Wind Energy Resource Assessment of Poland

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Summary

This wind energy resource assessment of Poland has identified areas with good to outstanding resource potential for wind turbine applications. Annual average wind resource maps have been developed for Poland and for specific regions within Poland. The wind resource maps highlight the major resource areas and provide estimates of the wind energy resource potential for typical well-exposed sites.

The average energy in the wind near the ground is expressed as a wind class power. The higher the wind power class, the higher the average wind energy. In general, areas with class 4 or greater resource are suitable for grid-connected windfarms using advanced wind turbine technology currently available or under development. In Poland, class 4 or greater areas are predominantly located along the Baltic Sea coast, and in the southern mountain region on exposed ridges and in wind corridors. Also, many exposed hills and ridge crests in the interior of Poland are estimated to have at least class 3 resource. Many of these areas may be suitable for development in the near future with further improvements in wind turbine technology.

Information from a global meteorological data set was the main source of surface data used in this assessment. This data set is composed of hourly surface weather observations collected and stored from sources such as the Global Telecommunications System. Meteorological parameters were extracted from the hourly observations and used to create statistical summaries of wind characteristics at weather stations located at city, airport, and mountaintop locations. Other types of information evaluated in the assessment were summarized historical climatological data, ship data from offshore marine areas, and upper-air wind data. The various data were screened and evaluated for their usefulness in preparing the wind resource assessment. Much of the surface data from land-based weather stations was determined to be from sheltered sites and was not very useful in assessing the wind resource. However, enough surface stations were determined to be well exposed to the prevailing wind and useful in the assessment to give a high degree of confidence to the estimates presented on the resource maps.

A more detailed identification of areas with potentially good to outstanding wind resource in Poland was done by applying various innovative techniques both newly developed and previously used in other wind resource assessments. In areas where existing site data were available from exposed locations, the measured wind resource was compared to the estimated wind resource derived using the innovative techniques. Overall, quite good agreement existed between the measured and the estimated wind resource.

This assessment project supported activities being pursued by the U.S. government's interagency program to assist in overseas marketing and promote renewable energy exports. This assessment of Poland provides valuable information needed to facilitate wind energy development in Poland and the formation of joint ventures between U.S. and Polish wind energy companies.

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Introduction

In 1981, a world-wide energy resource assessment map was prepared by the Pacific Northwest Laboratory (PNL)[a] (Cherry et al. 1981). While this world-wide assessment map is useful for identifying broad-scale features of the wind resource, considerably greater spatial variability exists in most regions of the world than is shown on the world-wide map. In some areas, the initial wind resource estimates may be incorrect because of inaccuracies or limitations in the database that was used and the techniques applied in extrapolating the wind resource from the data.

The purpose of this assessment was to produce a more detailed wind energy resource assessment of Poland for use in identifying potentially suitable areas for wind turbine applications. This updated assessment was completed using substantially more detailed data than was used in the world-wide assessment. Also, more sophisticated techniques of estimating the wind resource were used because the techniques could be applied in regional and local areas. Existing methodologies used in previous wind resource assessments by PNL for the United States (Elliott et al. 1987b), the Caribbean and Central America (Elliott et al. 1987a), Australia (Elliott and Gower 1988), and the Pacific Islands (Elliott and Davis 1988) were evaluated for their applicability and usefulness in updating the wind resource estimate for Poland. New techniques of displaying and interpreting statistical data using a comprehensive computer software package were developed and tested to aid in a more accurate assessment of all of the regions in Poland.

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Assessment Methodology

Surface Data

Review of Sources with Summarized Wind Resource Data

Various sources of summarized surface wind data and previous wind energy assessments were reviewed and evaluated for use in this wind resource assessment. Useful summarized climatological data were found in the *World Survey of Climatology* (Wallen 1977) and in a report produced by the U.S. government (National Intelligence Survey 1966) on the general climate of Poland. The Polish organizations that had summarized surface wind data included the Institute of Meteorology and Water Management (IMWM), which is the national meteorological service of Poland; the Institute for Building, Mechanization, and Electrification in Agriculture (IBMER); the University of Warsaw; and other academic institutions. Preliminary wind energy resource maps for Poland produced by IMWM and based on techniques used in the *European Wind Atlas* (Troen and Petersen 1989) were also reviewed. The maps show the estimated wind energy in kWh/m^2 for 20-m (Kukla 1991) and 30-m above-ground levels (Lorenc 1991) based on surface data from 1966 to 1985. A comparison between the 30-m map produced by the IMWM and the wind energy resource map produced by our analysis is in the final section of this report.

Surface Data Set

A global meteorological data set, DATSAV2 Surface Climatic Database, was the main source of surface data used in this assessment. The data set is composed of hourly surface weather observations collected and stored from sources such as the Global Telecommunications System. The period of record available at the time of purchase of the data set was primarily 1973 to 1991, although for many stations in Poland there was also information for the period of 1952 to 1963.

Meteorological parameters such as wind direction, wind speed, temperature, sea-level pressure, and altimeter setting were extracted from the hourly observations and used to create statistical summaries of wind characteristics. Most of the stations in Poland transmitted synoptic observations every 3 hours, eight times a day. Major airports in Poland transmitted synoptic observations every 3 hours, until the mid 1980s when METAR (Meteorological Aviation Routine Weather Report) observations began to be transmitted twice an hour.

In addition, summarized historical surface wind data for three locations in Poland not included in the DATSAV2 data set were analyzed. Overall, surface wind data from 81 locations were evaluated in this wind resource assessment of Poland. Of these stations, 24 were located at airports, two were mountaintop stations, and the rest were city locations. Maps of the stations are presented in Figures 1 and 2. Information on anemometer location, height, and station history was not available. The anemometer heights at these stations were assumed to be close to 10 m, the standard anemometer height of the World Meteorological Organization (WMO), because most of the stations belonged to the WMO synoptic network.

Each station in the DATSAV2 data set is identified by a unique six-digit number based on the WMO numbering system for the stations in Poland. In the DATSAV2 data set, the station at Gdansk is identified as 121500. Sometimes, however, the data from one DATSAV2 station had to be divided into separate station numbers. The most common reason to divide the data was a significant change in the latitude and longitude of the observations. As an example, the observations of latitude and longitude from Gdansk indicated that during 1974 the observations from station 121500 moved from the city of Gdansk to the airport. Data with the original latitude and longitude were assigned to station 121500, while data from the Gdansk Airport was assigned to the new station, 121501.

After an initial evaluation of the DATSAV2 data set, 78 locations in Poland were found to have sufficient wind data to be subject to further analysis. The lack of station names and latitude and longitude data caused an additional 33 stations with wind data to not be included in this assessment.

Upper-Air Wind Data

Upper-air wind data can be useful in establishing vertical profiles of wind speed and direction in the lower atmospheric boundary layer. The data can also be useful in extrapolating the wind energy resource on hilltops and ridge crests.

PNL obtained a 10-year period (1982 to 1991) of the National Center for Atmospheric Research archive of the National Meteorological Center upper-air observational data (Automated Data Processing reports). This data set contains daily processed radiosonde data from stations throughout the world at 00, 06, 12, and 18Z (Greenwich Mean Time). Wind information was available for the surface, the mandatory pressure levels (1000 mb, 850 mb, 700 mb, 500 mb), the significant pressure levels as determined by the vertical profile of temperature and moisture (different for each upper-air observation), and specified geopotential heights above the surface (different for each upper-air observation). PNL found that the wind data at the mandatory pressure levels were the most abundant and useful in this assessment. For stations at relatively low elevations, 1000-mb wind data were available. At the coastal station of Leba, the average height of the 1000-mb level is about 120 to 140 m above mean sea level. At the inland stations of Poznan and Warsaw, the average height of the 1000-mb level is about 25 to 40 m above ground. The 850-mb wind helped to extrapolate the wind resource to exposed higher terrain such as hilltops and ridge crests. The wind data at these mandatory levels combined with temperature data at the same levels produced wind power density profiles that refined the analysis.

Data from 11 upper-air stations in northeastern Europe were used in this analysis. Four upper-air stations were located in Poland. These stations were in Leba, Poznan, Warsaw, and Wroclaw. The other seven stations were in countries bordering Poland including Germany, the Czech and Slovak Republics, Ukraine, Belarus, Lithuania, and Russia. All the stations except Wroclaw, which had radiosonde data once a day, launched radiosondes at least twice a day, with some stations having radiosonde data up to four times a day.

Calculation of Wind Power Density

The wind resource at a site can be described by the mean wind speed, but the mean speed by itself is not an adequate parameter to accurately define the wind energy potential. The energy in the wind is proportional to the sum of the cube of the instantaneous or short-term average wind speed and the air density. The mean wind energy flux (E), which is also referred to as the wind power density, (in units of W/m^2) was computed by

$$E = \frac{1}{2n} \sum_{i=1}^{n} \rho_i V_i^3$$

where

n = the number of observations in the averaging period
ρ_i = the air density (kg/m^3) at a particular observation time
V_i = the wind speed (m/s) at the same observation time.

If the temperature, T (K), and the station pressure, P (mb), were available at a particular observation time, the air density was computed by

$$\rho = P/RT$$

where

R = gas constant (0.287).

If temperature or station pressure was not available, air density was estimated as a function only of station elevation, Z (m), by

$$\rho = 1.2 - (1.194 \times 10^{-4})Z.$$

The wind resource maps in this report estimate the resource in terms of wind power class (Table 1) ranging from class 1 (the lowest wind power density) to class 7 (the highest). Each class represents a range of mean wind power density or equivalent mean speed at specified heights above ground. The 10-m level is a standard international anemometer height for surface wind data, and wind turbine hub heights are generally 30 m to 50 m above the ground. In Table 1, a 1/7 power law (see Appendix A) was used to adjust the wind power densities from the surface to the turbine hub heights for open sites with low roughness.

