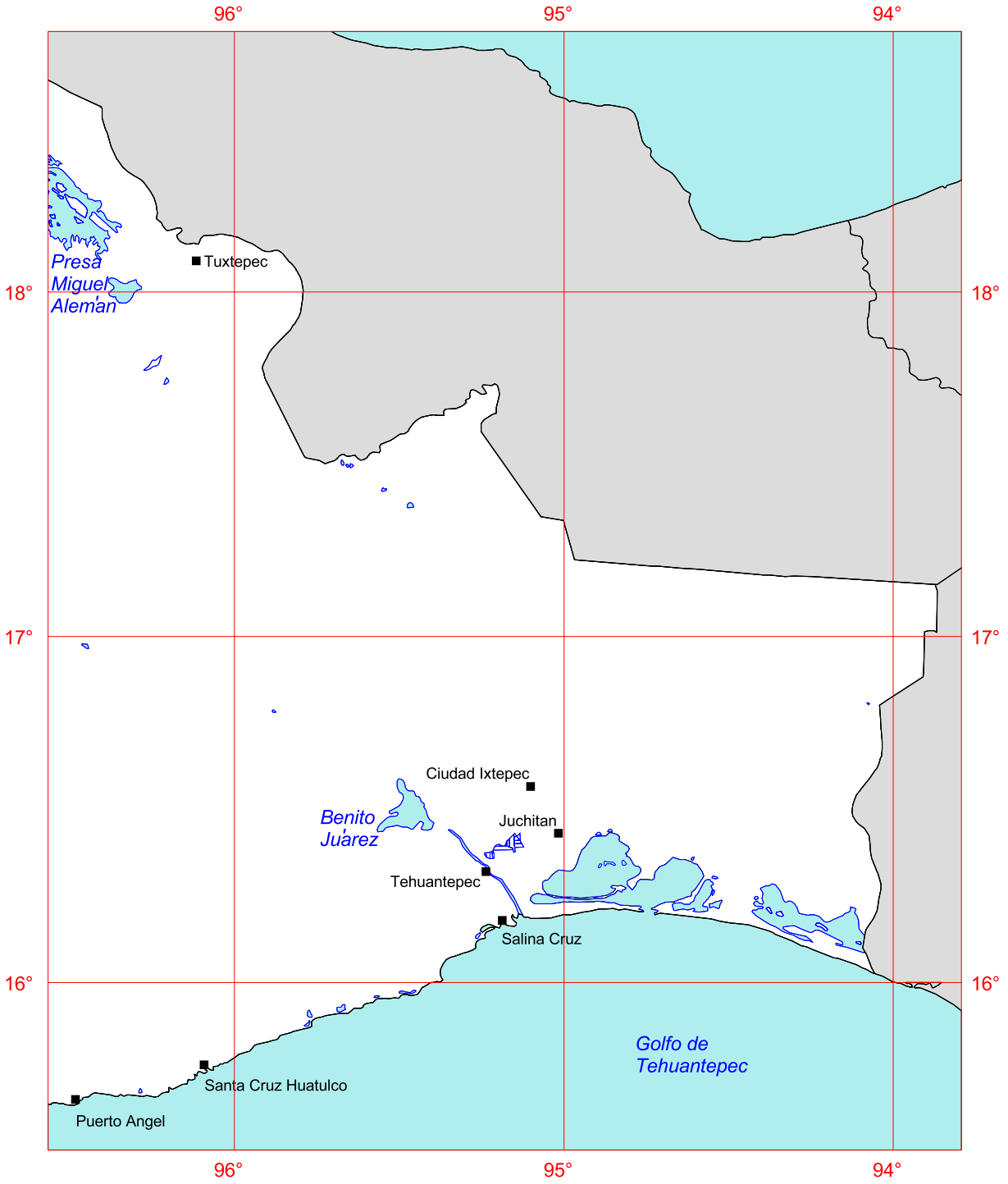
U.S. Agency for International Development

U.S. Department of Energy
National Renewable Energy Laboratory

JUL-2003 1.6.8

Figure 6-8

Eastern Oaxaca - Political Base Map



20 0 20 40 60 80 100 Kilometers

Legend

■ Town or ■ **Capital**

Lake or Lagoon

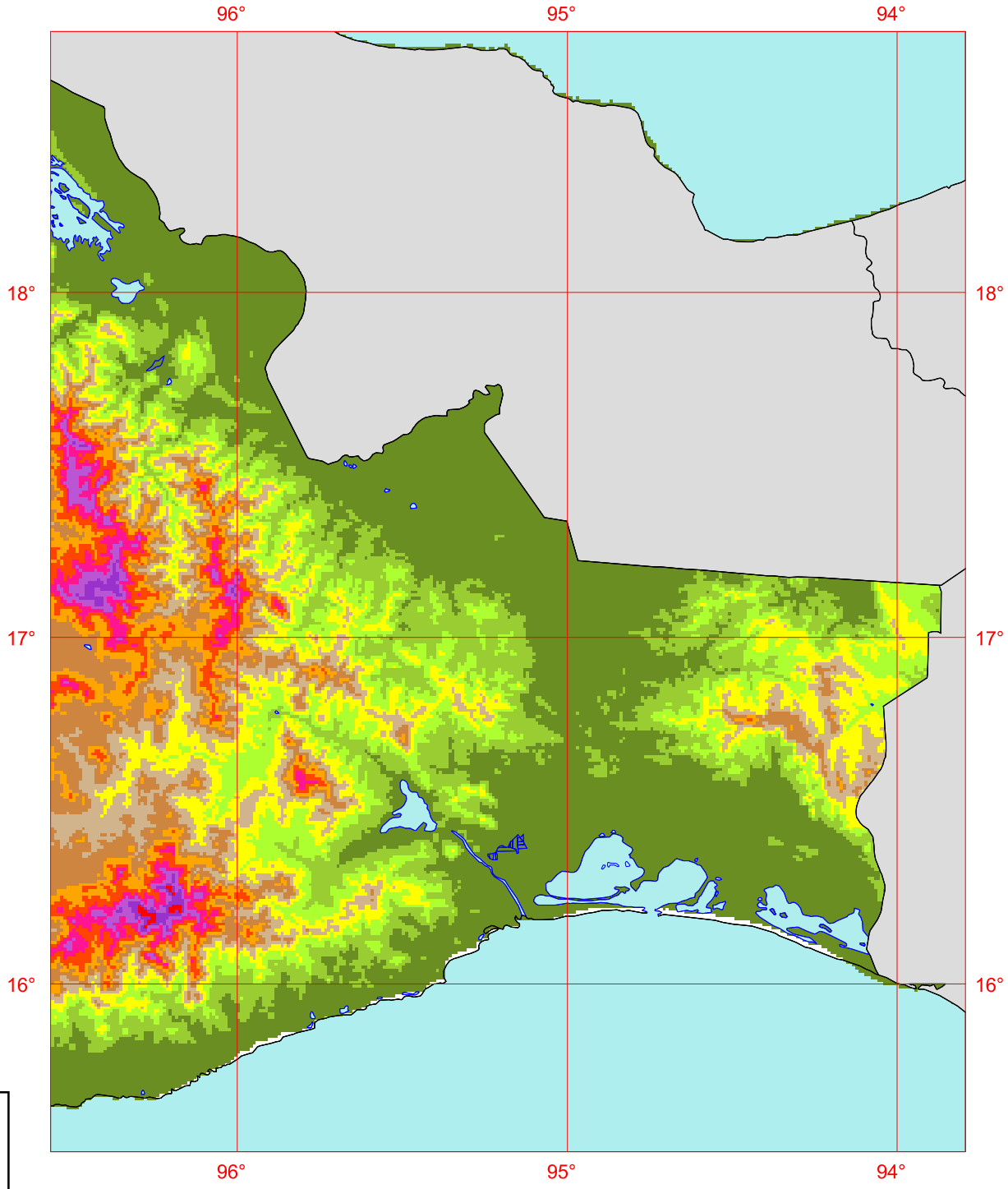
U.S. Agency for International Development

U.S. Department of Energy
National Renewable Energy Laboratory

JUL-2003 2.6.9

Figure 6-9

Eastern Oaxaca - Elevation Map



Elevation
Meters

3600
3300
3000
2700
2400
2100
1800
1500
1200
900
600
300
0

The elevation values are averaged over 1 km^2.

20 0 20 40 60 80 100 Kilometers

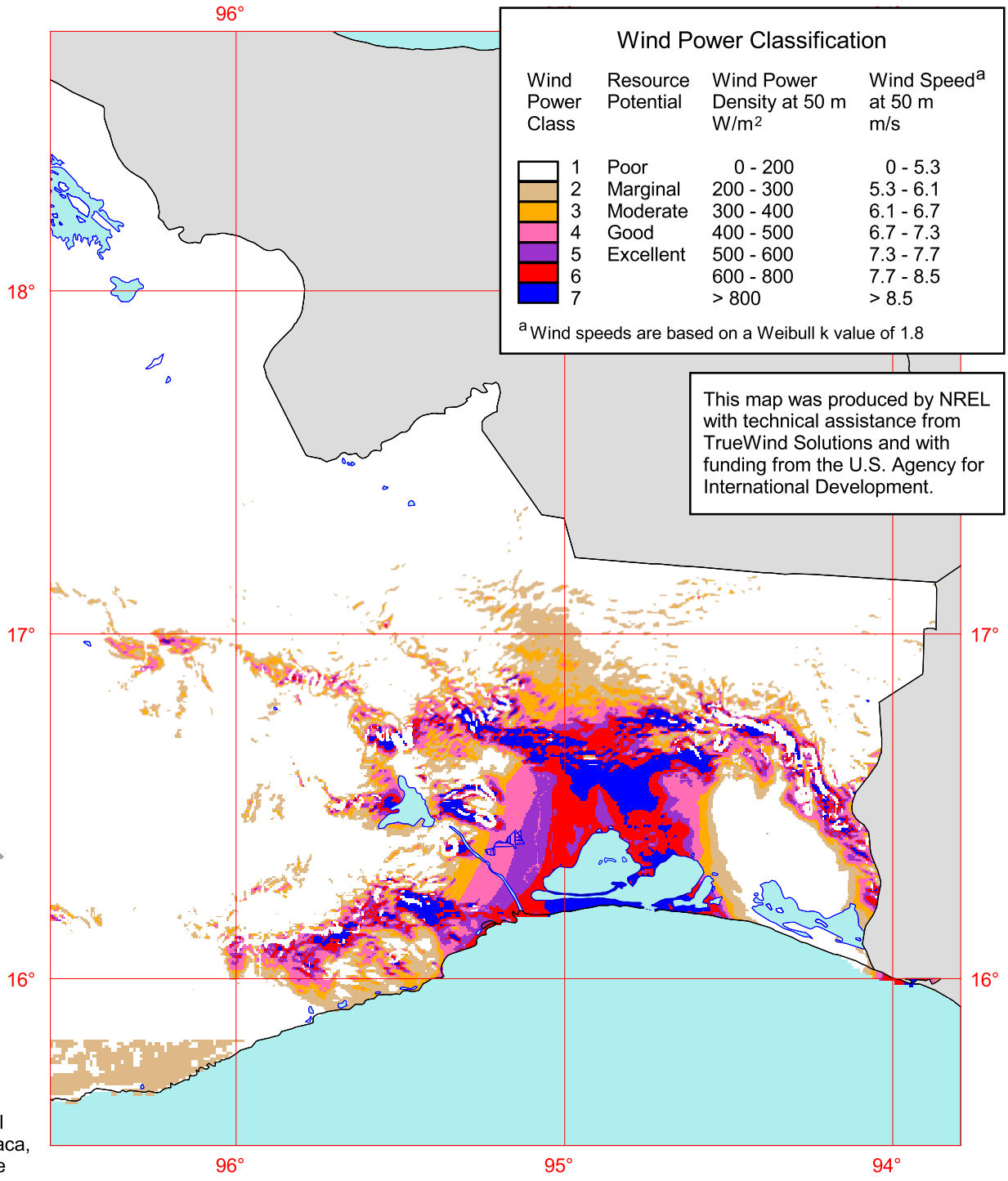
U.S. Agency for International Development

U.S. Department of Energy
National Renewable Energy Laboratory

NREL/TP-2003 2.6.10

Figure 6-10

Eastern Oaxaca - Wind Resource Map



Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m²	Wind Speed[a] at 50 m m/s
1	Poor	0 - 200	0 - 5.3
2	Marginal	200 - 300	5.3 - 6.1
3	Moderate	300 - 400	6.1 - 6.7
4	Good	400 - 500	6.7 - 7.3
5	Excellent	500 - 600	7.3 - 7.7
6		600 - 800	7.7 - 8.5
7		> 800	> 8.5

[a] Wind speeds are based on a Weibull k value of 1.8

This map was produced by NREL with technical assistance from TrueWind Solutions and with funding from the U.S. Agency for International Development.

Secretaría de Energía (SENER)

Gobierno del Estado de Oaxaca, Secretaria de Desarrollo Industrial y Comercial (SEDIC)

Comision Federal de Electricidad

Instituto de Investigaciones Electricas

Comision Nacional del Agua (CONAGUA)

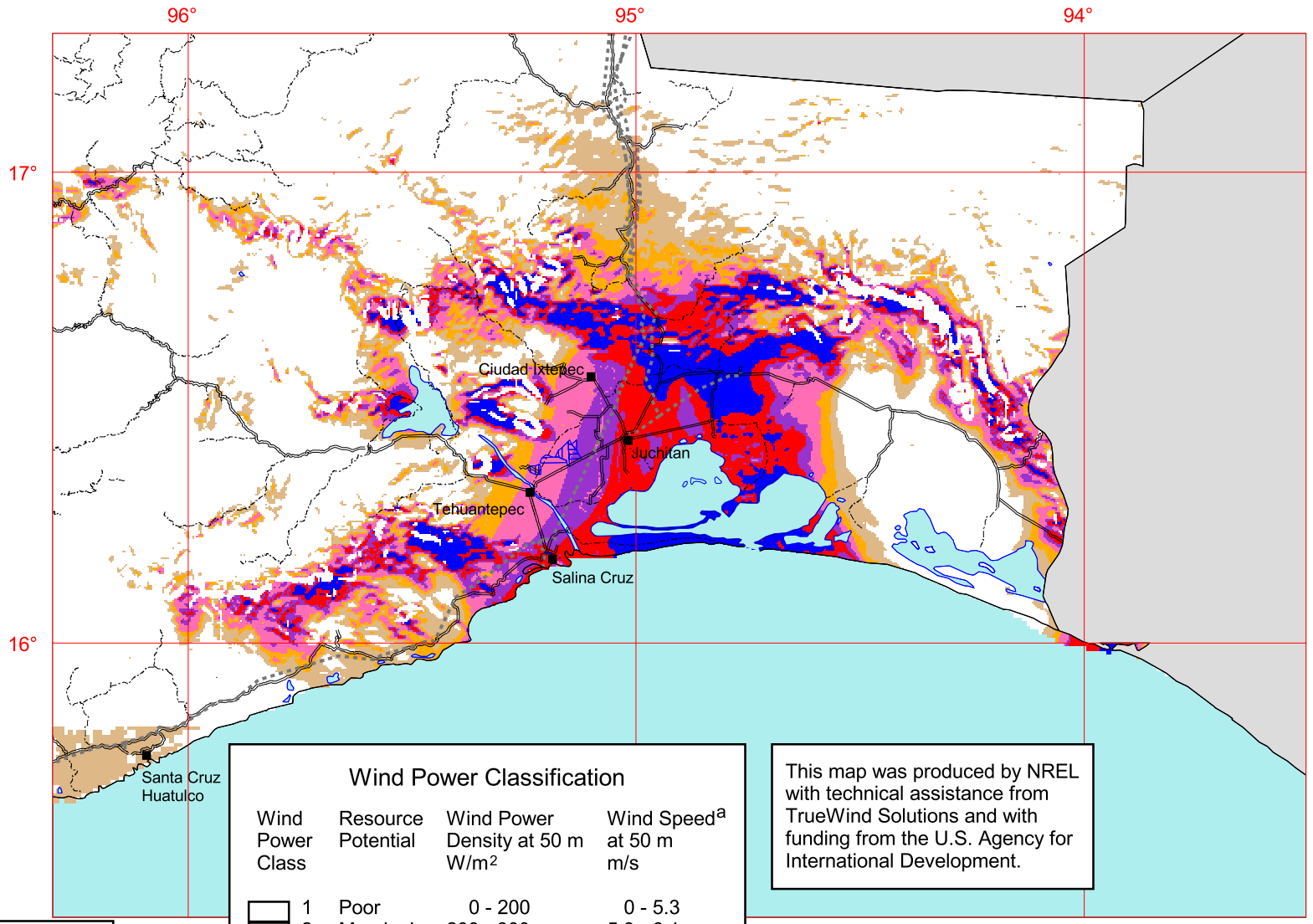
20 0 20 40 60 80 100 Kilometers

U.S. Agency for International Development

U.S. Department of Energy National Renewable Energy Laboratory

Figure 6-11

Isthmus Region of Oaxaca - Wind Resource Map



Secretaría de Energía (SENER)

Gobierno del Estado de Oaxaca, Secretaria de Desarrollo Industrial y Comercial (SEDIC)

Comision Federal de Electricidad

Instituto de Investigaciones Electricas

Comision Nacional del Agua (CONAGUA)

Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m²	Wind Speed[a] at 50 m m/s
1	Poor	0 - 200	0 - 5.3
2	Marginal	200 - 300	5.3 - 6.1
3	Moderate	300 - 400	6.1 - 6.7
4	Good	400 - 500	6.7 - 7.3
5	Excellent	500 - 600	7.3 - 7.7
6		600 - 800	7.7 - 8.5
7		> 800	> 8.5

[a] Wind speeds are based on a Weibull k value of 1.8

This map was produced by NREL with technical assistance from TrueWind Solutions and with funding from the U.S. Agency for International Development.

Legend

- Town or Capital
- Transmission Line
- Paved Road
- Unpaved Road

20 0 20 40 60 80 Kilometers

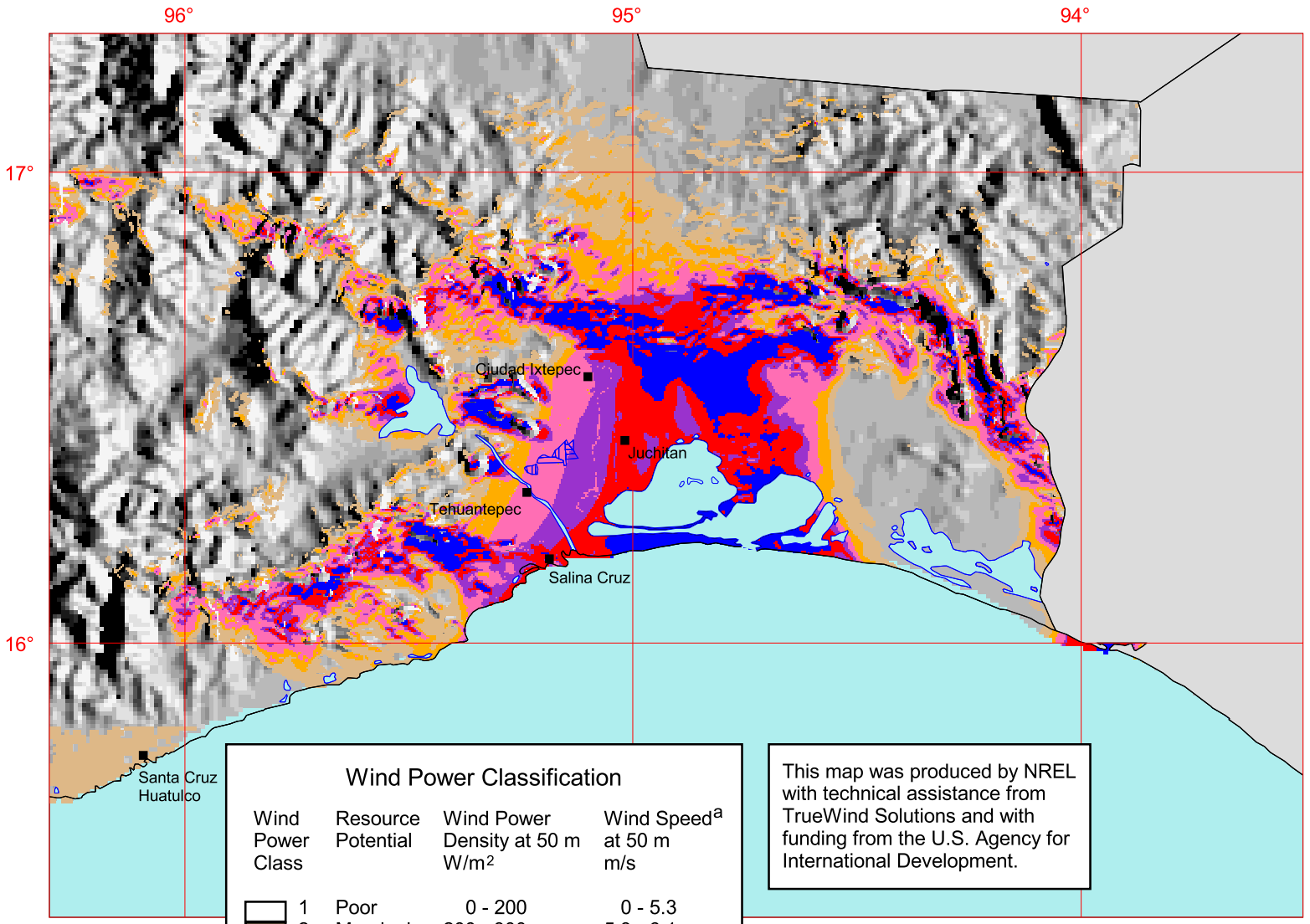
U.S. Agency for International Development

U.S. Department of Energy
National Renewable Energy Laboratory

NREL-2003 1.6.12

Figure 6-12

Isthmus Region of Oaxaca - Wind Resource Map



Secretaría de Energía (SENER)

Gobierno del Estado de Oaxaca, Secretaria de Desarrollo Industrial y Comercial (SEDIC)

Comision Federal de Electricidad

Instituto de Investigaciones Electricas

Comision Nacional del Agua (CONAGUA)

Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m²	Wind Speed[a] at 50 m m/s
1	Poor	0 - 200	0 - 5.3
2	Marginal	200 - 300	5.3 - 6.1
3	Moderate	300 - 400	6.1 - 6.7
4	Good	400 - 500	6.7 - 7.3
5	Excellent	500 - 600	7.3 - 7.7
6		600 - 800	7.7 - 8.5
7		> 800	> 8.5

[a] Wind speeds are based on a Weibull k value of 1.8

This map was produced by NREL with technical assistance from TrueWind Solutions and with funding from the U.S. Agency for International Development.

Legend

■ Town or ■ **Capital**

20 0 20 40 60 80 Kilometers

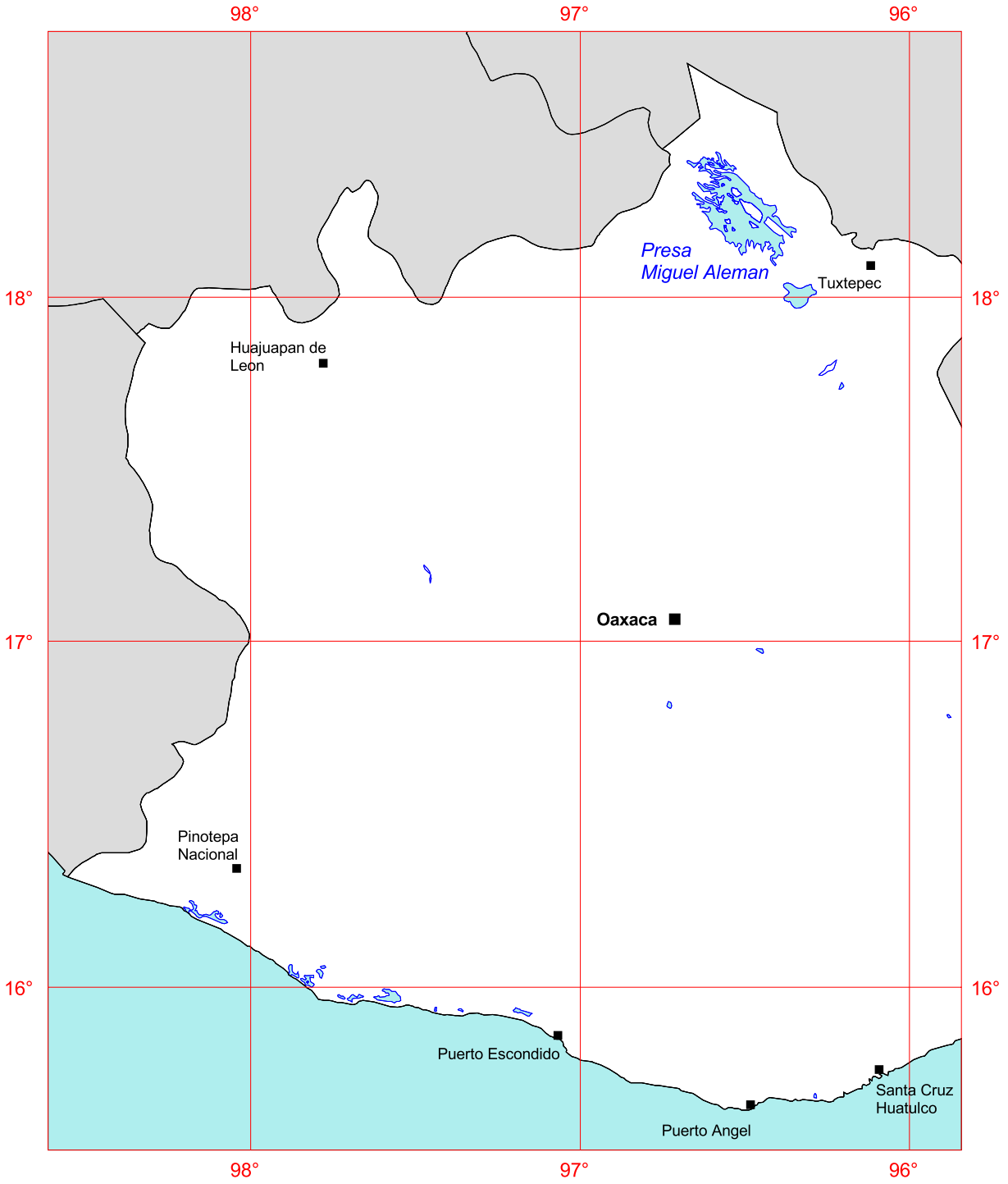
U.S. Agency for International Development

U.S. Department of Energy
National Renewable Energy Laboratory

DRAFT-2003 1.6.13

Figure 6-13

Western Oaxaca - Political Base Map



20 0 20 40 60 80 100 Kilometers

Legend

■ Town or ■ **Capital**

Lake or Lagoon

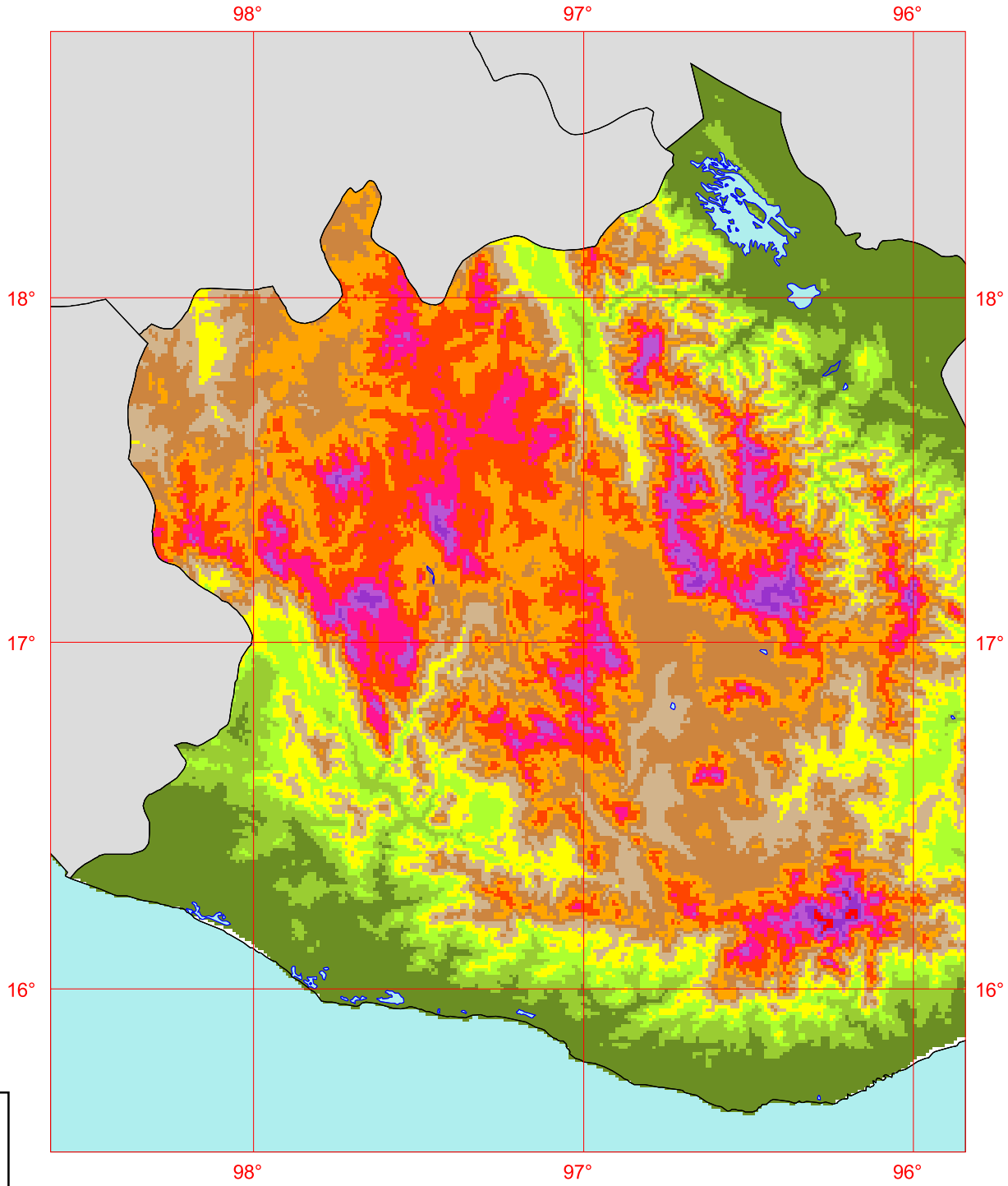
U.S. Agency for International Development

U.S. Department of Energy
National Renewable Energy Laboratory

NREL/TP-2003 1.6.14

Figure 6-14

Western Oaxaca - Elevation Map



Elevation
Meters
3600
3300
3000
2700
2400
2100
1800
1500
1200
900
600
300
0

20 0 20 40 60 80 100 Kilometers

The elevation values are averaged over 1 km^2.

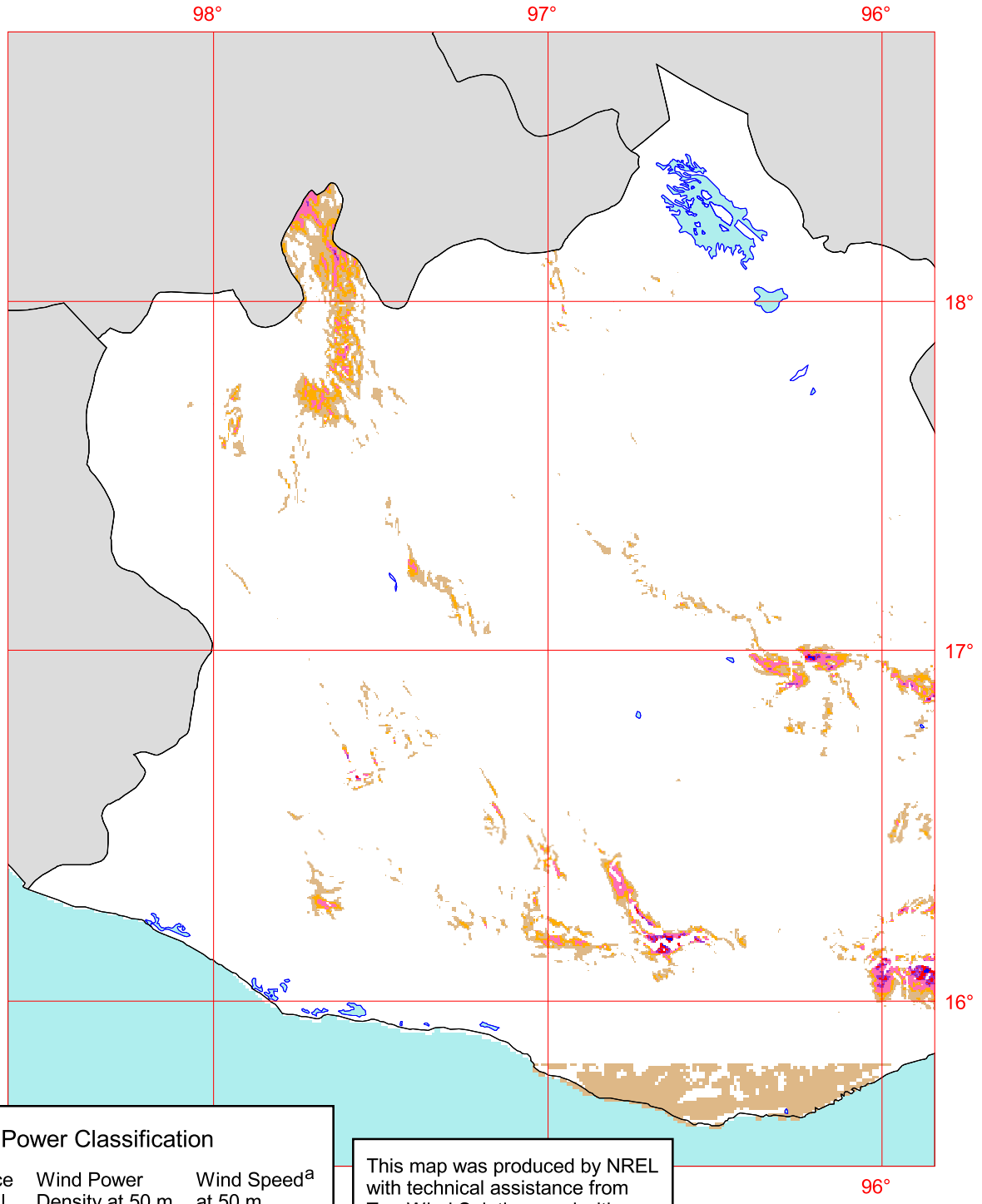
U.S. Agency for International Development

U.S. Department of Energy
National Renewable Energy Laboratory

NREL-2003 1.6.15

Figure 6-15

Western Oaxaca - Wind Resource Map



Secretaría de Energía (SENER)

Gobierno del Estado de Oaxaca, Secretaria de Desarrollo Industrial y Comercial (SEDIC)

Comision Federal de Electricidad

Instituto de Investigaciones Electricas

Comision Nacional del Agua (CONAGUA)

Wind Power Classification

Wind Power Class	Resource Potential	Wind Power Density at 50 m W/m²	Wind Speed[a] at 50 m m/s
1	Poor	0 - 200	0 - 5.3
2	Marginal	200 - 300	5.3 - 6.1
3	Moderate	300 - 400	6.1 - 6.7
4	Good	400 - 500	6.7 - 7.3
5	Excellent	500 - 600	7.3 - 7.7
6		600 - 800	7.7 - 8.5
7		> 800	> 8.5

[a] Wind speeds are based on a Weibull k value of 1.8

This map was produced by NREL with technical assistance from TrueWind Solutions and with funding from the U.S. Agency for International Development.

20 0 20 40 60 80 100 Kilometers

U.S. Agency for International Development

U.S. Department of Energy National Renewable Energy Laboratory

Figure 6-16

7.0 Wind Electric Potential

7.1 Introduction

The wind resource classifications in Table 7.1 match those shown on the wind resource maps for Oaxaca. The installed capacity in the table represents net wind electric potential not reduced by factors such as land-use exclusions. The methods for converting the wind resource to wind electric potential are those used regularly by NREL. The assumptions used for the wind potential calculations are listed at the bottom of Table 7.1.

Each color-coded square kilometer on the map has an assigned annual wind power density at the 50-m height expressed in units of W/m^2. NREL uses a simple formula to compute the potential installed capacity for grid cells with an annual wind power density of 300 W/m^2 and greater. If the wind power density of a grid cell was less than 300 W/m^2, then the potential installed capacity was set equal to zero. Another scenario presented in this section included only those grid cells with an annual average power density of 400 W/m^2 and greater.

7.2 Wind Electric Potential Estimates

We estimate that there are about 6600 km^2 of land areas with good-to-excellent wind resource potential in Oaxaca. Approximately 4400 sq km^2 of the 6600 km^2 of windy land is considered to have excellent wind resource potential. The proportion of windy land and potential wind capacity in each wind power category is listed in Table 7.1. This windy land represents more than 7% of the total area (not including lagoons) of 91,500 km^2. Using a conservative assumption of 5 MW per km^2, this windy land could support more than 3,000 MW of potential installed capacity. Additional studies are required to accurately assess the wind electric potential, considering factors such as the existing transmission grid and accessibility.

If additional areas with moderate wind resource potential (or good for rural power applications) are considered, the estimated total windy land area (as shown in Table 7.1) increases to more than 8800 km^2, or almost 10% of the total land area of Oaxaca. This amount of windy land could support more than 44,000 MW of installed capacity.

Table 7.1 Oaxaca – Wind Electric Potential

Good-to-Excellent Wind Resource at 50 m

Wind Resource Utility Scale	Wind Class	Wind Power at 50 m W/m^2	Wind Speed at 50 m m/s*	Total Area km^2	Percent Windy Land	Total Capacity Installed MW
Good	4	400 – 500	6.7 – 7.3	2,263	2.5	11,300
Excellent	5	500 – 600	7.3 – 7.7	1,370	1.5	6,850
Excellent	6	600 – 700	7.7 – 8.5	1,756	1.9	8,800
Excellent	7	> 800	> 8.5	1,248	1.4	6,250
Total				6,637	7.3	33,200

Moderate-to-Excellent Wind Resource at 50 m (Utility Scale)

Wind Resource Utility Scale	Wind Class	Wind Power at 50 m W/m^2	Wind Speed at 50 m m/s*	Total Area km^2	Percent Windy Land	Total Capacity Installed MW
Moderate	3	300 – 400	6.1 – 6.7	2,234	2.4	11,150
Good	4	400 – 500	6.7 – 7.3	2,263	2.5	11,300
Excellent	5	500 – 600	7.3 – 7.7	1,370	1.5	6,850
Excellent	6	600 – 700	7.7 – 8.5	1,756	1.9	8,800
Excellent	7	> 800	> 8.5	1,248	1.4	6,250
Total				8,870	9.7	44,350

*** Wind speeds are based on an elevation of 2000 m and a Weibull k value of 2.0**

Assumptions
Installed capacity per km^2 = 5 MW
Total land area of Oaxaca = 91,500 km^2

References

Brower, M.; Bailey, B; Zack, J. (2001). "Applications and Validations of the MesoMap Wind Mapping System in Different Climatic Regimes." *Windpower 2001 Proceedings*, Washington, D.C., American Wind Energy Association.

Elliott, D. (2002). "Assessing the World's Wind Resources," *IEEE Power Engineering Review*. Vol. 22 (9), September 2002; pp. 4-9; NREL Report No. 33012.

Elliott, D.L., Schwartz, M.N. (1998). "Validation of Regional Wind Resource Predictions in the Northern Great Plains." *Windpower '98 Proceedings*, Washington, D.C., American Wind Energy Association.

Elliott, D.; Schwartz, M.; Nierenberg, R. (1999). "Wind Resource Mapping of the State of Vermont," NREL/CP-500-27507.

Elliott, D.; Schwartz, M.; George, R.; Haymes, S.; Heimiller, D.; Scott, G.; Kline, J. (2001). *Wind Energy Resource Atlas of the Dominican Republic*. 218 pp.; NREL/TP-500-27602.

Elliott, D.; Schwartz, M.; George, R.; Haymes, S.; Heimiller, D.; Scott, G.; McCarthy, E. (2001). *Wind Energy Resource Atlas of the Philippines*. 208 pp.; NREL/TP-500-26129.

Elliott, D.; Schwartz, M.; Scott, G.; Haymes, S.; Heimiller, D.; George, R. (2001). *Wind Energy Resource Atlas of Mongolia*. 215 pp.; NICH Report No. TP-500-28972.

Elliott, D.; Schwartz, M.; Scott, G.; Haymes, S.; Heimiller, D.; George, R. (2002). *Wind Energy Resource Atlas of Southeast China*. 163 pp.; NREL/TP-500-32781.

Heimiller, D.M., Haymes, S.R. (2001). Geographic Information Systems in Support of Wind Energy Activities at NREL: Preprint. 10 pp.: NREL/CP-500-29164.

Rohatgi, J.S.; Nelson, V. (1994). *Wind Characteristics: An Analysis for the Generation of Wind Power*, Alternative Energy Institute, West Texas A&M University, Canyon, TX, 239 pp.

Schwartz, M.N. (1999). *Wind Resource Estimation and Mapping at the National Renewable Energy Laboratory*. 8pp.; NICH Report No. CP-500-26245.

Schwartz, M.N.; Elliott, D.L. (1995). *Mexico Wind Resource Assessment Project*. NREL/TP-441-7809.

Schwartz, M.N.; Elliott, D.L. (1997). "The Integration of Climatic Data Sets for Wind Resource Assessment." *Proceedings of the 10th Conference on Applied Climatology,* Boston, Massachusetts, American Meteorological Society.

Schwartz, M; Elliott, D. (2001). *Remapping of the Wind Energy Resource in the Midwestern United States*: Abstract Preprint. 9 pp.; NICH Report No. AB-500-31083.

Wind Resource Assessment Handbook: Fundamentals for Conducting a Successful Monitoring Program. (April 1997). Prepared by AWS Scientific, Inc., NREL/SR-440-22223.

Appendix A

Surface Meteorological Stations
Tables and Analysis Summaries of Selected Stations

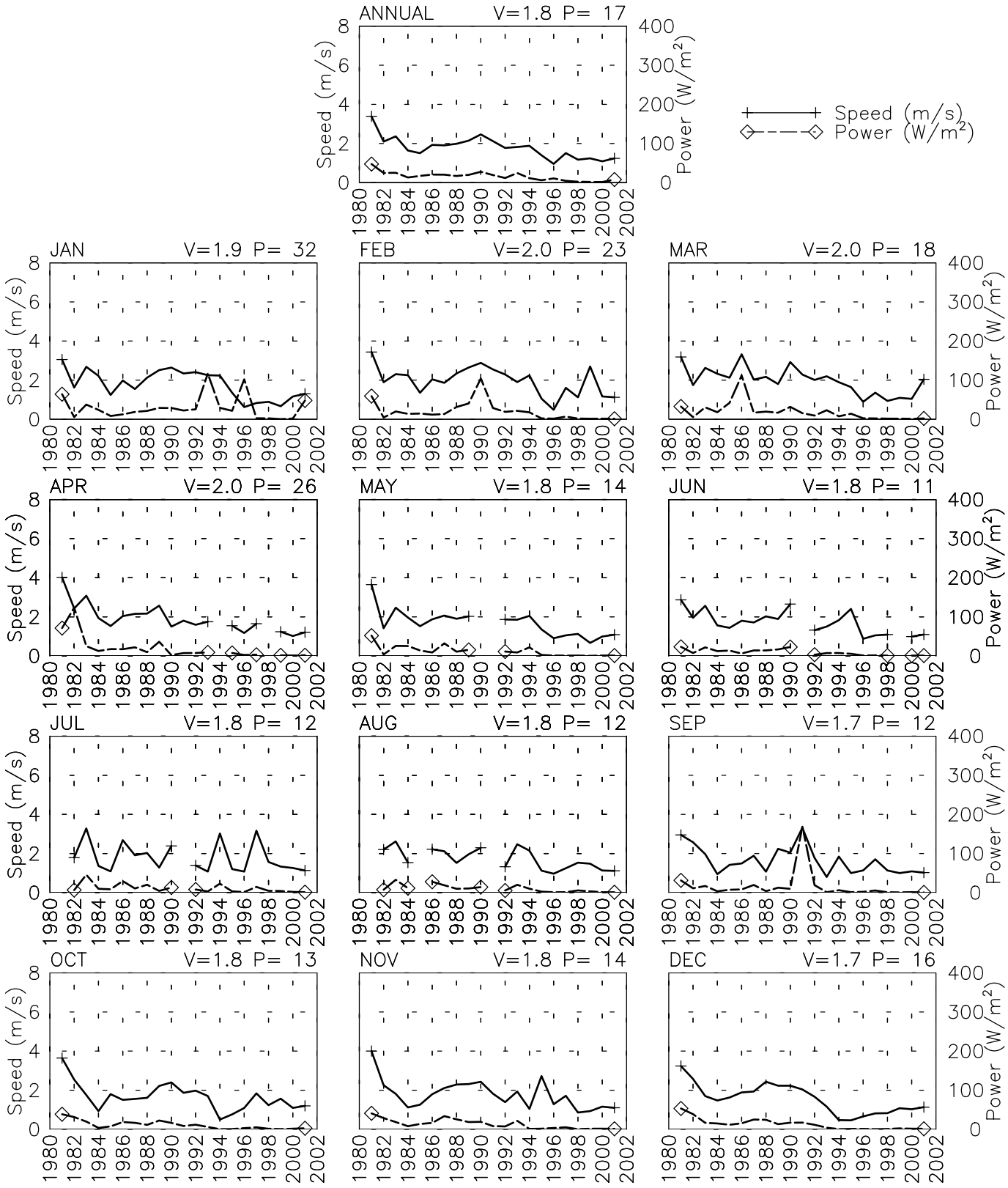
DATSAV2 Stations

Table A.1 DATSAV2 (GTS) Meteorological Stations in Oaxaca

WMO ID	Name	Lat N	Lon W	Elev	WS	WP	Period of Record
767755	Oaxaca/Xoxocotlan	16 58	96 43	1528	2.0	24	1976-2002
768485	Bahias De Huatulco	15 46	96 16	143	4.9	190	1989-1991
768556	Puerto Escondido	15 52	97 04	88	4.2	89	1989-1991
767750	Oaxaca	17 04	96 43	1550	1.4	13	1975-1991
768550	Puerto Angel	15 39	96 30	21	2.2	27	1982-1991
768330	Salina Cruz	16 10	95 12	6	4.9	218	1975-1993
767730	Huajuapan De Leon	17 48	97 40	1602	2.0	20	1982-1991
768300	Ixtepec-In-Oaxaca	16 33	95 05	61	3.4	69	1973-1977
768400	Arriaga	16 13	93 54	44	2.8	103	1975, 1982-2000
767375	Tehuacan	18 30	97 25	1679	2.3	52	1973-1977

SPEED AND POWER BY YEAR

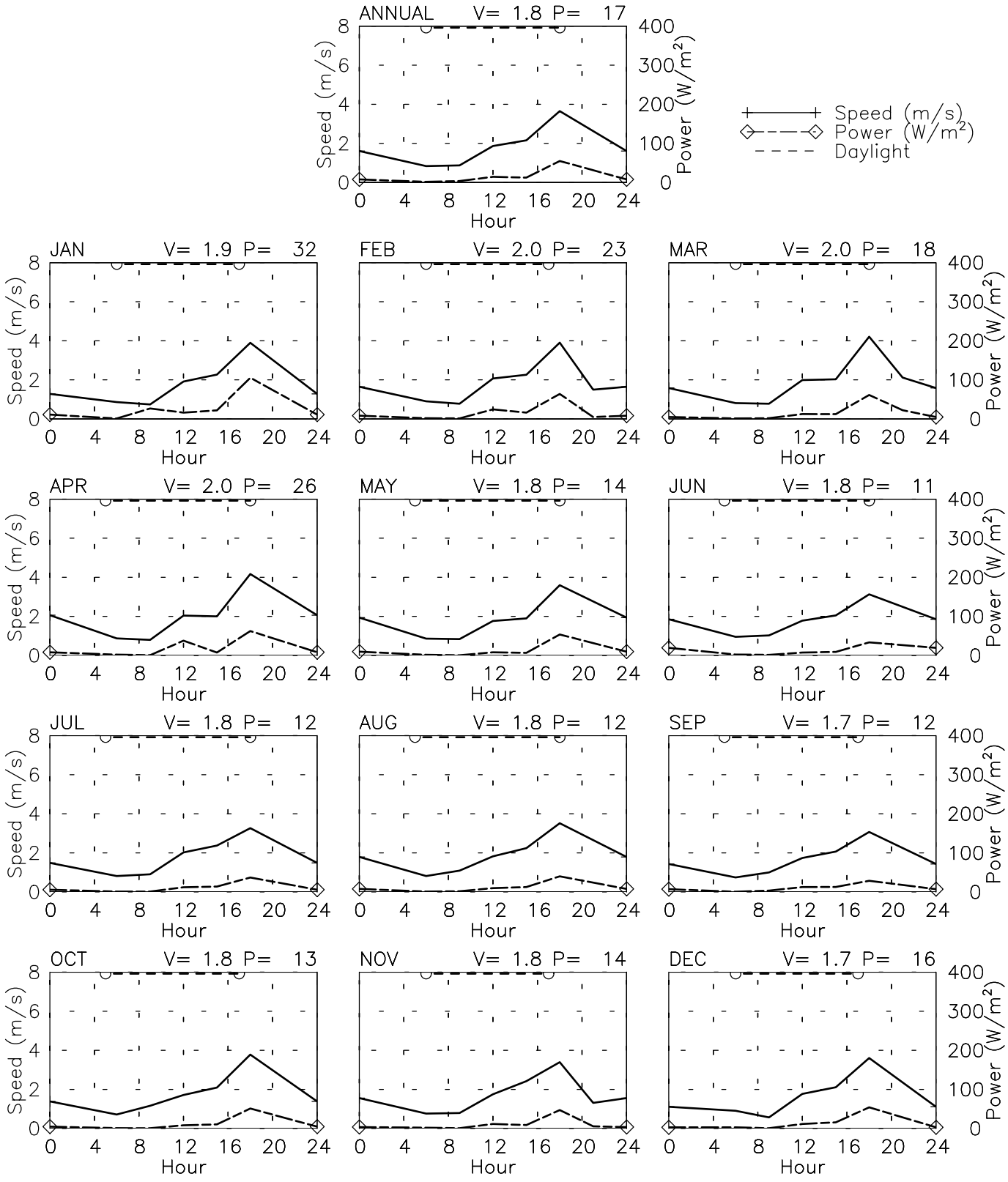
Huajuapan De Leon – 767730
17° 48' N 97° 47' W – Elev 1602m *LST=GMT –6 hours NT= –7
01/81–12/01



Thu Jun 26 13:09:14 2003

SPEED AND POWER BY HOUR

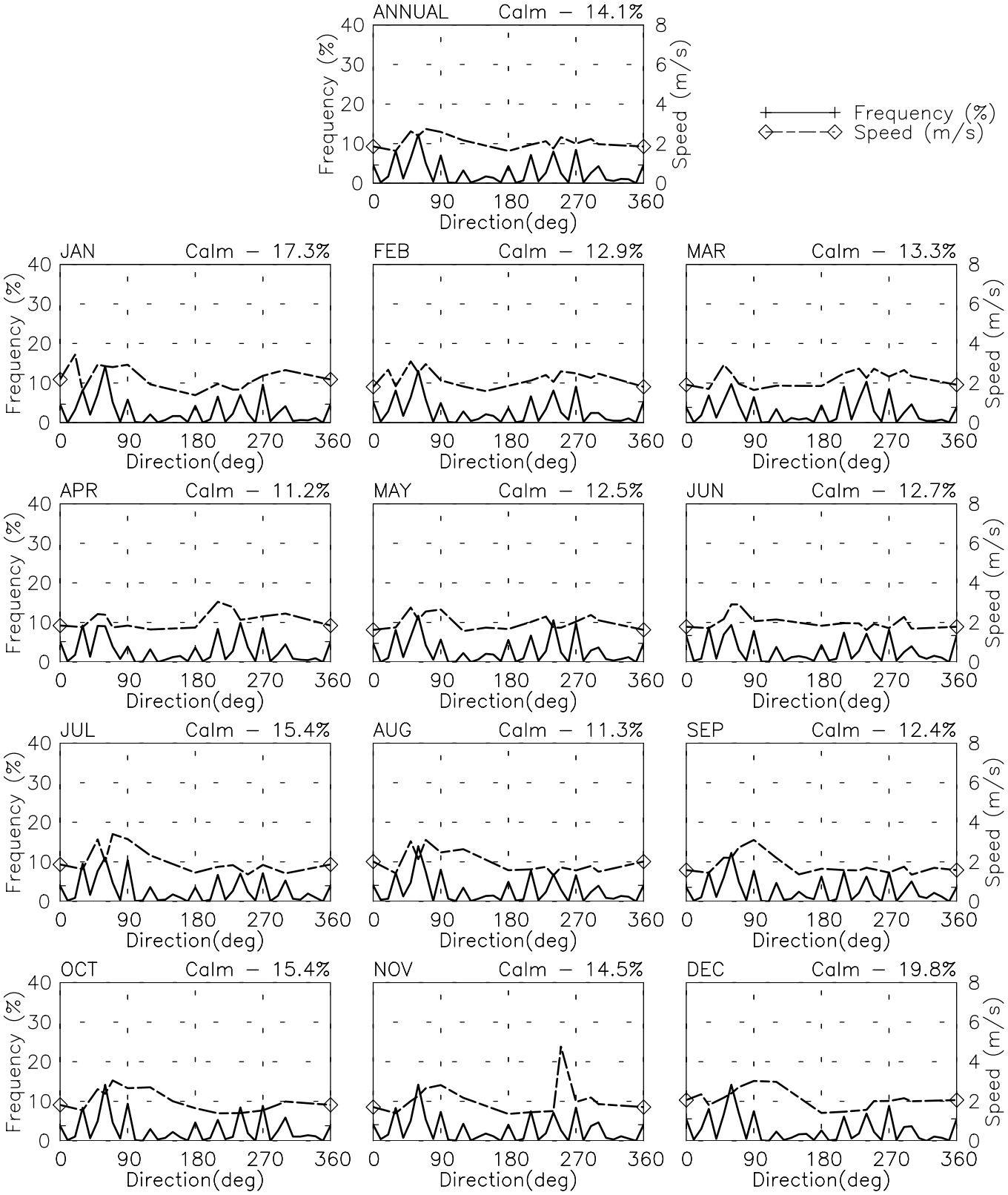
Huajuapan De Leon – 767730
17° 48' N 97° 47' W – Elev 1602m *LST=GMT –6 hours NT= –7
01/81–12/01



Thu Jun 26 13:09:15 2003

FREQUENCY AND SPEED BY DIRECTION

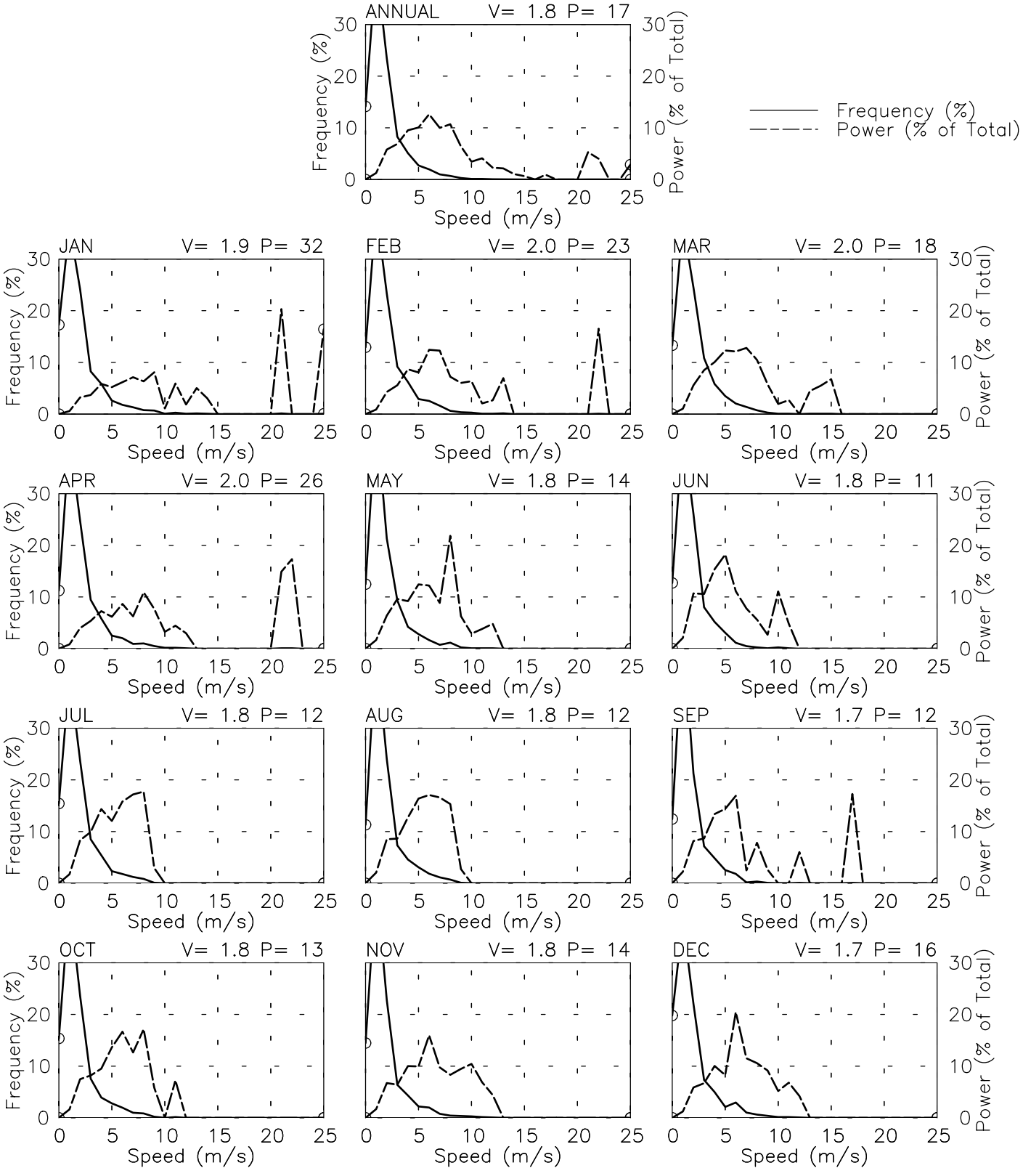
Huajuapan De Leon – 767730
17° 48' N 97° 47' W – Elev 1602m *LST=GMT –6 hours NT= –7
01/81–12/01



Thu Jun 26 13:09:16 2003

FREQUENCY OF SPEED & PERCENT OF POWER BY SPEED

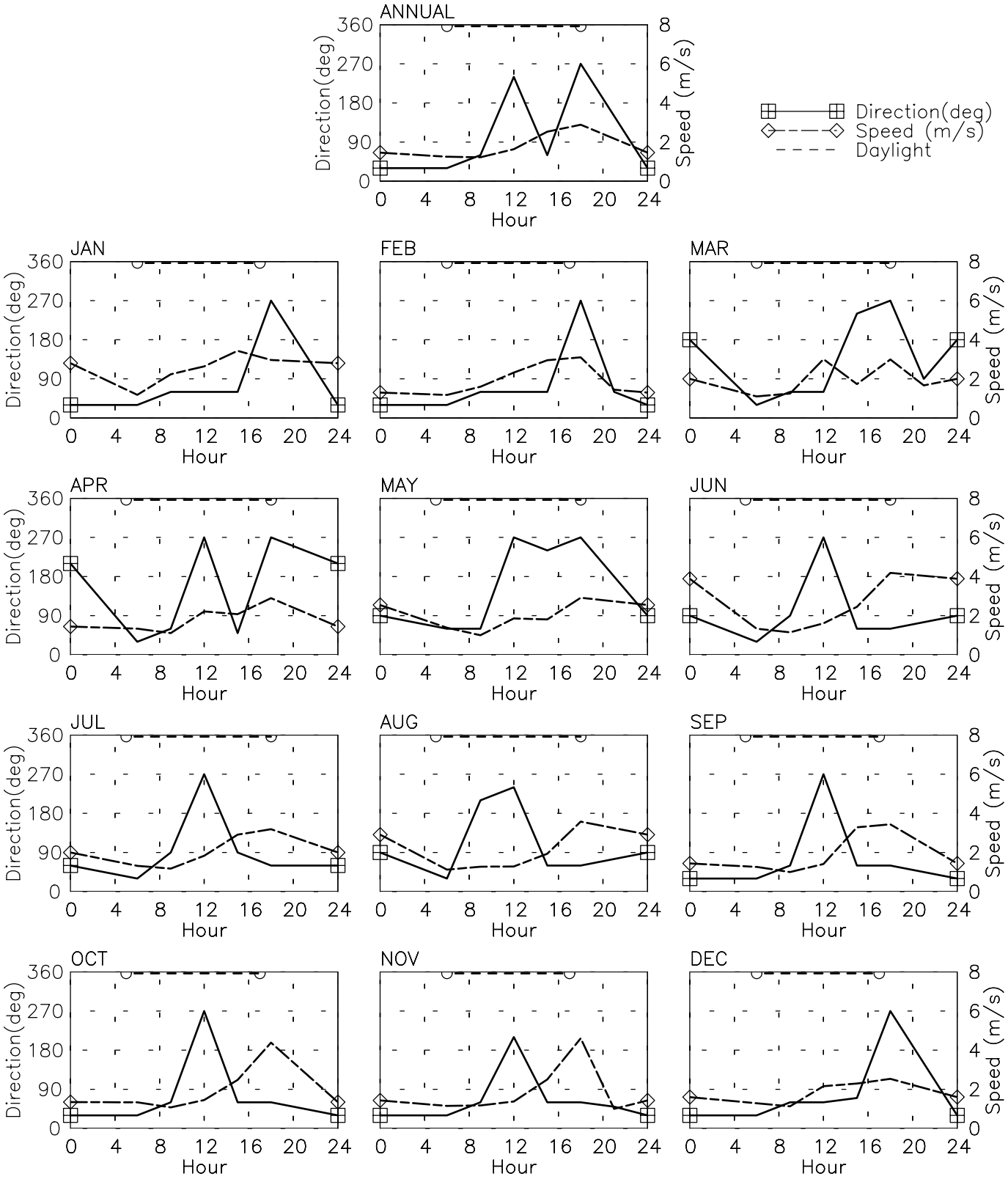
Huajuapan De Leon – 767730
17° 48' N 97° 47' W – Elev 1602m *LST=GMT –6 hours NT= –7
01/81–12/01



Thu Jun 26 13:09:17 2003

PREVAILING DIRECTION & SPEED BY HOUR

Huajuapan De Leon – 767730
17° 48' N 97° 47' W – Elev 1602m *LST=GMT –6 hours NT= –7
01/81–12/01



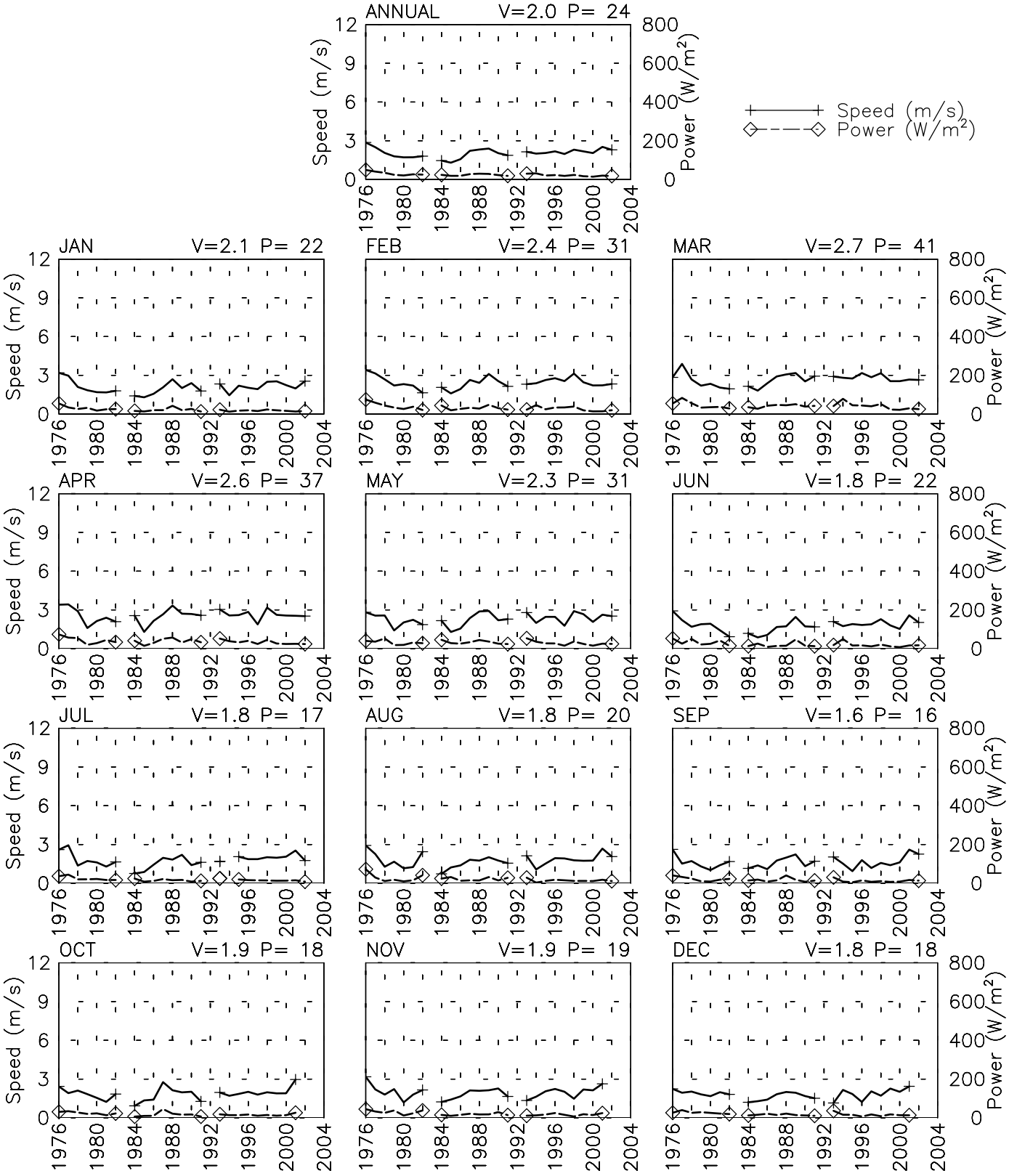
Thu Jun 26 13:09:17 2003

SPEED AND POWER BY YEAR

OAXACA/XOXOCOTLAN – 767755

16° 58' N 96° 43' W – Elev 1528m *LST=GMT −6 hours NT= −6

01/76–12/82 01/84–12/91 01/93–09/02



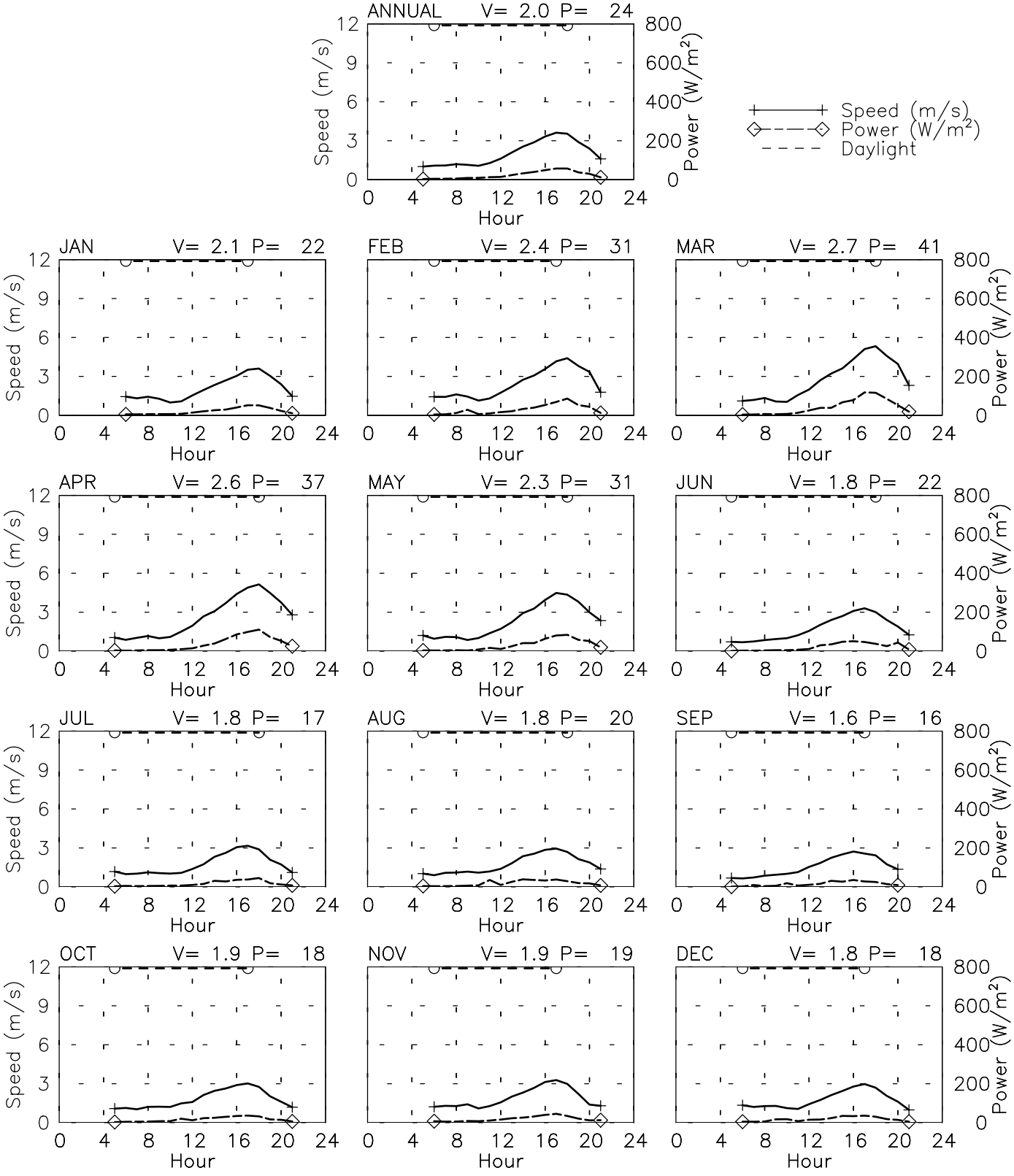
Tue Jun 24 10:03:39 2003

SPEED AND POWER BY HOUR

OAXACA/XOXOCOTLAN – 767755

16° 58' N 96° 43' W – Elev 1528m *LST=GMT –6 hours NT= –6

01/76–12/82 01/84–12/91 01/93–09/02



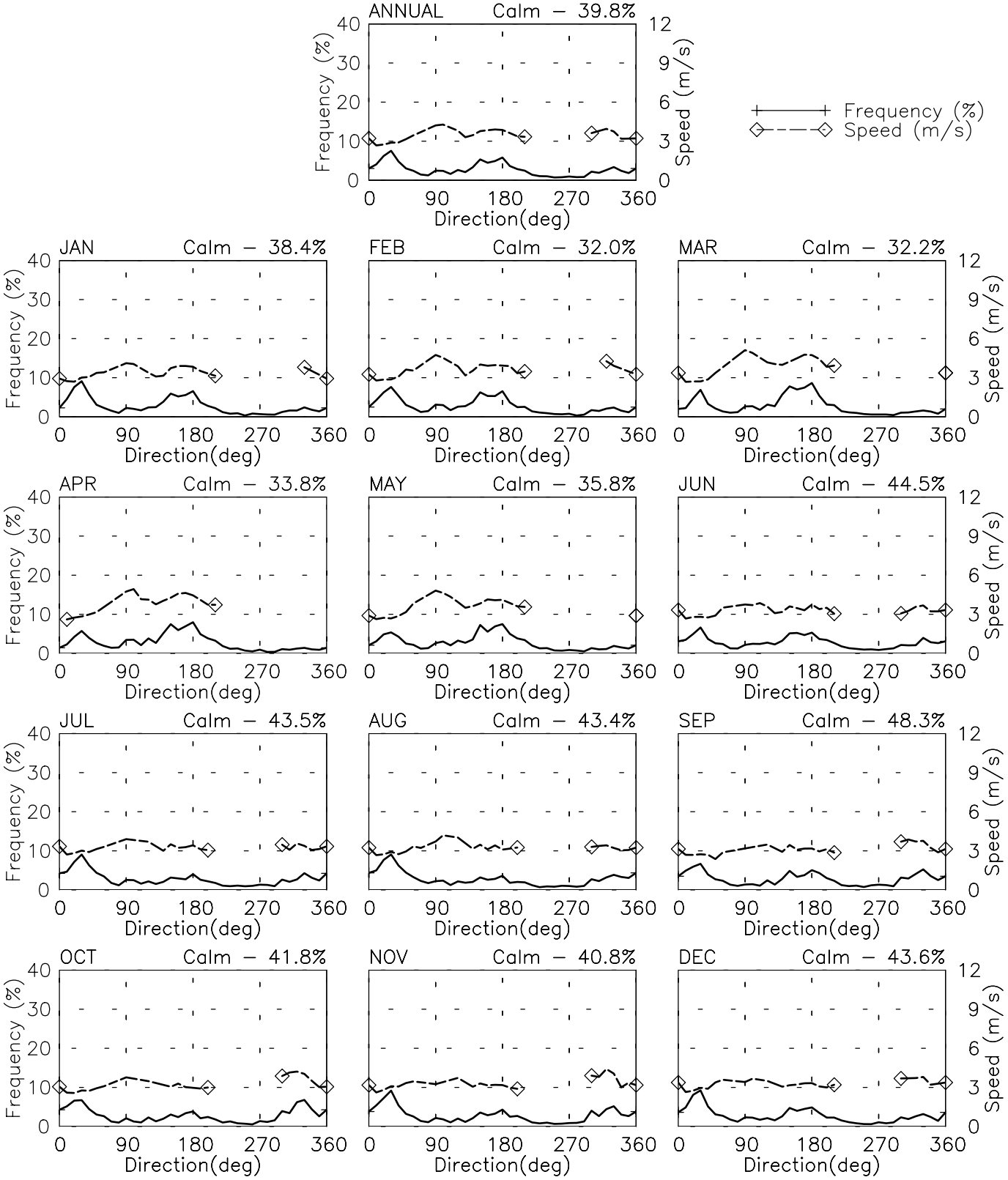
Tue Jun 24 10:03:41 2003

FREQUENCY AND SPEED BY DIRECTION

OAXACA/XOXOCOTLAN – 767755

16° 58' N 96° 43' W – Elev 1528m *LST=GMT –6 hours NT= –6

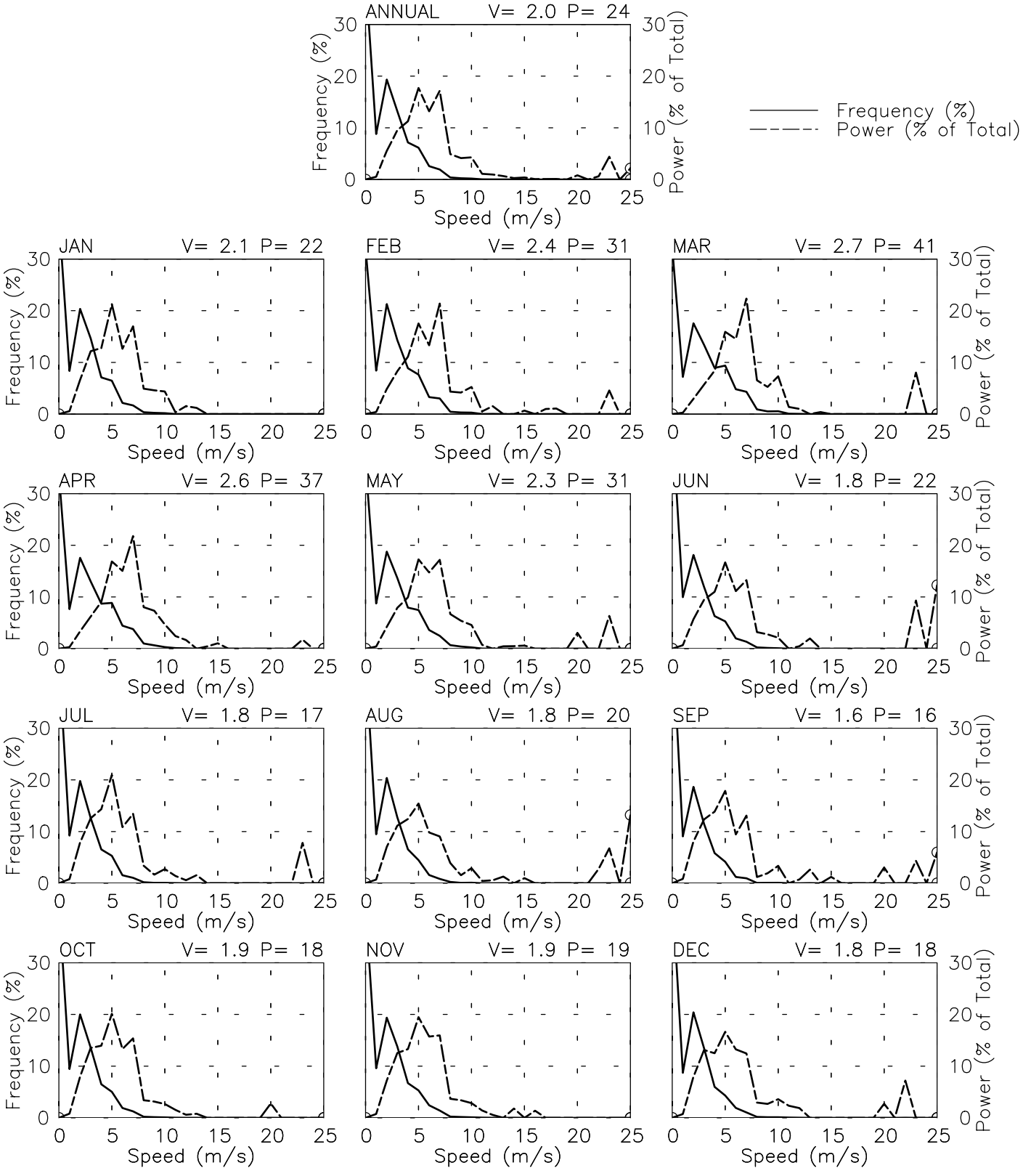
01/76–12/82 01/84–12/91 01/93–09/02



Tue Jun 24 10:03:42 2003

FREQUENCY OF SPEED & PERCENT OF POWER BY SPEED

OAXACA/XOXOCOTLAN – 767755
16° 58' N 96° 43' W – Elev 1528m *LST=GMT –6 hours NT= –6
01/76–12/82 01/84–12/91 01/93–09/02