Graphical Plots of Wind Characteristics

A comprehensive data processing package was written to convert the wind data in the DATSAV2 and upper-air data sets to statistical summaries of the wind characteristics at each station in a graphical form. The primary statistical summaries of surface data used in this assessment include the interannual variability of the wind speed and power, the average wind speed and wind power density on an annual and monthly basis, the frequency distribution of wind speed, the mean wind speed by direction, and the diurnal variability of wind speed and power. Other statistical plots for a given station used in the

Table 1. Classes of Wind Power Density

Wind Power Class	10 m (33 ft)[a] Wind Power Density, W/m²	10 m (33 ft)[a] Speed[b], m/s (mph)	30 m (98 ft)[a] Wind Power Density, W/m²	30 m (98 ft)[a] Speed[b], m/s (mph)	50 m (164 ft)[a] Wind Power Density, W/m²	50 m (164 ft)[a] Speed[b], m/s (mph)
	0	0	0	0	0	0
1						
	100	4.4 (9.8)	160	5.1 (11.4)	200	5.6 (12.5)
2						
	150	5.1 (11.5)	240	5.9 (13.2)	300	6.4 (14.3)
3						
	200	5.6 (12.5)	320	6.5 (14.6)	400	7.0 (15.7)
4						
	250	6.0 (13.4)	400	7.0 (15.7)	500	7.5 (16.8)
5						
	300	6.4 (14.3)	480	7.4 (16.6)	600	8.0 (17.9)
6						
	400	7.0 (15.7)	640	8.2 (18.3)	800	8.8 (19.7)
7						
	1000	9.4 (21.1)	1600	11.0 (24.7)	2000	11.9 (26.6)

[a] Vertical extrapolation of wind power density and wind speed are based on the 1/7 power law.
[b] Mean wind speed is estimated assuming a Rayleigh distribution of wind speeds and standard sea-level air density. The actual mean wind speed may differ from these estimated values by as much as 20%, depending on the actual wind speed distribution and elevation above sea level.

analysis included the number of observations on an annual, monthly, and hourly basis, and station and sea-level pressure by month. A complete set of the surface data plots for Leba is in Appendix B. The speed and power plots of upper-air winds at radiosonde stations in and around Poland were valuable in estimating the wind resource at levels just above the surface at certain stations and the wind resource over mountain summits and ridge crests. A plot of the mean wind speeds at the surface and two pressure levels aloft for Warsaw is presented in Figure 3.

Quality of Surface Data

A visual inspection of the surface plots from the DATSAV2 data set enabled quick screening of various characteristics of the wind measured at stations in a particular area. After the inspection, the wind characteristics at stations with the higher wind resource in Poland were analyzed in more detail. The visual inspection of the data also revealed trends and/or peculiarities in the observation data at some stations that called into question the quality of the data.

The data from Suwalki, in northeastern Poland, provides a good example of a trend in the surface wind data. A steady downward trend in wind speed and power density on an annual basis exists from 1973 to 1991 (Figure 4). The number of observations per year is fairly constant throughout the period. This trend in the data could lead to quite different conclusions about the wind resource at Suwalki depending on the period of record used in the analysis. An analysis of the wind resource at Sulwalki using the data from 1990 to 1991 would lead to the conclusion that the average wind speed was about 3.5 m/s and wind power density about 65 W/m². In contrast, using data from 1975 to 1976, the conclusion would be that Suwalki had a mean wind speed of 4.5 m/s and a power density of 140 W/m^2, more than double the 1990 to 1991 power density. The higher speeds in the 1970s were not an abnormally windy period at Suwalki, but rather a period before a significant downward trend occurred. A steady downward trend of wind speed at a station frequently indicates either a site becoming less exposed to the prevailing wind because of increased vegetation or other obstructions around the site, or possibly a degradation in the anemometer used at that site. A better representation of the wind resource at Suwalki can be gathered from the period during the 1970s rather than the most recent data.

A second type of data peculiarity can be seen in the time series from Mlawa in east-central Poland (Figure 5). The surface wind speeds from 1952 to 1963 are lower by 1 m/s compared to the values recorded from 1973 to 1991. The surface wind speeds from 1952 to 1963 are 50% of the values calculated from 1973 to 1991. The exposure of the anemometer at Mlawa is much better in the more recent period of record than from 1952 to 1963. This could be because of a change in anemometer location or a change of the sensor itself between 1963 and 1973. A more accurate representation of the wind resource at exposed areas near Mlawa can be achieved by using the data from 1973 to 1991 as opposed to the data from 1952 to 1963. However, a slight downward trend from 1973 to 1991 exists at Mlawa so data from a period before a significant trend began should be used.

At other stations in Poland, such as the Poznan Airport in west-central Poland (Figure 6), the anemometer seemed to have been better exposed in the period from 1952 to 1963 than in the period from 1973 to 1991. A more accurate representation of the wind resource can be made by using the earlier data.

Development of a Wind Resource Assessment Map

Surface wind data that was most representative of the wind resource at a particular station was used as a first step in producing an accurate analysis of the Polish wind resource. A time series review of wind data from the stations in Poland showed that a complete set of wind data from a long period of record (20 years, for example) was not necessarily representative of the station's wind resource. Inspections of the time series of wind data showed a significant trend or other data peculiarities, such as those at Suwalki and Mlawa, affected a number of surface stations. To minimize the amount of unrepresentative data used, the wind characteristics from the affected stations were calculated from periods considered to be most representative of the wind resource at each particular station. Subjectively choosing the representative period of record at each station was difficult at times. The interannual plots were screened for number of observations, trends in the wind speed and power density, abnormally windy or calm periods, and any sudden increases or decreases in wind speed and power. In general, representative periods of record from these stations were between 3 and 7 years in length. While the monthly values of the shorter period of record may depart significantly from the long-term mean, the information from representative periods of record gave a good overview of the wind resource at a station.

The representative annual average wind speeds and power densities for each station were then plotted on a base map. It became obvious from looking at this base map and topographical maps that some stations were better exposed to the prevailing wind direction(s) than other nearby stations. In-depth analysis of the statistical summaries such as frequency and speed by direction, frequency of speed, and speed and power by hour enabled the most exposed stations to be identified. The wind speed and power densities at the exposed stations were considered typical for other areas of like terrain in the various regions in Poland.

Wind power densities at turbine hub heights (30 m or 50 m) were determined by using the 1/7 power law at airfields and exposed stations to adjust the values from the surface data set and by analyzing wind data from levels just above the surface taken at the radiosonde locations. The wind power on ridge crests was estimated from the extrapolation of mandatory level upper-air data and surface data from high elevation stations. The estimates from the upper-air data were compared to and reconciled with the estimates derived from the DATSAV2 data to ensure a consistent analysis in all regions of Poland.

The wind power estimates on the maps apply to areas well exposed to the wind, free of local obstructions. These terrain features include open plains, tablelands, and hilltops. The wind resource maps, while identifying general areas of good wind resource, do not depict the variability caused by local terrain features. These terrain features can cause the wind resource to vary considerably over short distances, especially in areas of coastal, hilly, and mountainous terrain. In addition, this assessment does not discuss land with good wind resource that may not be available for wind energy development because of land-use restrictions or environmental exclusion, such as national parks and natural areas.

Discussion of the Poland Wind Resource

Geography and Wind Climatology

Poland is in eastern Europe between 49° N and 55° N latitude, and 14° E and 23° E longitude. It is bordered by other European countries except for the northwestern section, which is bordered by the Baltic Sea. The terrain in much of Poland consists of plains and river valleys of low elevation (0 to 150 m above sea level) that gradually rise in elevation toward the south. Low hills and ridges (200 to 500 m above sea level) are dispersed throughout Poland, especially in the north and south-central regions. The highest elevations in Poland are in the extreme south. Here, the Sudeten Mountains, in southwest Poland, and the Carpathian Mountains, in southeast Poland, have peaks that rise close to 2000 m in elevation.

Poland is a zone of prevailing westerlies the entire year. The prevailing wind directions in Poland are from the southwest to west except for local areas in the southern mountains affected by channeling. The southwest and west-southwest winds, caused by large pressure differences associated with synoptic weather systems, are the strongest winds in Poland and are most frequent during the autumn and winter months. The westerly winds during the summer months (June through September) are associated with weaker pressure gradients and mean speeds are significantly lower (2 to 3 m/s) than the winter westerlies in most of Poland. Easterly winds are most frequent from February through May. These easterlies tend to be northeast along the Baltic coast west of the Hel Peninsula and in extreme northeastern Poland, and more east to southeast over the rest of the Poland. October is a transition month between the summer westerlies and the winter southwesterlies. During this period, easterly and southwesterly winds predominate except along the immediate Baltic coast where southwest winds prevail.

The highest wind resource at low elevations is found across the northern part of Poland, especially at sites exposed to an overwater fetch of the prevailing west winds. The wind resource at low elevations decreases toward southern Poland, so exposed sites on the southern plain have a wind resource that is one power class lower than exposed sites on the central and northern plains. In contrast, the wind resource at higher elevation sites such as hills and ridges changes more slowly from northern to southern Poland because the north-south gradient of the speeds of the winds aloft is relatively small. Thus, the wind power class on the exposed higher hills and ridges in southern Poland is the same as on the hills and ridges in northern Poland.

The mountainous region along the southern Polish border effectively block the low-level flow of westerly winds except in significant gaps between the mountain ranges. The winds accelerate through these corridors, and areas of high wind resource lie downwind of these gaps especially in wide valley areas where significant quantities of land are exposed to the downslope winds. Exposed ridges, not blocked from the prevailing winds by other terrain, also have a high resource in this area. In contrast, sheltered valleys blocked from the winds by surrounding ridges have the lowest wind resource in this area.

Average Annual Wind Resource

The power class values used in the discussion of the wind resource distribution are the values for the most exposed sites in a particular area. The best sites in Poland are those exposed to the prevailing westerly winds and the easterly winds that are prevalent during late winter and spring. Areas that are forested or otherwise sheltered from the winds have class 1 resource. An overall map of the wind resource in Poland is presented in Figure 7.

Areas designated class 4 or greater are suitable for grid-connected wind turbine applications using advanced wind turbine technology available today or under development (Hock et al. 1992). Many areas with class 3 resource may be suitable for development in the near future with further improvements in wind turbine technology. Figure 8 shows the areas with class 3 and greater resource in Poland.

Areas of Poland with wind class 4 resource and higher are on the Baltic coast and in the southern mountain region, except for an isolated area on a high ridge near Kielce in south-central Poland. The class 4 locations near the Baltic coast are the primary sites having good exposure to southwest and west winds with trajectories either across the Baltic Sea, or across the large lakes and lagoons just inland from the immediate coast. The areas in the southern mountain region with class 4 and higher wind resource are in wind corridors downwind of broad gaps or passes in the mountain ranges or on ridge crests exposed to the west winds.

Class 3 resource areas in Poland are found along the Baltic coast at the secondary exposed sites subject to an overland trajectory of the west winds, on the higher unforested hills and ridge crests of the northern and south-central plain, and on the higher foothills of the southern mountains.

Class 2 resource areas are found on the exposed plains in central and northern Poland, along the western shore of Gdansk Bay, and on the lower foothills of the southern mountains.

Class 1 resource areas are found on exposed plains in southern Poland (south of approximately 50° 30' N), on sheltered valleys in the southern mountains, and on river valleys and forested areas in central and northern Poland.