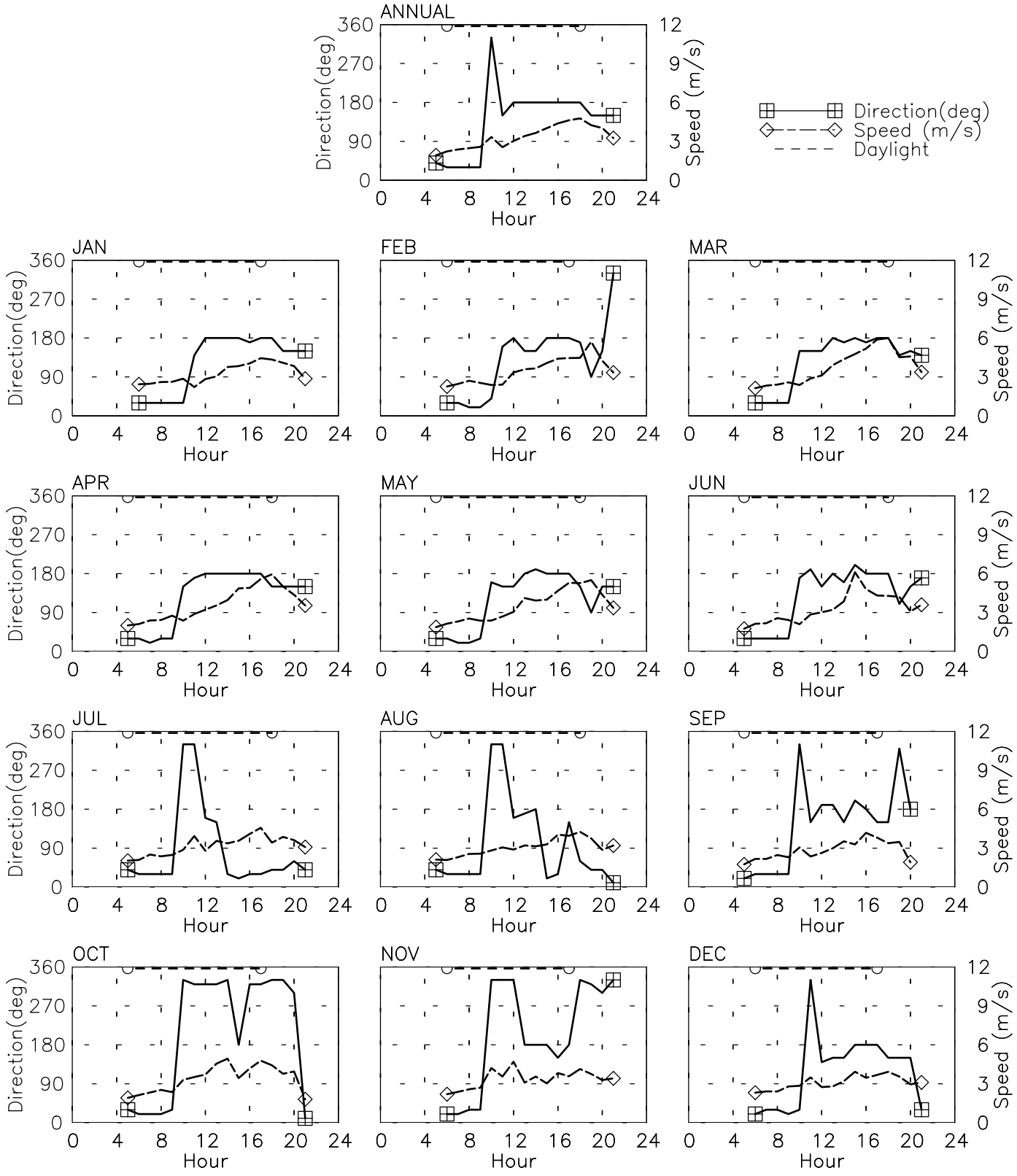
Tue Jun 24 10:03:42 2003

PREVAILING DIRECTION & SPEED BY HOUR

OAXACA/XOXOCOTLAN – 767755

16° 58' N 96° 43' W – Elev 1528m *LST=GMT –6 hours NT= –6

01/76–12/82 01/84–12/91 01/93–09/02



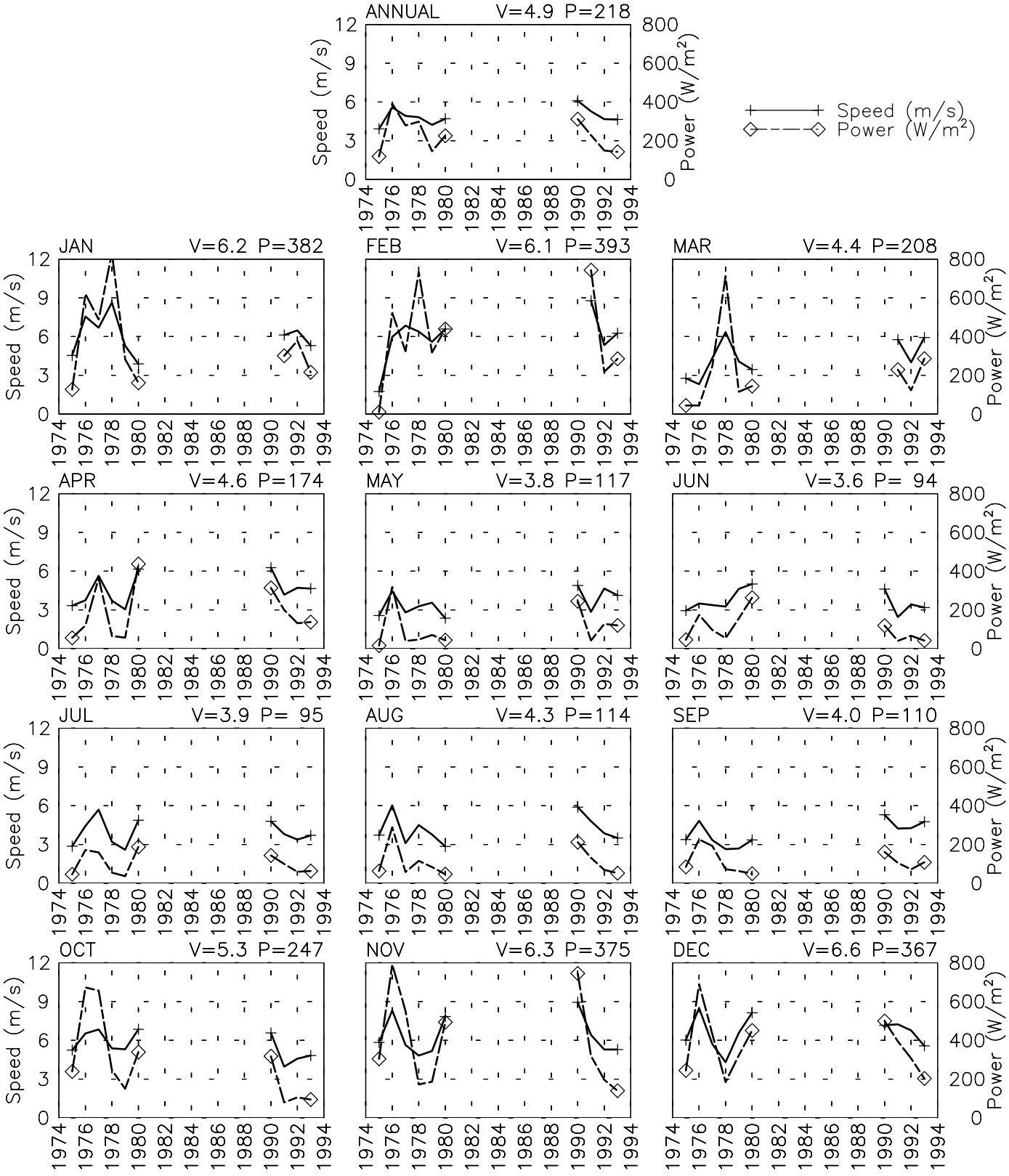
Tue Jun 24 10:03:43 2003

SPEED AND POWER BY YEAR

SALINA CRUZ – 768330

16° 10' N 95° 12' W – Elev 6m *LST=GMT –6 hours NT= –6

01/75–12/80 04/90–12/93



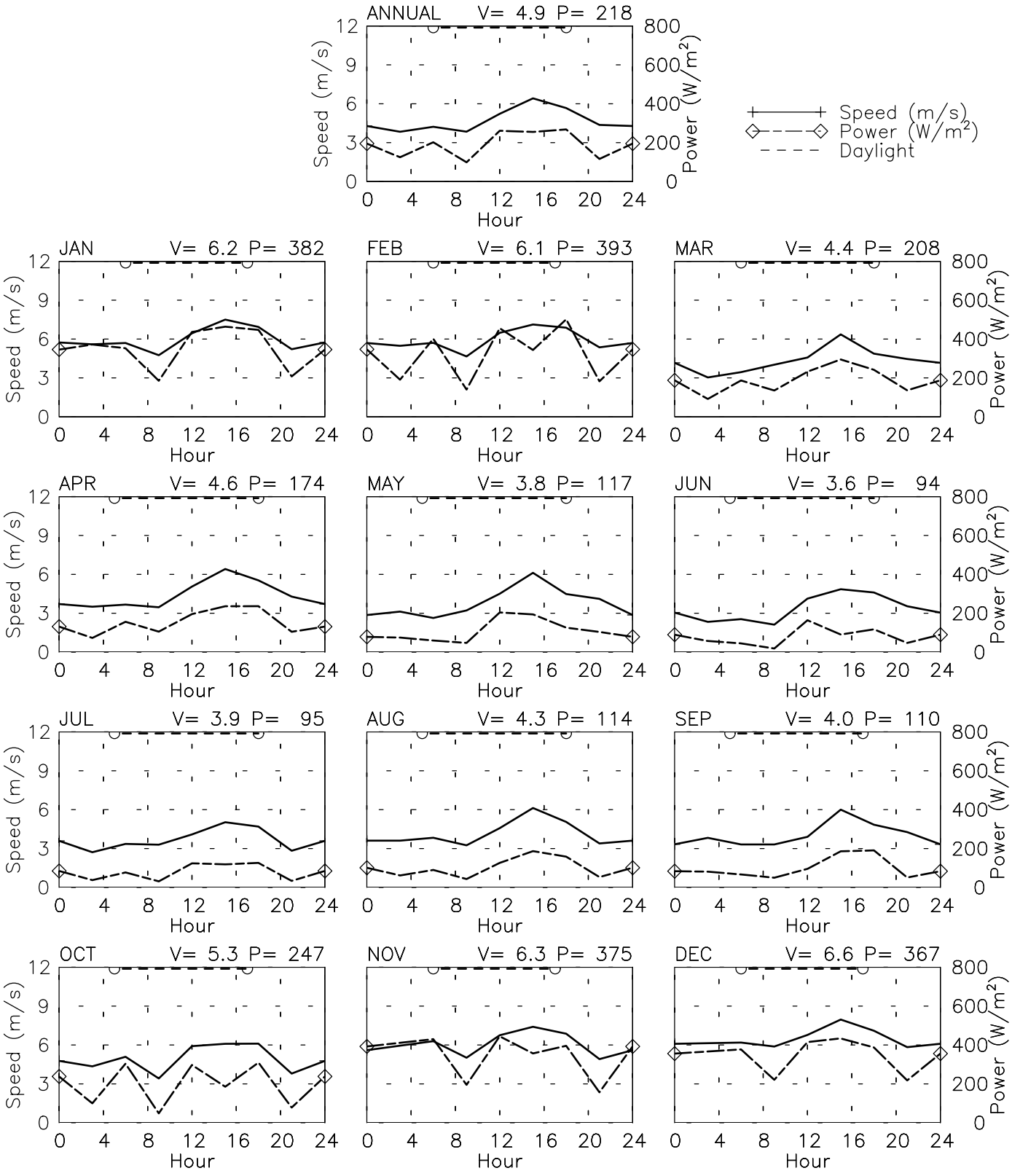
Tue Jun 24 10:03:24 2003

SPEED AND POWER BY HOUR

SALINA CRUZ – 768330

16° 10' N 95° 12' W – Elev 6m *LST=GMT –6 hours NT= –6

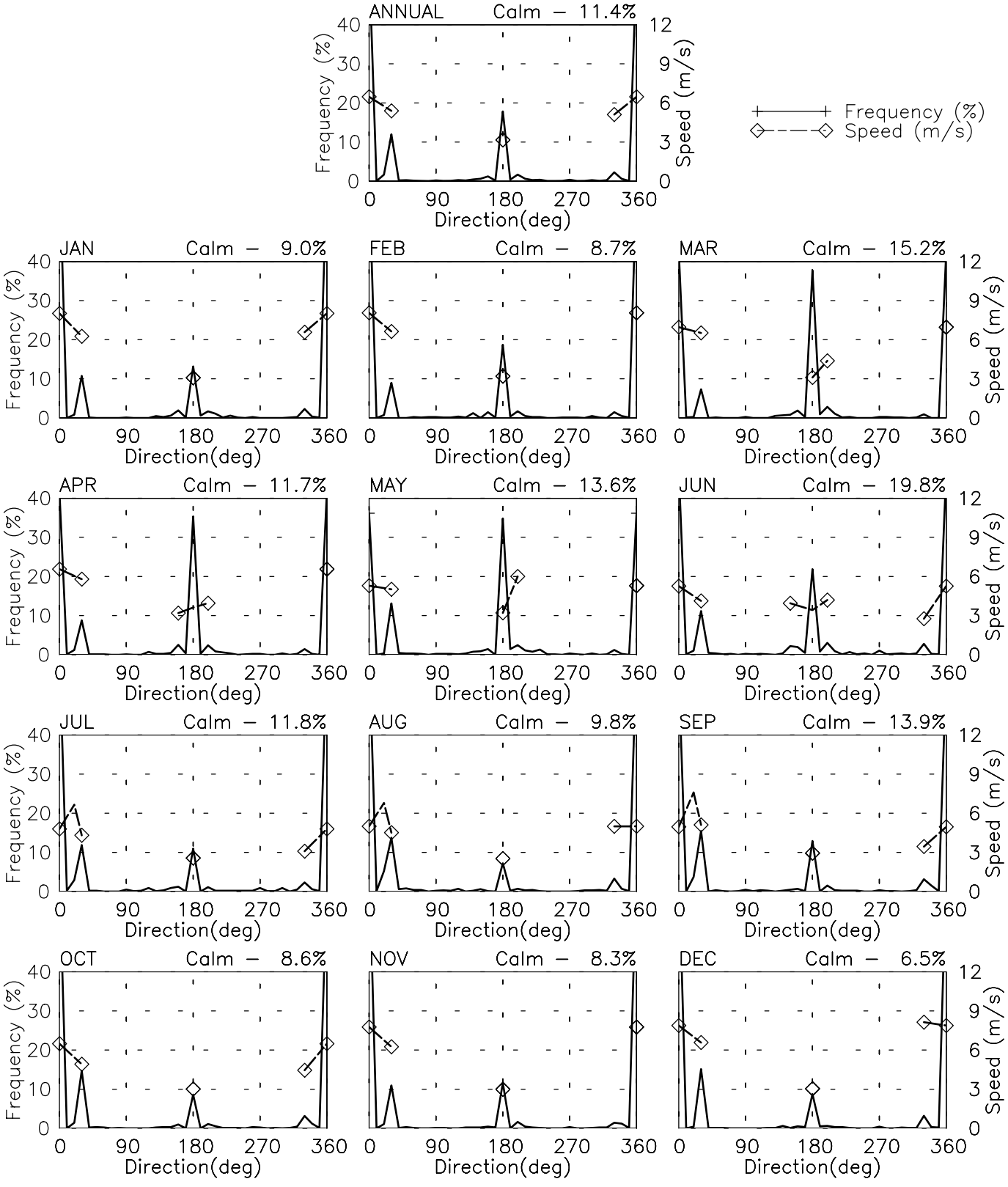
01/75–12/80 04/90–12/93



Tue Jun 24 10:03:25 2003

FREQUENCY AND SPEED BY DIRECTION

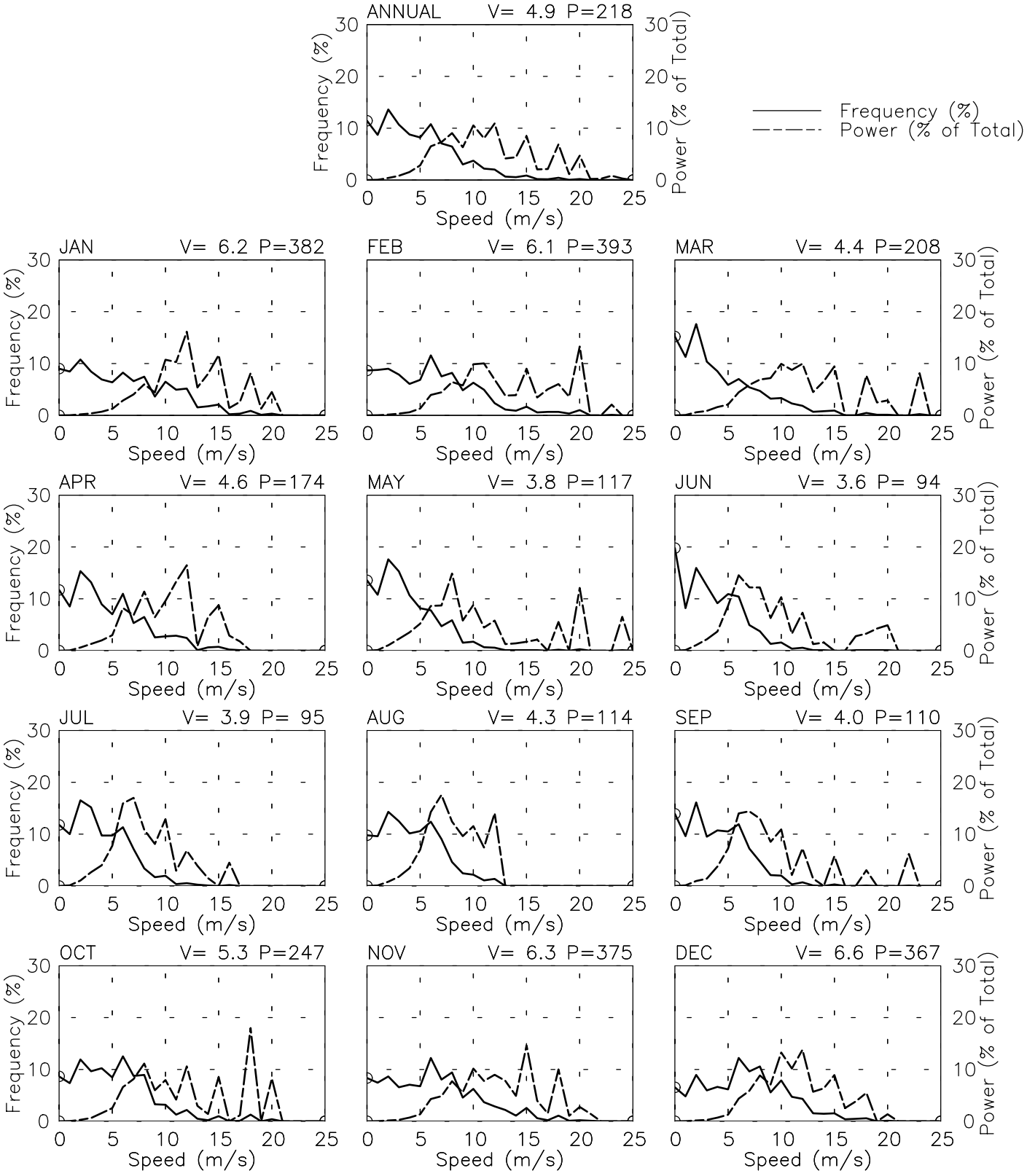
SALINA CRUZ – 768330
16° 10' N 95° 12' W – Elev 6m *LST=GMT –6 hours NT= –6
01/75–12/80 04/90–12/93



Tue Jun 24 10:03:26 2003

FREQUENCY OF SPEED & PERCENT OF POWER BY SPEED

SALINA CRUZ – 768330
16° 10' N 95° 12' W – Elev 6m *LST=GMT –6 hours NT= –6
01/75–12/80 04/90–12/93



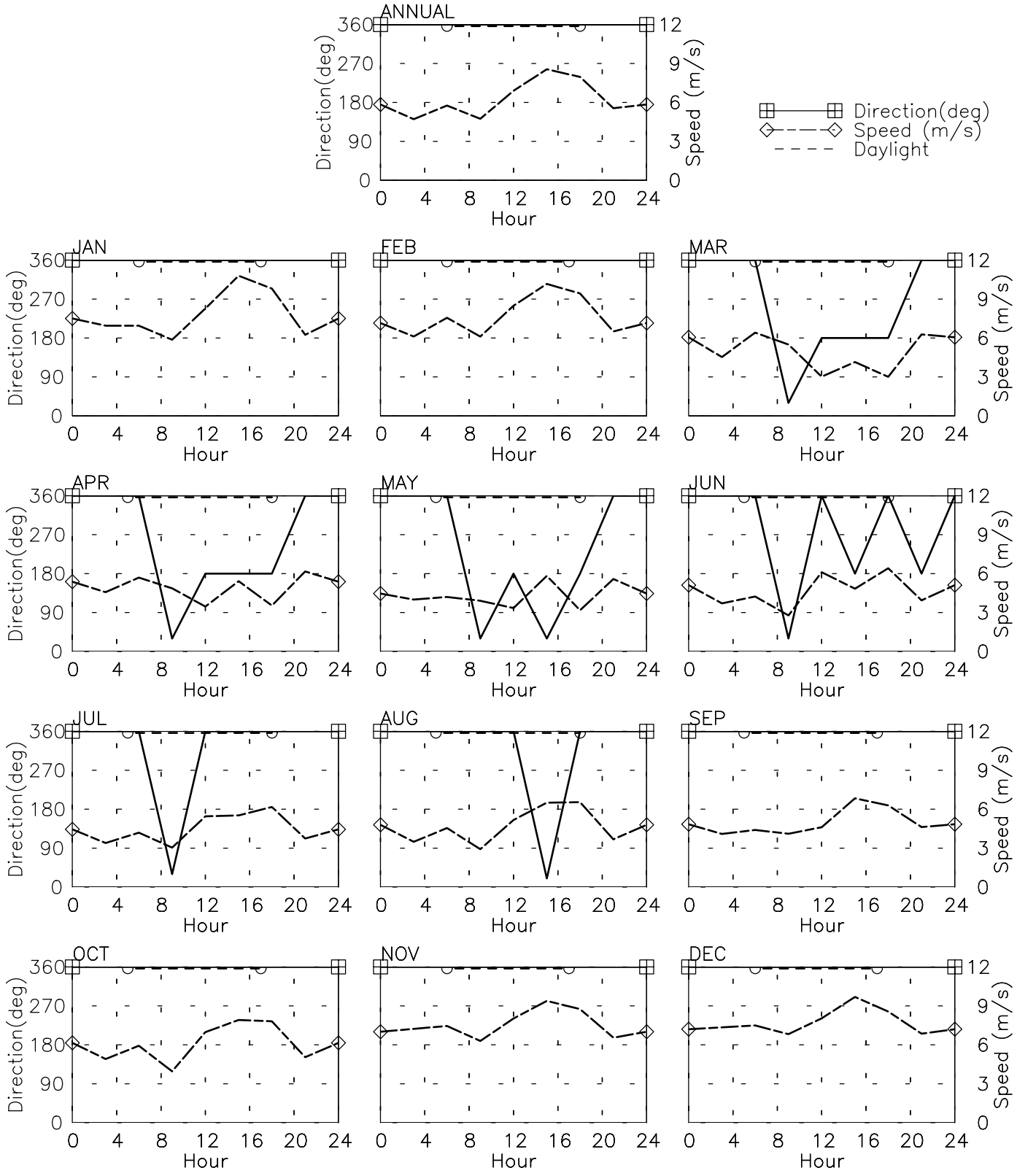
Tue Jun 24 10:03:27 2003

PREVAILING DIRECTION & SPEED BY HOUR

SALINA CRUZ – 768330

16° 10' N 95° 12' W – Elev 6m *LST=GMT –6 hours NT= –6

01/75–12/80 04/90–12/93



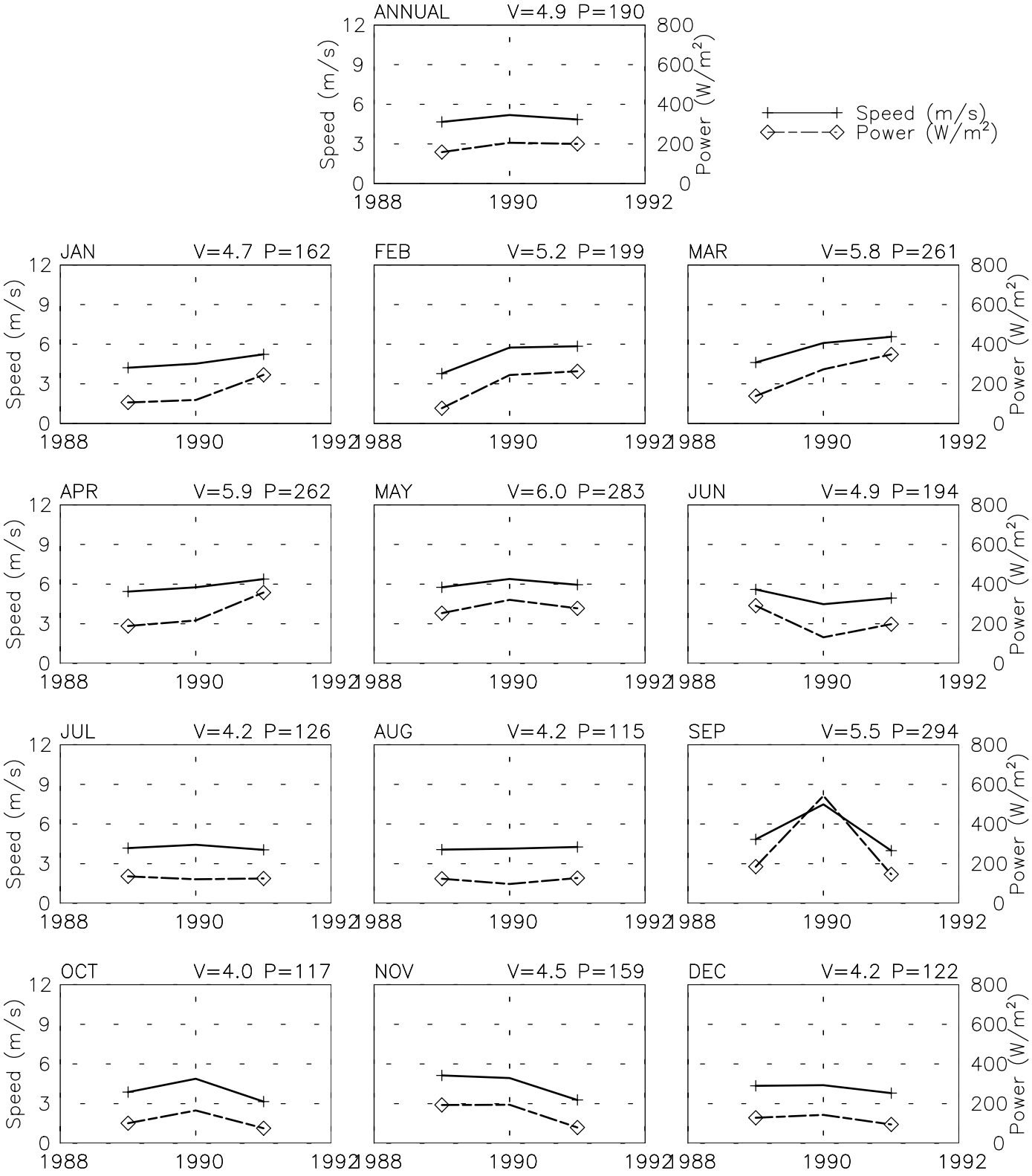
Tue Jun 24 10:03:27 2003

SPEED AND POWER BY YEAR

BAHIAS DE HUATULCO – 768485

15° 46' N 96° 16' W – Elev 143m *LST=GMT –6 hours NT= –6

01/89–12/91



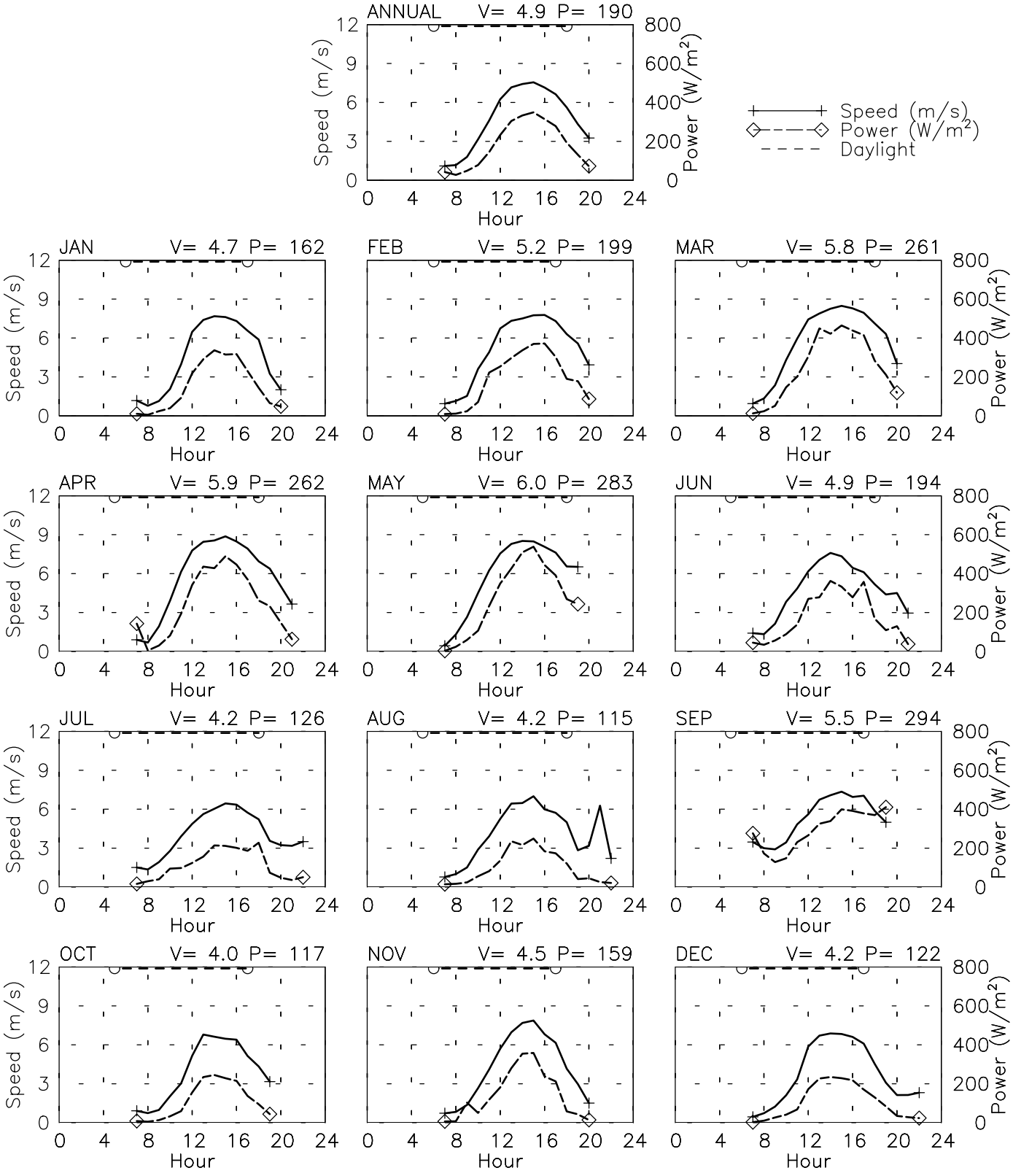
Tue Jun 24 10:03:28 2003

SPEED AND POWER BY HOUR

BAHIAS DE HUATULCO – 768485

15° 46' N 96° 16' W – Elev 143m *LST=GMT –6 hours NT= –6

01/89–12/91



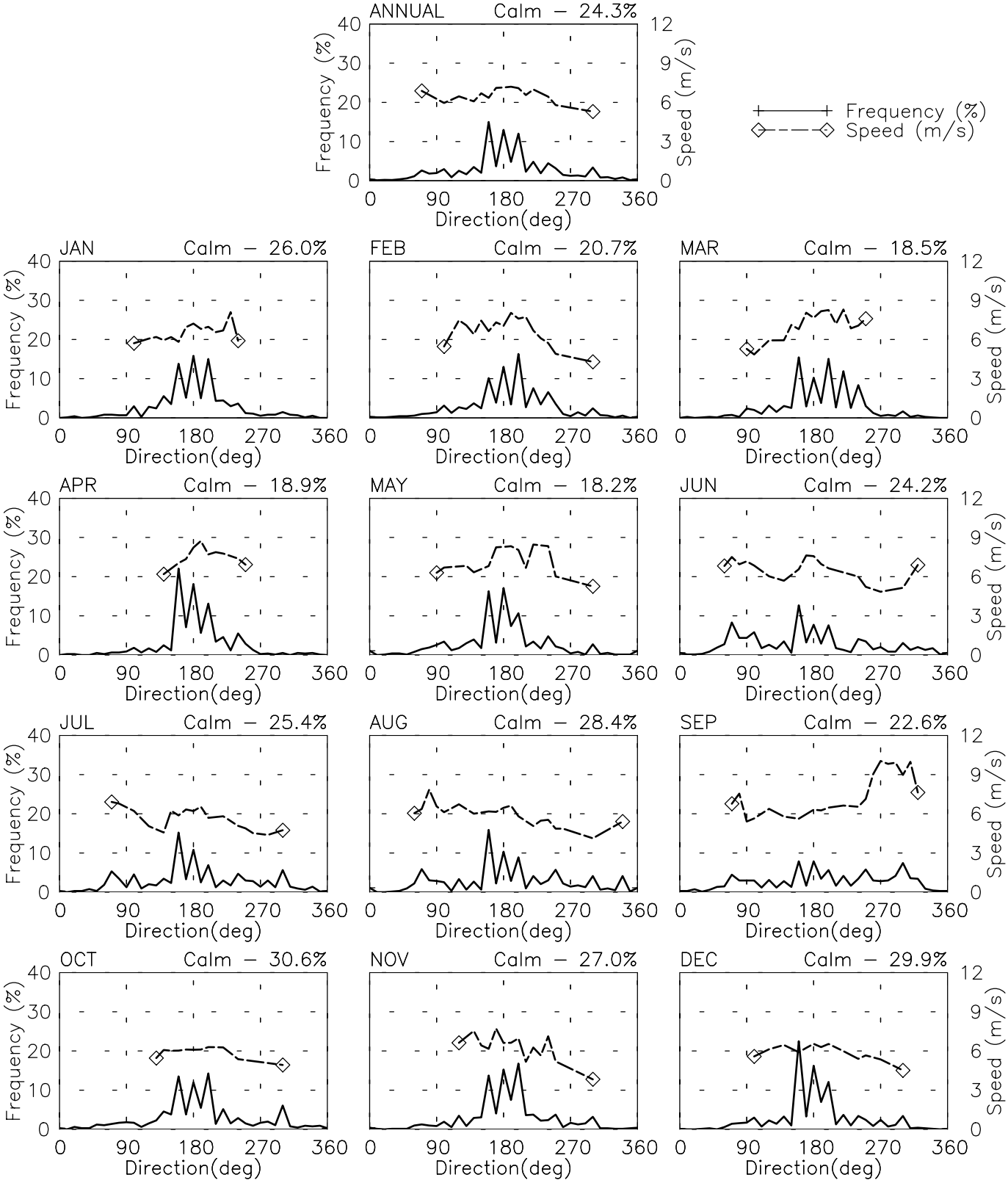
Tue Jun 24 10:03:29 2003

FREQUENCY AND SPEED BY DIRECTION

BAHIAS DE HUATULCO – 768485

15° 46' N 96° 16' W – Elev 143m *LST=GMT –6 hours NT= –6

01/89–12/91



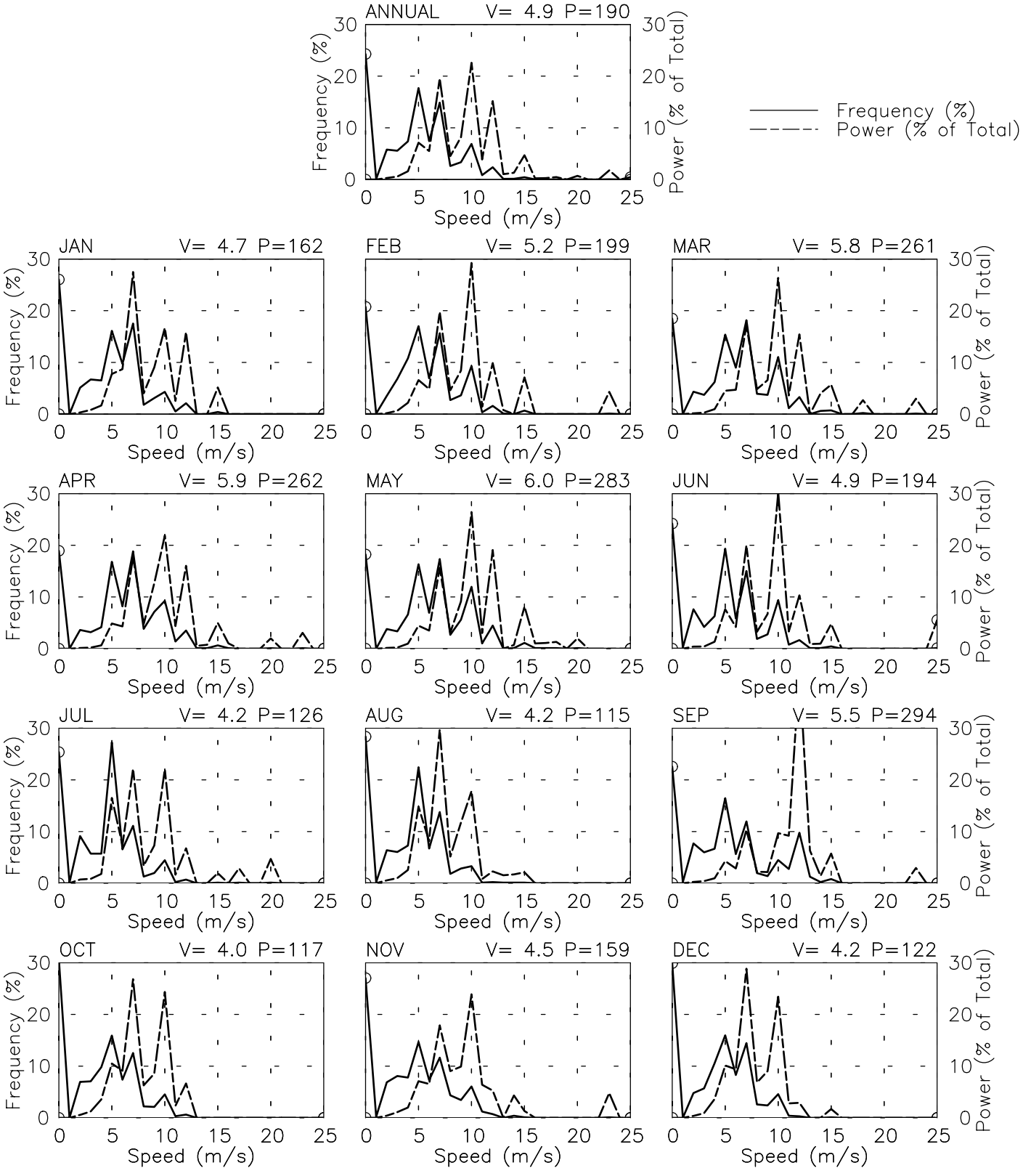
Tue Jun 24 10:03:30 2003

FREQUENCY OF SPEED & PERCENT OF POWER BY SPEED

BAHIAS DE HUATULCO – 768485

15° 46' N 96° 16' W – Elev 143m *LST=GMT −6 hours NT= −6

01/89–12/91



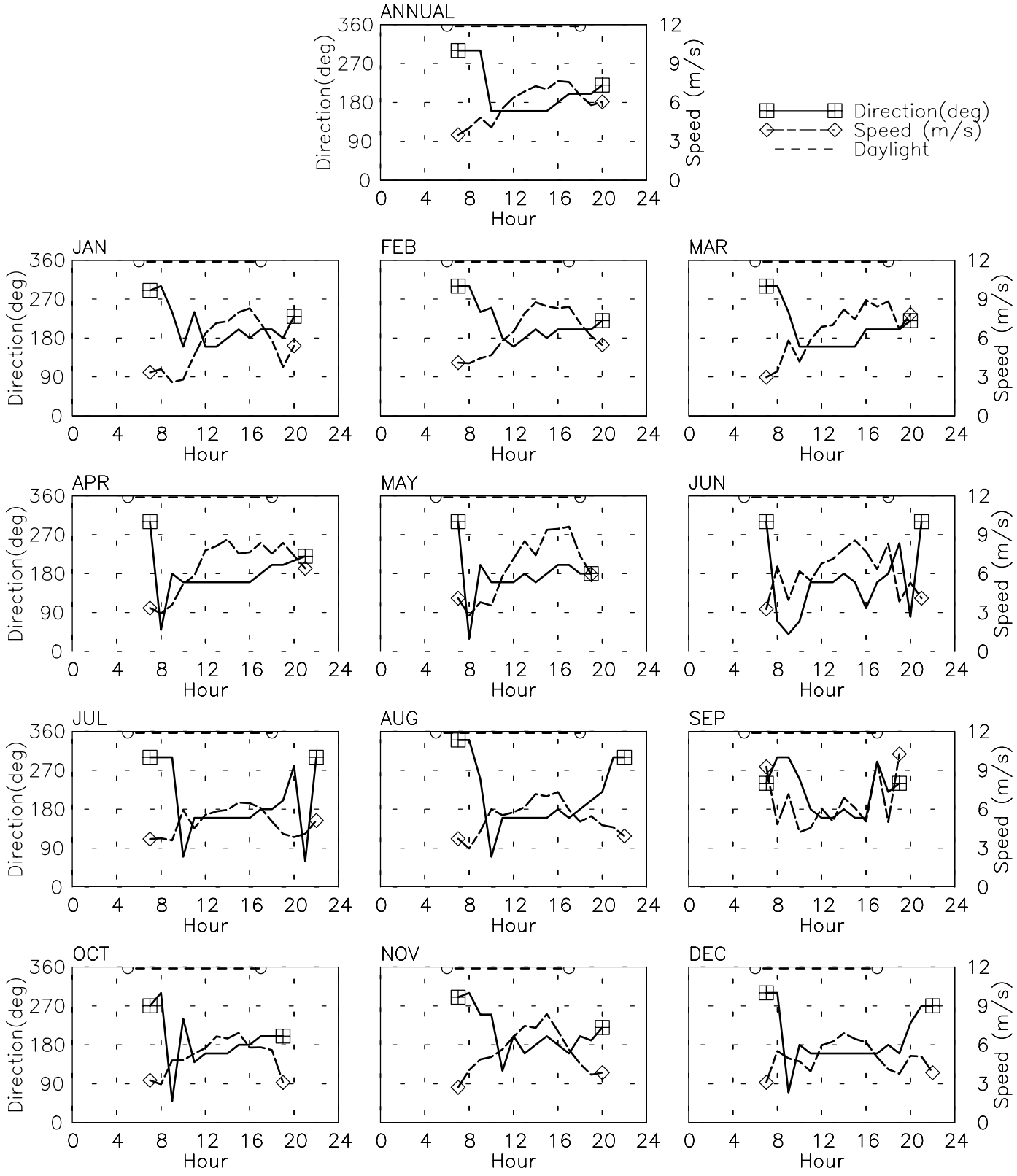
Tue Jun 24 10:03:30 2003

PREVAILING DIRECTION & SPEED BY HOUR

BAHIAS DE HUATULCO – 768485

15° 46' N 96° 16' W – Elev 143m *LST=GMT –6 hours NT= –6

01/89–12/91



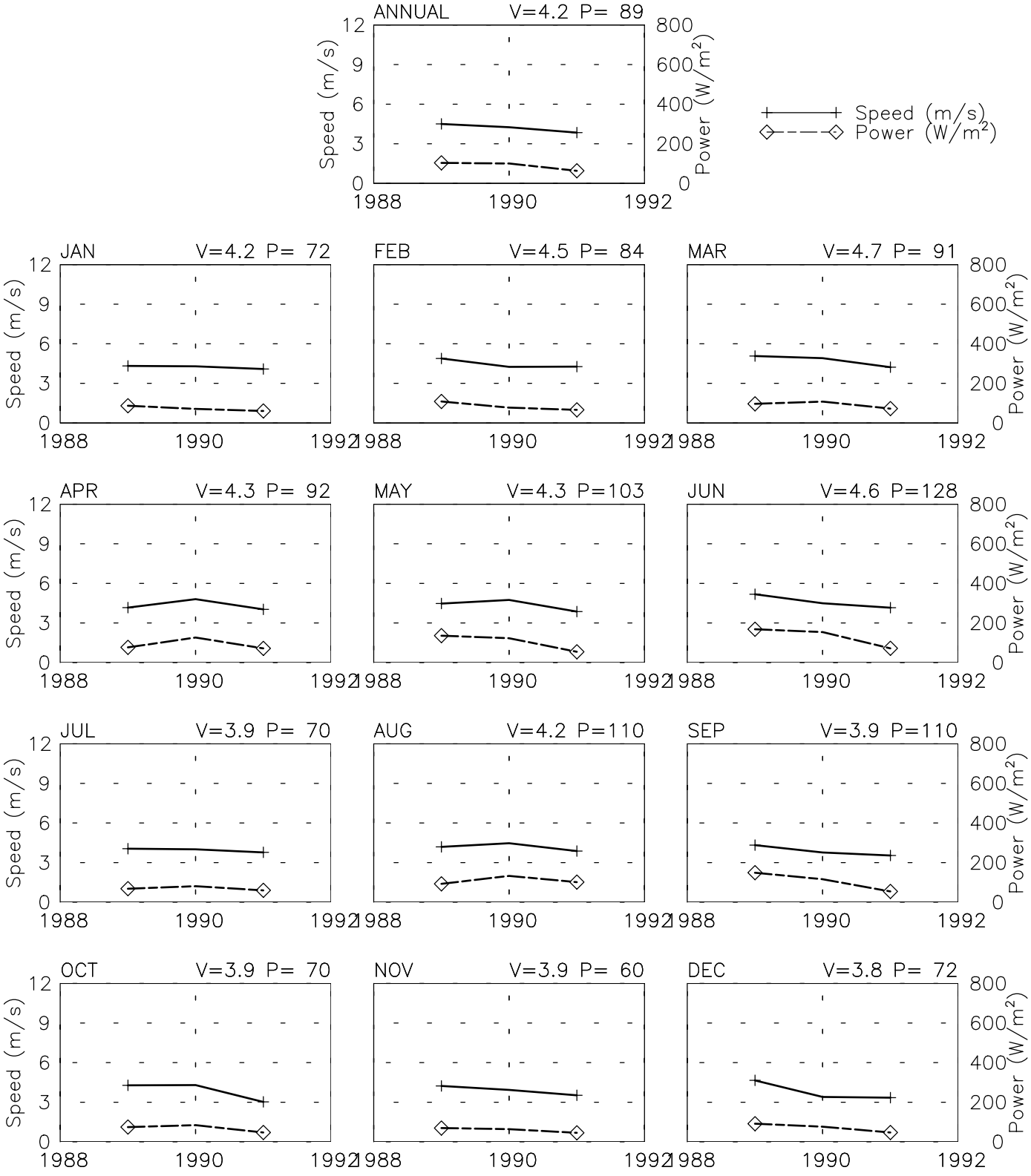
Tue Jun 24 10:03:31 2003

SPEED AND POWER BY YEAR

PUERTO ESCONDIDO – 768556

15° 52' N 97° 04' W – Elev 88m *LST=GMT –6 hours NT= –6

01/89–12/91



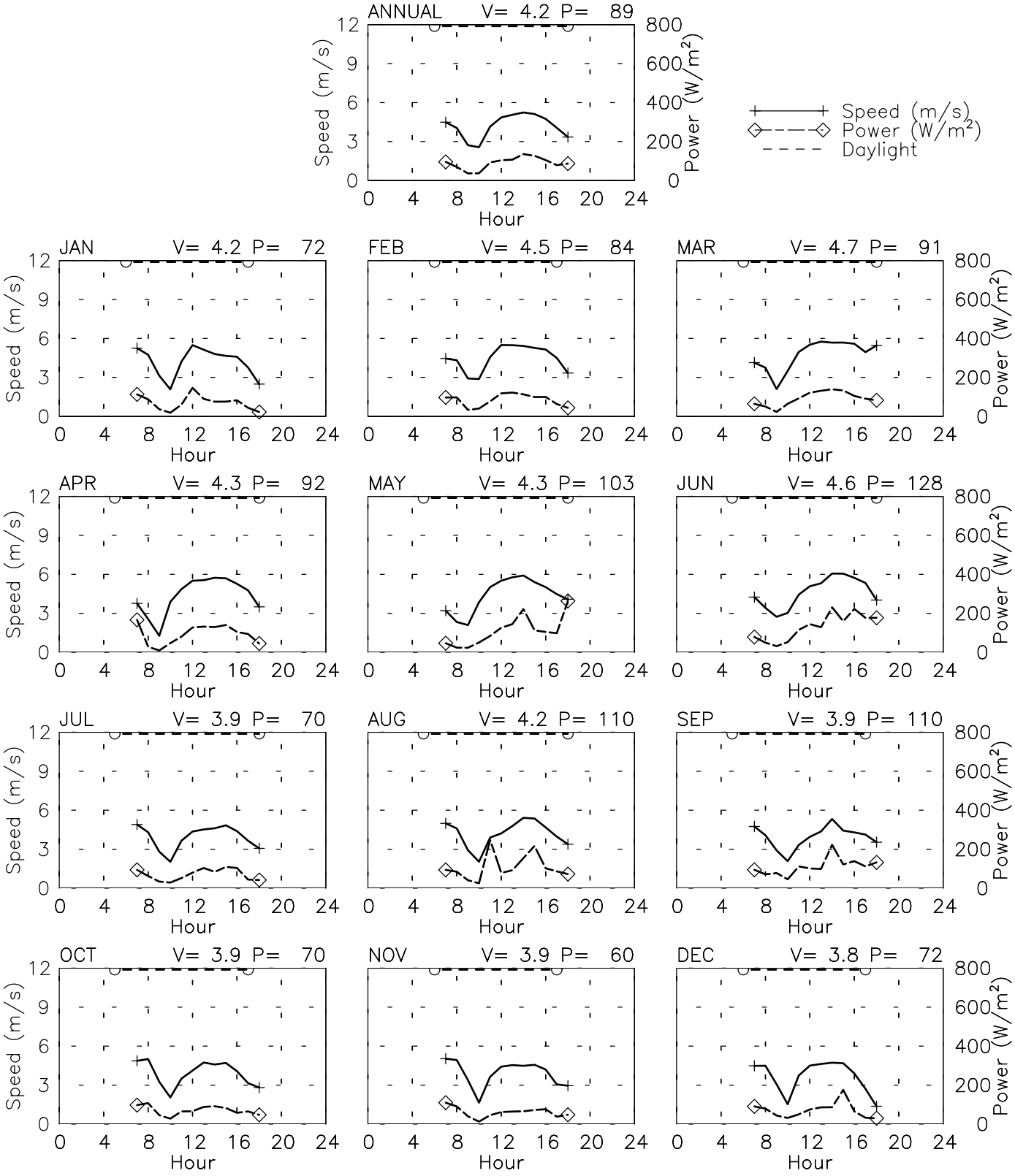
Tue Jun 24 10:03:32 2003

SPEED AND POWER BY HOUR

PUERTO ESCONDIDO – 768556

15° 52' N 97° 04' W – Elev 88m *LST=GMT −6 hours NT= −6

01/89–12/91



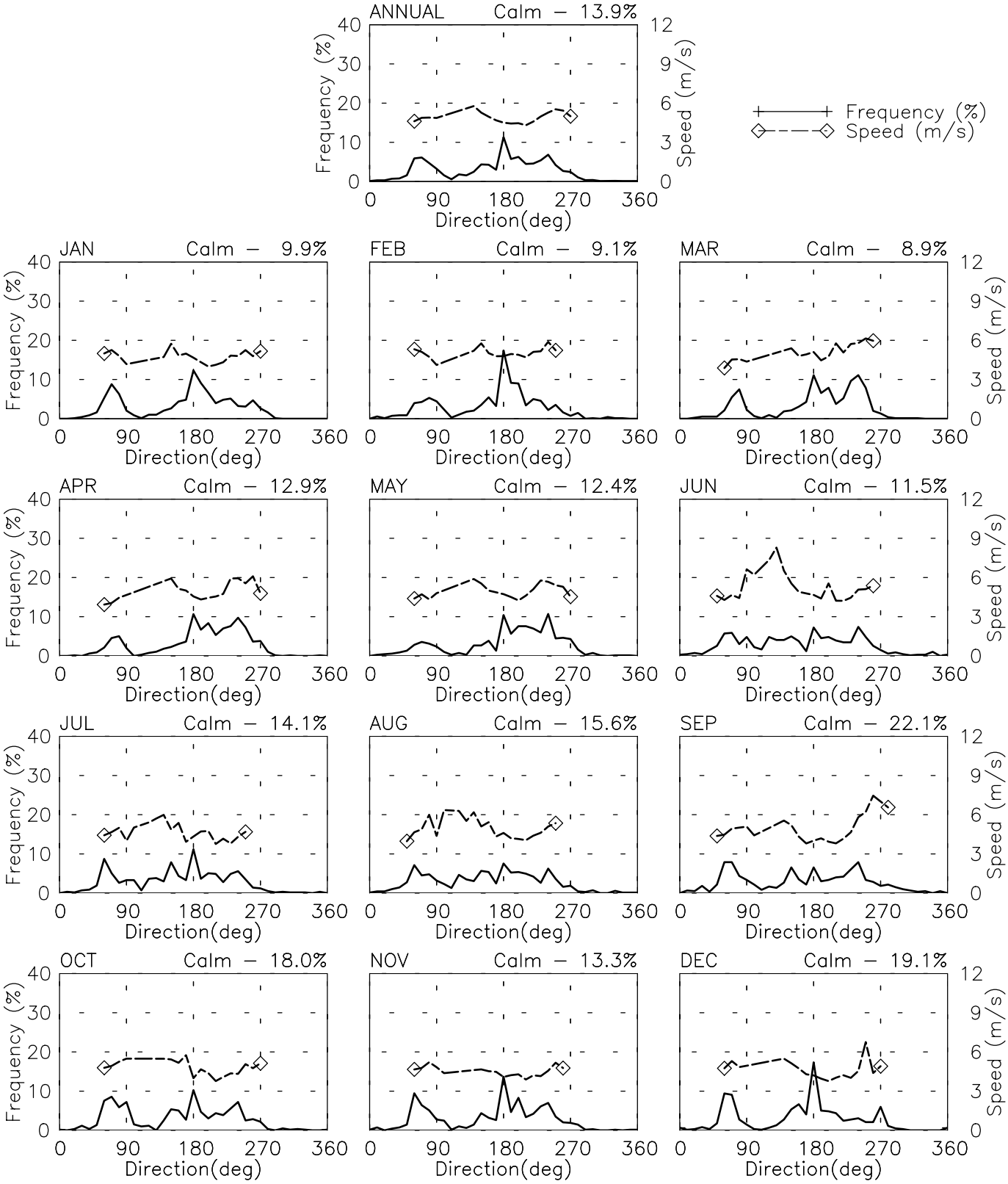
Tue Jun 24 10:03:33 2003

FREQUENCY AND SPEED BY DIRECTION

PUERTO ESCONDIDO – 768556

15° 52' N 97° 04' W – Elev 88m *LST=GMT –6 hours NT= –6

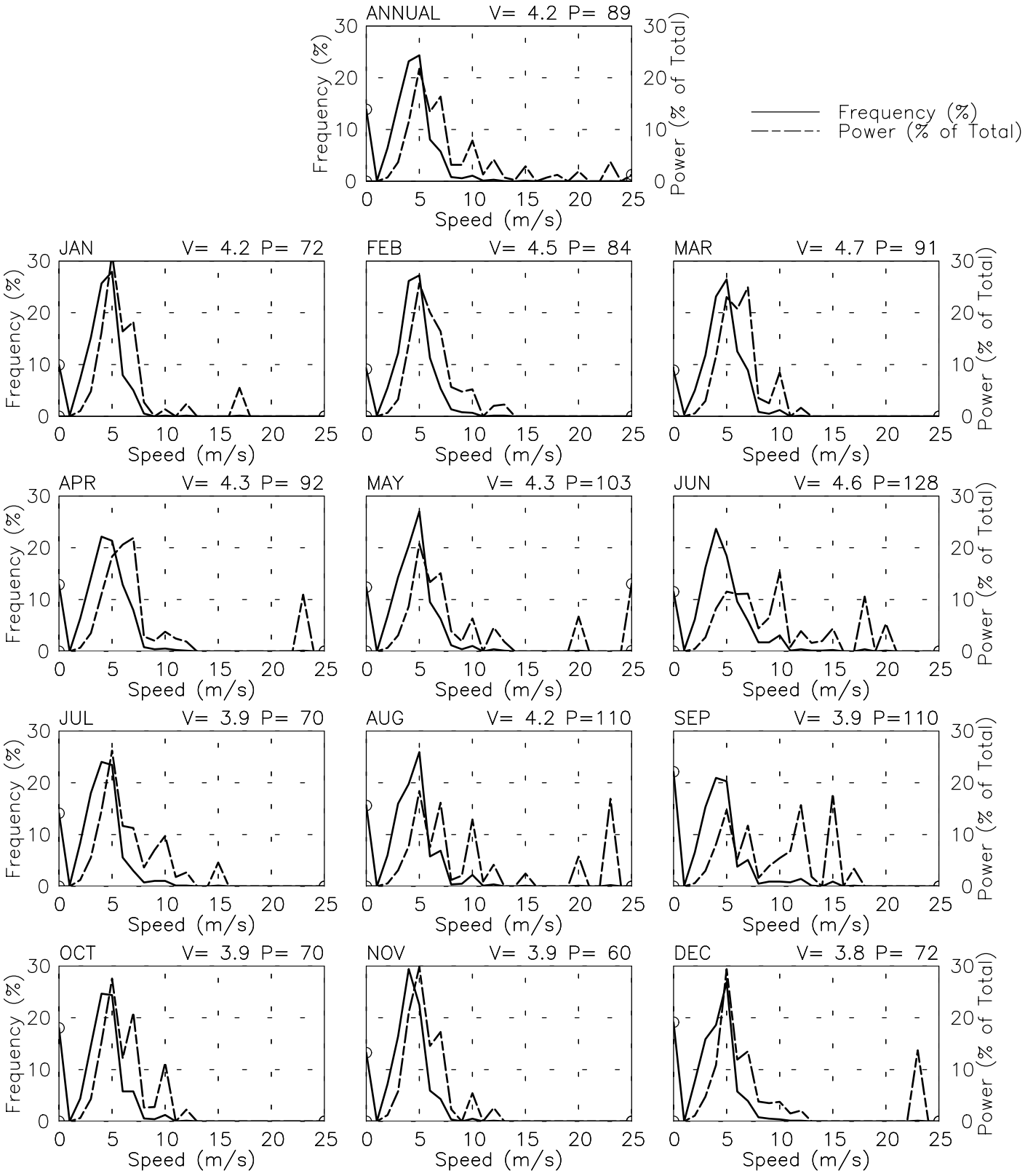
01/89–12/91



Tue Jun 24 10:03:33 2003

FREQUENCY OF SPEED & PERCENT OF POWER BY SPEED

PUERTO ESCONDIDO – 768556
15° 52' N 97° 04' W – Elev 88m *LST=GMT –6 hours NT= –6
01/89–12/91



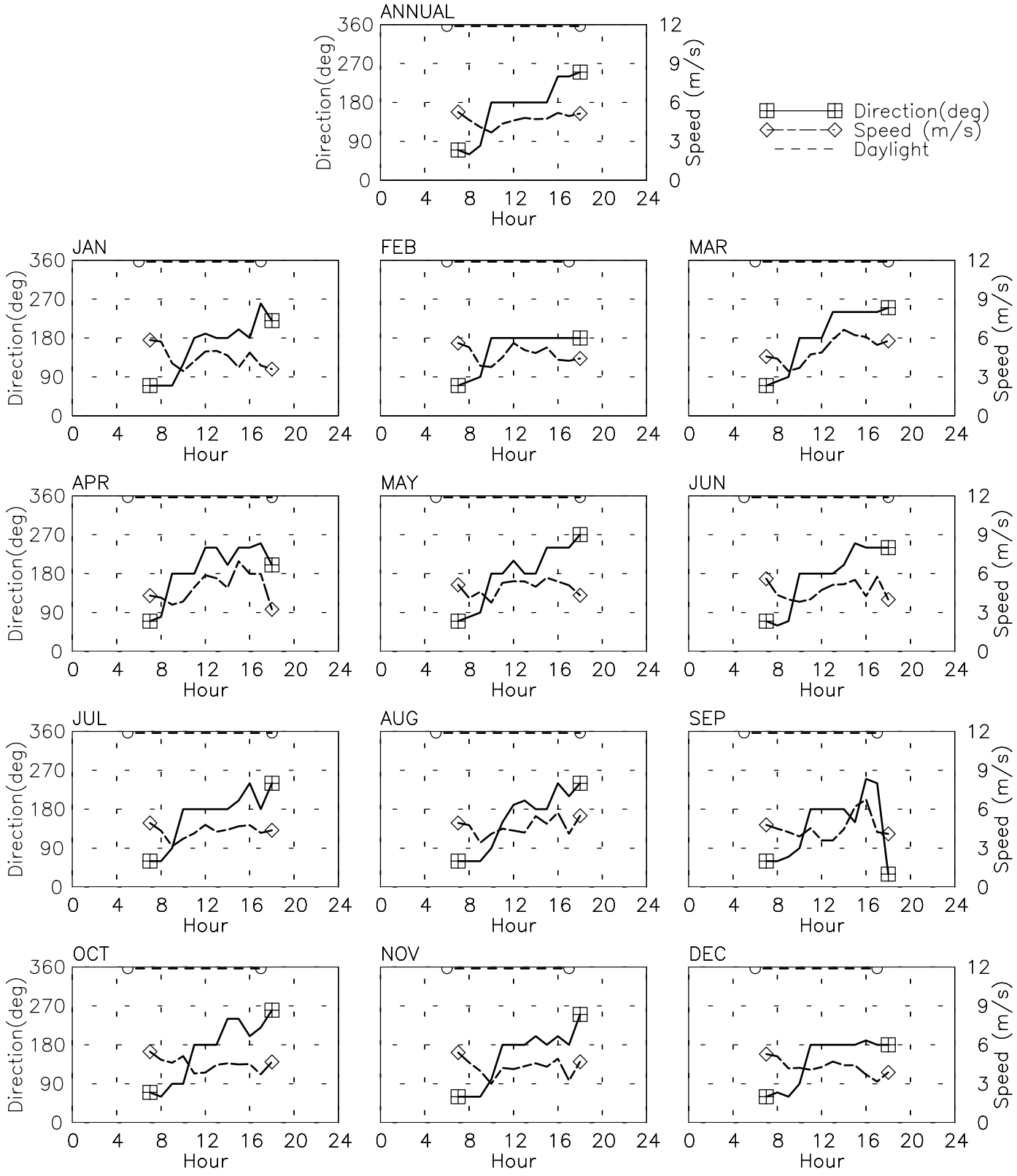
Tue Jun 24 10:03:35 2003

PREVAILING DIRECTION & SPEED BY HOUR

PUERTO ESCONDIDO – 768556

15° 52' N 97° 04' W – Elev 88m *LST=GMT –6 hours NT= –6

01/89–12/91



Tue Jun 24 10:03:36 2003

Appendix B

Surface Meteorological Stations

National Water Commission Sites

Table B.1 National Water Commission Wind Measurement Sites (ordered by wind speed)

Name	LatD	LatM	LatS	LonD	LonM	LonS	Elev	WS
CNA, Puerto Angel, Oaxaca	15	2	50	96	2	50	91	7.00
CNA, Ciudad Alemán, Veracruz	18	11	21	96	5	51	29	5.56
Guevea De Humboldt	16	47	20	95	22	18	600	5.00
Santa Maria del Mar	16	13	17	94	56	41	6	5.00
Tiltepec								5.00
Ixtayutla	16	34	20	97	40	0	510	4.70
CNA, Loma Bonita, Oaxaca	18	1	26	95	5	52	30	4.17
Cuicatlan	17	48	0	96	57	0	595	4.00
El Limón (Tlacamama Jamiltepec)								4.00
Guigovelaga	16	52	0	95	27	0	715	4.00
La Ceiba (Sta Maria Colotepec)	15	31	45	97				4.00
Rio Grande	15	59	0	97	25	0	36	4.00
San Jose del Pacifico	16	10	0	96	30	0	2320	4.00
San Juan Cieneguilla	17	46	0	98	18	0	2260	4.00
San Juan Lajarcia	16	30	30	95	56	22	795	4.00
San Juan Mixtepec	17	18	0	97	50	0	1750	4.00
Santa Catarina	17	41	0	97	56	0	1250	4.00
Santiago Chazumba	18	10	16	97	44	43	1560	4.00
Santiago Teotongo	17	43	0	97	32	0	2000	4.00
Santiago Teotongo								4.00
Sarabia (Juchitan)	17	4	16	95	1	22	80	4.00
Silacoyopan	17	30	0	98	8	0	1440	4.00
SJuan Btsta Cuicatlán								4.00
Sn Agustin Tlacotepec								4.00
Suchixtlahuaca	17	43	45	97	22	0	1875	4.00
Telixtlahuaca	17	17	57	96	54	22	1728	4.00
Totolapan	16	40	13	96	18	25	800	4.00
Yanhuitlán								4.00
Zacatepec	17	9	0	96	56	0	900	4.00
Tomatal número 3	16	29	30	98	17	0	40	3.90
El Encino	17	48	0	98	3	0	1310	3.70
La Blanca(Sto Domingo Ingenio)	16	35	37	94	41	40	40	3.70
El Porvenir								3.60
Etla	17	10	0	96	48	0	1450	3.60
Comitancillo								3.50
Km. 51+740	16	25		95	43		40	3.50
Santo Domingo Barrio Bajo								3.50
Tecnológico								3.40
CNA, Huajuapan de León, Oaxaca	17	49	37.6	97	48	22		3.33
Tehuantepec	16	19	0	95	14	5		3.10
El Fortín	17	4	0	96	43	0	1700	3.00
Ixtepec	16	33	8	95	5	5	57	3.00
Jamiltepec	16	17	0	97	50	0	80	3.00
Km. 33+190	16	34		95	16		41	3.00

La Cumbre	16	51	3	95	27	21	1320	3.00
San Francisco del Mar	16	21	35	94	34	46	10	3.00
San Isidro	15	44	21	96	32	41	14	3.00
San Juan Ihualtepec	17	42	0	98	19	0	3240	3.00
San Martin Itunyoso	17	10	0	97	51	0	1820	3.00
Santa Maria Coatlan	16	51	24	95	31	56	1250	3.00
Santa Maria Xadani	16	21	38	95	1	16	6	3.00
Santa Maria Zaniza	16	39	4	97	20	17	1200	3.00
Santiago Tamazola	18	42	2	98	11	0	1680	3.00
Sn Antonio Monteverde	17	30	0	97	48	0	2400	3.00
Sn Francisco Yosocuta	17	43	0	97	51	0	1320	3.00
Sntiago Chilixtlahuca	17	44	0	97	53	0	1830	3.00
Sntos Reyes Tepejillo	17	26	0	97	55	0	2000	3.00
Sta. Cruz Rio Venado	17	2	0	97	59	0	1000	3.00
Tapanatepec	16	24	9	94	12	58	42	3.00
Teposcolula	17	30	42	97	29	22	1940	3.00
Tezoatlán	17	40	1	97	48	0	1535	3.00
Tilatongo	17	17	18	97	22	41	2250	3.00
Yautepec Ecatepec	16	17	30	95	52	50	1716	3.00
Chahuites	16	17	0	94	12	0	35	2.70
Coixtlahuaca	17	42	0	97	19	0	2080	2.70
El Morro Tehuantepec	16	7	0	95	17	0	60	2.60
Cosoltepec	18	15	0	97	42	0	1700	2.50
Guivicia								2.50
Jaltepec	17	19	17	97	13	9	1950	2.50
San Pedro Huamelula	16	1	0	95	40	0	108	2.50
Huamelula	16	1	0	95	40	0	108	2.30
Juchitán	16	26	57	95	1	28	10	2.20
Zapotitlán Lagunas	17	39	0	98	25	0	1380	2.20
Candelaria	15	55	4	96	29	29	380	2.00
Chalcatongo	17	1	0	97	35	0	2250	2.00
Chilapa de Díaz	17	35	0	97	37	0	2000	2.00
Coyotepec	16	57	25	96	42	3	1460	2.00
El Barrio	16	47	0	95	5	0	230	2.00
El Encino	17	48	0	98	3	0	1310	2.00
El Hicago	16	57	0	94	31	0	250	2.00
El Marqués	16	26	5	95	22	26	98	2.00
Huitzo	17	17	0	96	53	0	1554	2.00
Jalapa del Marqués	17	3	58	96	52	43	1652	2.00
Jalatengo	15	59	30	96	30	39	1260	2.00
Reyes Mantecon	16	54	26	96	43	32	1471	2.00
S Andres Chicahuaxtla	17	4	0	97	50	0	2500	2.00
San Andres Lagunas	17	34	22	97	31	26	2250	2.00
San Antonio Huitepec	16	55	38	97	9	4	2375	2.00
San Baltazar Loxicha	16	4	6	96	47	40	525	2.00
San Bartolo Yautepec	16	25	52	95	58	25	778	2.00

San Isidro Chacalapa	15	51	21	95	56	1	71	2.00
San Jeronimo Taviche								2.00
San Jorge Nuchita	17	40	0	98	7	0	1130	2.00
San Jose Lachiguiri	16	23	0	96	20	0	1800	2.00
San Juan Copala	17	10	0	97	57	0	1640	2.00
San Juan Guelavia	16	57	18	96	32	52	1596	2.00
San Juan Nochixtlan	18	6	0	97	38	0	1100	2.00
San Pedro Huamelula	16	1	0	95	40	0	108	2.00
Santa Maria Zoquitlan	16	33	0	96	22	0	1003	2.00
Santiago Minas	16	25	22	97	13	53	920	2.00
Sn. Lrnzo Vst Hermosa	17	58	0	98	0	0	1900	2.00
Snt Cruz Tierra Negra	17	13	7	95	26	37	280	2.00
Tamazulapan	17	40	0	97	35	0	1770	2.00
Tapanala	15	57	47	95	43	22	37	2.00
Teojomulco								2.00
Tezoaltlan II	17	40	1	97	47	46	1580	2.00
Zimatlán de Álvarez	16	52	27	96	45	14	1501	2.00
Zapotitlan Palmas	17	53	0	97	48	0	848	1.90
Huajuapan de León	17	48	0	97	46	0	1575	1.60
San Pedro Nopala								1.60
Yodocono de Porfirio Díaz	17	23	0	97	21	0	2310	1.60
Jalapa del Valle	15	59	30	96	30	39	1260	1.40
Agua Fría	17	13	42	98	0	0	1800	1.20
Cozoaltepec	15	47	23	96	43	35	100	1.00
Diaz Ordaz	16	59	51	96	25	57	1750	0.90
Guadalupe de Membrillos	18	42	2	97	36	31	2500	0.60
Chacalapa	15	48	53	96	27	56	240	0.30
Nejapan de Madero								0.20
Chacalapa	15	48	53	96	27	56	240	0.10
San Juan Guichicovi	16	57	51	95	5	42	220	0.00
Tepelmeme	17	53	0	97	22	0	2060	0.00
Huatulco	15	49	0	96	19	0	250	
Santa Maria Chimalapa	16	54	28	94	41	23	260	
Santiago Yosondua	17	43	0	97	51	0	2000	
Santo Domingo Zanatepec	16	29	0	94	21	0	35	
Sto. Domingo Zanatepec	16	29	0	94	21	0	35	

Missing data are indicated by blank values. Locations have not been verified and some are known to be wrong. LatD, LatM and LatS are North latitude in degrees, minutes and seconds. LonD, LonM and LonS are West longitude in degrees, minutes and seconds. Elev is elevation in meters above sea level. Wind speed is in meters per second. Typical anemometer height was specified as 7m above ground level.

Table B.2 Monthly Wind Speeds at Selected National Water Commission Stations

Name	Ann	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Santa Maria del Mar	5	6	6	4	4	4	2	4	4	4	6	6	4
Tiltepec	5	2	4	4	4	4	6	6	6	6	6	6	6
Guevea De Humboldt	5	4	4	5	5	5.6	5	5	4.6	4	4.6	6	5
Ixtayutla	4.7	2	5	3	5.8	4.5	4	6	5.7	3.8	4	5.6	8
Sn Agustin Tlacotepec	4	4	2	4	4	4	4	4	4	4	4	2	2
San Jose del Pacifico	4	4	4	4	4	4	4	2	4	4	2	6	2
San Juan Lajarcia	4	5	5	4	6	5	4	4	4	4	4	4	4
San Juan Cieneguilla	4	4	4	6	2	6	2	2	2	6	2	2	4
San Juan Mixtepec	4	4	2	2	2	2	4	4	2	6	4	4	6
S Juan Btst Cuicatlán	4	4	4	4	4	4	4	4	4	4	4	4	4
Zacatepec	4	4	4	4	4	4	4	4	4	4	4	4	4
Sarabia (Juchitan)	4	2	4	4	4	4	4	4	4	4	4	4	4
Silacoyopan	4	4	4	4	4	4	4	4	4	4	4	4	4
Suchixtlahuaca	4	4	4	4	4	4	4	4	4	4	4	4	4
Santiago Teotongo	4	4	4	4	4	4	4	4	4	4	4	4	4
Santa Catarina	4	3	2	2	2	2	4	7	6	3	4	4	2
Santiago Chazumba	4	4	4	2	4	4	4	4	4	4	4	4	4
Totolapan	4	4	4	4	4	4	4	4	4	4	4	4	4
Santiago Teotongo	4	4	4	4	4	4	2	6	4	6	2	2	2
Telixtlahuaca	4	4	4	4	4	2	4	4	4	4	4	4	4
Cuicatlan	4		4	4	4	4					4	4	4
Guigovelaga	4		1			1			4	4	1		2
El Limón (Tlacamama	4	4.4	5	5.6	5.7	4	3	4	4.5	4.7	4	4	4
Rio Grande	4	4	4	4	4	4	4	4	4	4	4	4	4
Yanhuitlán	4	4	3	4	3	4	4	3	4	3	2	5	5
La Ceiba (Santa Mar	4	4	4	4.6	6.5	4	4	4	4	4	4	4	2

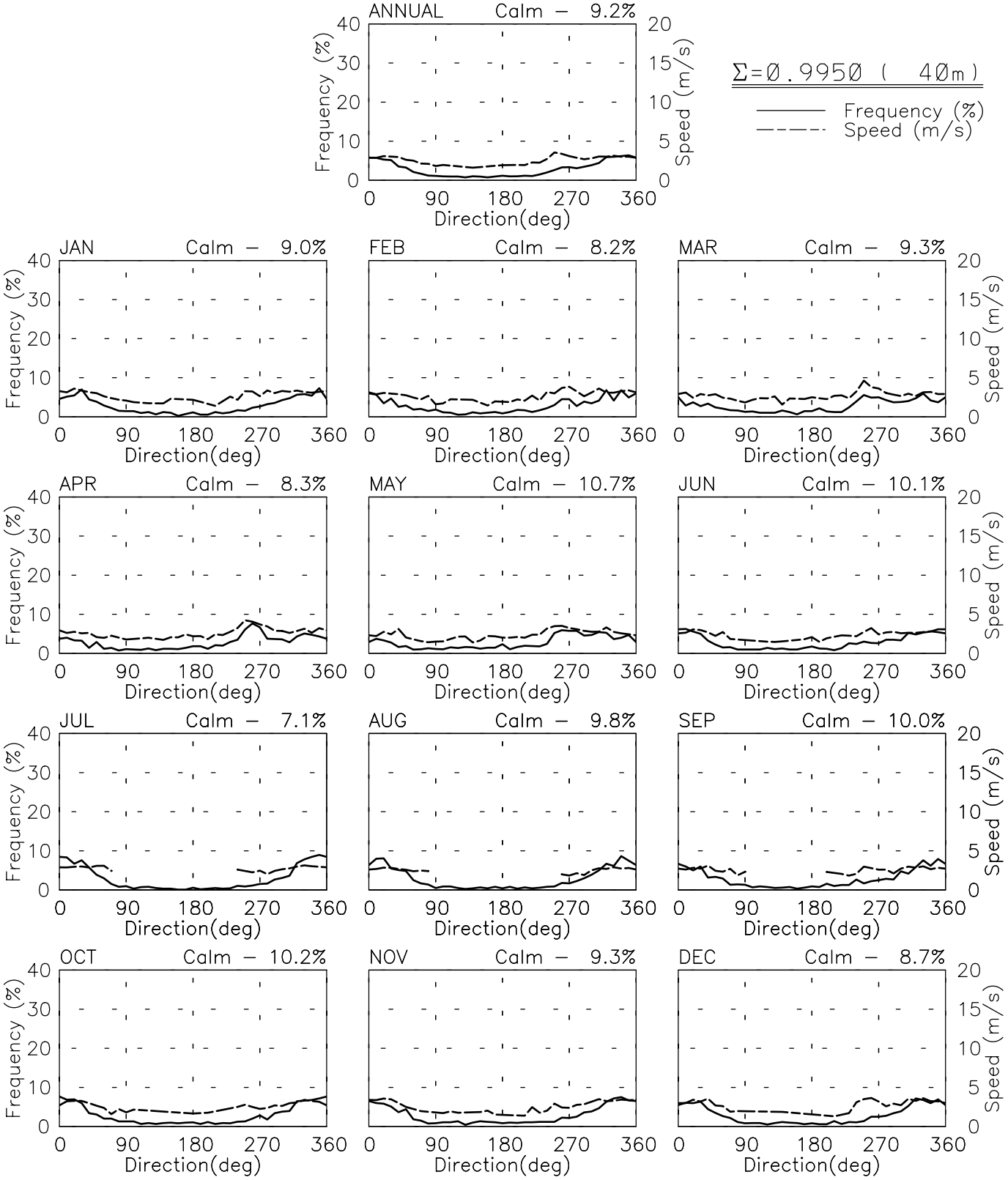
Appendix C

Reanalysis Upper Air Wind Data

Analysis Summaries

FREQUENCY & SPEED BY DIRECTION (SIGMA)

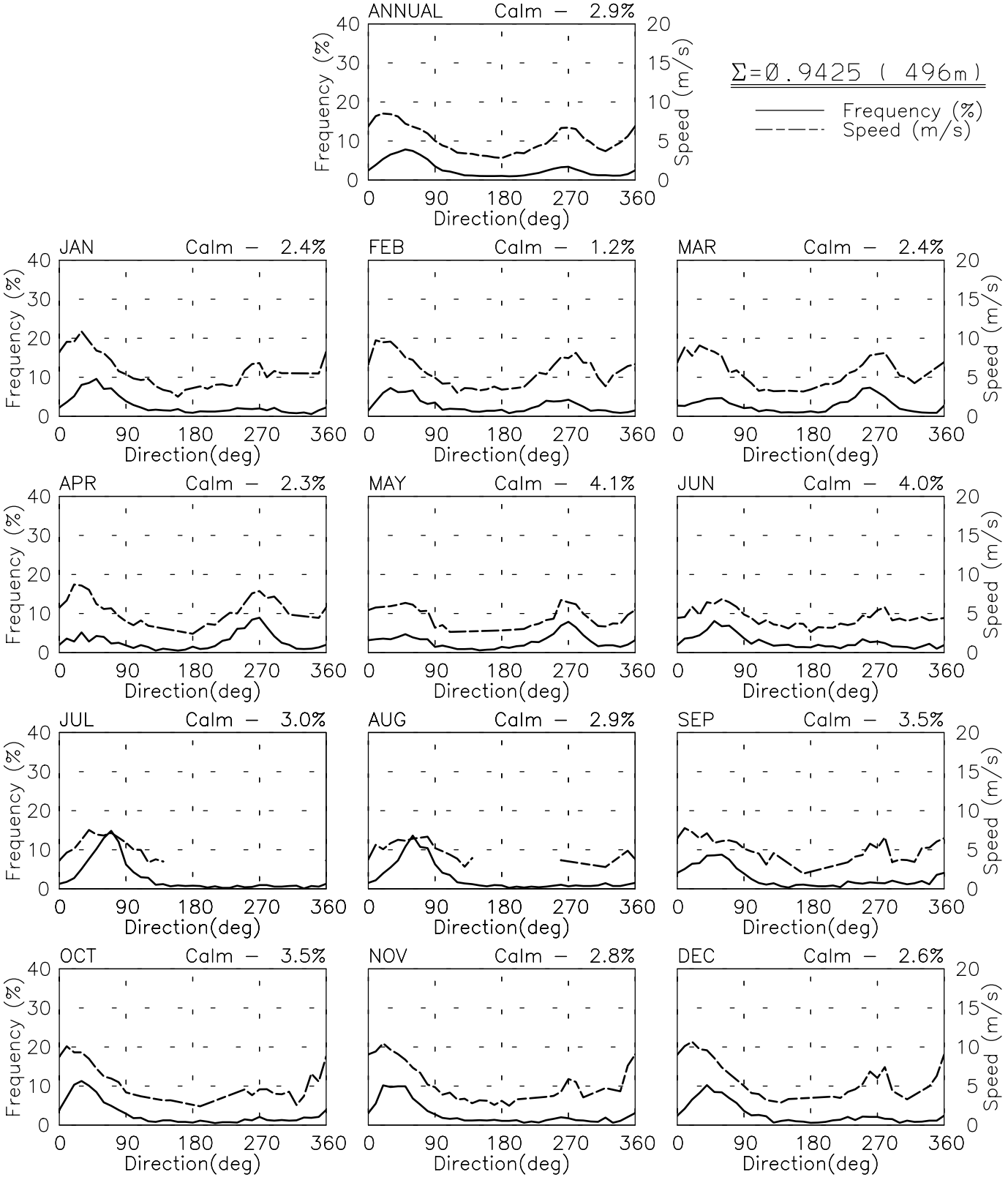
Reanalysis T62 Gauss – 07244 – 0500 LST
18° 05' N 97° 30' W – Elev 1328m
01/58–12/97



Tue Jun 24 14:36:42 2003

FREQUENCY & SPEED BY DIRECTION (SIGMA)

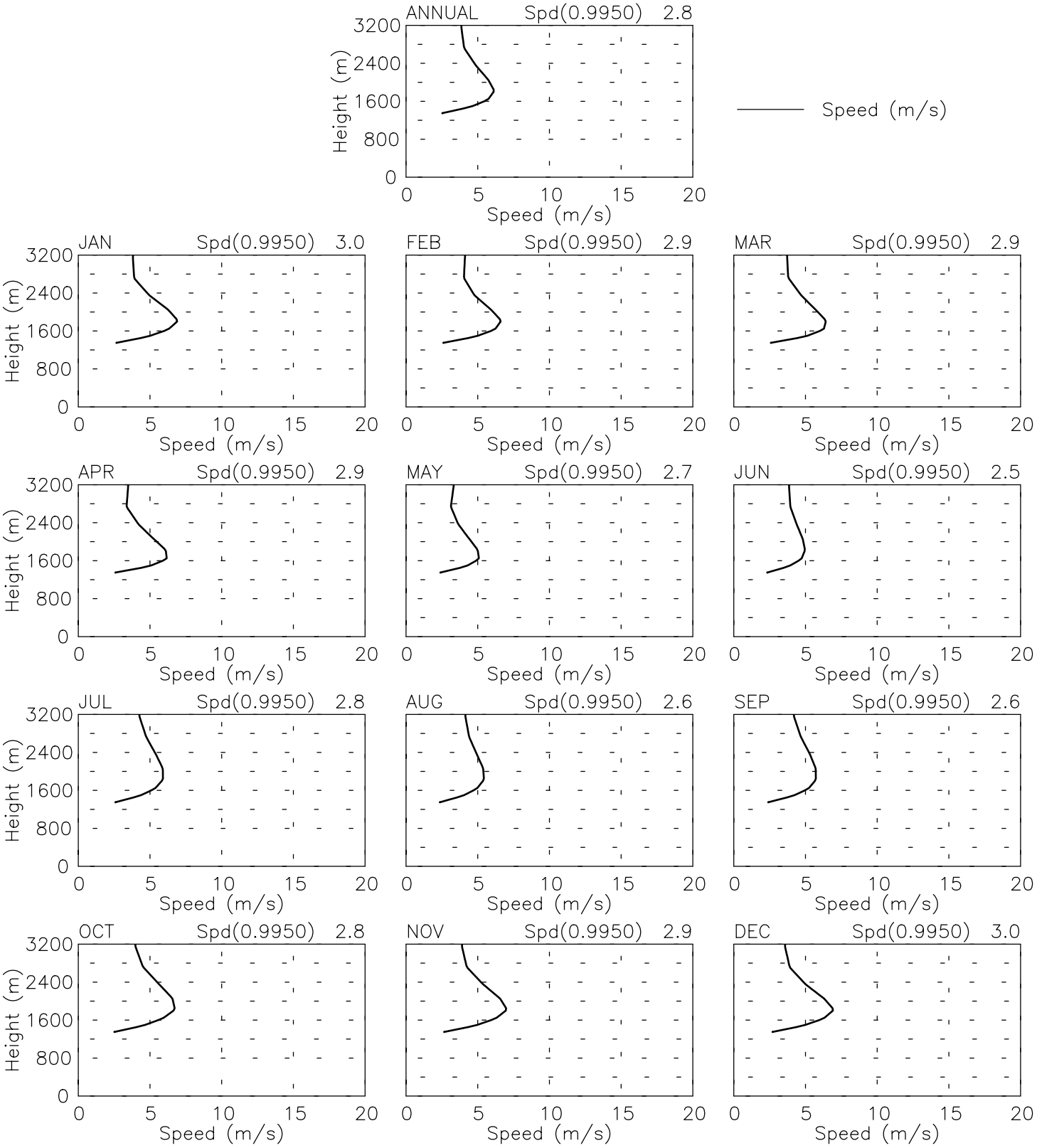
Reanalysis T62 Gauss – 07244 – 0500 LST
18° 05' N 97° 30' W – Elev 1328m
01/58–12/97



Tue Jun 24 14:36:43 2003

VERTICAL WIND SPEED PROFILE BY HEIGHT

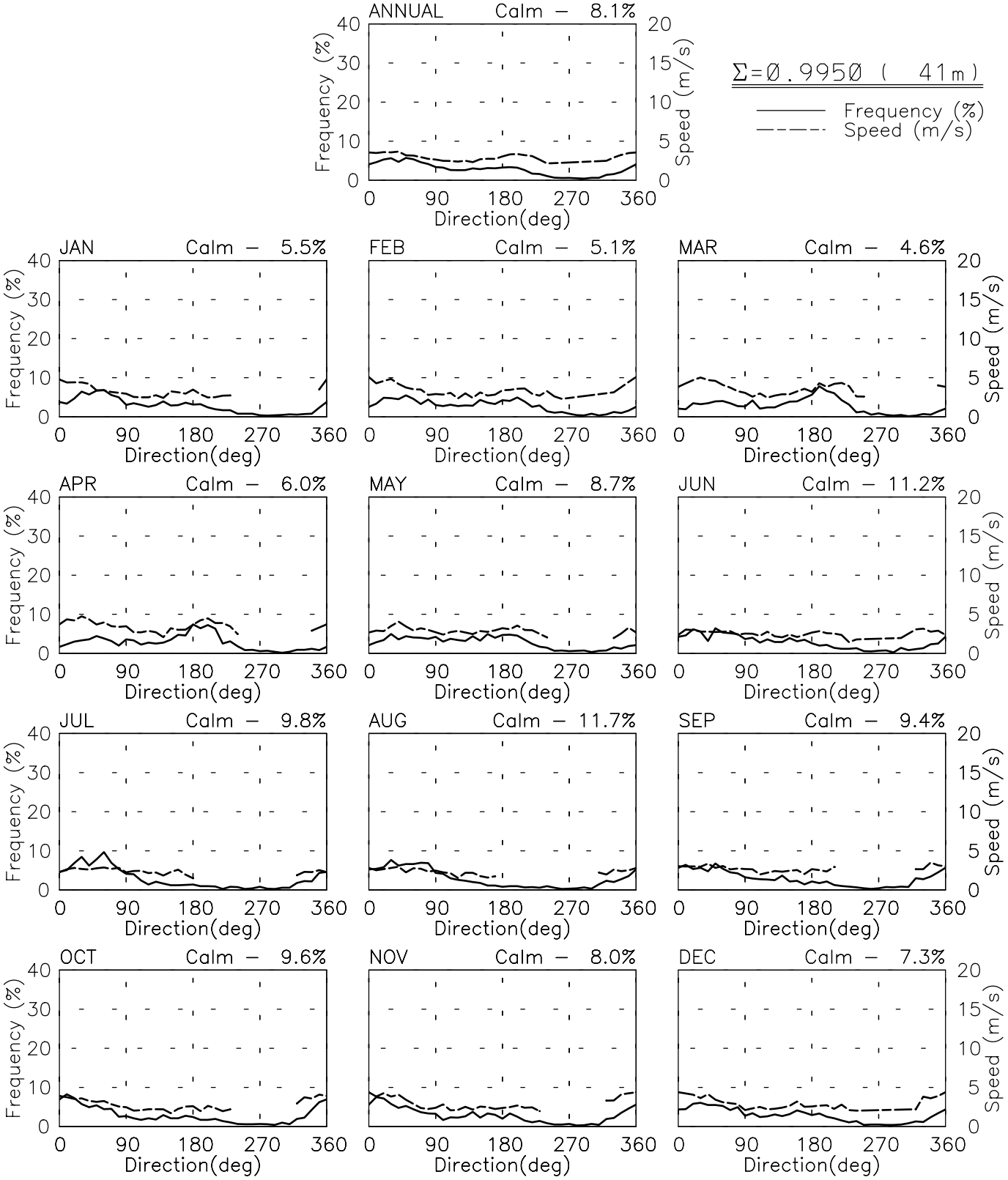
Reanalysis T62 Gauss – 07244 – 0500 LST
18° 05' N 97° 30' W – Elev 1328m
01/58–12/97



Tue Jun 24 14:31:58 2003

FREQUENCY & SPEED BY DIRECTION (SIGMA)