Sectional Wind Resource Maps

Four areas (Baltic coast, interior plains, higher hills and ridges in the interior, and the southern mountain region) are discussed to provide greater detail about the average annual wind resource distribution. A sectional wind resource map and graphs of wind characteristics from selected surface stations accompany each summary.

Baltic Coast

This section details the estimated resource within 1 or 2 km of the Baltic coast. Figure 9 is a map of the wind resource along the Baltic Sea and its peninsulas, inland lakes, and lagoons. The western end of the analyzed area starts at the city of Swinoutscie, along the German border, and goes south; the area ends on the land located on the eastern shore of the Szczecinski Lagoon. The Baltic shoreline generally runs in a east-northeast direction from the German border until the Hel Peninsula. The Hel Peninsula extends east-southeast into Gdansk Bay. The town of Hel is located at the southern tip of the peninsula. The mainland runs south along the west shore of Gdansk Bay to the city of Gdansk. The shoreline curves eastward and then northeastward with Wislan Spit separated from the rest of the mainland by the Wislan Lagoon.

Leba is located west of the Hel Peninsula along the southern shore of the Baltic Sea. Leba is 1 to 2 km inland, near the eastern shore of Lake Lebzko, which extends 10 to 15 km west-southwest from the town. This results in southwest and west-southwest winds that have a significant overwater trajectory when they arrive at Leba. This station was determined to be the best exposed site of all the stations in the DATSAV2 data set that were along the Baltic coast. The average annual wind power density at Leba is 235 W/m^2, a high class 4 resource (Table 2). The period from 1973 to 1991 was used as the representative period for Leba. November to March are the peak power months. The frequency and speed by direction indicate that moderate to strong southwest and west-southwest winds averaging 7 to 9 m/s dominate the annual wind profile. The mean speed of the northeast winds, which are most prevalent during April and May, is around 5 m/s. The frequency by speed indicates a broad distribution of wind speeds for the entire year.

The information from Leba supported by historical data from Darlowo (Table 3) led to the estimate of class 4 resource at primary exposed sites on the Baltic coast. Primary sites are defined as areas with an overwater fetch of southwest and west-southwest winds. These primary sites are located along the coast where the shoreline is aligned closer to north-south resulting in the prevailing west winds being onshore, on the eastern shores of the inland lakes and lagoons, on the peninsulas and spits, and on exposed hills close to the shore. There may be isolated areas at exposed primary sites that have a class 5 resource. This increase in power class may occur at locations where the west winds are locally accelerated by terrain factors or where the northeast winds are stronger than they are at Leba. Secondary exposed sites along the Baltic coast are those sites exposed to southwest and west-southwest winds with some overland fetch. Because of frictional and thermal effects, the wind speeds of overland west winds are about 1 to 2 m/s slower than the speeds of west winds with an overwater fetch. The power class at the secondary exposed sites is class 3 resource. These secondary exposed sites are located where the shoreline is aligned more east-west and the prevailing winds are parallel to the shore or slightly offshore. The portion of the Baltic coast estimated to have class 2 resource extends from north of Gdansk around the south end of Gdansk Bay to the Wislan Spit. A class 2 resource was assigned because this region is exposed to west and southwest winds with long overland trajectories.

Table 2. Wind Data for Exposed Baltic Coast Station

Station	Rep. Years	Mean Wind Speed (m/s)	Power Density (W/m^2)
Leba	1973-1991	5.3	235

Table 3. Summarized Historical Wind Data for Darlowo (1930-1939)

Season	Power Density (W/m^2)	Power Class
Winter (Dec-Feb)	278	5
Spring (Mar-May)	252	5
Summer (Jun-Aug)	182	3
Autumn (Sep-Nov)	252	5
Annual	259	5

Interior Plains

The terrain in much of interior Poland consists of flat or gently sloping plains that gradually rise in elevation from north to south. The open plains are broken by river valleys, forested areas, and hills and ridges. The wind resource in the river valleys and forested areas is class 1. Open exposed plains in most of interior Poland are class 2 resource, with the extreme southern section having class 1 resource. (Figure 10).

Three of the better exposed sites on the plains are Poznan Airport and Mlawa in the class 2 area, and Wroclaw Airport in the class 1 area. Poznan Airport is located in west-central Poland, and Mlawa is to the north-northwest of Warsaw. The terrain around Poznan is fairly flat while Mlawa is on relatively flat, gently sloping terrain with open fetch to the prevailing westerly winds. Wroclaw Airport is located on a flat plain in southwestern Poland about 100 km north of the Sudeten Mountains. The representative years (Table 4) at Mlawa and Wroclaw Airport were chosen because of downward trends at both locations while anemometer exposure appeared best during the 1950s at Poznan. The average annual wind speeds at Poznan and Mlawa are about 4.3 to 4.4 m/s with wind power densities just over 100 W/m^2, a low class 2 resource. Upper-air data from the 1000-mb level, which is a few tens of meters above the surface at Poznan and Warsaw, also supports class 2 resource in central Poland. The annual average wind speed at Wroclaw Airport is about 3.3 m/s with wind power density of 76 W/m^2. The major difference in wind resource between the north-central and southern plains region is the stronger westerly winds averaging around 6 m/s on an annual basis at Poznan Airport and

Table 4. Wind Data for Exposed Stations on Interior Plain

Station	Rep. Years	Mean Wind Speed (m/s)	Power Density (W/m^2)
Poznan Arpt.	1957-1963	4.4	116
Mlawa	1974-1978	4.3	112
Wroclaw Arpt.	1974-1976	3.3	76

Mlawa compared to the westerly winds at Wroclaw (4 to 5 m/s). This difference is apparent from April through October. Another difference is the greater frequency of calm conditions at the Wroclaw Airport, especially during the summer months.

The central and northern plains have wind of at least class 2 resource for 6 to 8 months including 2 months of class 3 resource. In contrast, the extreme southern section of the Polish plains have class 2 and higher resource for only 2 to 3 months of the year. The boundary between the class 2 and class 1 areas extends from 51° 30' N at the western border to approximately 49° 45' N along the eastern border of Poland.

Hills and Ridges of Interior Poland

Figure 11 shows the wind resource estimates for the most prominent areas of hills and ridges in interior Poland. Major concentrations of these areas occur in northern and south-central Poland. The wind resource at exposed locations on the hills and ridges is class 3 resource in both northern and southern Poland except for a higher ridge (elevation near 600 m) near Kielce where a class 4 resource is estimated. Other minor or isolated hills and ridges not shown on Figure 11 may have a class 3 resource.

Two well-exposed stations in northern Poland, Gdansk Airport and Suwalki, are located on plateaus in higher elevation areas. Gdansk Airport is located west of Gdansk city on a plateau with open exposure to the prevailing westerly winds at an elevation of 138 m, over 100 m higher than the city. An extensive area of hills and ridges with elevations of 200 to 300 m is about 10 km southwest through northwest of the airport and extends westward roughly parallel to the Baltic coast. Suwalki is located in extreme northeastern Poland on a plateau over 180 m in elevation. Hills and ridges that reach heights of 300 m lie to the north of the city. The representative years at Suwalki (Table 5) were chosen because of the downward trend, discussed previously in the Quality of Surface Data section. The mean annual wind speeds at both locations are between 4.5 and 5.0 m/s with wind power densities between 140 and 165 W/m^2. Some differences exist between Gdansk Airport and Suwalki in the distribution of the wind resource throughout the year, but overall, the pattern is about the same for both locations. Westerly winds averaging between 6 and 8 m/s predominate from November to January and are maintained around 5 to 6 m/s during summer. The winds are a high class 2 resource to low class 3 resource. The wind resource at these plateau stations is estimated to be lower than the resource at exposed sites at higher elevations because of the increase of wind speeds with height. The higher hills and ridges in northern Poland were estimated to have at least a class 3 resource.

Table 5. Wind Data for Exposed Plateau Stations

Station	Rep. Years	Mean Wind Speed (m/s)	Power Density (W/m^2)
Gdansk Arpt.	1974-1991	4.9	165
Suwalki	1974-1978	4.6	142

The analysis of the wind resource on the hills and ridges of southern Poland presented a problem. No stations existed on plateaus or hills in southern Poland. However, wind data did exist from the radiosonde station at Wroclaw and more extensive radiosonde data at Lvov in Ukraine. The combined information from Wroclaw and Lvov lead to the estimates of class 3 resource on the hills and ridges in southern Poland. Lvov (elevation 323 m) is near the eastern Polish border situated on a gently sloping broad ridge that extends northwestward into eastern Poland south of Zamosc. The surface wind speeds at about 10 m from four daily radiosonde launch times averaged 5.4 m/s with a class 3 resource (160 W/m^2). Lvov was determined to be a well-exposed site, and it is estimated that a class 3 resource would also be found on hills and ridges in southern Poland at comparable latitudes. Furthermore, the 850-mb wind data from Wroclaw were comparable to the 850-mb winds at Poznan and Warsaw. The wind data from the upper-air stations indicated that the wind resource on exposed hills and ridges in southern Poland was as high as the resource on hills and ridges in northern and central Poland.

Southern Mountain Region

Two major mountain ranges, the Sudeten in southwestern Poland and the Carpathian in southeastern Poland, form a large complex terrain in extreme southern Poland. The highest peaks are located along the Czech and Slovak border with the highest peak, Kasprowy Wierch, almost 2000 m in elevation. Other mountain summits and ridge crests with elevations of 1000 m to 1400 m are interspersed in the area.

The high terrain serves as a permeable barrier to the prevailing west and southwest wind flow. The highest resource in this region is found on exposed ridge crests and in wind corridors downwind of gaps in the mountains through which the wind is channelled and accelerated. The specific location with highest wind resource is quite dependent on topography. Therefore, ranges of wind power classes were assigned for a given area. These ranges represent the expected regional wind power classes for exposed sites, though individual sites within an area may vary greatly in wind resource (Figures 12 and 13).

Except for two mountaintop stations, all stations in the DATSAV2 data set located in the southern mountain region were in sheltered valley areas with low wind resource. However, summarized historical data were available for Krosno in southeastern Poland. Krosno is situated in a wind corridor downwind from a major break in the Carpathian Mountains. The data indicate wind of class 4 resource (Table 6), with a maximum wind resource during winter of class 6. Based on this data, wind corridors and exposed higher ridge crests were assigned classes 4-6 resource to account for local terrain influences on the wind resource. Valley areas and lower ridge crests were estimated to have classes 1-3 depending on the amount of sheltering. Classes 5-7 were estimated for the highest ridge crests (above 1500 m).

Table 6. Summarized Historical Wind Data for Krosno (1939-1942)

Season	Power Density (W/m^2)	Power Class
Winter (Dec-Feb)	310	6
Spring (Mar-May)	274	5
Summer (Jun-Aug)	100	2
Autumn (Sep-Nov)	212	4
Annual	247	4

Information did exist in the DATSAV2 data set from two mountaintop locations, Kasprowy Wierch and Sniezka Mountain (Table 7). The average wind speed and wind power density on Sniezka Mountain are extraordinary. The average wind speed of over 12 m/s is at least 2 m/s higher than the free air speed at 850 mb, the level closest in elevation to Sniezka Mountain. This high wind speed is caused by acceleration of the flow over the ridge crest. The data from these two mountaintop stations point out the tremendous variability of the resource in this region. Site specific measurements must be made to accurately assess the wind resource in the southern mountain region.

Intra-annual Wind Resource Patterns

Figure 14 shows the monthly distribution of the wind resource across Poland from the Baltic coast (Leba) to the southern plains (Wroclaw Airport) based on complete data from the DATSAV2 data set. The absolute values of the wind speed and power from a particular station may not be completely accurate because of trends or other peculiarities in the data but the overall patterns from these locations can be used for comparative purposes. The distribution is similar for all locations and is a simple pattern. The wind resource is highest from November through March with the peak wind speed and power in December and January. The wind resource reaches a minimum from May through August. The speed and power increase steadily from this minimum towards the winter maximum.

Table 7. Wind Data for Exposed Mountain Stations

Station	Period	Mean Wind Speed (m/s)	Power Density (W/m^2)
Sniezka Mtn.	1952-1963 1973-1991	12.1	1420
Kasprowy Weirch	1952-1963 1973-1991	6.8	411

The exposed area wind resource patterns discussed in the following sections are based on the climatological wind flow patterns rather than the calendar months. The calendar months are provided for each season. Thus, some overlap exists between the seasons in these discussions.

Late Autumn - Early Winter Wind Resource (November through January)

During these months, mean upper and surface wind speeds in Poland are strongest. Class 3 and above wind resource can be found at exposed sites throughout most of Poland except in the southern plains region where class 2 resource is found. The primary exposed areas along the Baltic coast are estimated to have class 6 resource. Class 6 areas are also found in the wind corridors and exposed ridge crests in the southern mountain region. In fact, the very highest exposed ridge crests can have class 7 and higher resource during this time of year, though these areas may be too inaccessible for much wind energy development. Class 4 resource is found at the secondary exposed locations along the Baltic coast, in the higher foothills of the southern mountains, and on the hills and ridges in northern and south-central Poland.

Late Winter - Spring Wind Resource (February through May)

Easterly winds are most prominent during these months. These winds are not quite as strong as the winter westerlies. These winds combined with a decrease in the strength of the upper-level westerlies leads to lower wind resource across Poland as compared to the period from November through January. February and March have the highest resource during this period with decreasing resource during April and May. The wind resource pattern across Poland during this period is close to the annual average pattern. Class 7 resource is still found on the highest peaks in the southern mountains. The wind corridors and the exposed ridges in the southern mountains have class 4-5 resource. The primary exposed areas along the Baltic coast have class 4 resource. Class 3 resource is found at secondary exposed sites along the Baltic coast, in the southern mountain foothills, and on the hills and ridges in northern and south-central Poland. Class 2 resource occurs on exposed sites on the northern and central plain, and class 1 resource occurs at the exposed sites on the southern plain.

Summer Wind Resource (June through September)

The upper-air and surface winds are weakest during these months, and class 1 resource is wide spread in Poland. Class 3-4 resource occurs on the highest peaks in the southern mountains, with class 2 resource in the wind corridors. Class 3 resource occurs at the primary exposed sites along the Baltic coast.

Early Autumn Wind Resource (October)

October is a transition month with surface winds displaying characteristics of both spring and winter. Over most of Poland, east and southwest winds are about equal in frequency except along the Baltic coast. Aloft, the westerlies increase from their summertime speeds and the resource at high elevation stations increase quite a bit from the summer level. Class 7 resource is again found on the highest peaks in the southern mountains. Class 4 resource occurs at the primary exposed sites on the Baltic coast because of the predominance of the southwest winds. Classes 3-4 occur in the wind corridors and the southern mountain exposed ridges. Classes 2-3 are found on the hills and ridges in northern and south-central Poland and in the southern mountain foothills. The plains of northern and central Poland have a resource of classes 1-2 with the southern plains having class 1 resource.

Diurnal Wind Pattern

The diurnal distribution of the wind resource throughout the year is quite similar throughout most of Poland whether the station is a coastal site (Leba), on the open plain (Poznan Airport), or a plateau station (Gdansk Airport). Figures 15-17 show the diurnal pattern of wind speed and direction for these stations. At all locations in Poland, the period from November to February, when synoptic weather systems are strongest and solar insolation the least, has little diurnal variation in the wind resource. The average wind speed is around 6 m/s for the windier stations and 5 m/s at other sites. The diurnal variation of wind speed and power increases in March. Most locations have the largest spread in summer, the time of the weakest synoptic weather systems and greatest solar insolation. The peak winds during summer occur in early afternoon with the lowest speeds recorded in the early morning. The variation between the peak and the lowest average wind speeds is about 2.5-3 m/s. The diurnal variation decreases through early autumn as the synoptic weather systems intensify until the diurnal distribution of wind speed and power again becomes nearly flat by November.

The diurnal pattern at Hel, a marine station at the tip of a peninsula, (Figure 18) is much flatter throughout the year. Hel has little diurnal variation from October through March, and the peak variation in summer is generally less than 1 m/s. The peak winds at Hel in summer occur in the afternoon.

The diurnal pattern on the high mountaintops during summer differs from the pattern at low elevation sites. The strongest winds at the mountain locations occur at night and the lowest wind speeds are recorded at midday (Figure 19).

Comparison of Wind Energy Map Produced by IMWM with PNL Analysis

Figure 20 is a wind energy map (in kWh/m^2 per year) for heights 30 m above ground level produced by the IMWM (Lorenc 1991). The wind energy values on the map were derived by adjusting raw 10-m data from 52 meteorological stations to 30-m values using a power law coefficient (see Appendix A). A comparison between the IMWM and PNL analyses shows significant differences in both the distribution and the overall quantity of the wind resource in Poland.

Table 8 shows wind power class as well as wind power density (W/m^2) at 30 m and the corresponding values of kWh/m^2. The IMWM map shows class 1 resource (less than 1400 kWh/m^2) over Poland except for areas along the Baltic Coast and a part of northeastern Poland where class 2 resource (1500-2000 kWh/m^2) is indicated. PNL's analysis estimated that exposed areas in most of Poland have at least class 2 resource, with class 3 and higher resource on the higher hills and ridges, along the Baltic coast, and in regions of the southern mountain area.

Table 8. Comparison of Wind Power Class and Values of kWh/m^2

Wind Power Class	Power Density (W/m^2) at 30 m	Values of kWh/m^2
1	0-160	0-1400
2	160-240	1400-2100
3	240-320	2100-2800
4	320-400	2800-3500

The resource distribution of the resource on the IMWM map shows strong gradients in the wind energy in northeastern and central Poland that are not present on the PNL analysis. These gradients seem to result from the adjustment of raw data from the meteorological stations without accounting for anemometer exposure, terrain considerations, and any data peculiarities at each station. Based on an analysis of the general wind flow and the wind data from exposed sites, a physical basis did not exist that would justify including these gradients on the PNL analysis.

The wind energy contours on the IMWM map do not take into account terrain features or whether the trajectories of the prevailing winds are over land or over water. In the southern mountain region, the contours do not indicate the variability of the wind energy resource in that area or the higher wind resource over the exposed ridges. Along the Baltic coast, the highest wind energy contour lines on the IMWM map are concentrated on the shoreline where the east-west alignment produces an overland trajectory of the power-producing southwest winds. The highest wind energy sites along the Baltic coast should be where the shoreline is oriented more north-south, and in other areas downwind of large lakes and lagoons.

In summary, the wind energy contours on the map produced by the IMWM are based on the raw 10-m data adjusted to 30 m and do not seem to account for differences in the quality of data among the stations. The wind energy resource maps produced by PNL were based on data from a greater number of stations and incorporated analyses of the quality of wind data, surface and upper-air flow patterns over Poland, anemometer exposure, and terrain effects in the final product.

Conclusions

This wind energy resource assessment of Poland has identified areas of good to outstanding resource potential for wind turbine applications. The accuracy and detail of this assessment was improved over previous studies by analyzing data from a recently released global meteorological surface data set and applying innovative wind resource assessment techniques. The detailed wind resource maps presented here should facilitate wind energy development in Poland and the formation of joint ventures between U.S. and Polish wind energy companies.