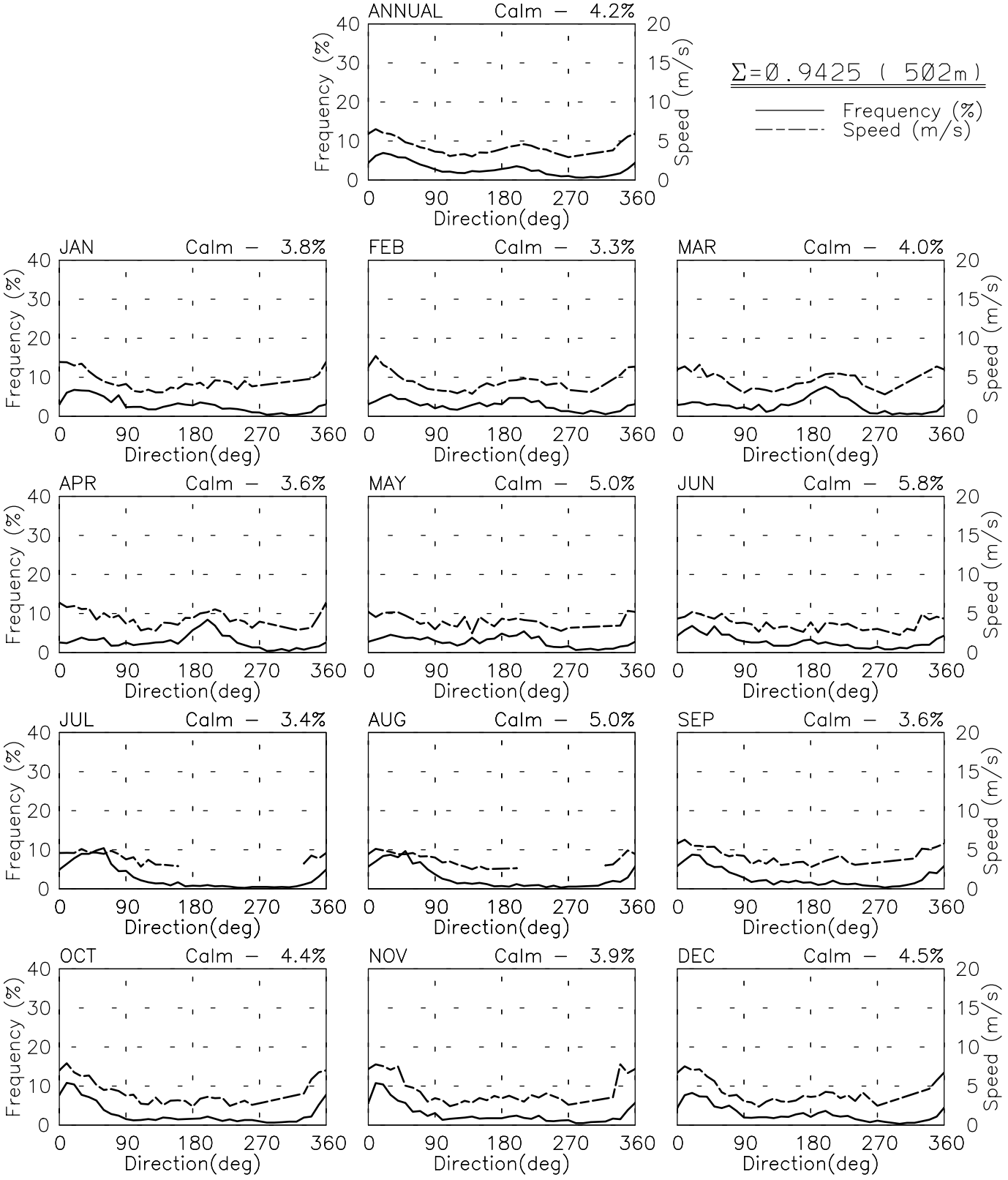
Reanalysis T62 Gauss – 07244 – 1700 LST
18° 05' N 97° 30' W – Elev 1328m
12/57–12/97



Wed Jul 2 14:54:36 2003

FREQUENCY & SPEED BY DIRECTION (SIGMA)

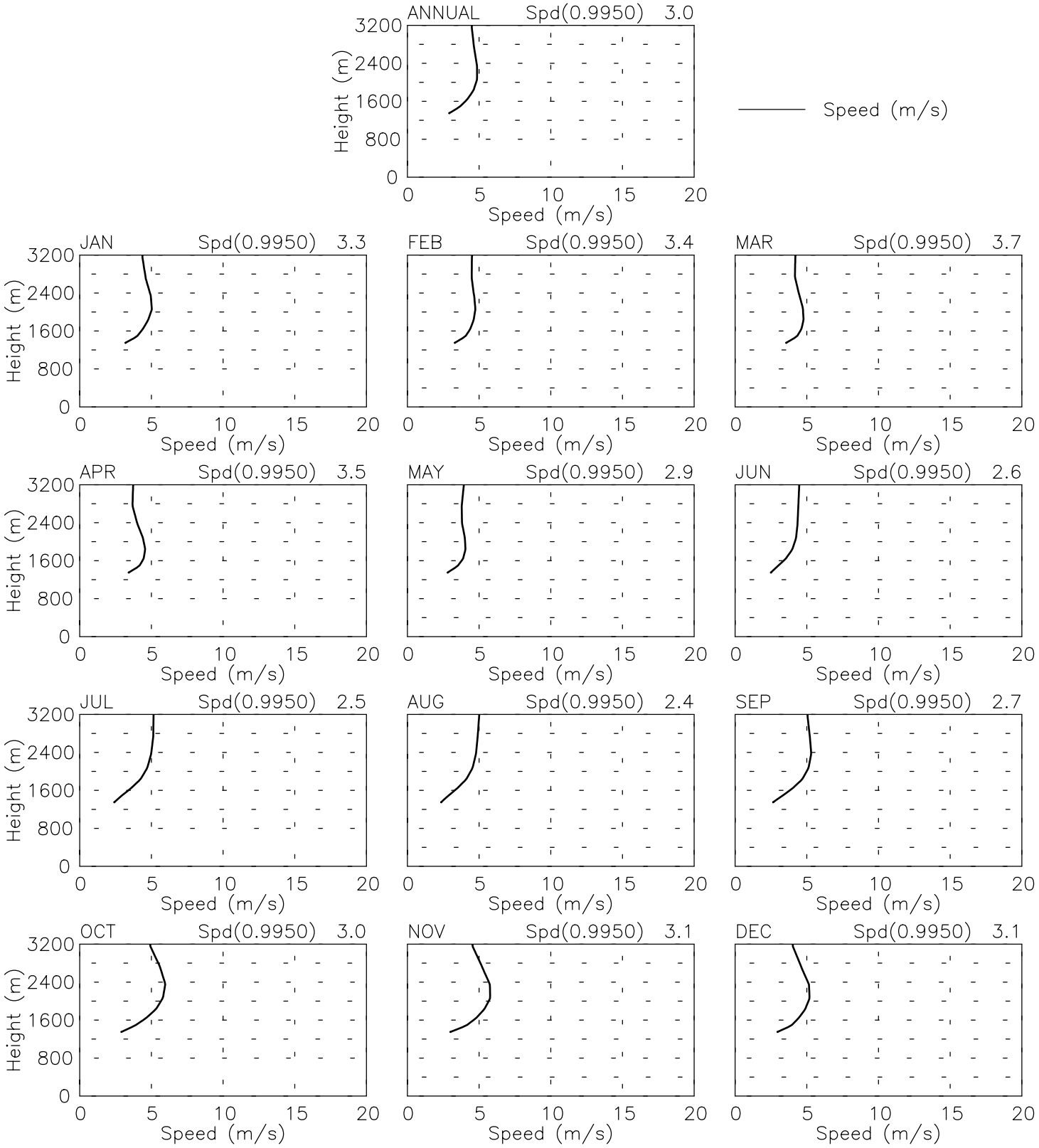
Reanalysis T62 Gauss – 07244 – 1700 LST
18° 05' N 97° 30' W – Elev 1328m
12/57–12/97



Wed Jul 2 14:54:36 2003

VERTICAL WIND SPEED PROFILE BY HEIGHT

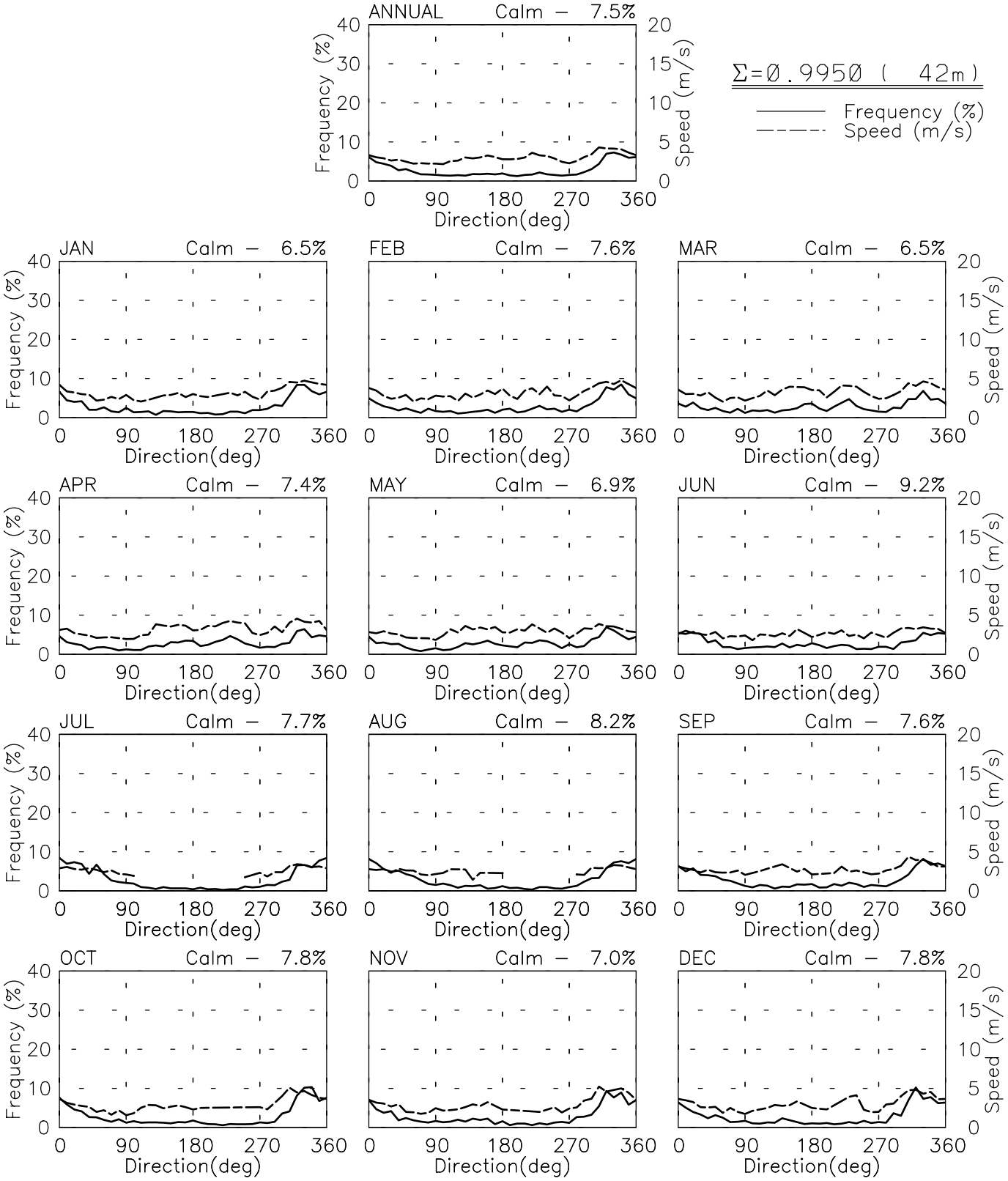
Reanalysis T62 Gauss – 07244 – 1700 LST
18° 05' N 97° 30' W – Elev 1328m
12/57–12/97



Wed Jul 2 14:54:35 2003

FREQUENCY & SPEED BY DIRECTION (SIGMA)

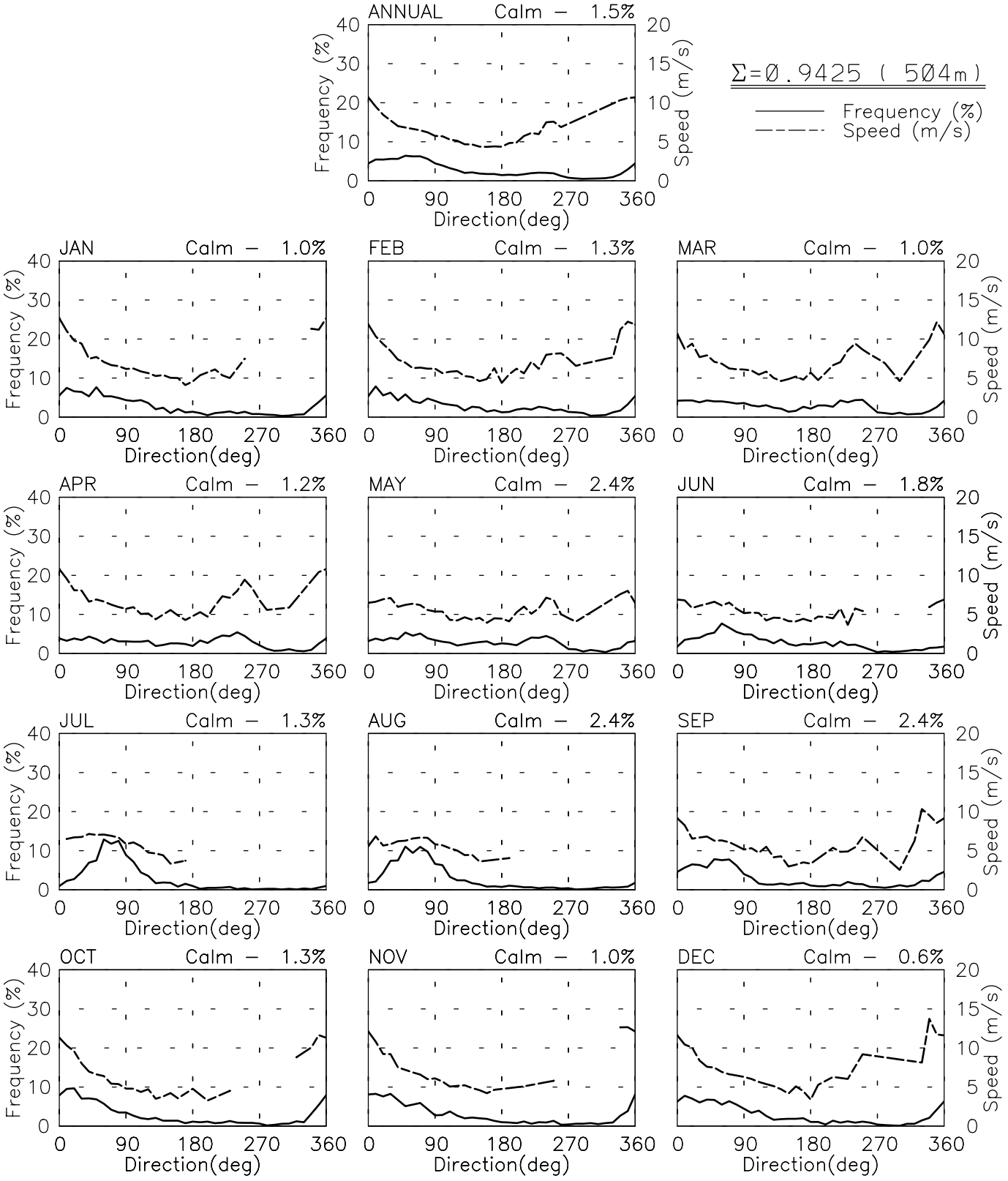
Reanalysis T62 Gauss – 07245 – 0600 LST
18° 05' N 95° 37' W – Elev 629m
01/58–12/97



Tue Jun 24 14:37:05 2003

FREQUENCY & SPEED BY DIRECTION (SIGMA)

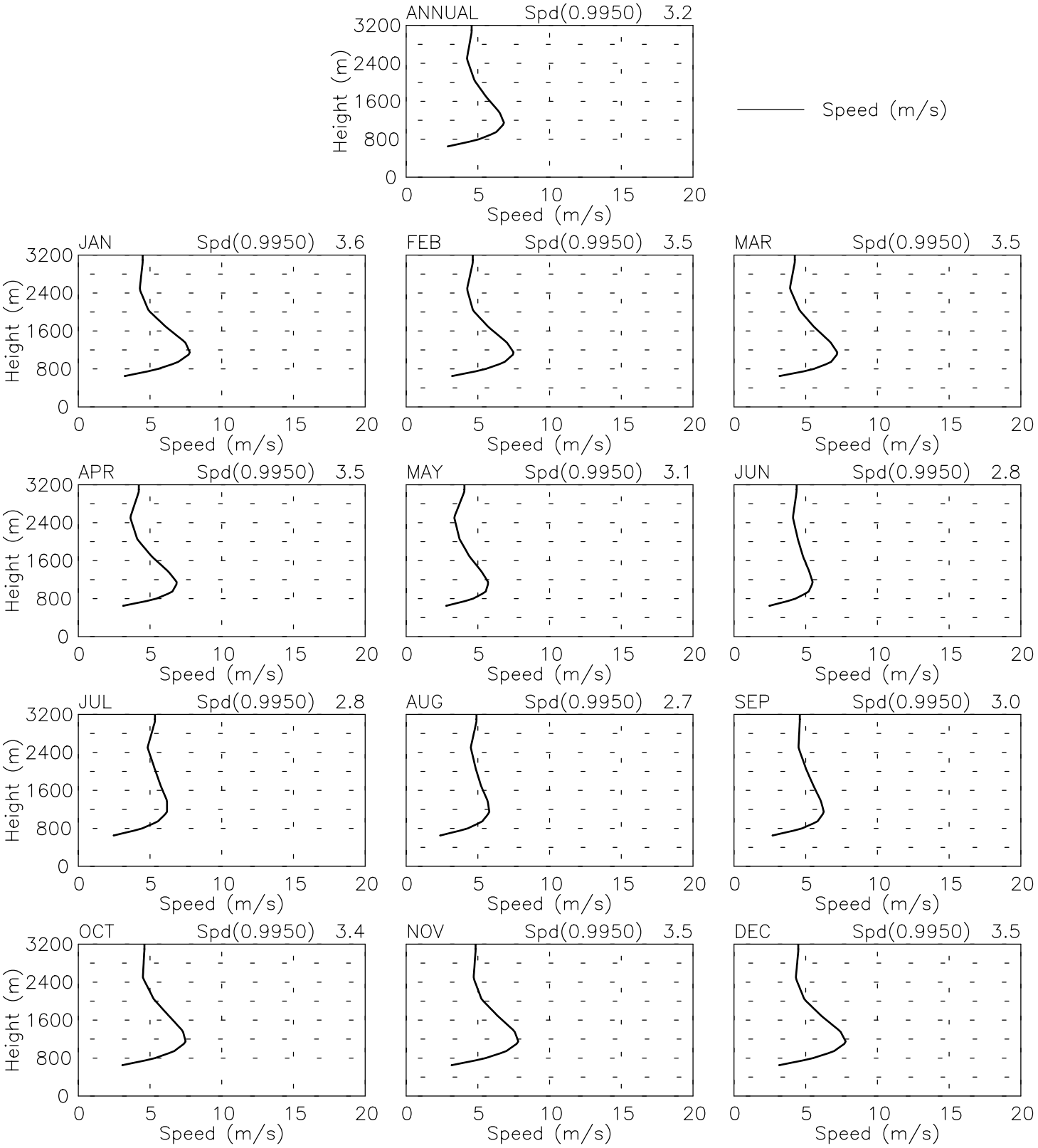
Reanalysis T62 Gauss – 07245 – 0600 LST
18° 05' N 95° 37' W – Elev 629m
01/58–12/97



Tue Jun 24 14:37:06 2003

VERTICAL WIND SPEED PROFILE BY HEIGHT

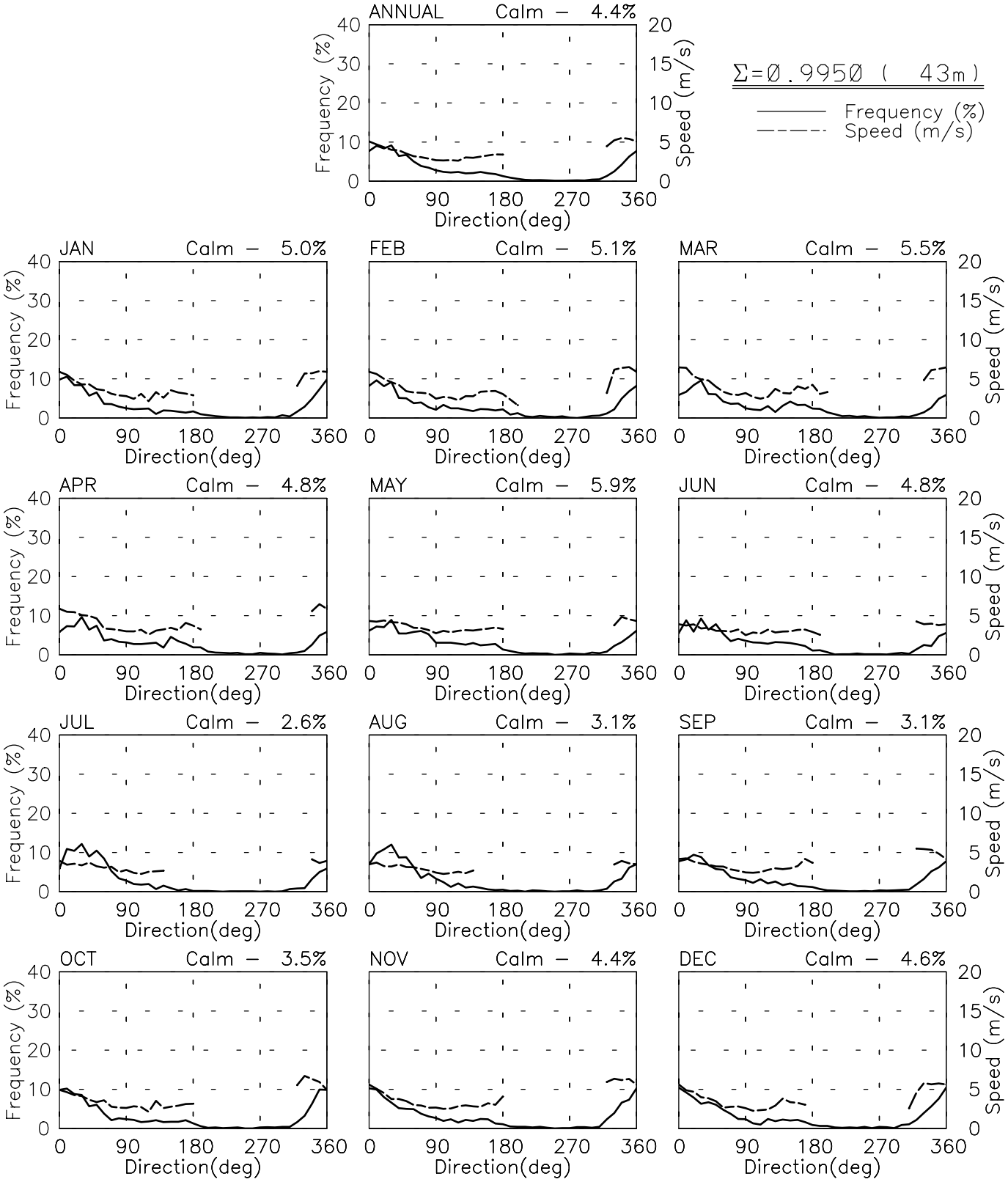
Reanalysis T62 Gauss – 07245 – 0600 LST
18° 05' N 95° 37' W – Elev 629m
01/58–12/97



Tue Jun 24 14:32:21 2003

FREQUENCY & SPEED BY DIRECTION (SIGMA)

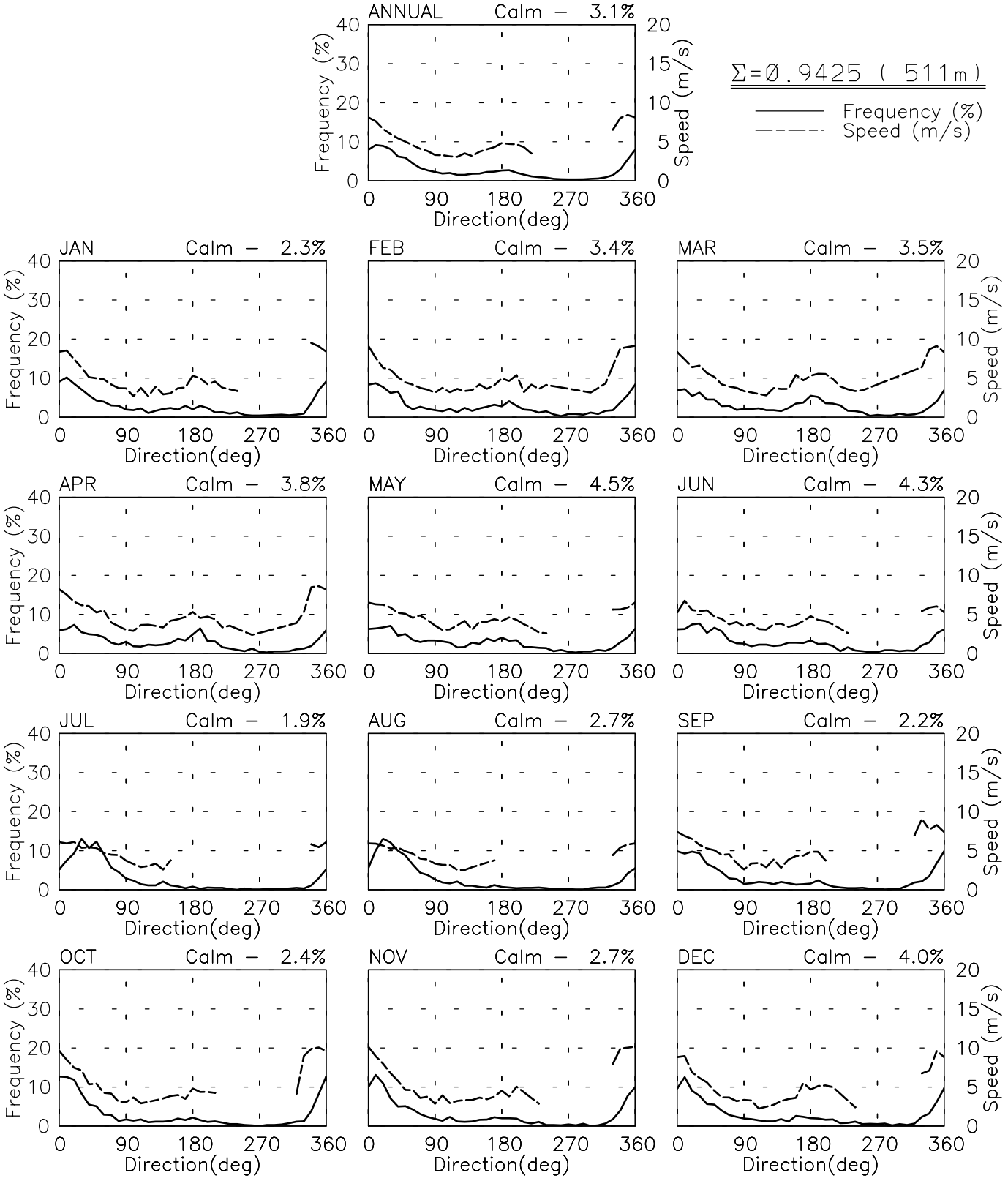
Reanalysis T62 Gauss – 07245 – 1800 LST
18° 05' N 95° 37' W – Elev 629m
12/57–12/97



Wed Jul 2 14:55:00 2003

FREQUENCY & SPEED BY DIRECTION (SIGMA)

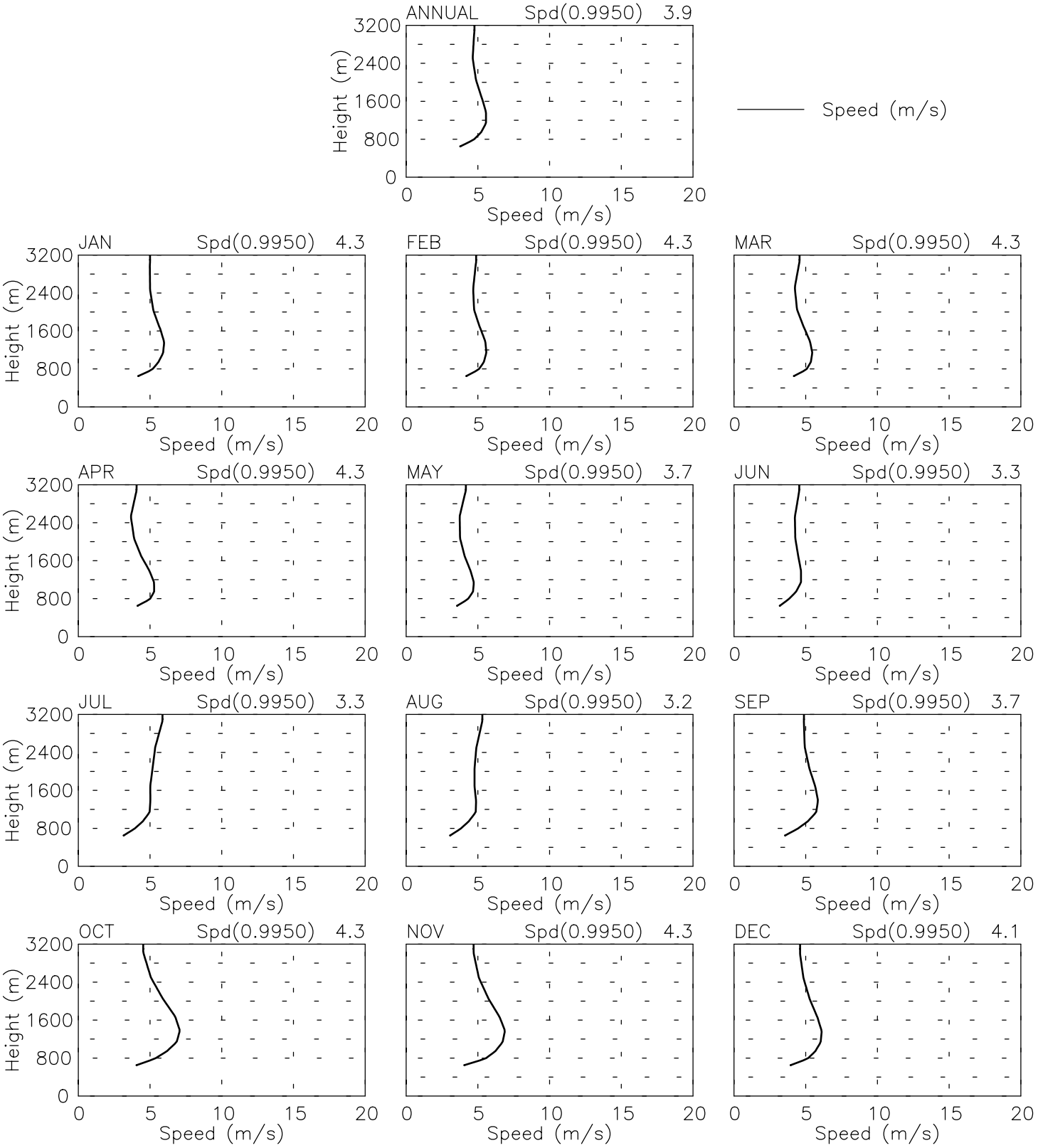
Reanalysis T62 Gauss – 07245 – 1800 LST
18° 05' N 95° 37' W – Elev 629m
12/57–12/97



Wed Jul 2 14:55:01 2003

VERTICAL WIND SPEED PROFILE BY HEIGHT

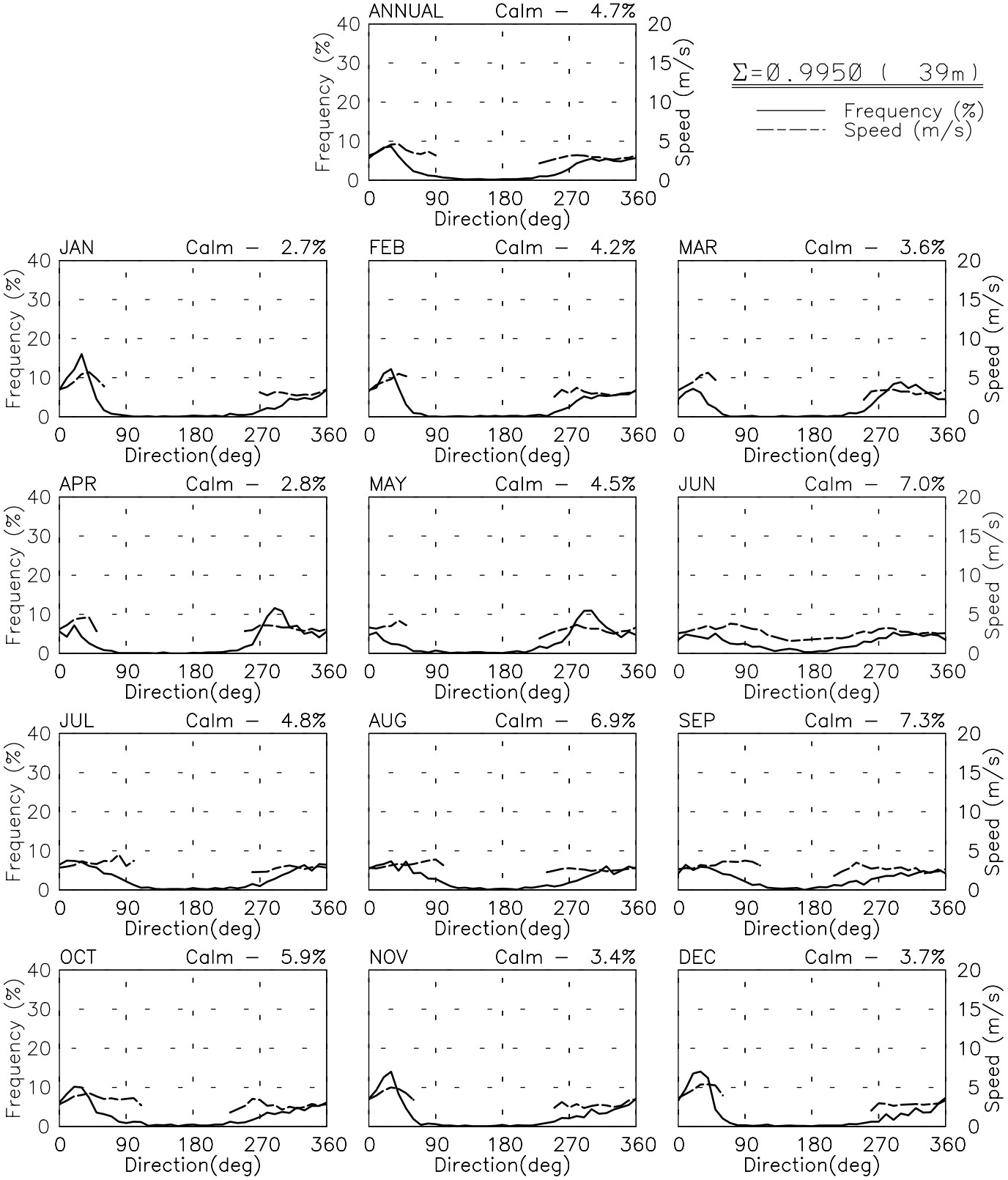
Reanalysis T62 Gauss – 07245 – 1800 LST
18° 05' N 95° 37' W – Elev 629m
12/57–12/97



Wed Jul 2 14:54:59 2003

FREQUENCY & SPEED BY DIRECTION (SIGMA)

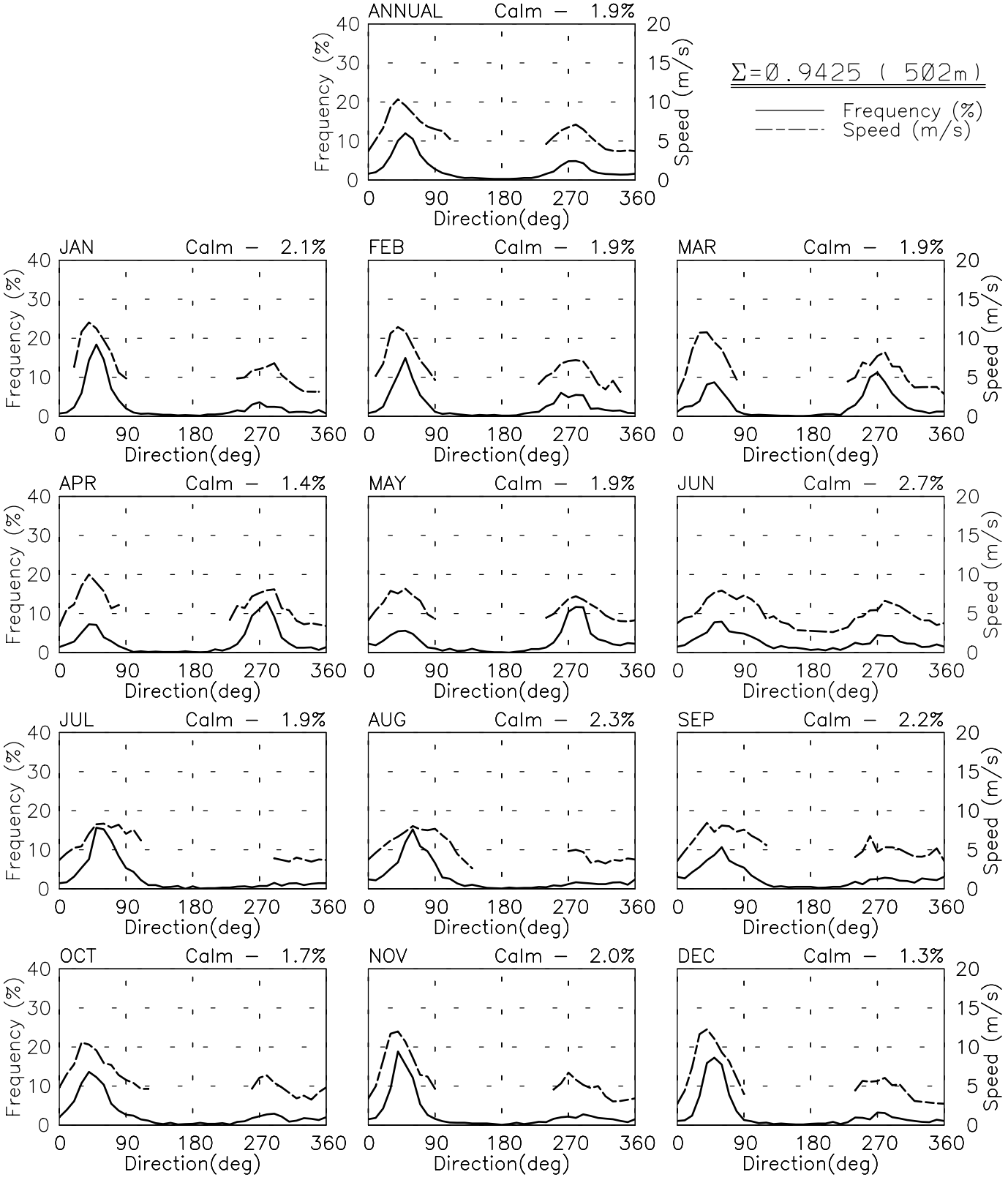
Reanalysis T62 Gauss – 07436 – 0500 LST
16° 11' N 97° 30' W – Elev 705m
01/58–12/97



Tue Jun 24 14:37:29 2003

FREQUENCY & SPEED BY DIRECTION (SIGMA)

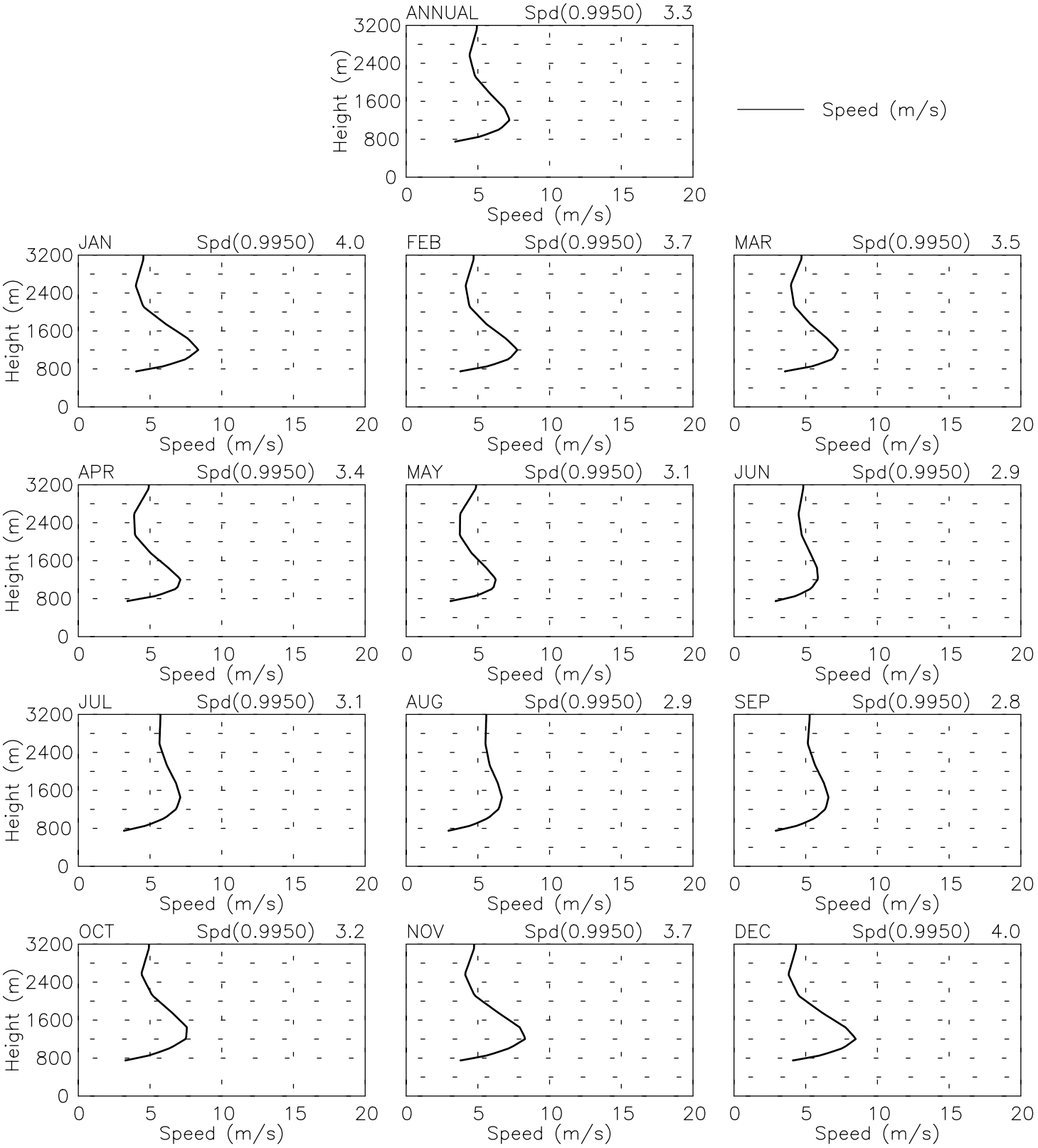
Reanalysis T62 Gauss – 07436 – 0500 LST
16° 11' N 97° 30' W – Elev 705m
01/58–12/97