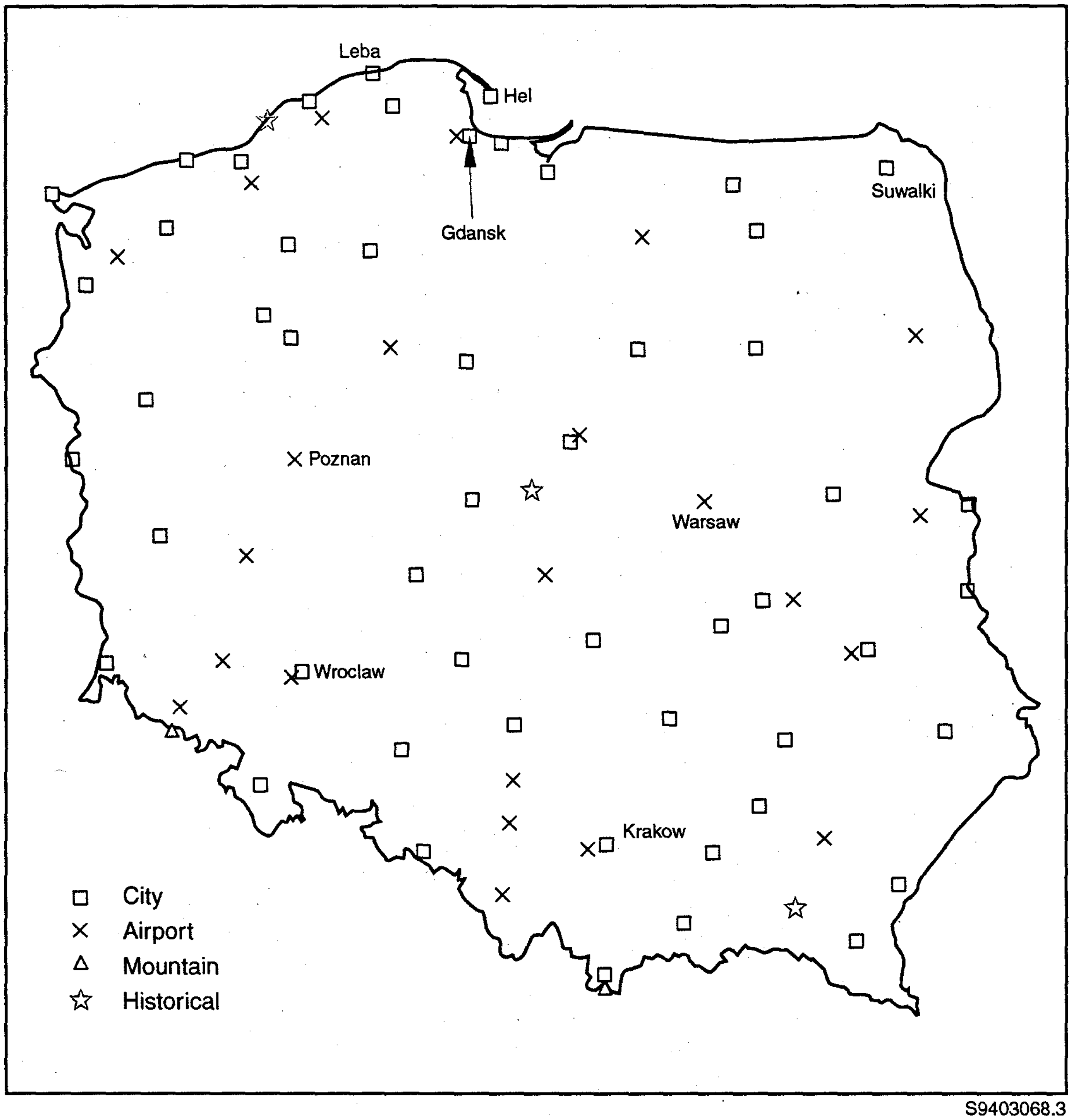


Figure 1. Locations and Types of Meteorological Stations with Wind Data in Poland

Figure 2. Names of Meteorological Stations with Wind Data in Poland

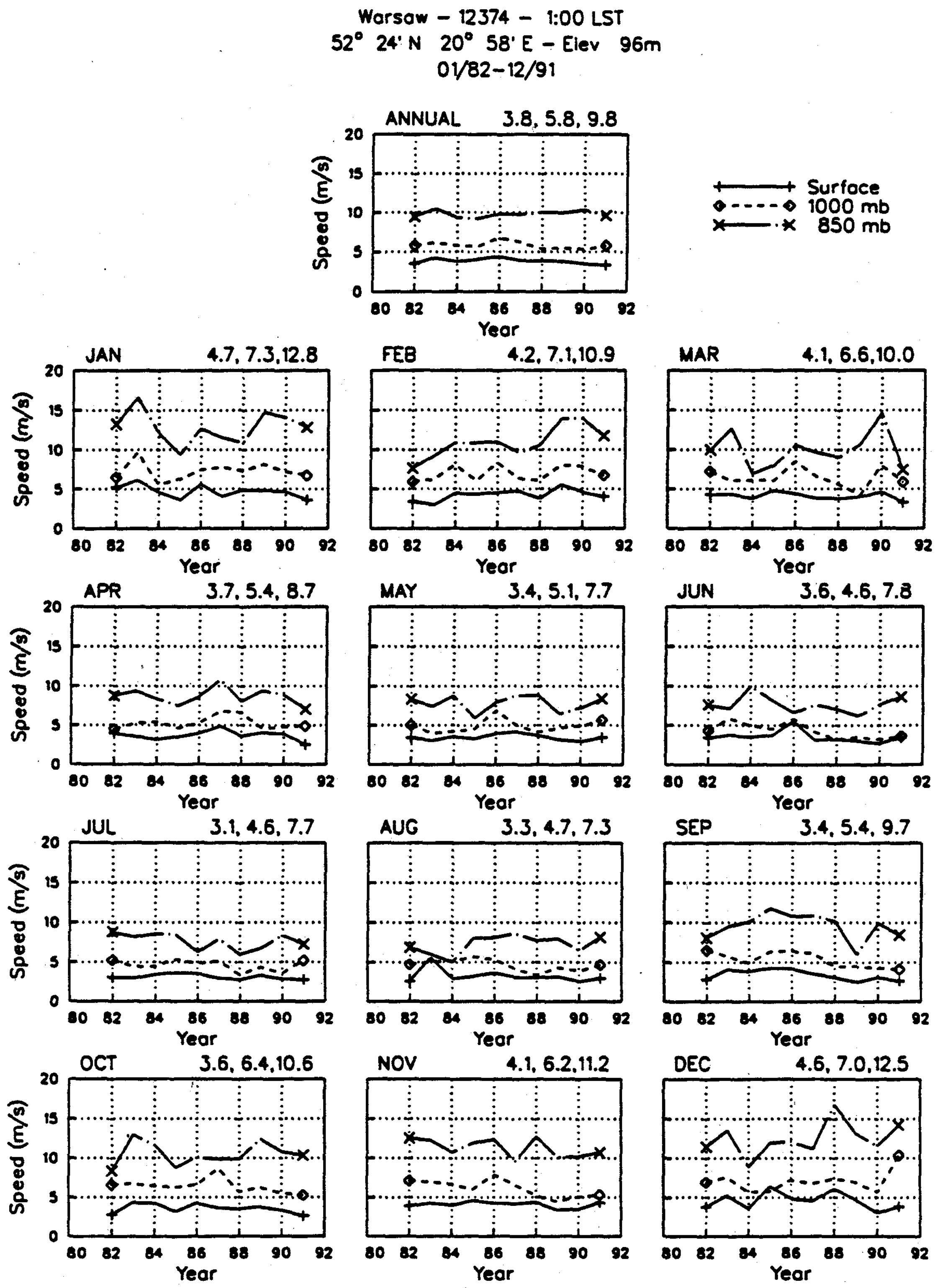


Figure 3. Wind Speed by Pressure Level and Year for Warsaw

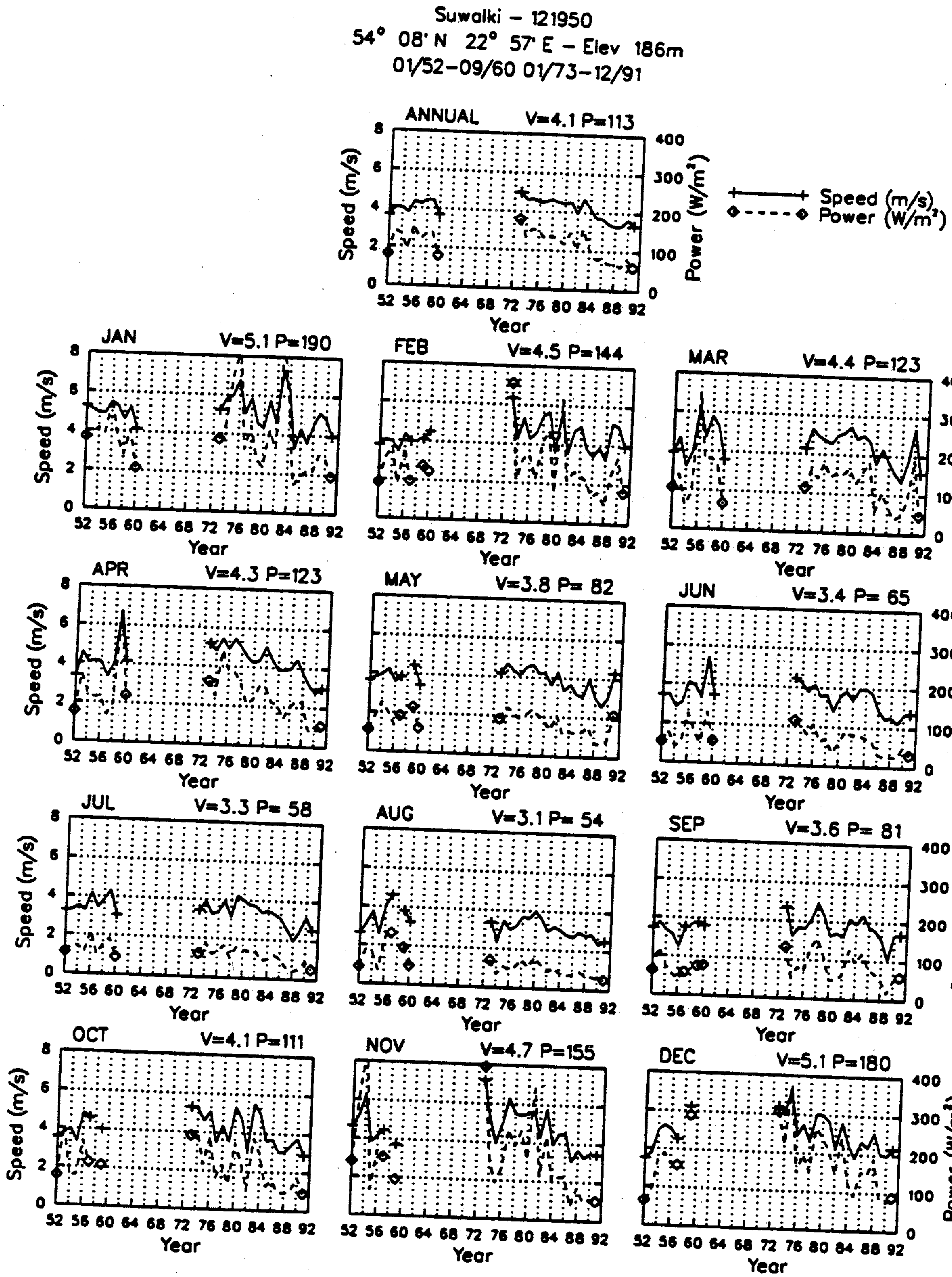


Figure 4. Wind Speed and Power by Year for Suwalki

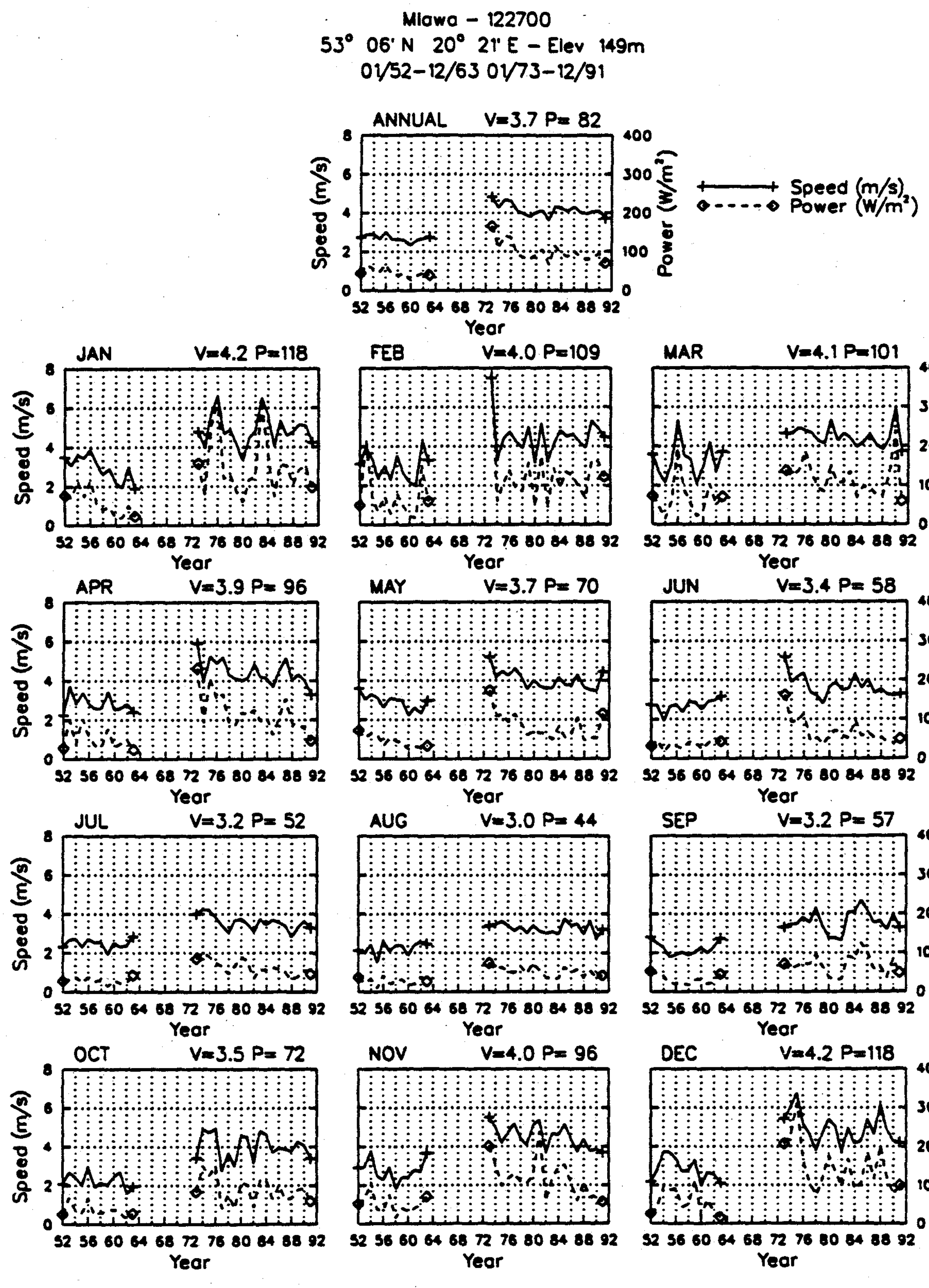