Tue Jun 24 14:37:30 2003

VERTICAL WIND SPEED PROFILE BY HEIGHT

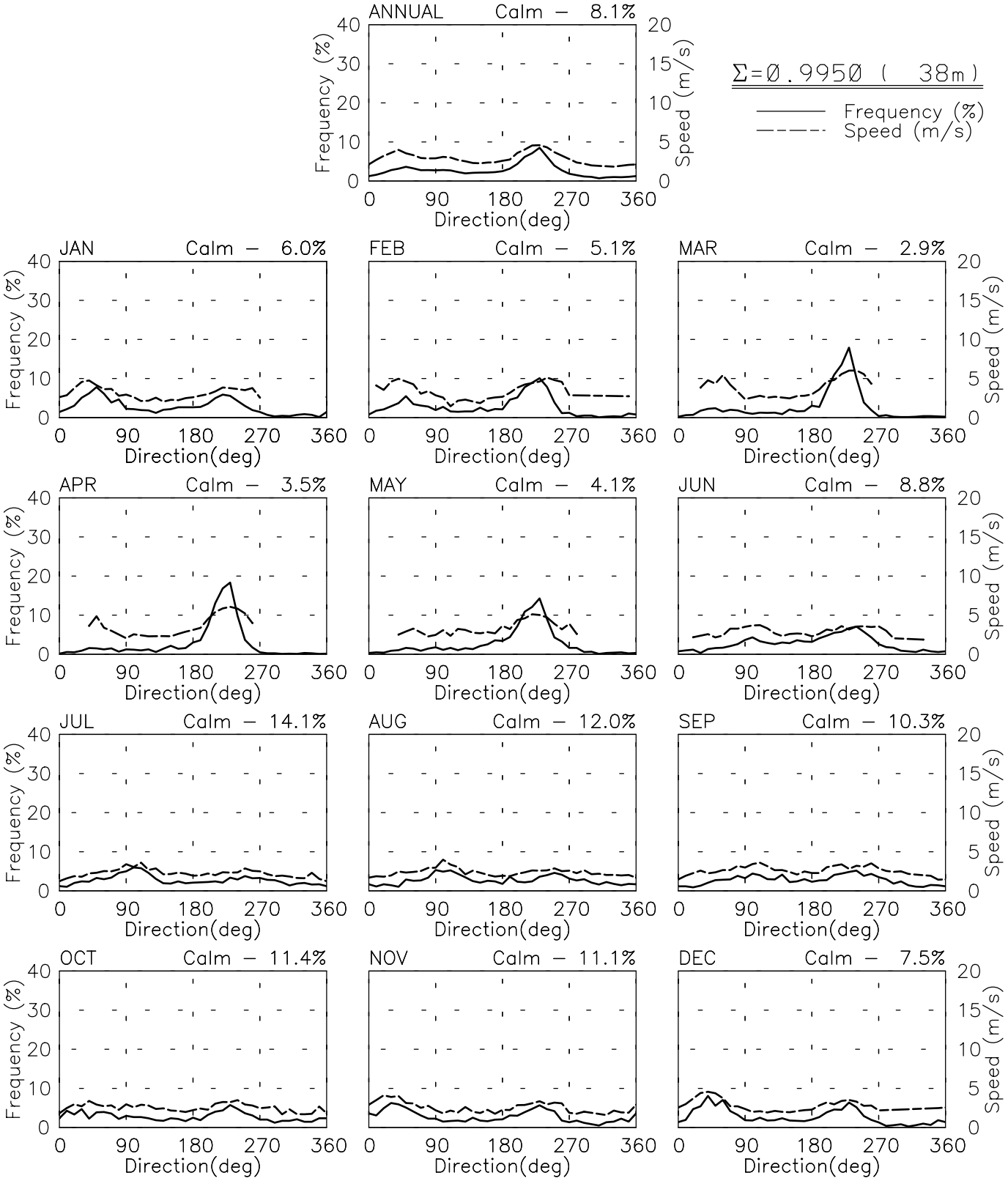
Reanalysis T62 Gauss – 07436 – 0500 LST
16° 11' N 97° 30' W – Elev 705m
01/58–12/97



Tue Jun 24 14:32:44 2003

FREQUENCY & SPEED BY DIRECTION (SIGMA)

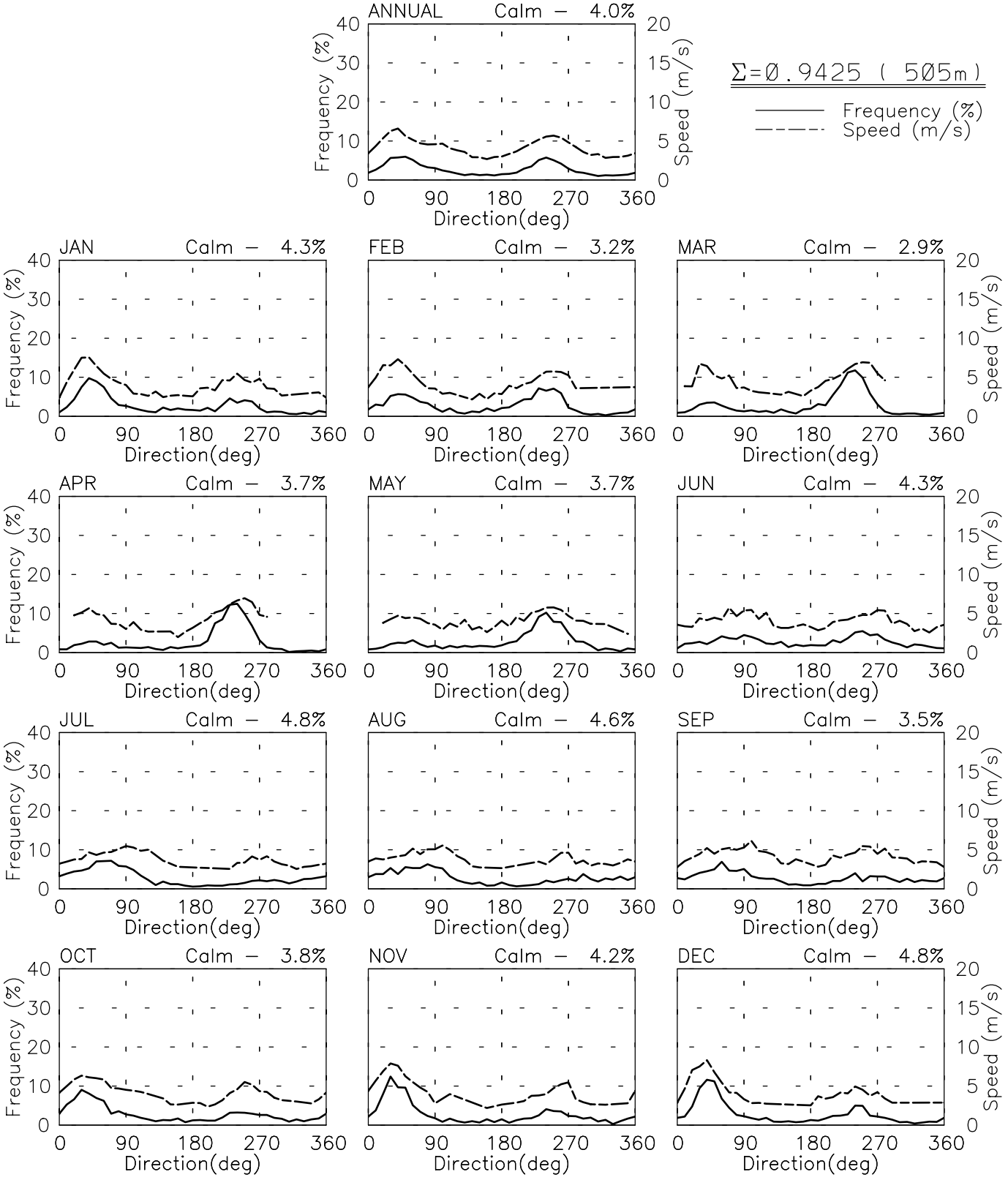
Reanalysis T62 Gauss – 07436 – 1700 LST
16° 11' N 97° 30' W – Elev 705m
12/57–12/97



Wed Jul 2 14:55:25 2003

FREQUENCY & SPEED BY DIRECTION (SIGMA)

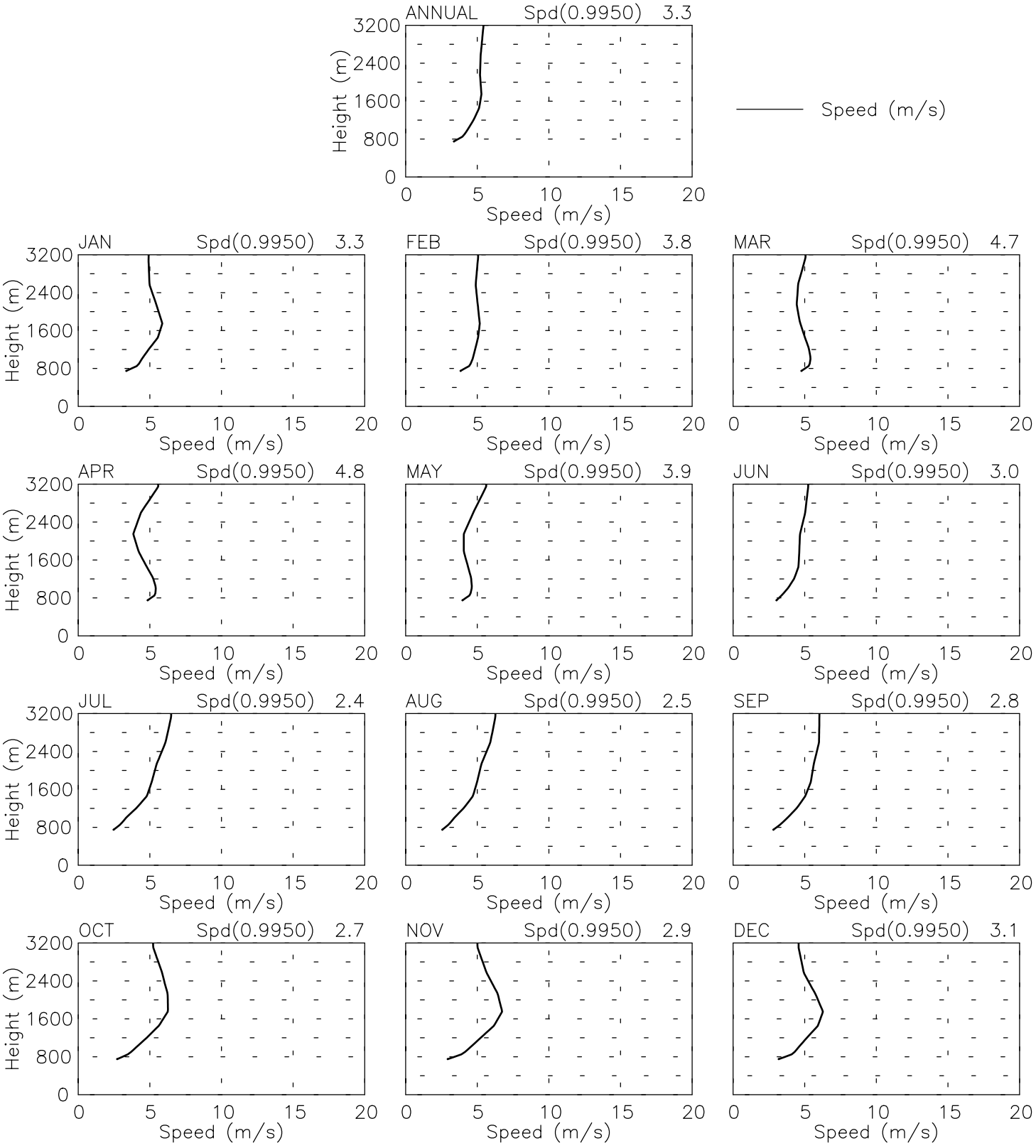
Reanalysis T62 Gauss – 07436 – 1700 LST
16° 11' N 97° 30' W – Elev 705m
12/57–12/97



Wed Jul 2 14:55:25 2003

VERTICAL WIND SPEED PROFILE BY HEIGHT

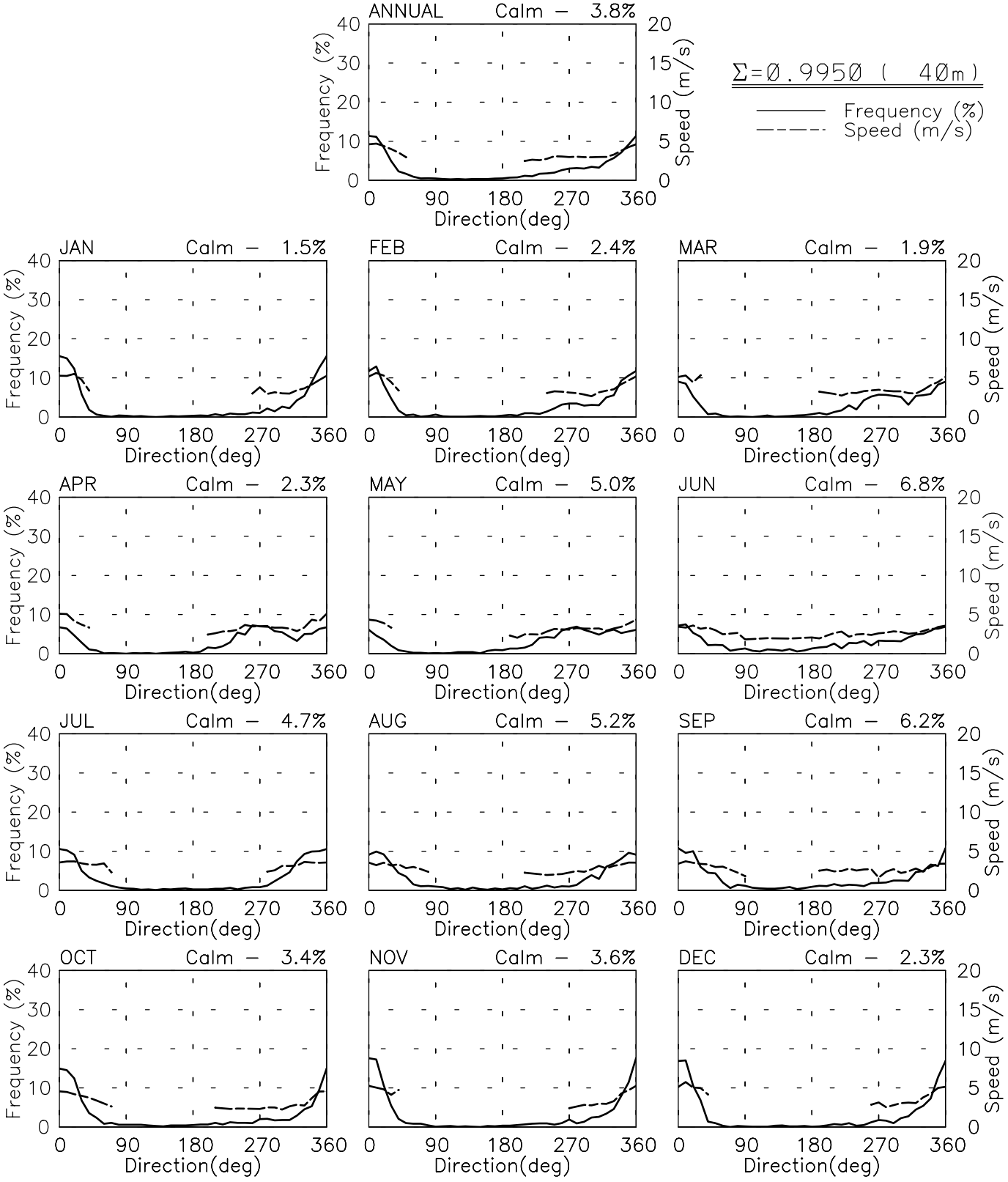
Reanalysis T62 Gauss – 07436 – 1700 LST
16° 11' N 97° 30' W – Elev 705m
12/57–12/97



Wed Jul 2 14:55:24 2003

FREQUENCY & SPEED BY DIRECTION (SIGMA)

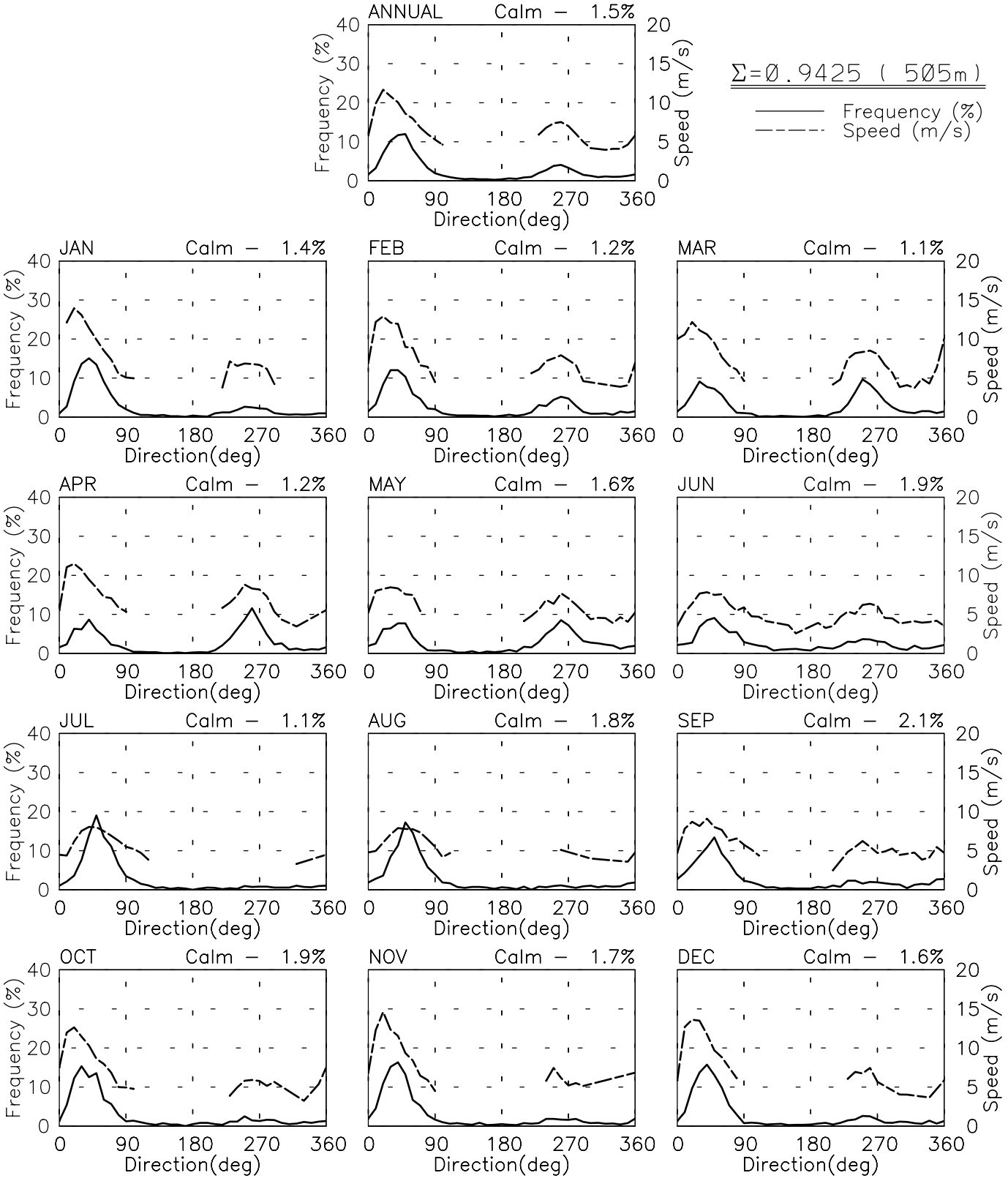
Reanalysis T62 Gauss – 07437 – 0600 LST
16° 11' N 95° 37' W – Elev 466m
01/58–12/97



Tue Jun 24 14:37:52 2003

FREQUENCY & SPEED BY DIRECTION (SIGMA)

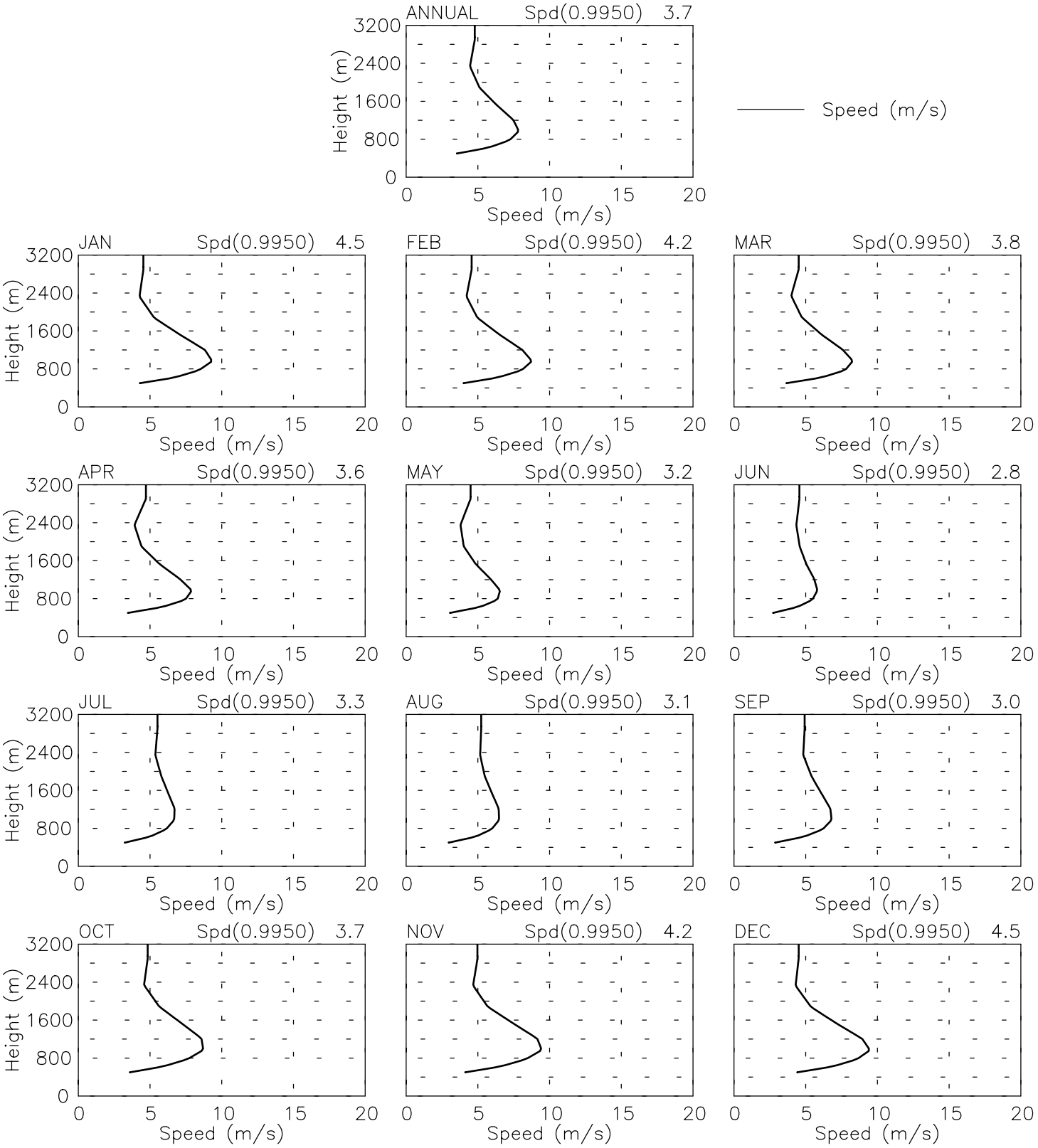
Reanalysis T62 Gauss – 07437 – 0600 LST
16° 11' N 95° 37' W – Elev 466m
01/58–12/97



Tue Jun 24 14:37:53 2003

VERTICAL WIND SPEED PROFILE BY HEIGHT

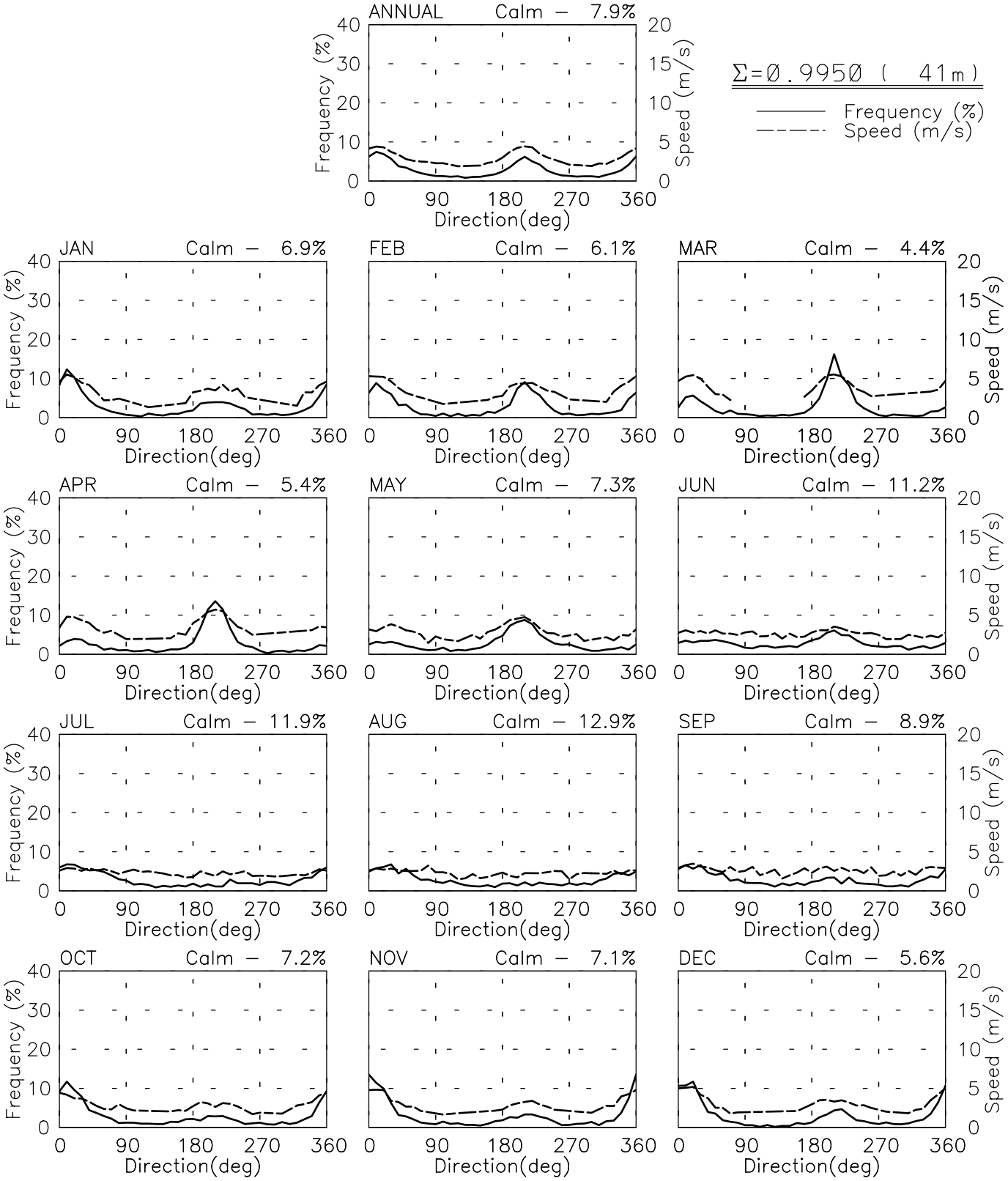
Reanalysis T62 Gauss – 07437 – 0600 LST
16° 11' N 95° 37' W – Elev 466m
01/58–12/97



Tue Jun 24 14:33:07 2003

FREQUENCY & SPEED BY DIRECTION (SIGMA)

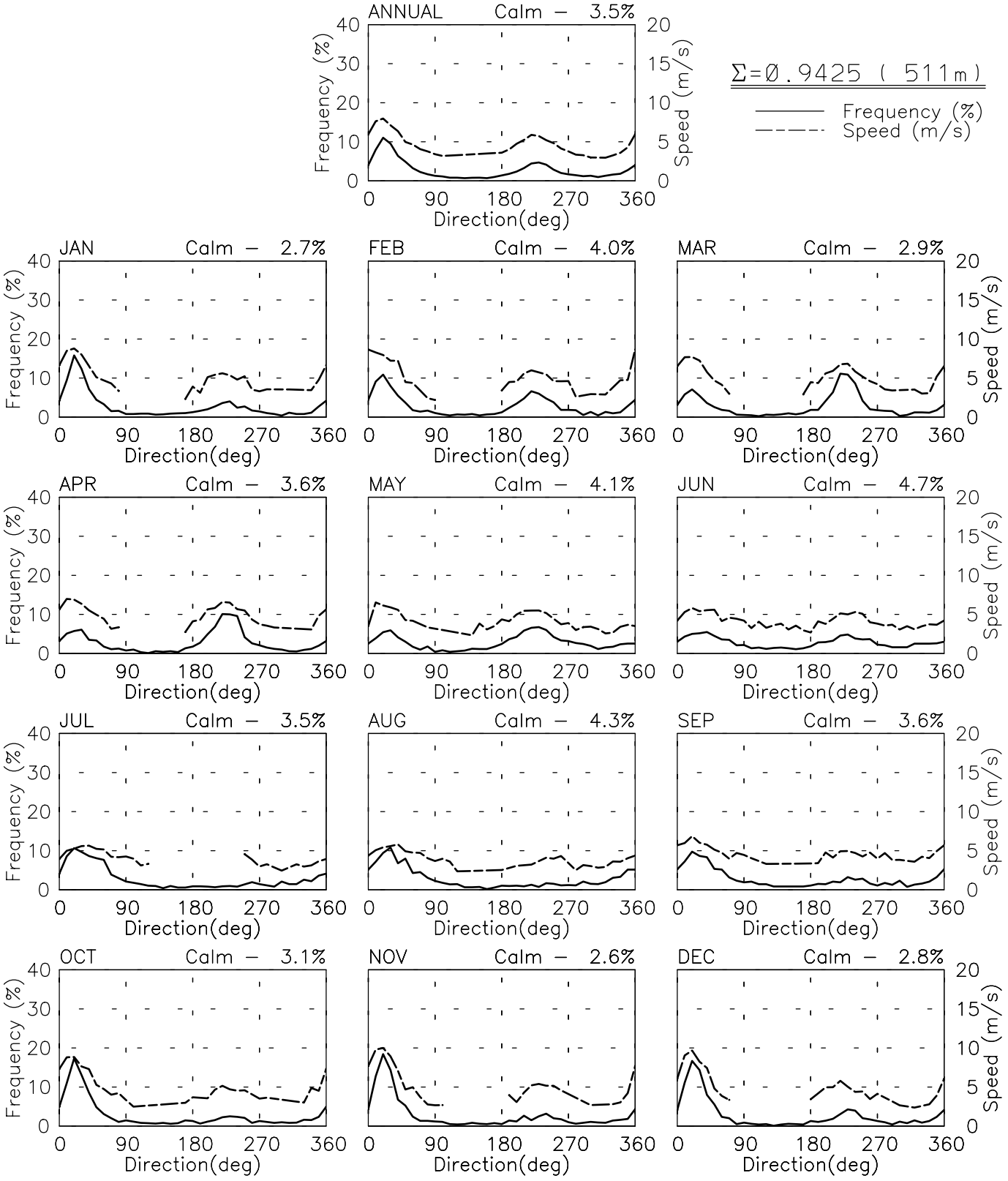
Reanalysis T62 Gauss – 07437 – 1800 LST
16° 11' N 95° 37' W – Elev 466m
12/57–12/97



Wed Jul 2 14:55:49 2003

FREQUENCY & SPEED BY DIRECTION (SIGMA)

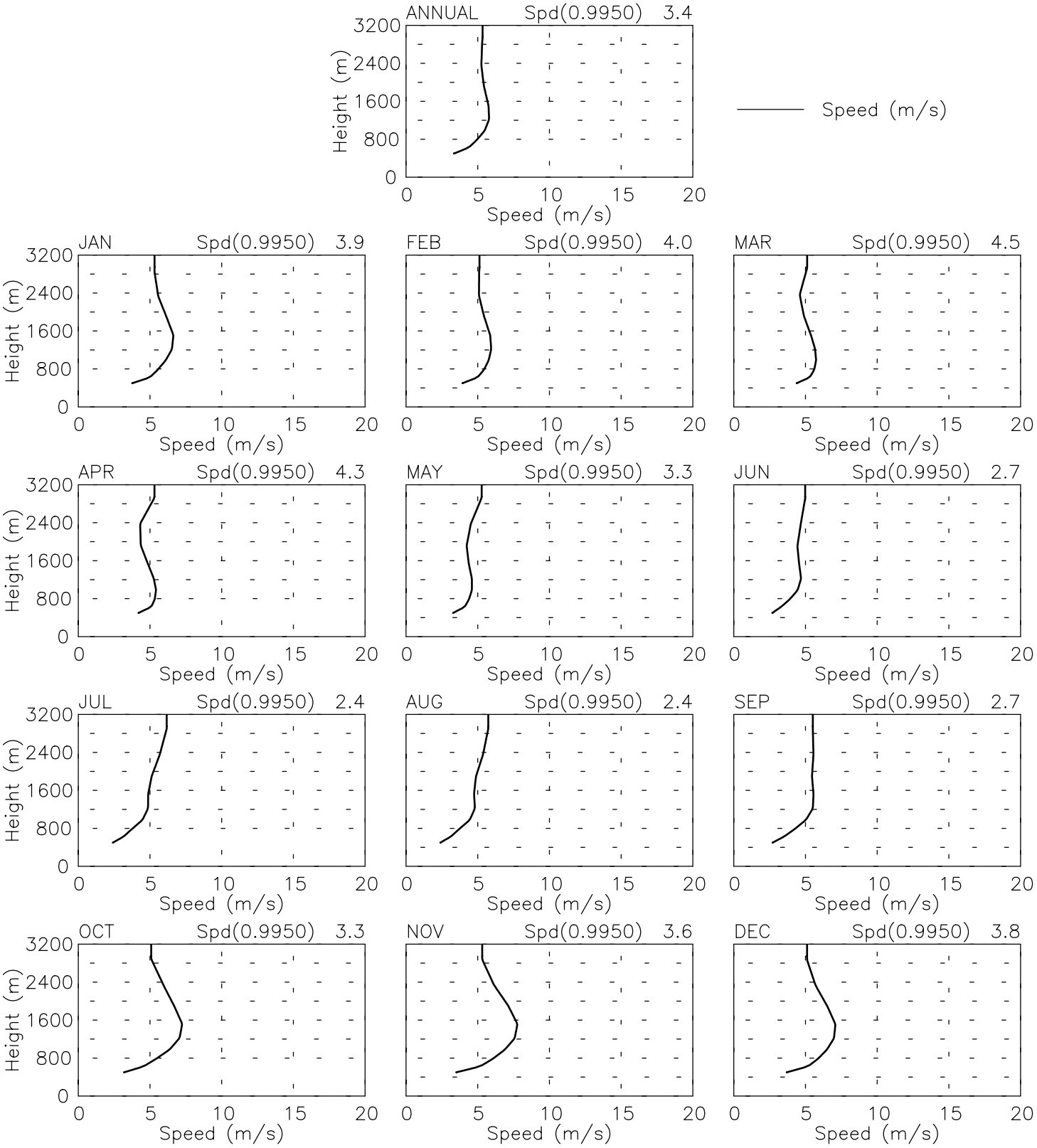
Reanalysis T62 Gauss – 07437 – 1800 LST
16° 11' N 95° 37' W – Elev 466m
12/57–12/97



Wed Jul 2 14:55:50 2003

VERTICAL WIND SPEED PROFILE BY HEIGHT

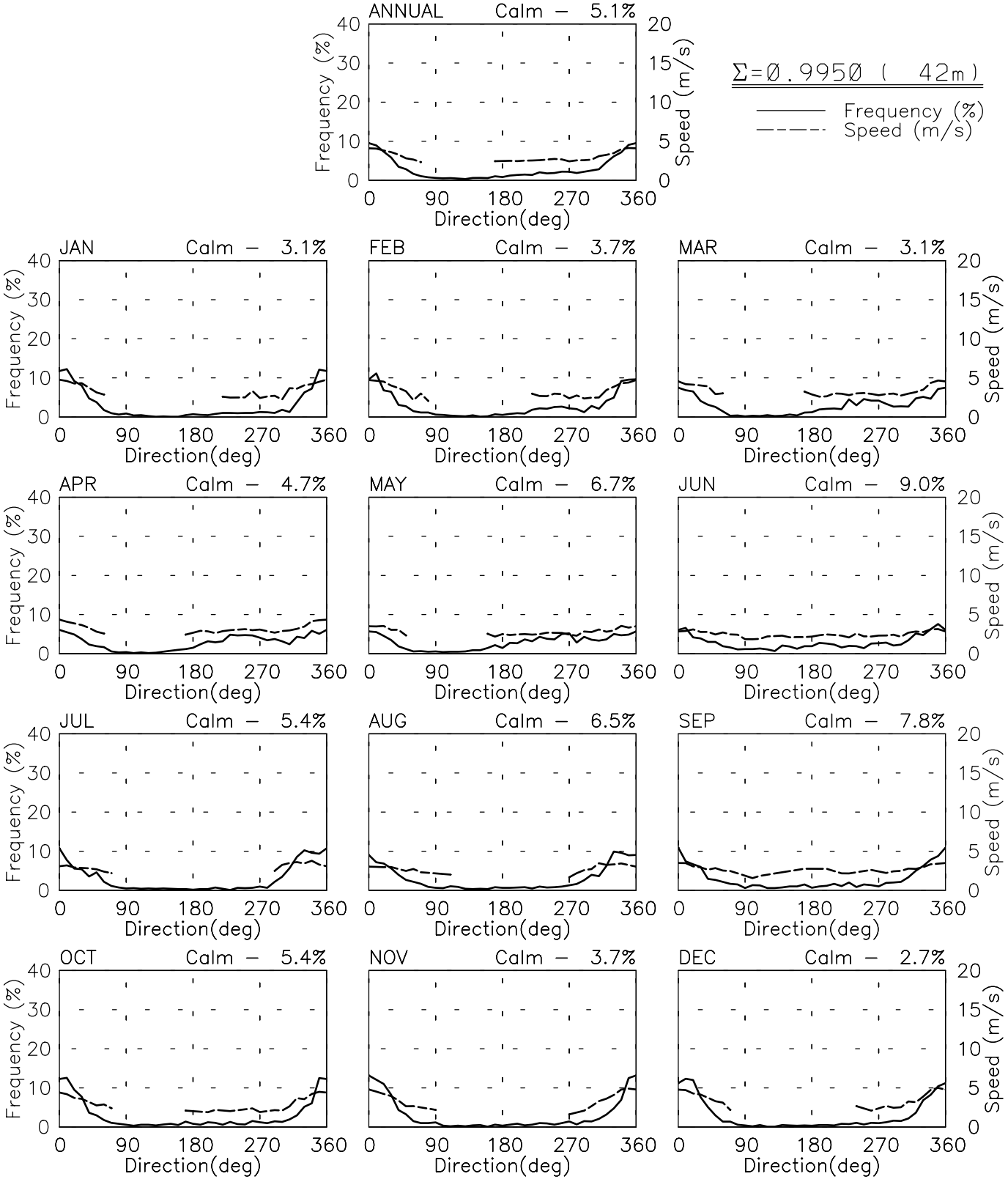
Reanalysis T62 Gauss – 07437 – 1800 LST
16° 11' N 95° 37' W – Elev 466m
12/57–12/97



Wed Jul 2 14:55:48 2003

FREQUENCY & SPEED BY DIRECTION (SIGMA)

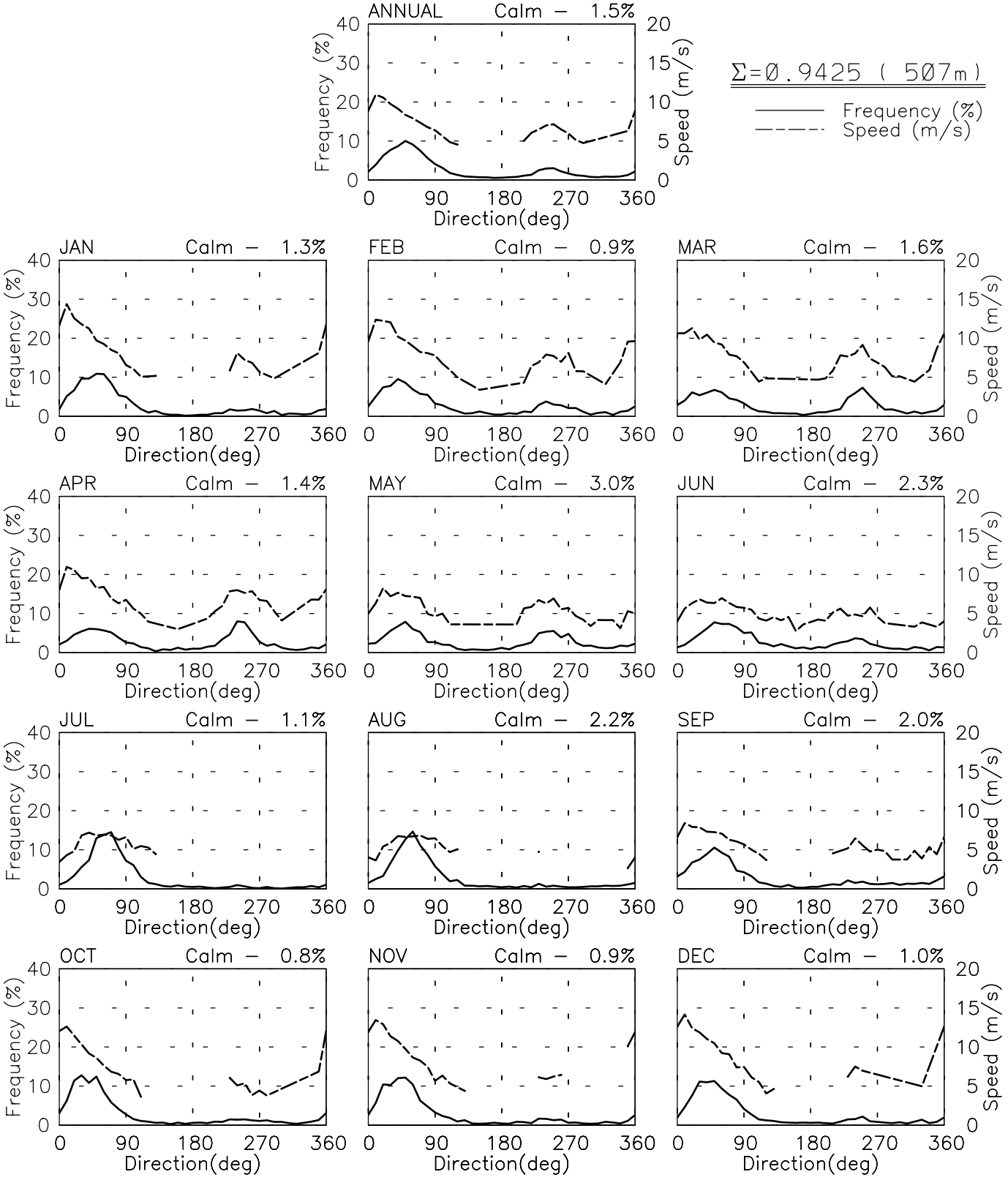
Reanalysis T62 Gauss – 07438 – 0600 LST
16° 11' N 93° 45' W – Elev 398m
01/58–12/97