Figure 5. Wind Speed and Power by Year for Mlawa

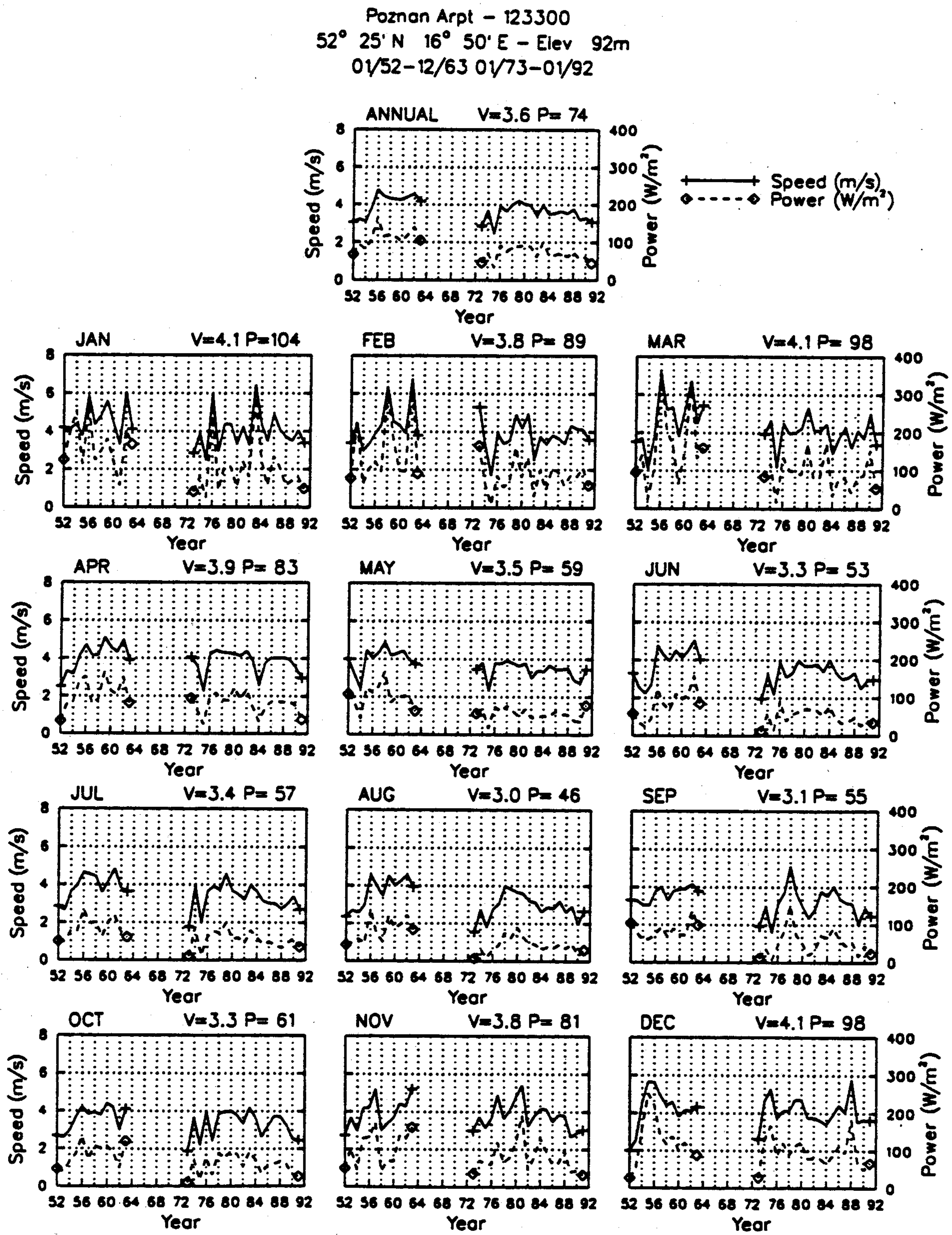


Figure 6. Wind Speed and Power by Year for Poznan Airport

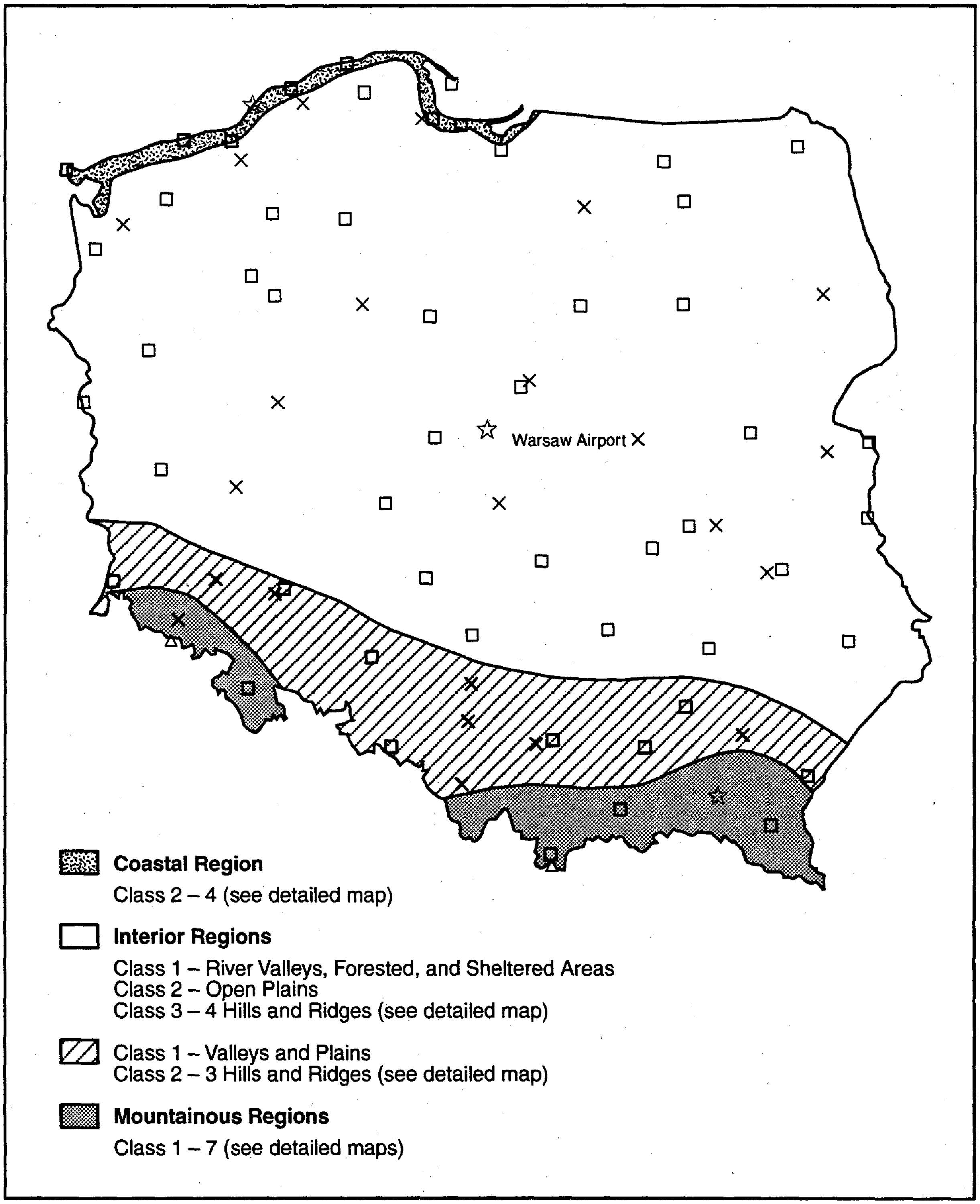


Figure 7. Wind Class Resource Map for Poland

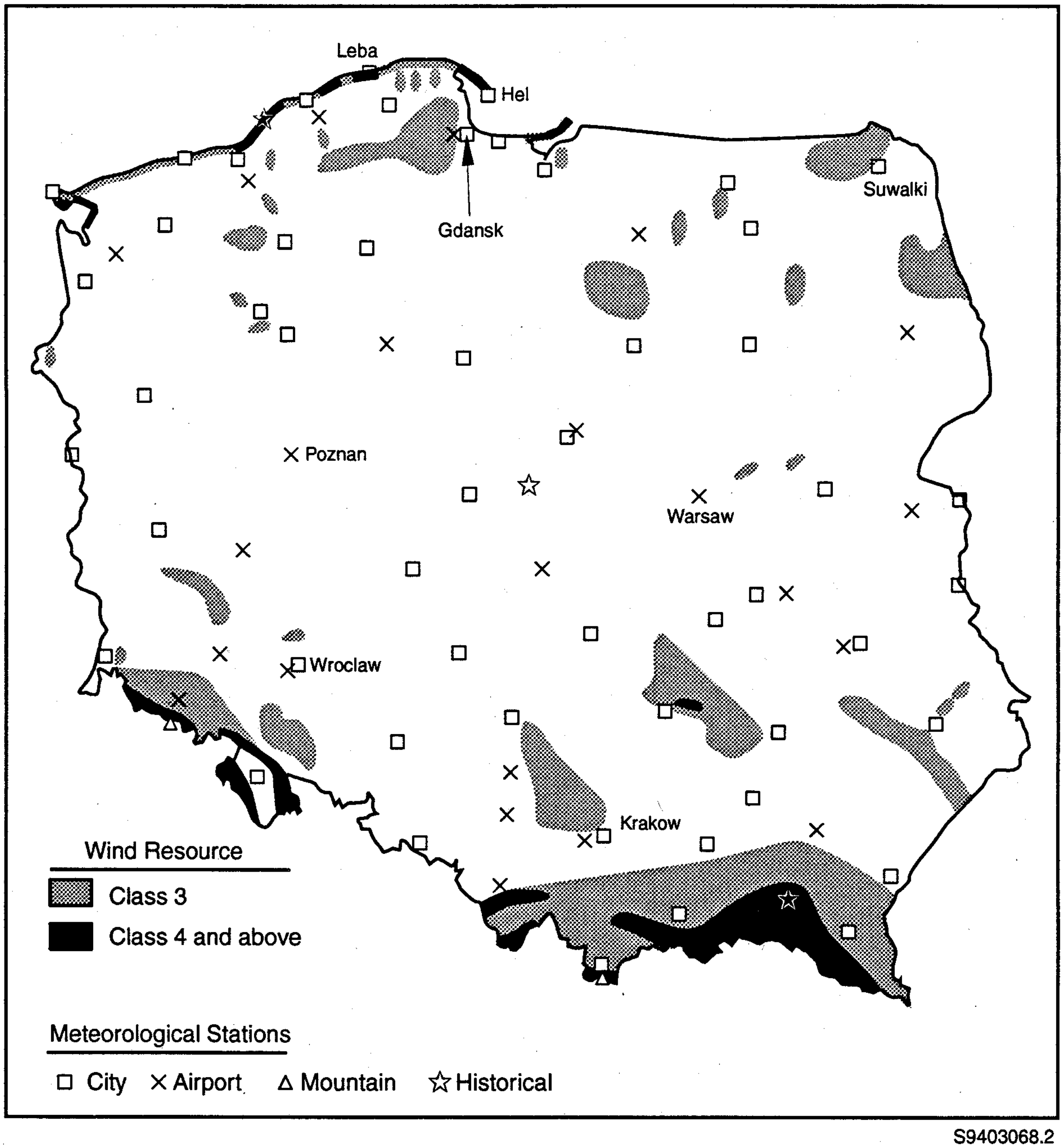
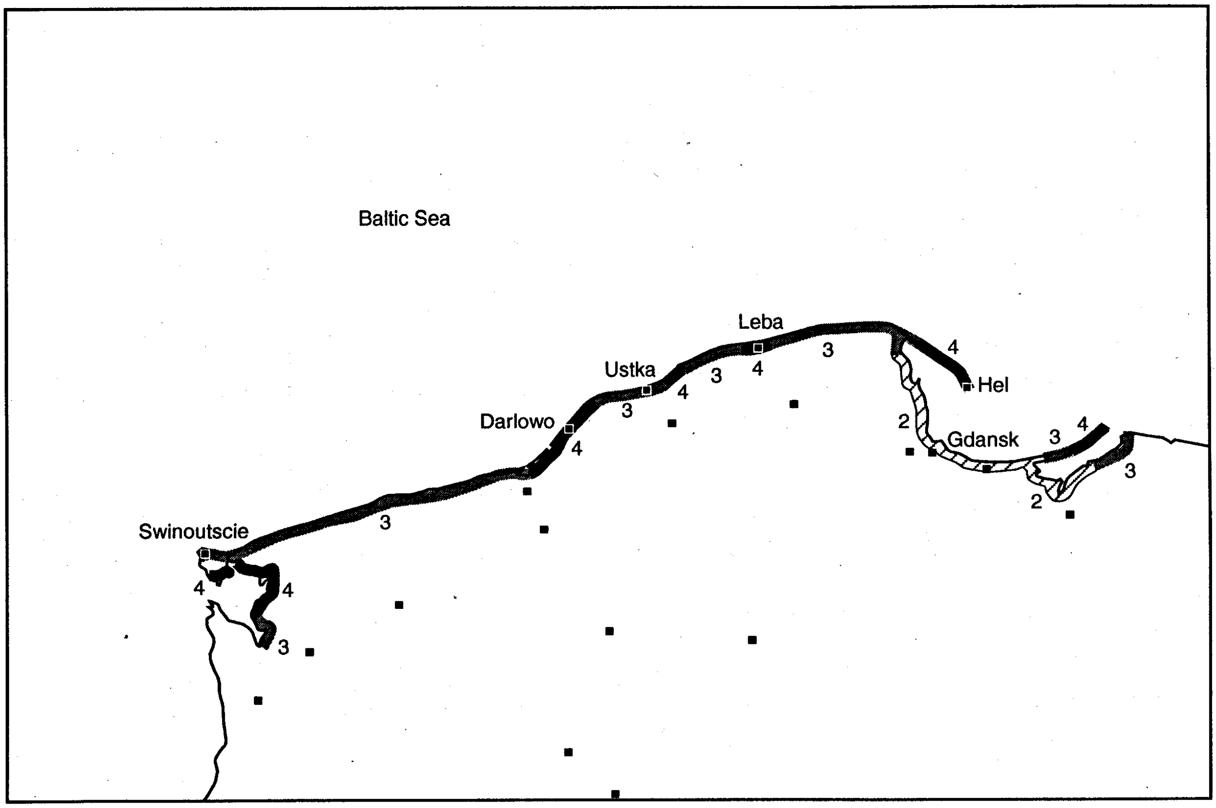