Tue Jun 24 14:38:16 2003

FREQUENCY & SPEED BY DIRECTION (SIGMA)

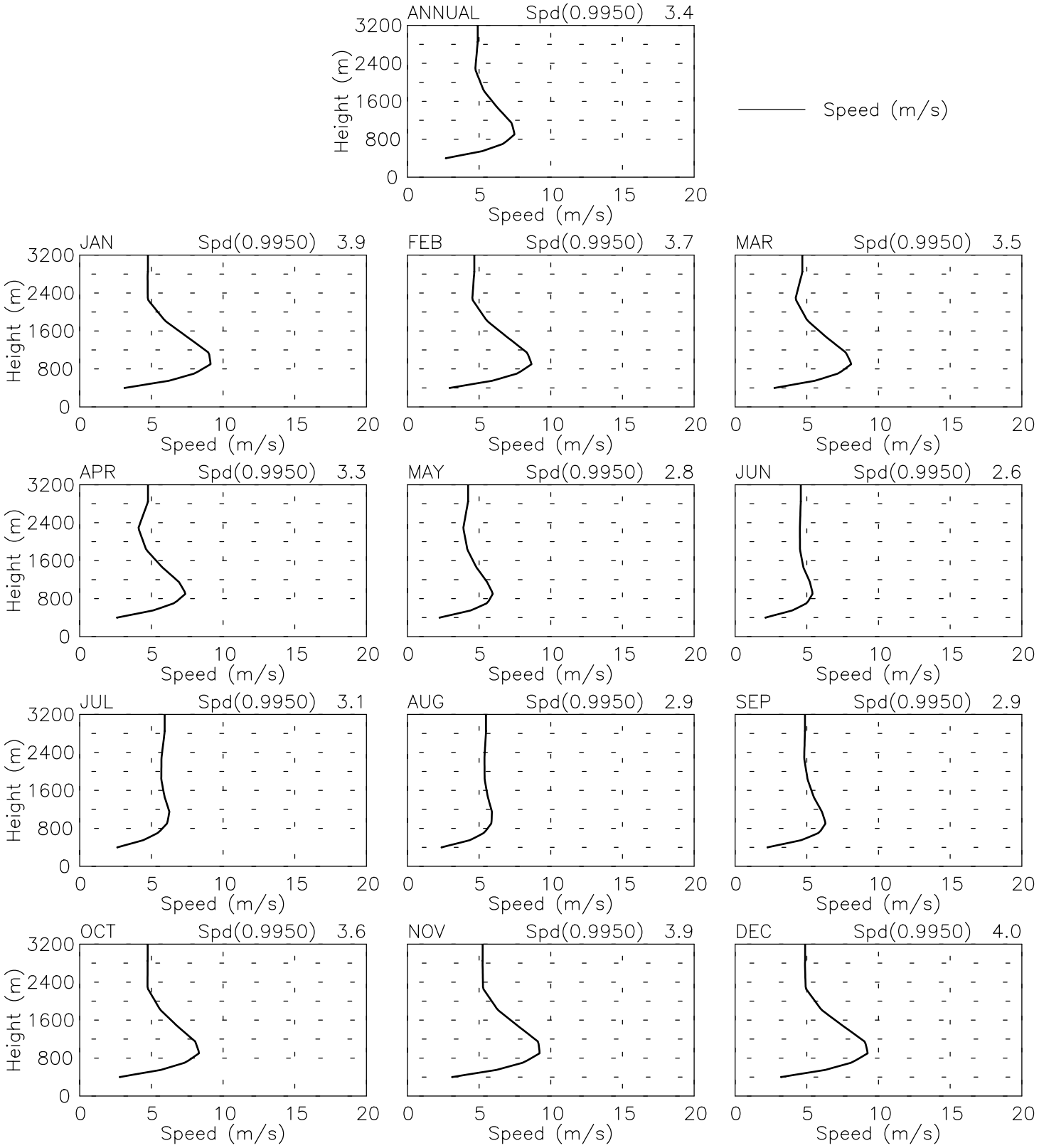
Reanalysis T62 Gauss – 07438 – 0600 LST
16° 11' N 93° 45' W – Elev 398m
01/58–12/97



Tue Jun 24 14:38:17 2003

VERTICAL WIND SPEED PROFILE BY HEIGHT

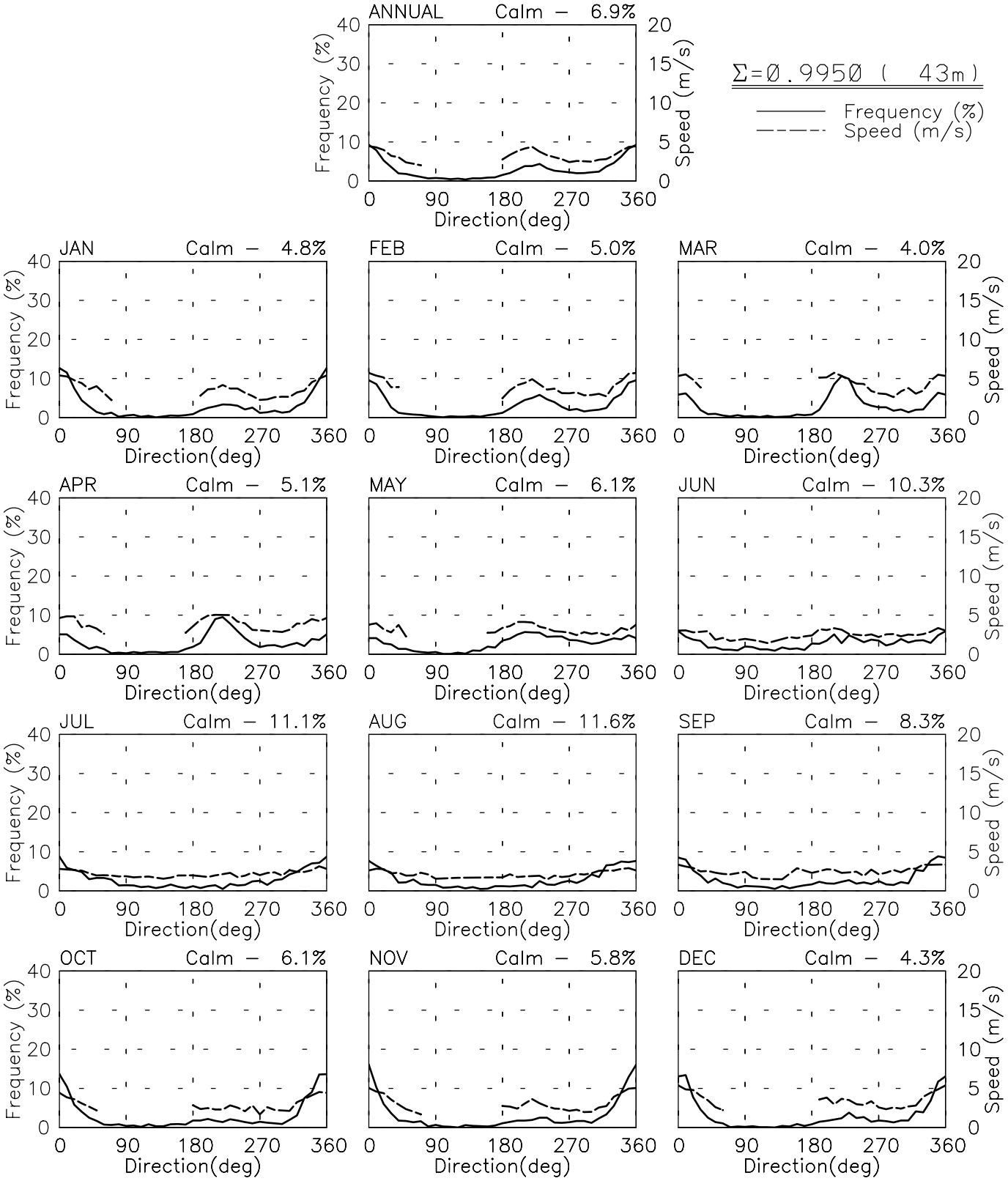
Reanalysis T62 Gauss – 07438 – 0600 LST
16° 11' N 93° 45' W – Elev 398m
01/58–12/97



Tue Jun 24 14:33:30 2003

FREQUENCY & SPEED BY DIRECTION (SIGMA)

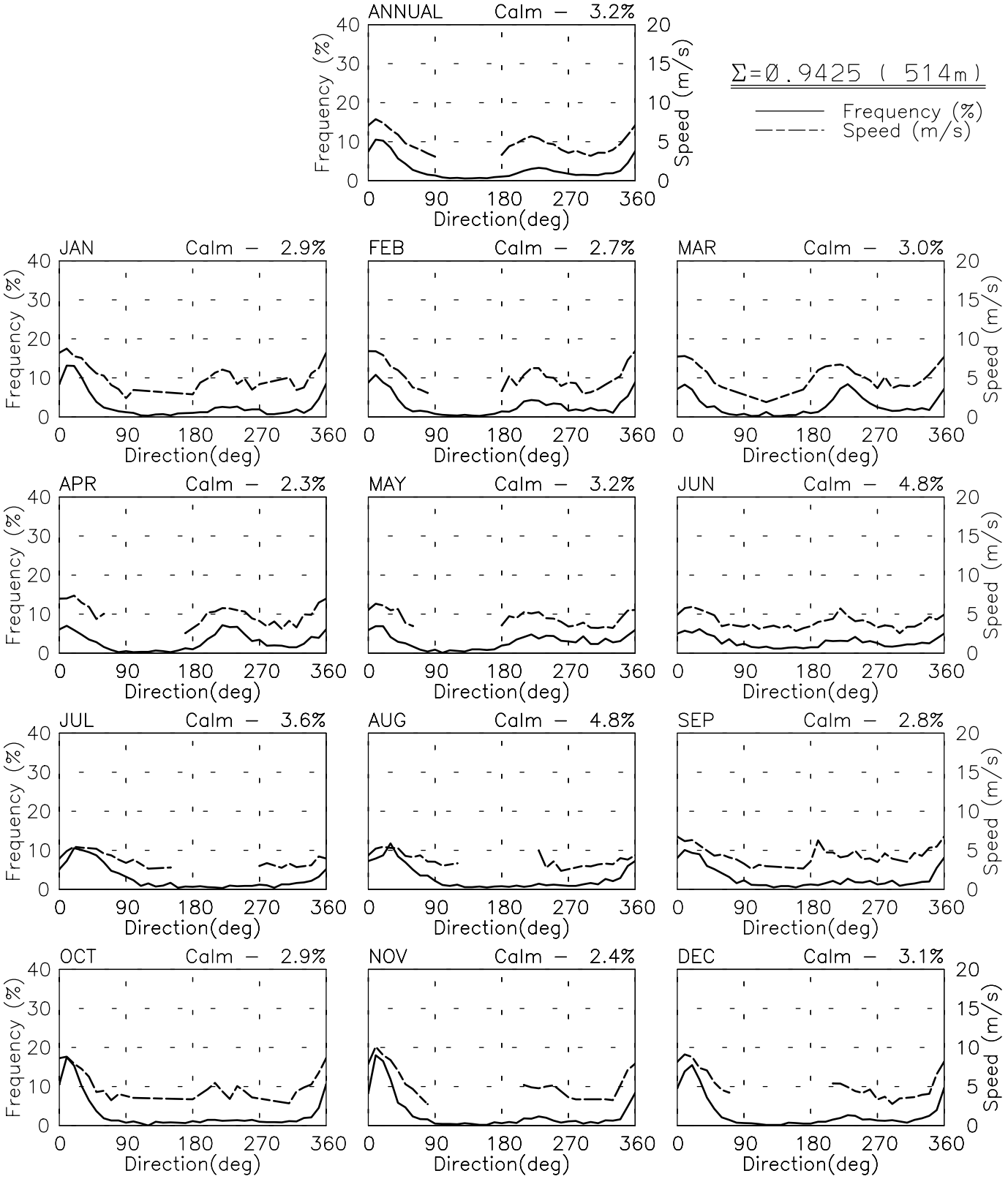
Reanalysis T62 Gauss – 07438 – 1800 LST
16° 11' N 93° 45' W – Elev 398m
12/57–12/97



Wed Jul 2 14:56:14 2003

FREQUENCY & SPEED BY DIRECTION (SIGMA)

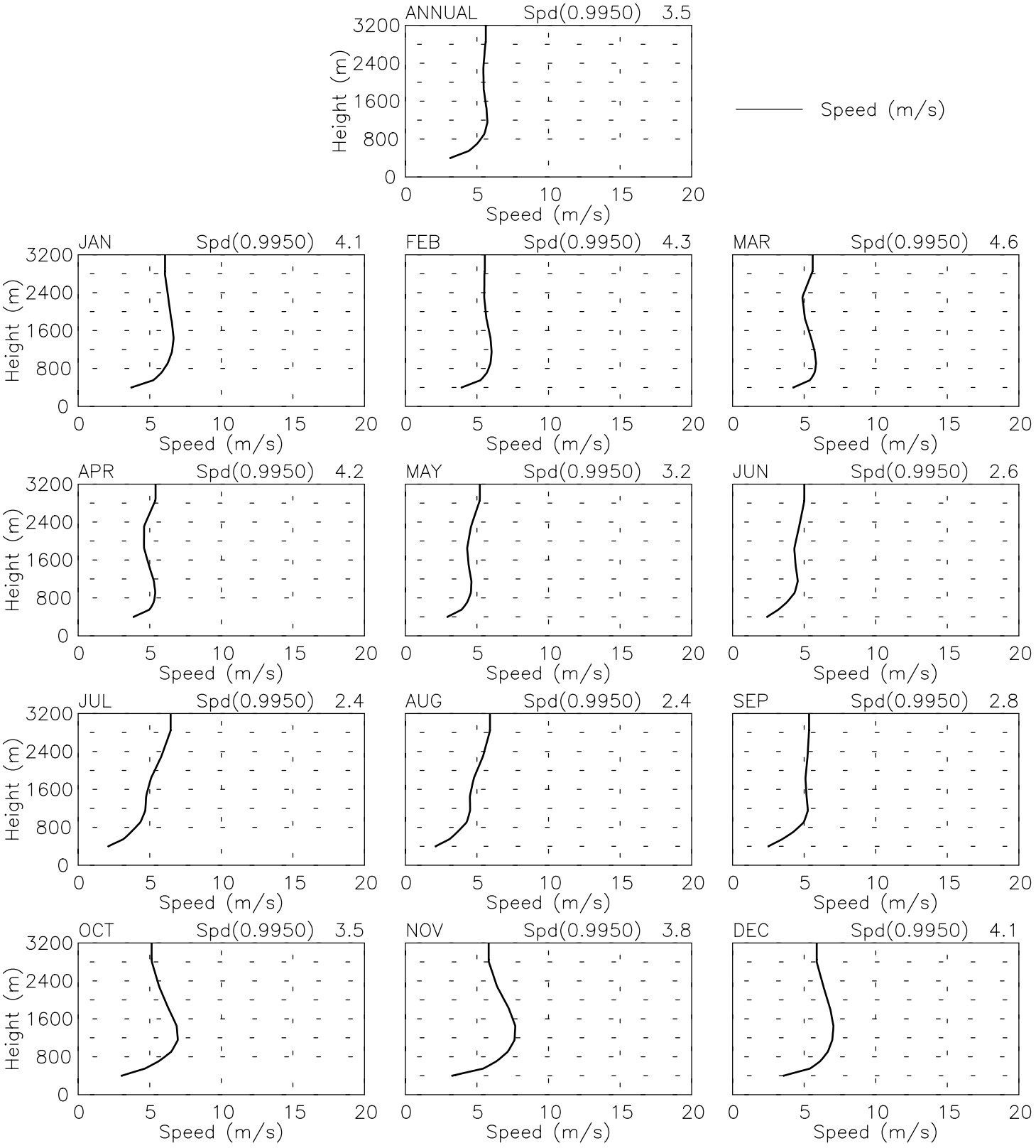
Reanalysis T62 Gauss – 07438 – 1800 LST
16° 11' N 93° 45' W – Elev 398m
12/57–12/97



Wed Jul 2 14:56:15 2003

VERTICAL WIND SPEED PROFILE BY HEIGHT

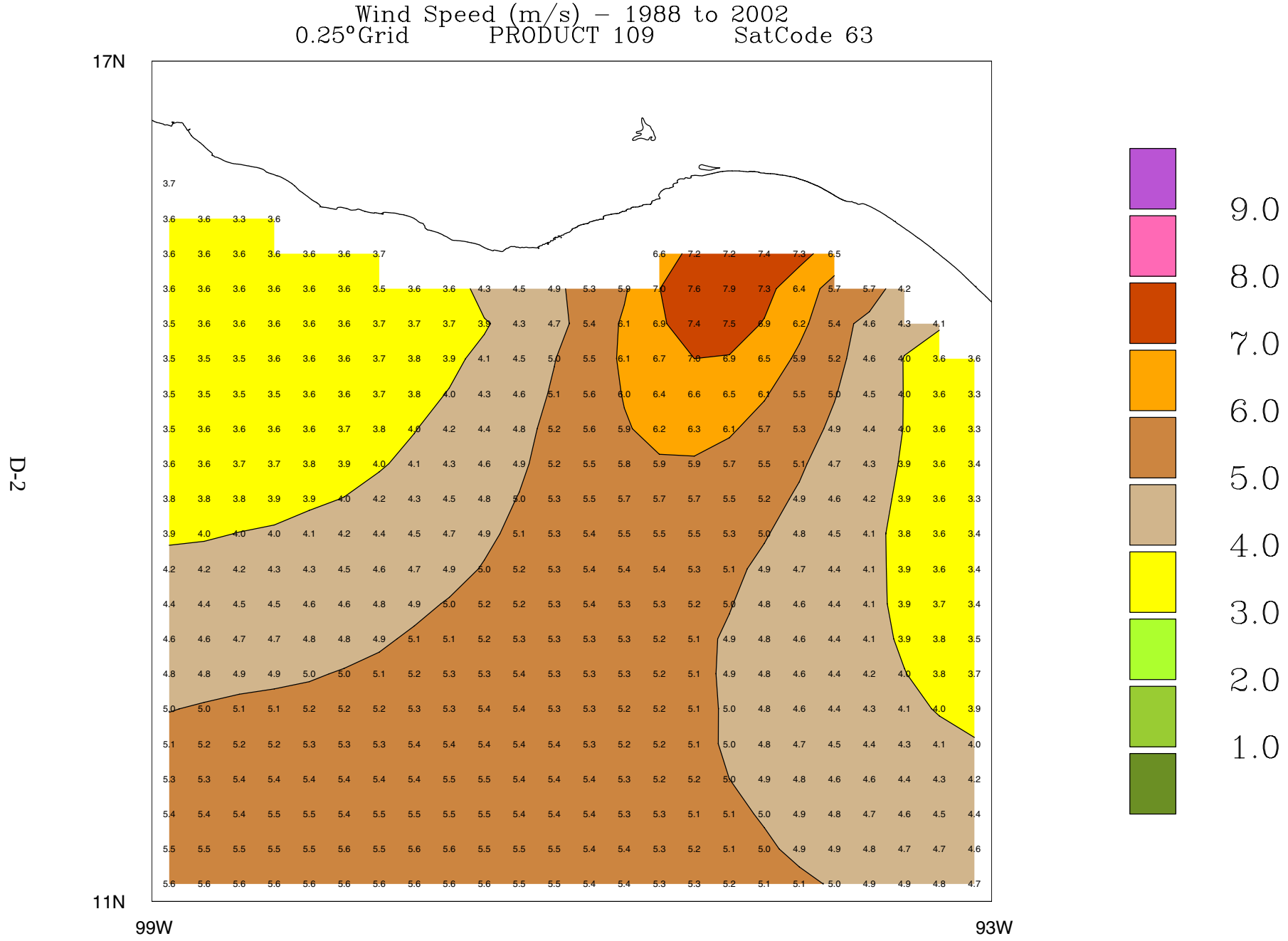
Reanalysis T62 Gauss – 07438 – 1800 LST
16° 11' N 93° 45' W – Elev 398m
12/57–12/97



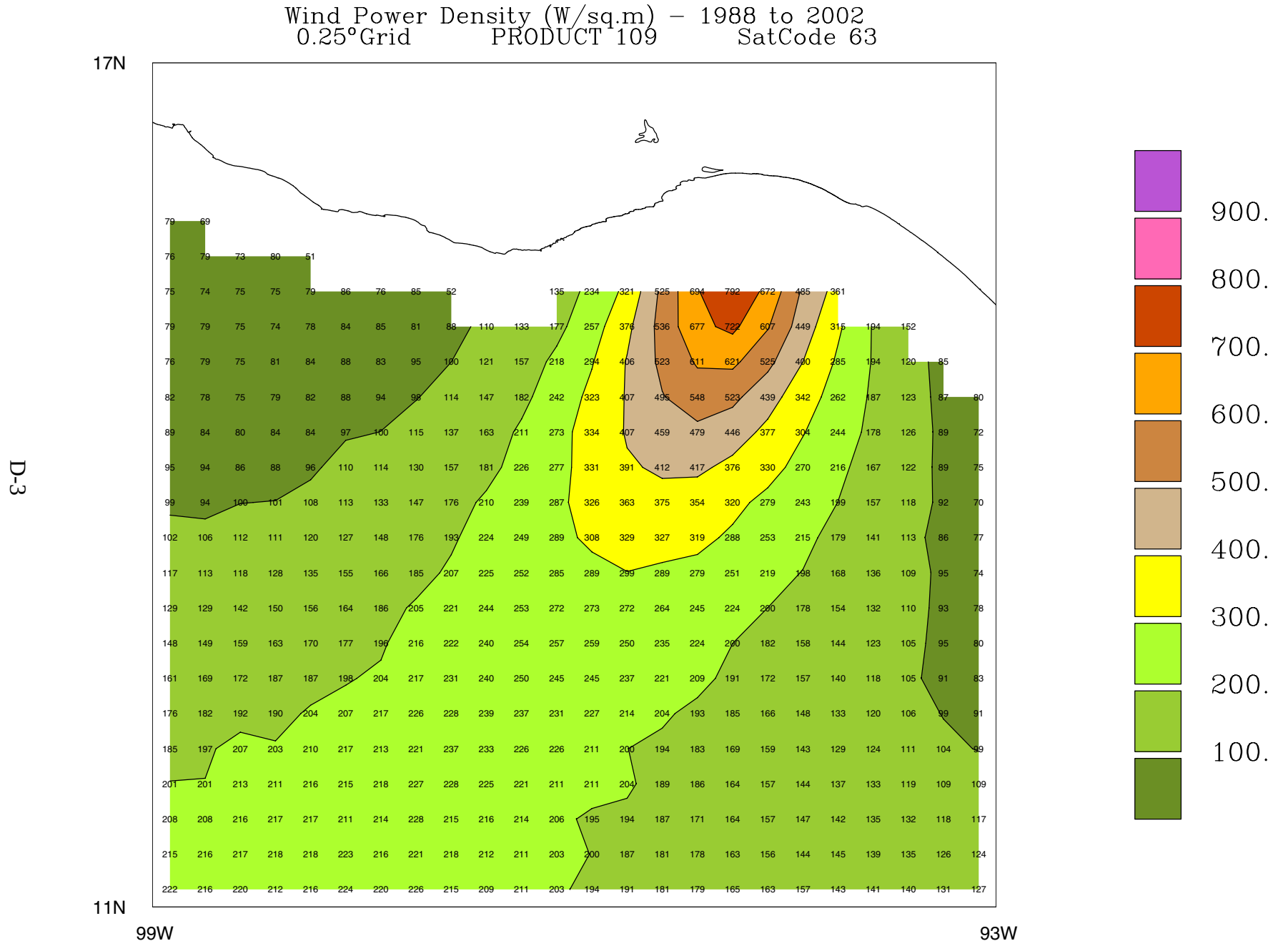
Wed Jul 2 14:56:13 2003

Appendix D

Ocean Satellite Wind Data

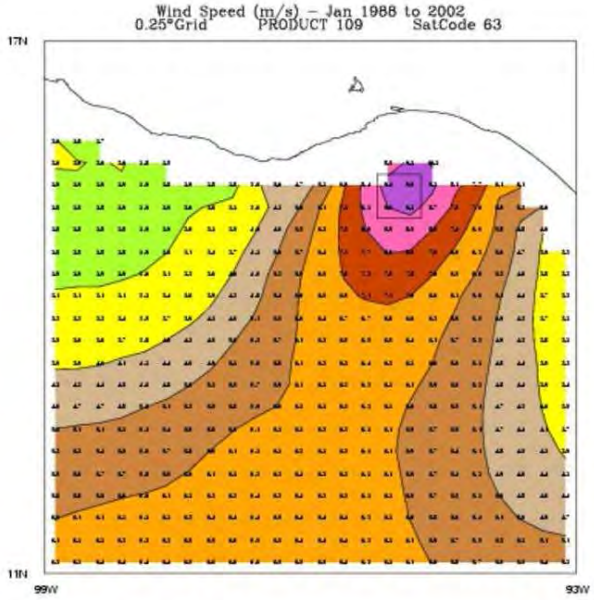

Wind Speed (m/s) – 1988 to 2002
0.25°Grid PRODUCT 109 SatCode 63
17N
11N
99W
93W
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0

D-2

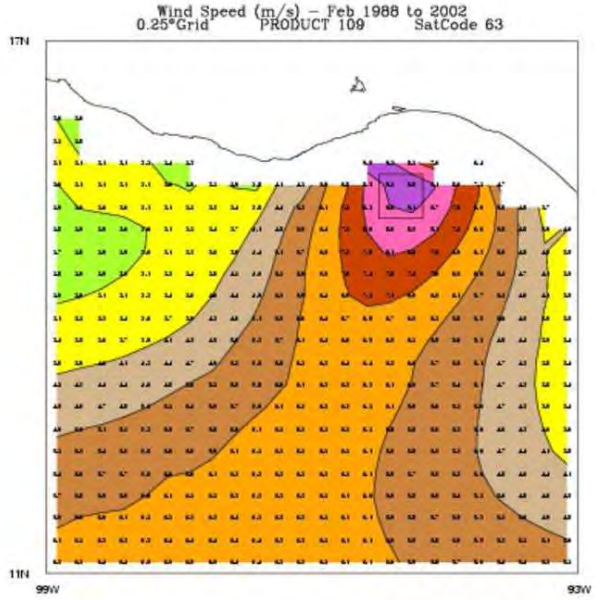

Wind Power Density (W/sq.m) – 1988 to 2002
0.25°Grid PRODUCT 109 SatCode 63
17N
11N
99W
93W
900.
800.
700.
600.
500.
400.
300.
200.
100.

D-3

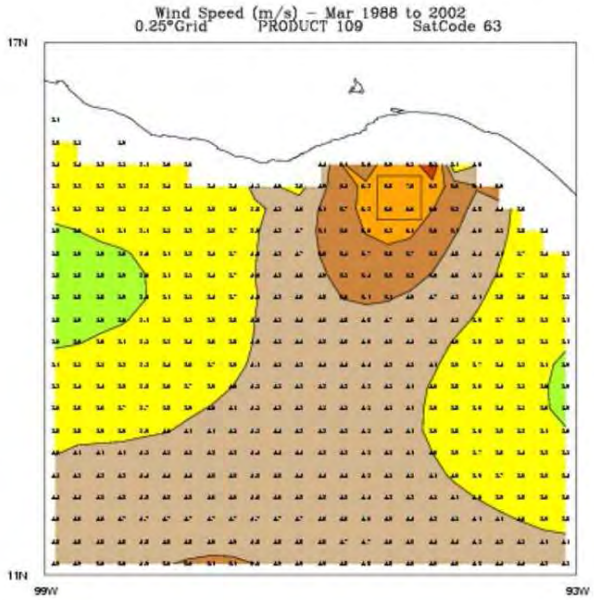
Jan



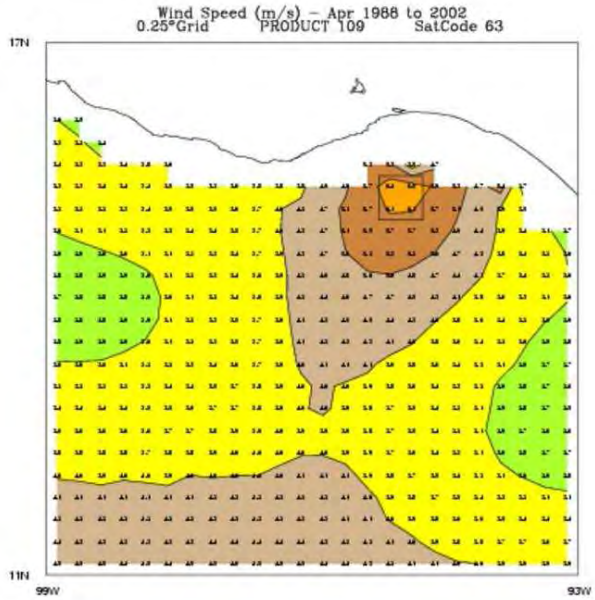
Feb

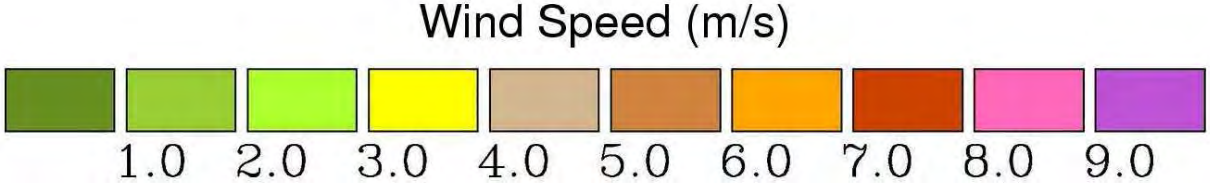


Mar

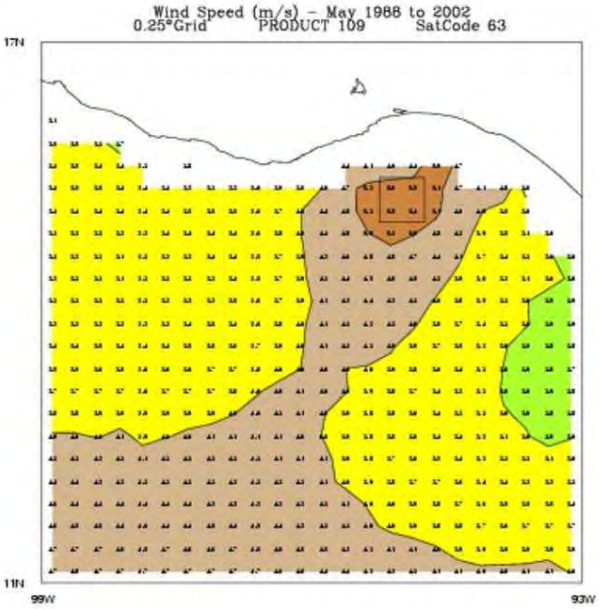


Apr

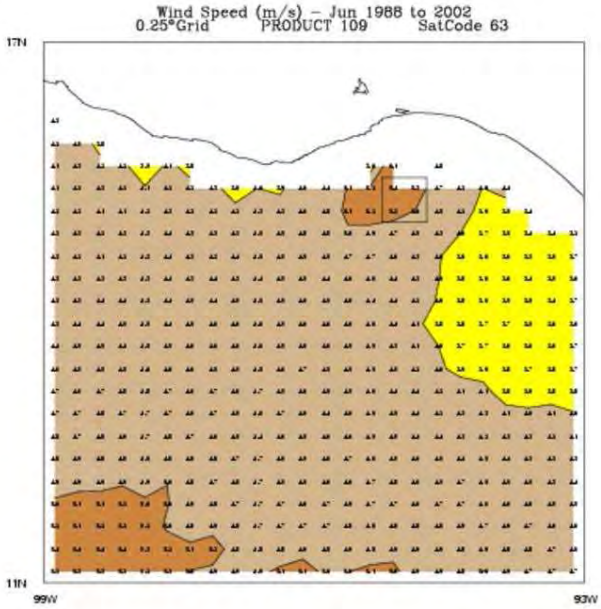




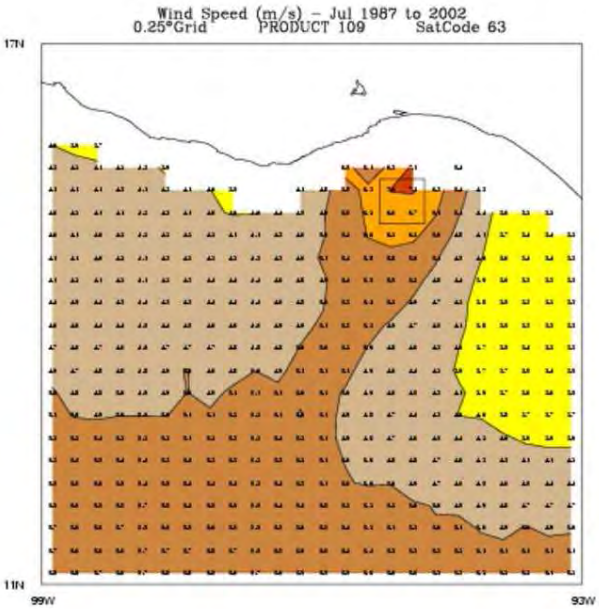
May



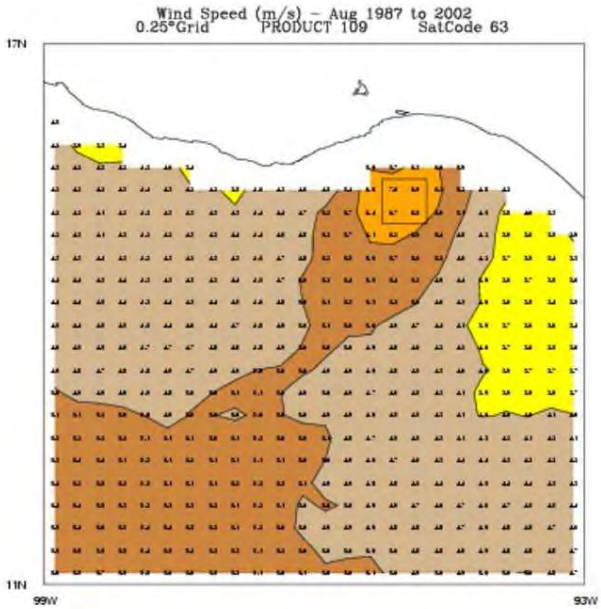
Jun

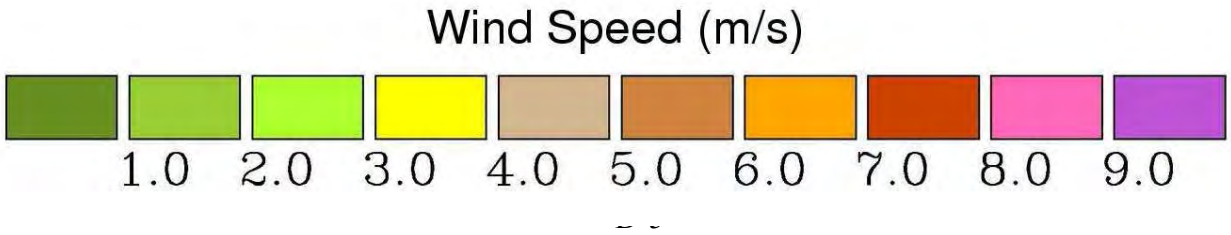


Jul

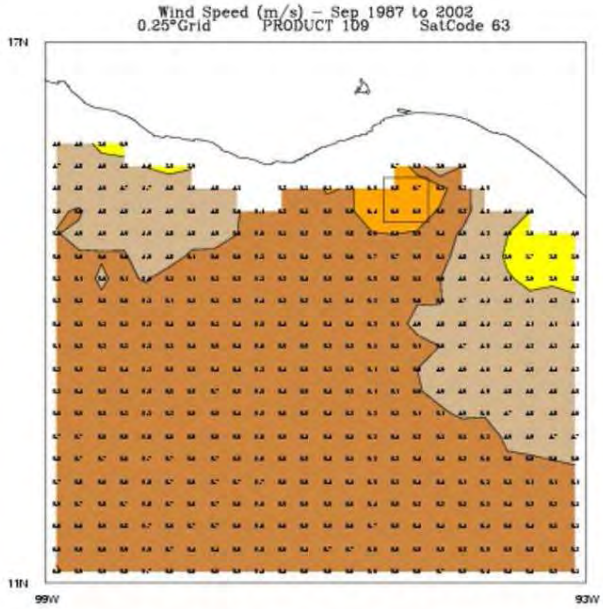


Aug

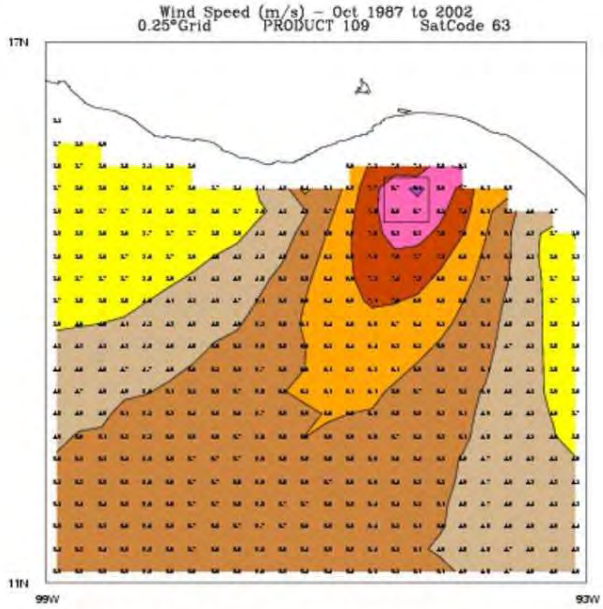




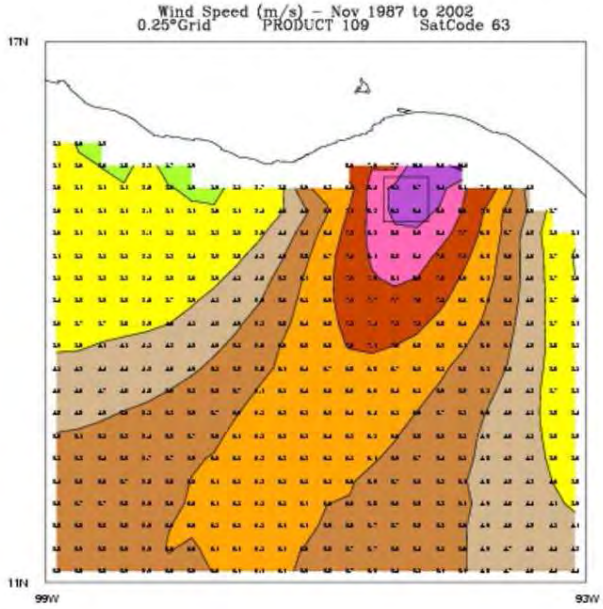
Sep



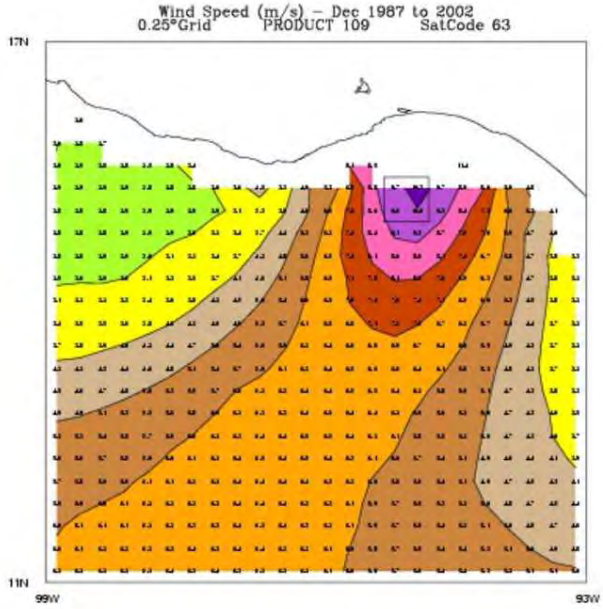
Oct

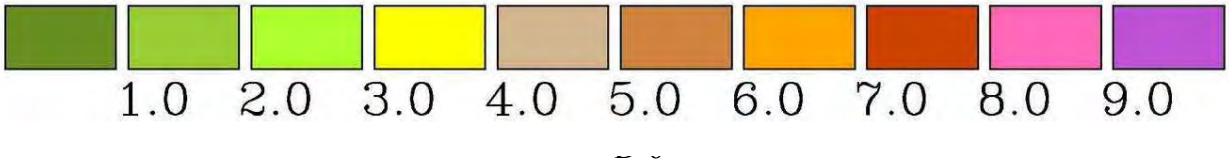


Nov

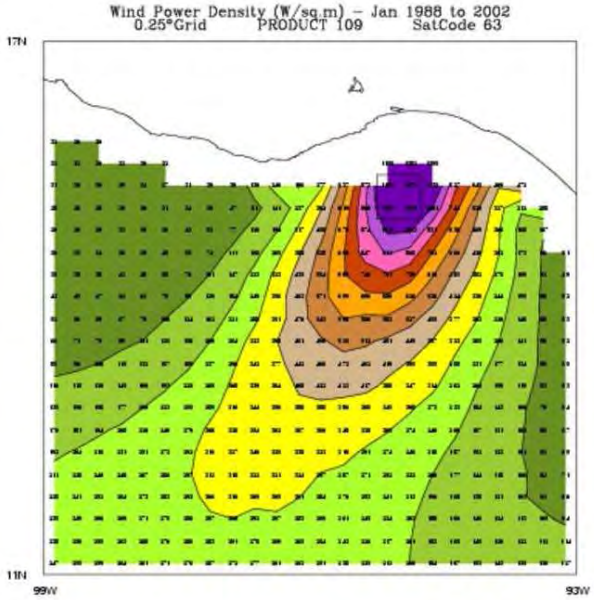


Dec

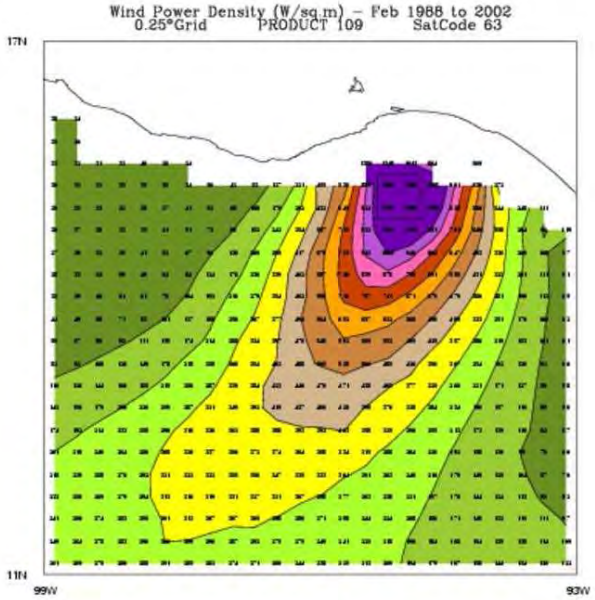




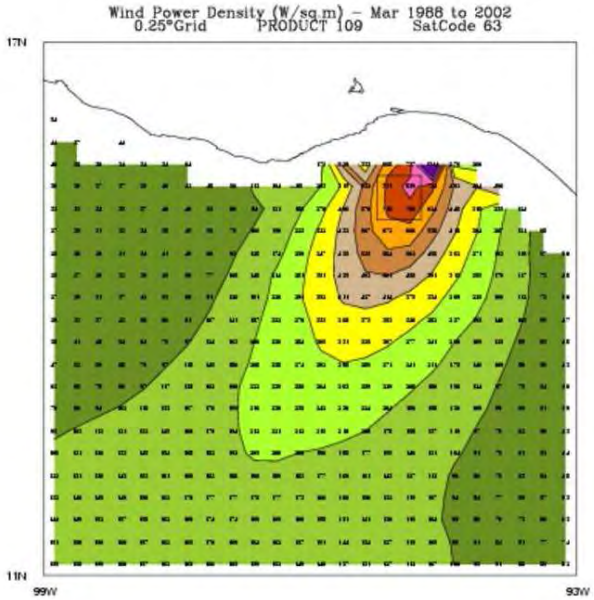
Jan



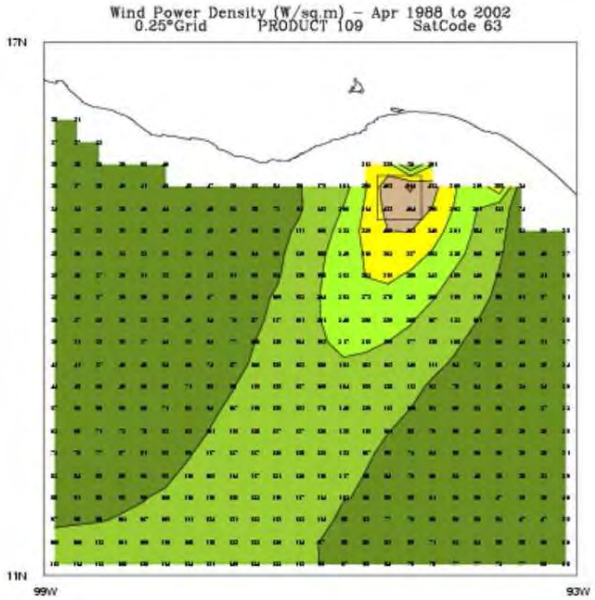
Feb

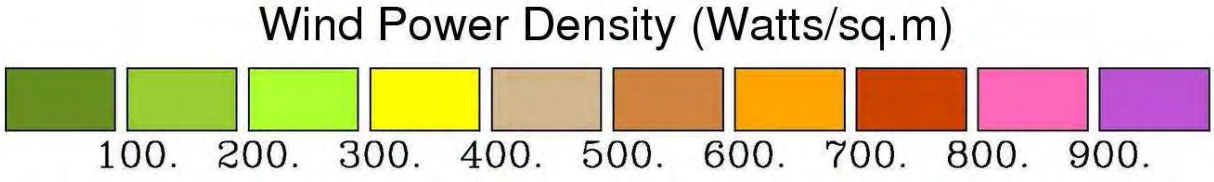


Mar

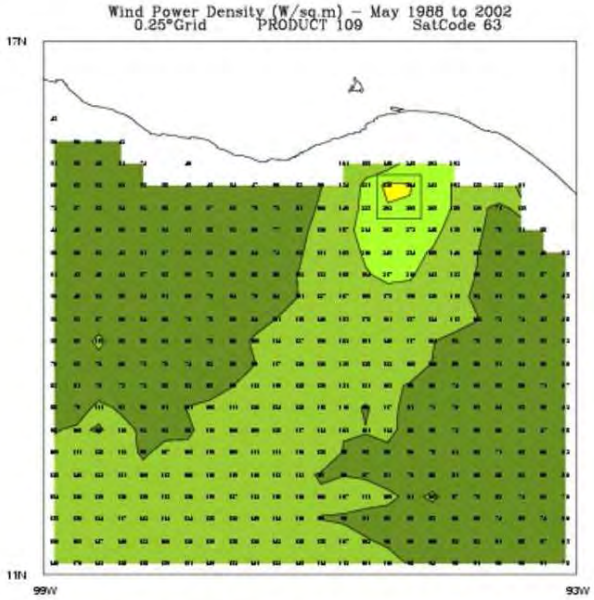


Apr

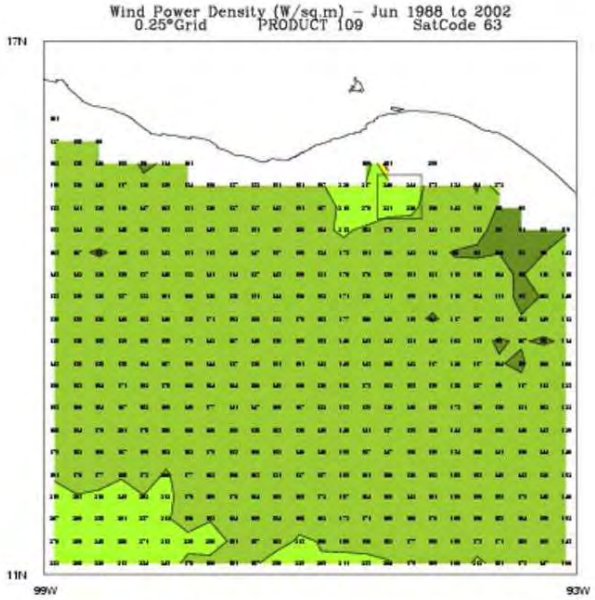




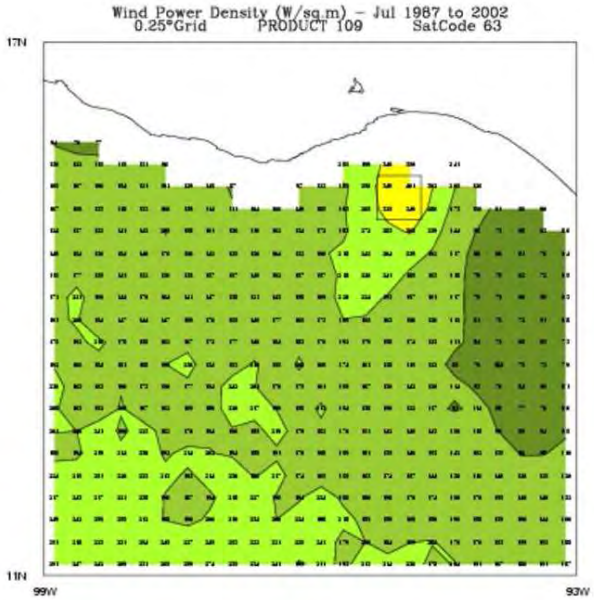
May



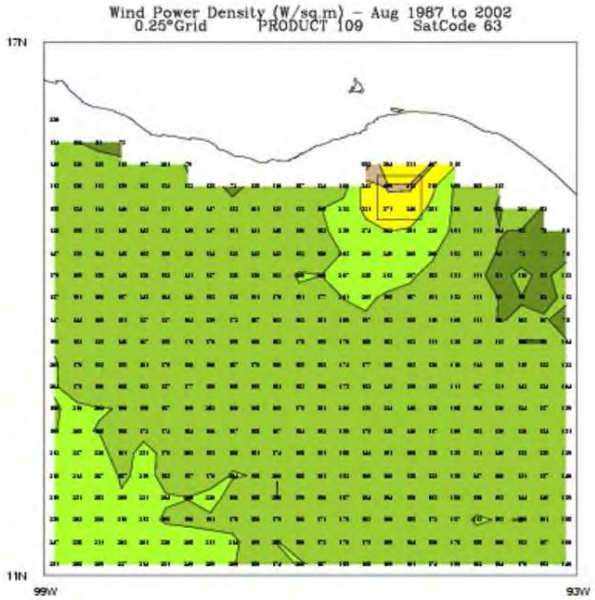
Jun

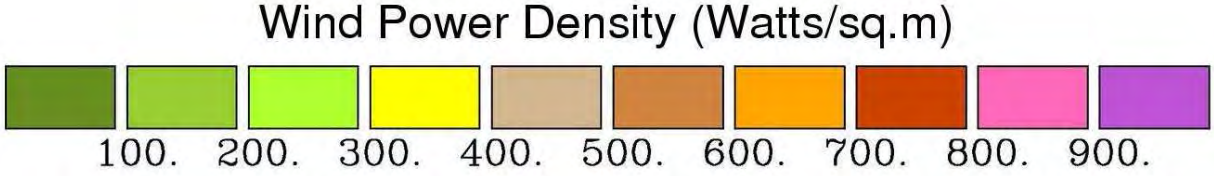


Jul

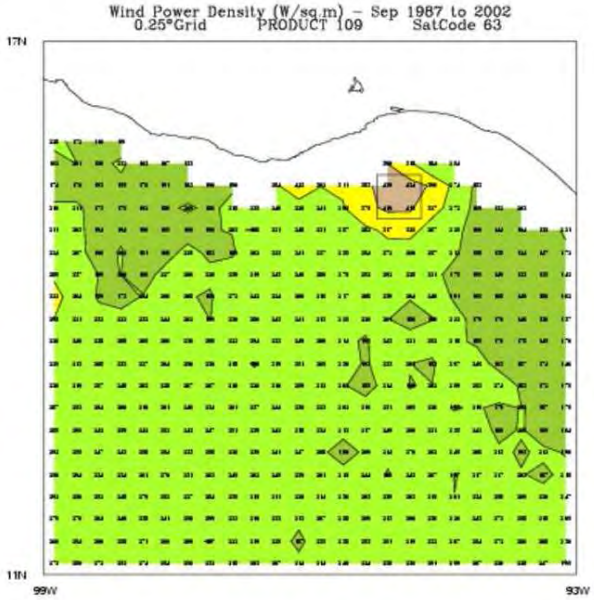


Aug

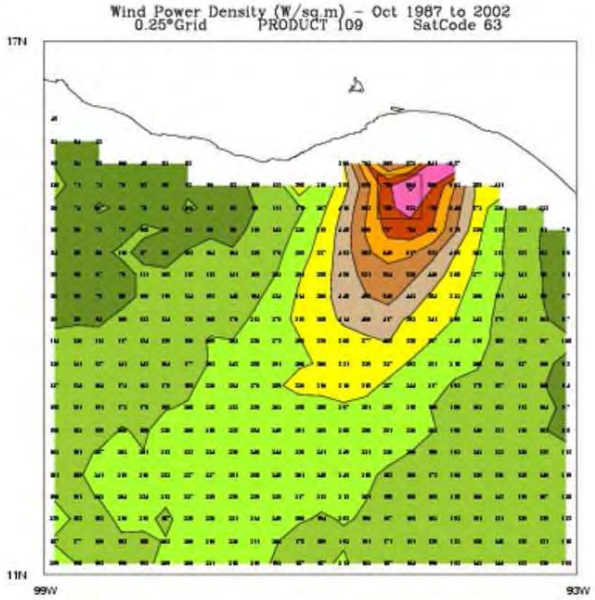




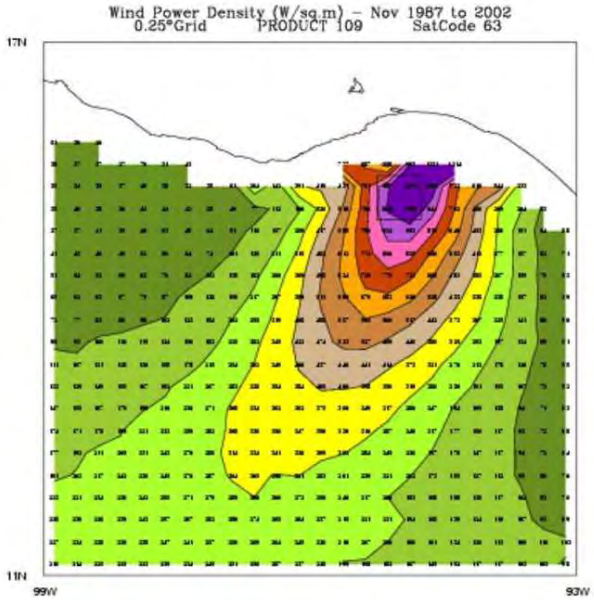
Sep



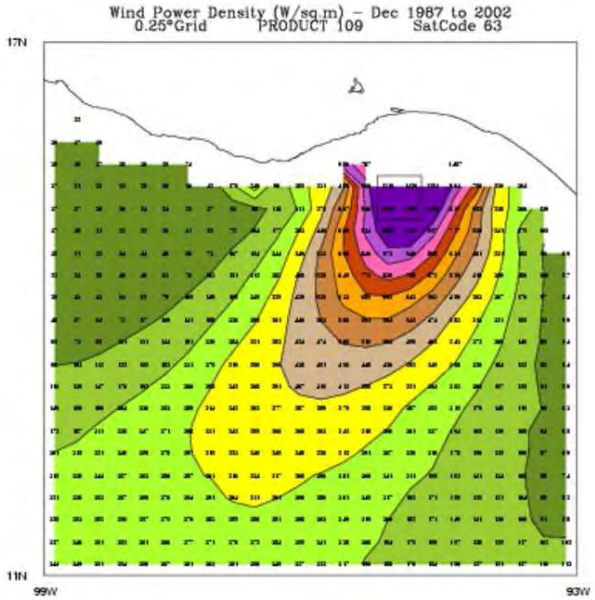
Oct

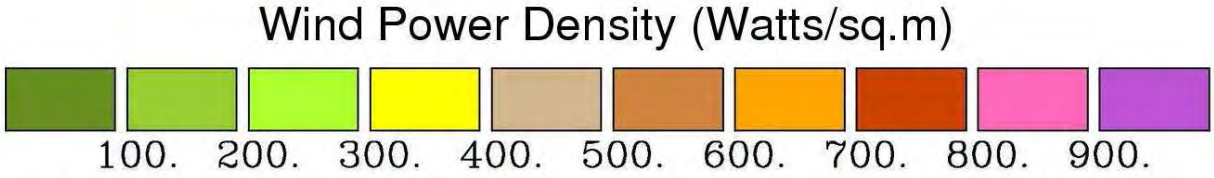


Nov

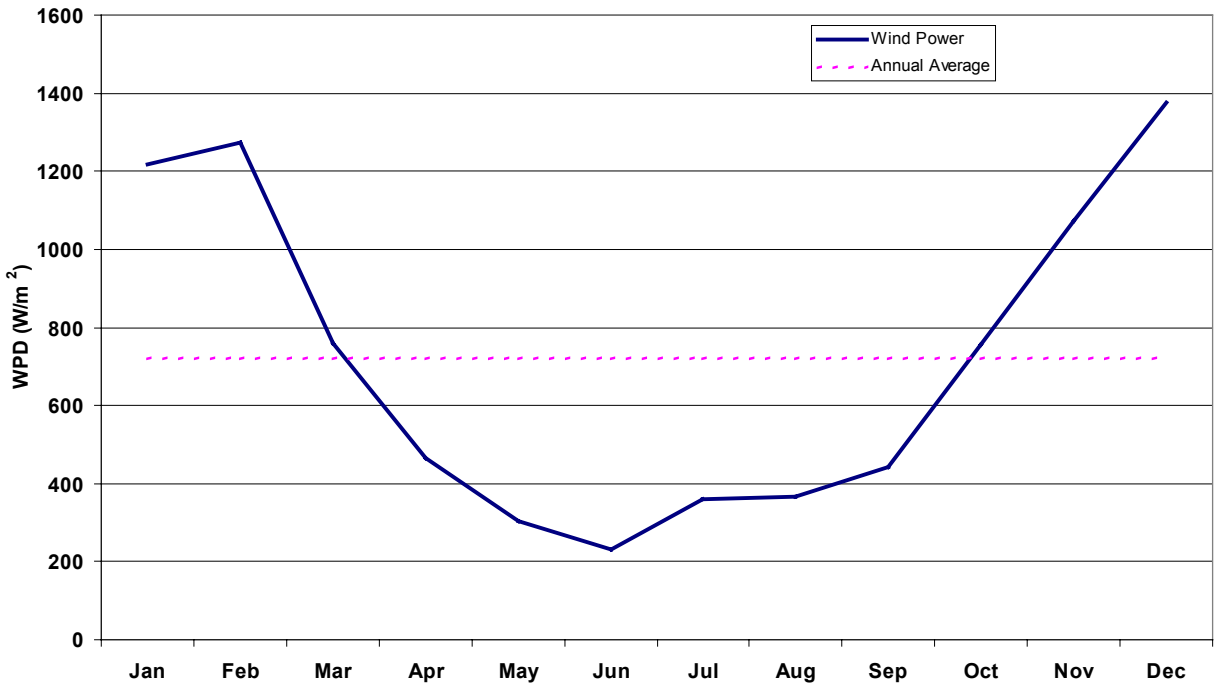


Dec

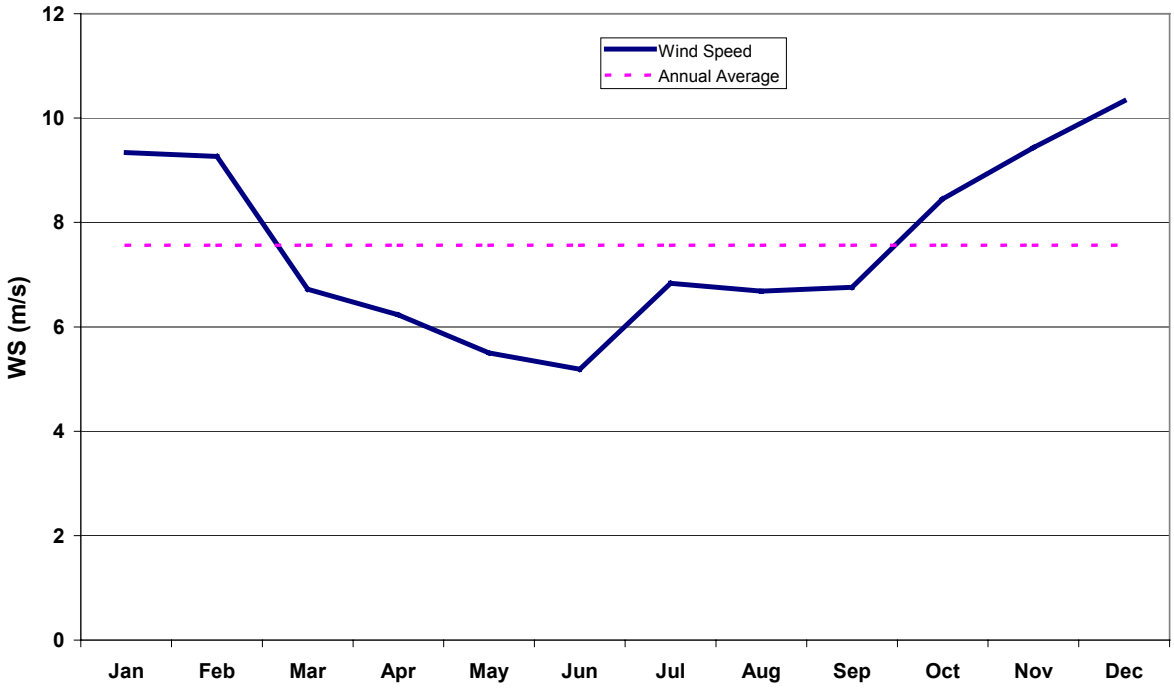




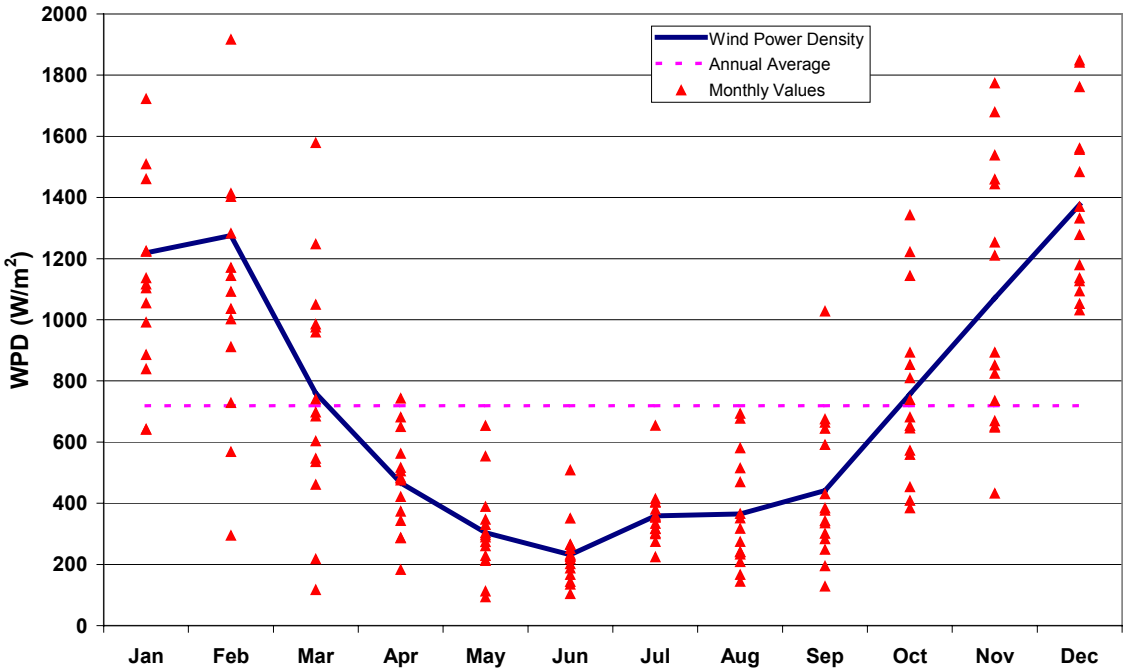
Oaxaca Offshore Region - Average Monthly Wind Power Densities



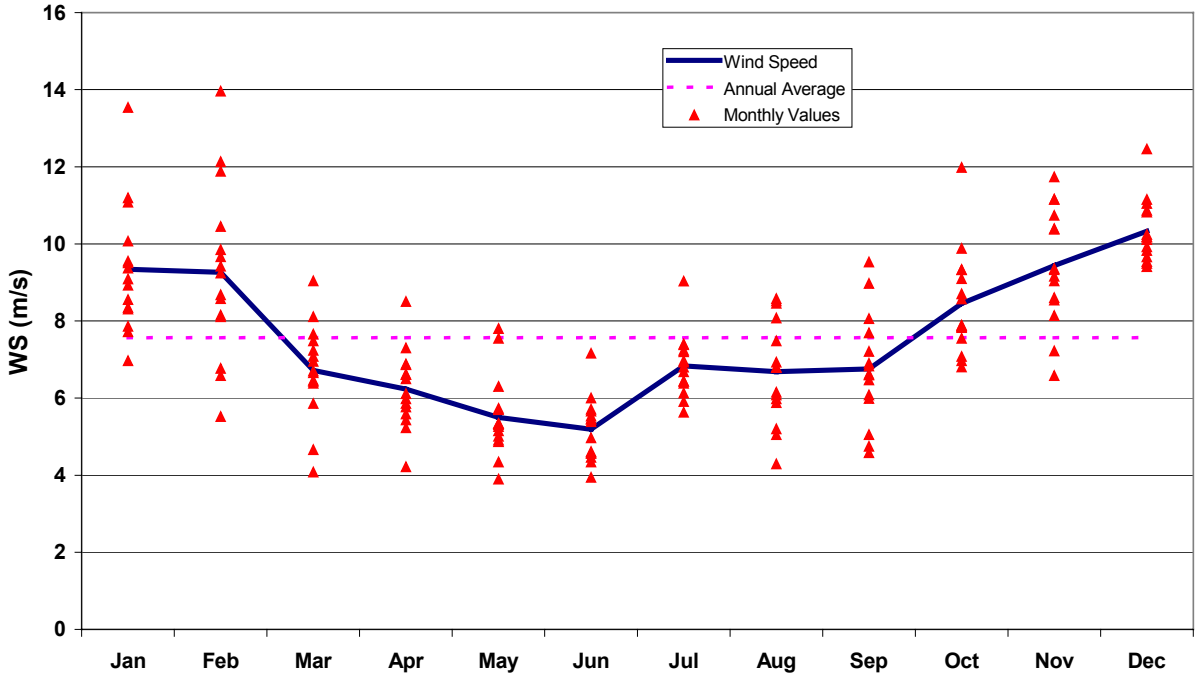
Oaxaca Offshore Region - Average Monthly Wind Speeds



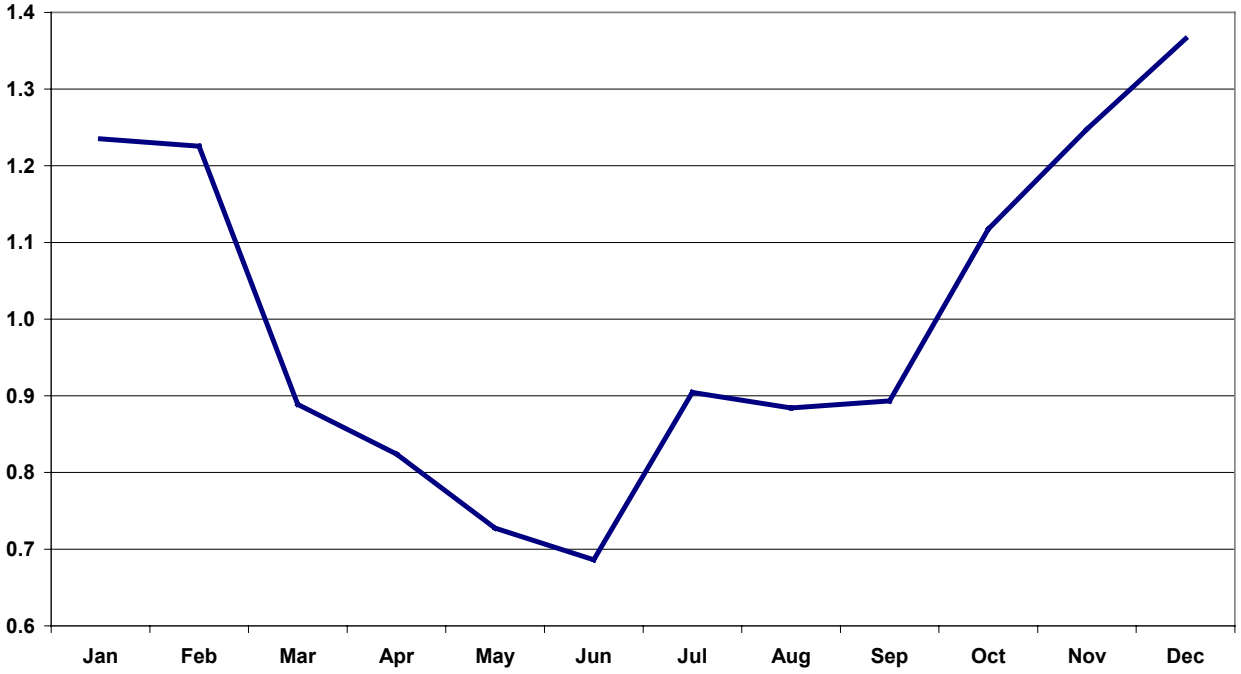
Oaxaca Offshore Region - Average Monthly Wind Power Densities



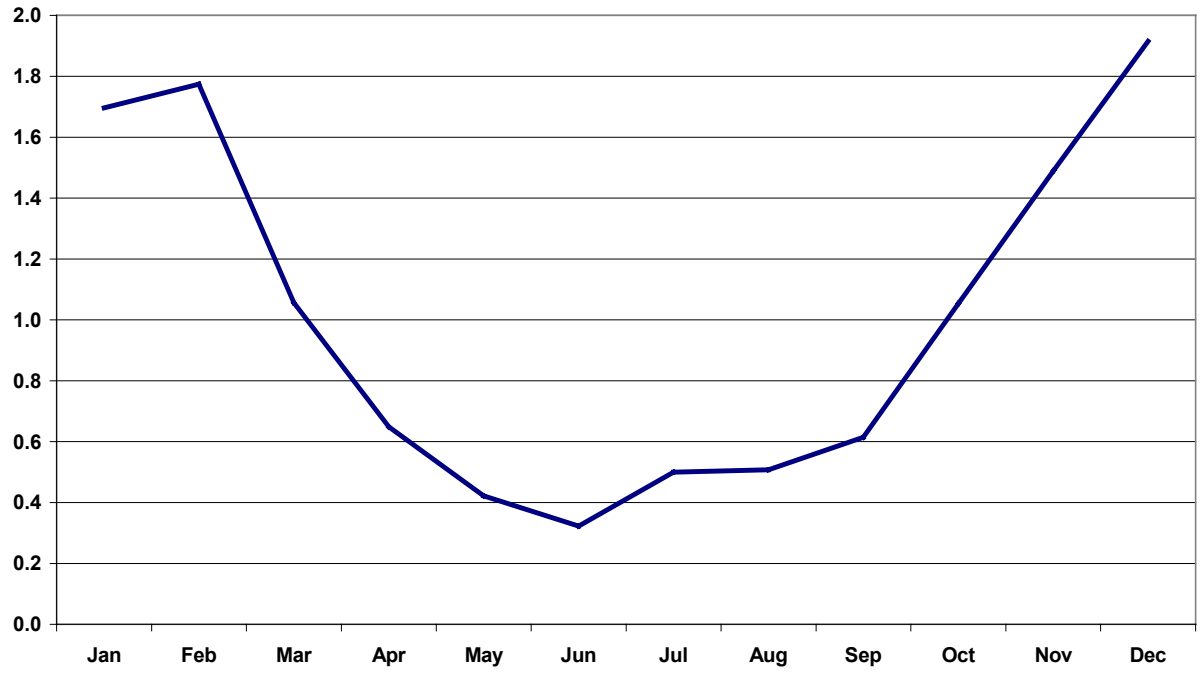
Oaxaca Offshore Region - Average Monthly Wind Speeds



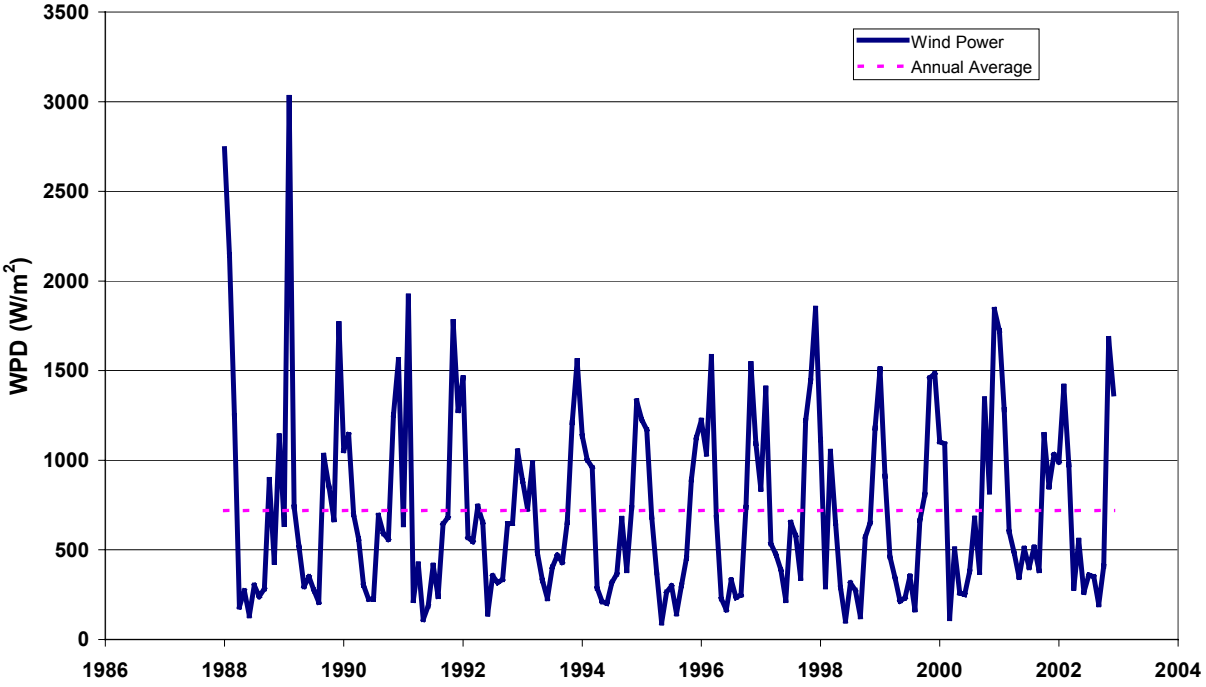
Oaxaca Offshore Satellite Normalized 10m Wind Speeds



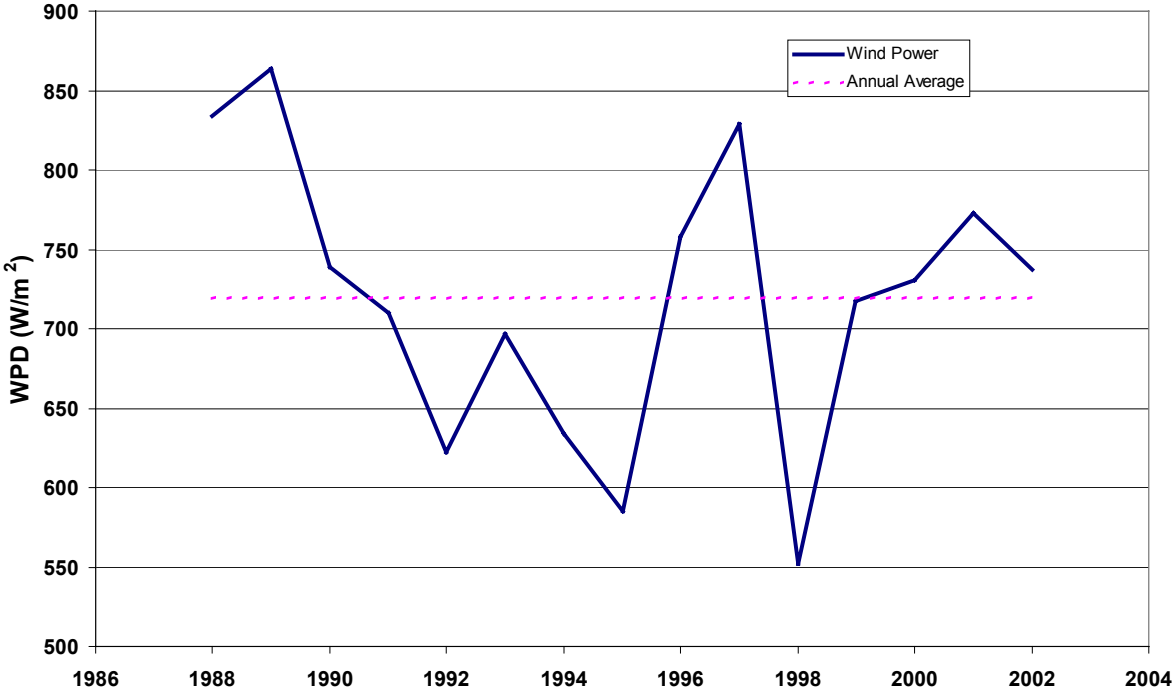
Oaxaca Offshore Satellite Normalized Wind Powers



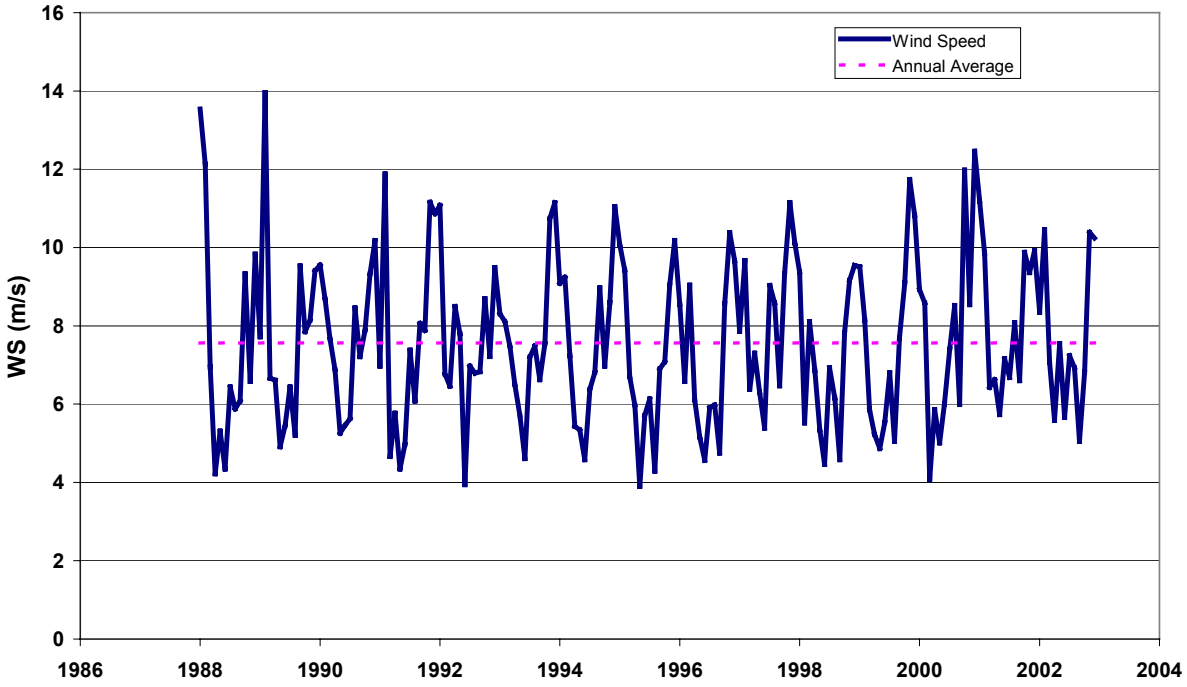
Oaxaca Offshore Region - Monthly Wind Power Densities



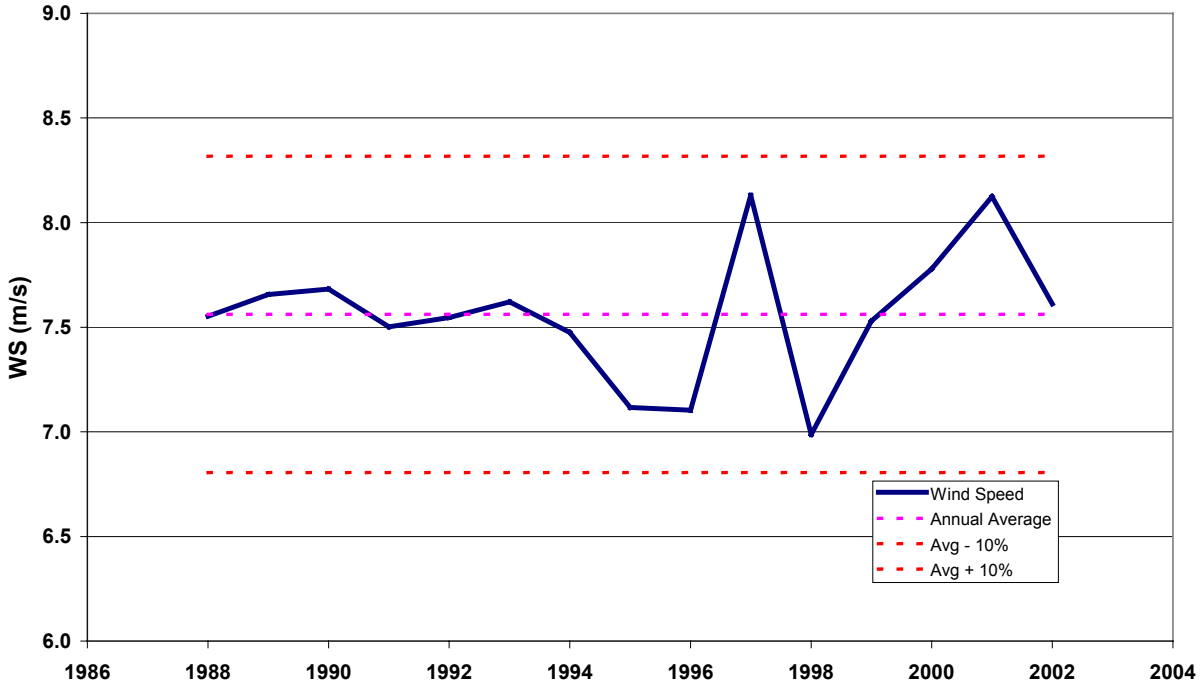
Oaxaca Offshore Region - Average Yearly Wind Power Density



Oaxaca Offshore Region - Monthly Wind Speeds



Oaxaca Offshore Region - Average Yearly Wind Speeds



REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	August 2003	Technical Report

4. TITLE AND SUBTITLE
Wind Energy Resource Atlas of Oaxaca

5. FUNDING NUMBERS
WF7C0310

6. AUTHOR(S)
D. Elliott, M. Schwartz, G. Scott, S. Haymes, D. Heimiller, R. George

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NREL/TP-500-34519

11. SUPPLEMENTARY NOTES
NREL Technical Monitor:

12a. DISTRIBUTION/AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The Oaxaca Wind Resource Atlas, produced by the National Renewable Energy Laboratory's (NREL's) wind resource group, is the result of an extensive mapping study for the Mexican State of Oaxaca. This atlas identifies the wind characteristics and distribution of the wind resource in Oaxaca. The detailed wind resource maps and other information contained in the atlas facilitate the identification of prospective areas for use of wind energy technologies, both for utility-scale power generation and off-grid wind energy applications.

14. SUBJECT TERMS
wind resource maps, Oaxaca, Mexico, wind characteristics and distribution

15. NUMBER OF PAGES
180

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

U.S. Agency for International Development

Secretaría de Energía (SENER)

Gobierno del Estado de Oaxaca, Secretaría de Desarrollo Industrial y Comercial (SEDIC)

Comision Federal de Electricidad

Instituto de Investigaciones Electricas

Comision Nacional del Agua (CONAGUA)

TrueWind Solutions, LLC

Prepared by
National Renewable Energy Laboratory
1617 Cole Boulevard • Golden, Colorado 80401-3393
A national laboratory of the U.S. Department of Energy
Managed by Midwest Research Institute • Battelle • Bechtel
for the U.S. Department of Energy under Contract No. DE-AC36-99-GO10337
NREL/TP-500-34519 • August 2003