Figure 8. Map of Areas in Poland with Class 3 and Above Wind Resource



S9312042.2

Figure 9. Wind Class Resource Map for Baltic Coast

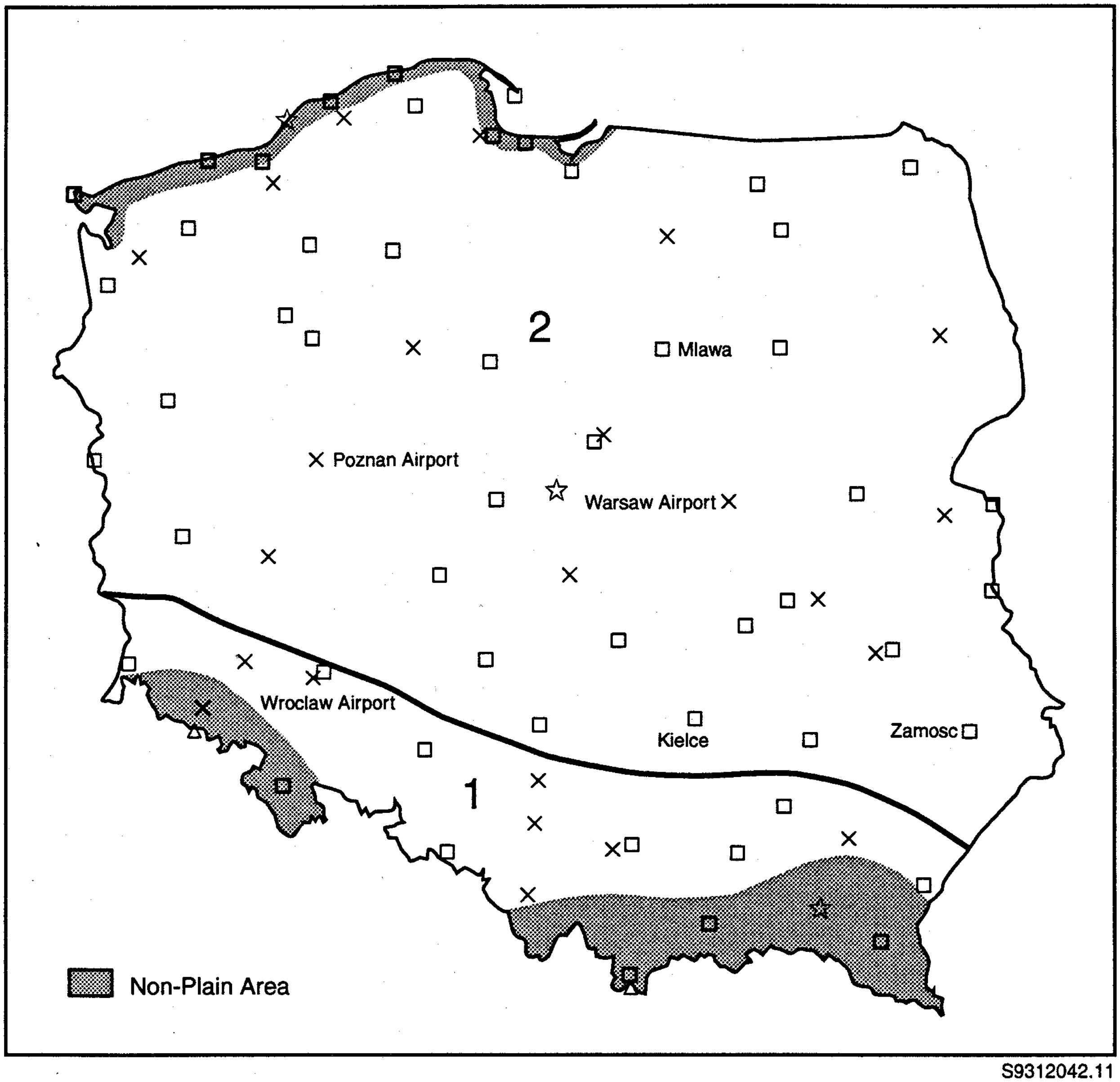


Figure 10. Wind Class Resource Map for Interior Plains of Poland

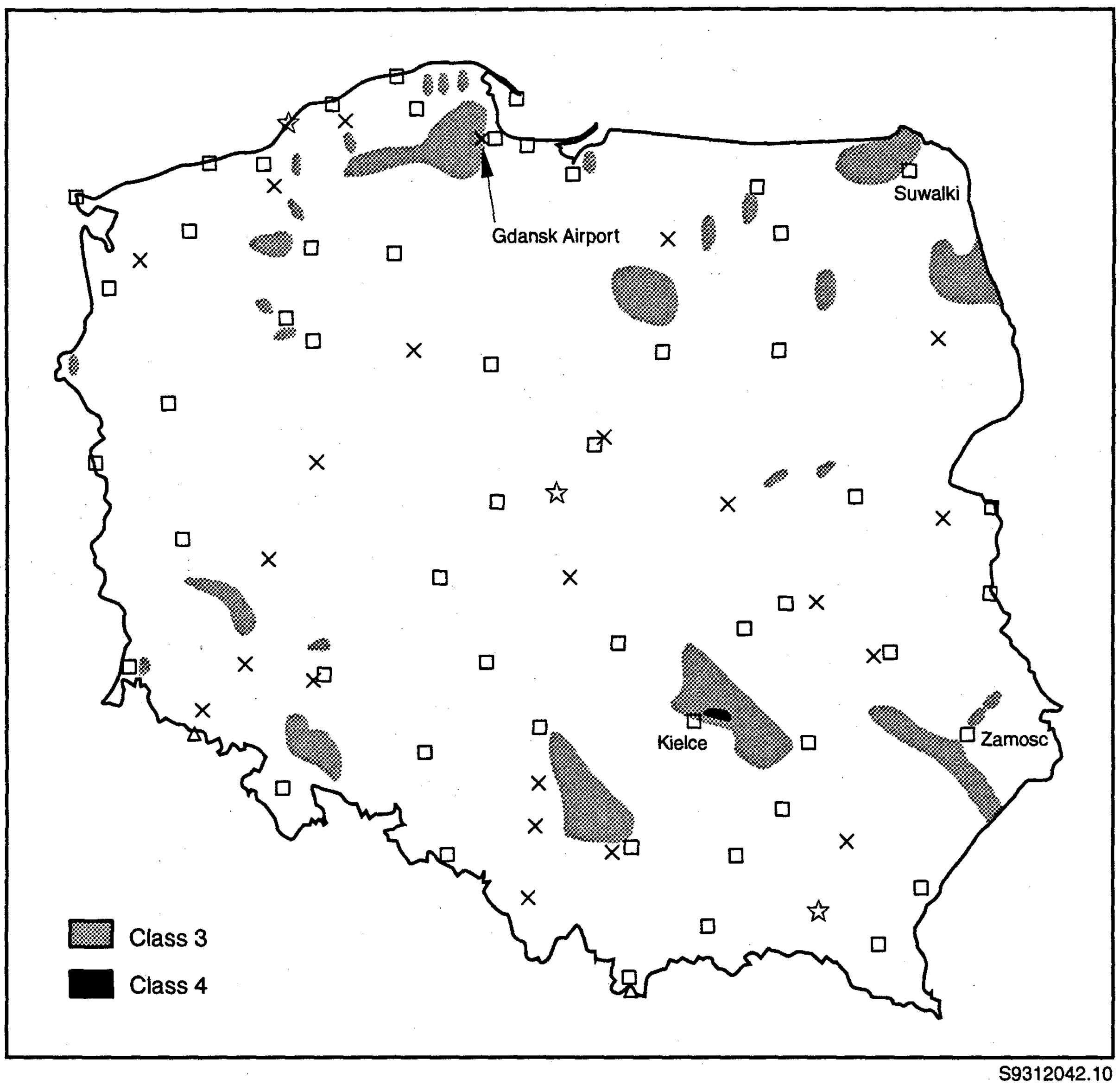
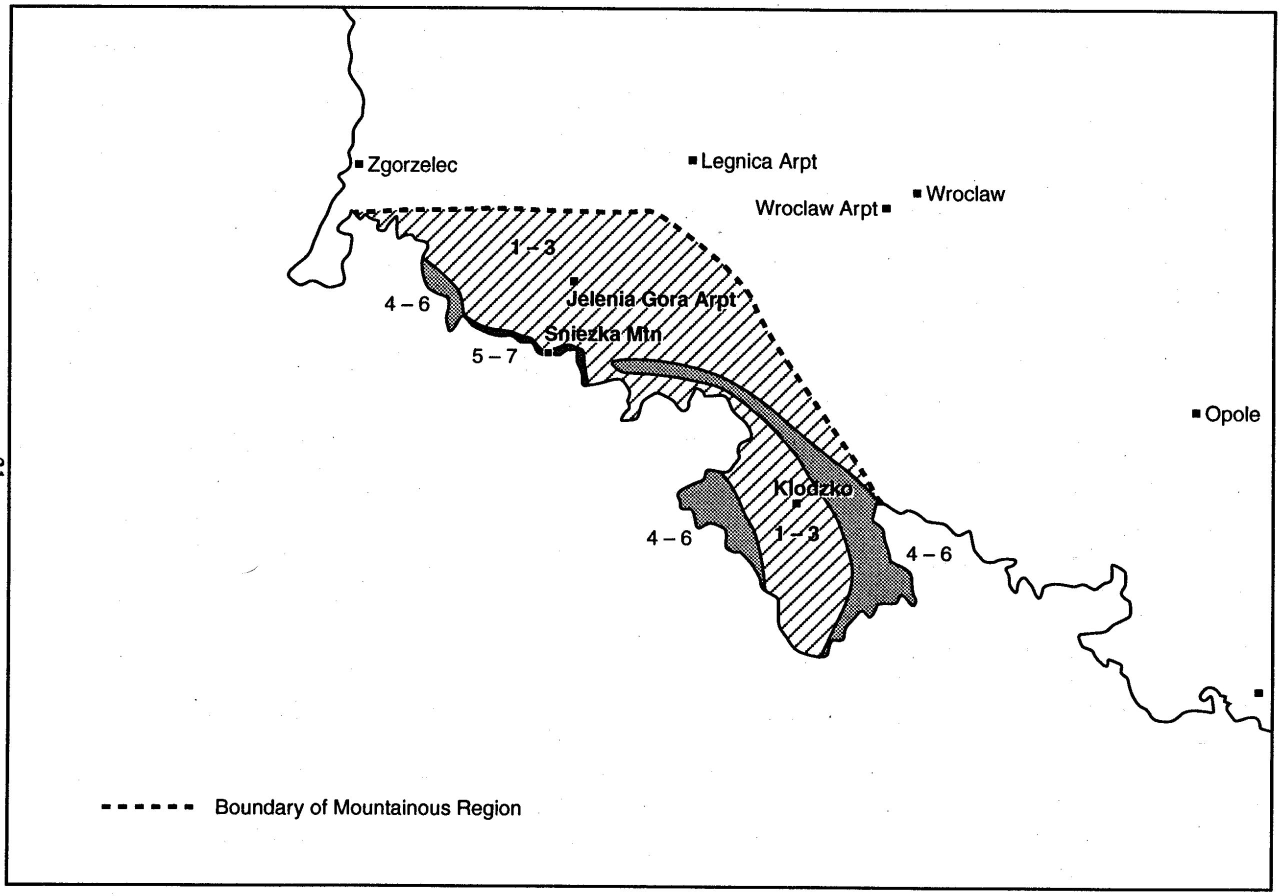
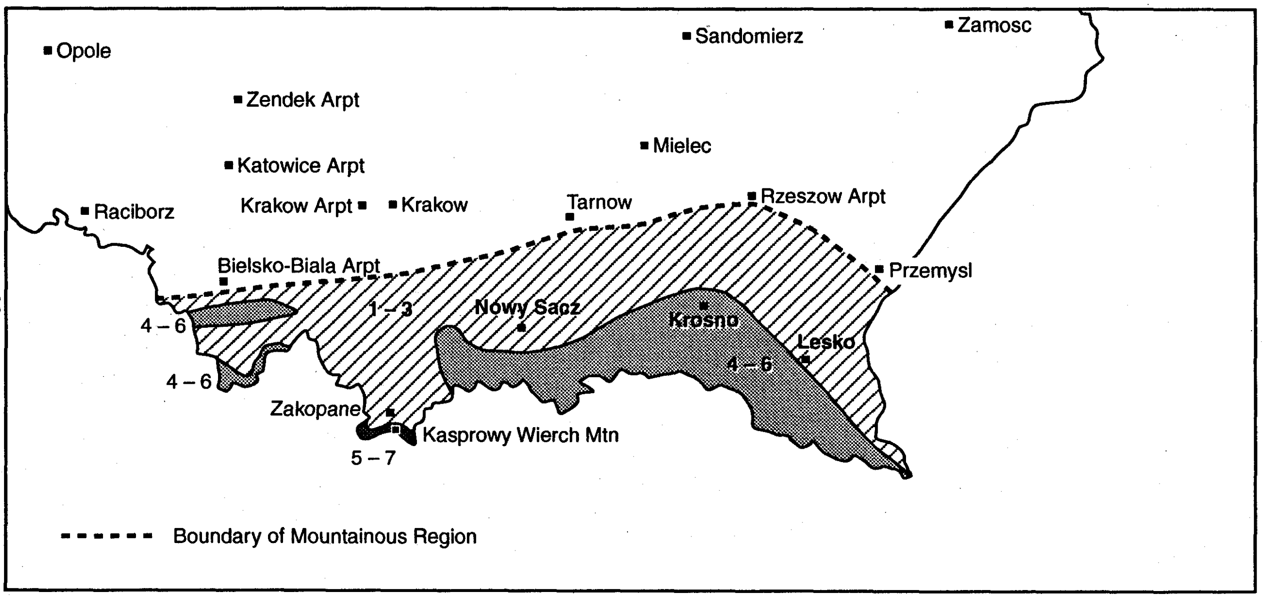


Figure 11. Wind Class Resource Map for Hills and Ridges of Poland



S9312042.6

Figure 12. Wind Class Resource Map for Southwestern Mountain Region of Poland



S9312042.4

Figure 13. Wind Class Resource Map for Southeastern Mountain Region of Poland

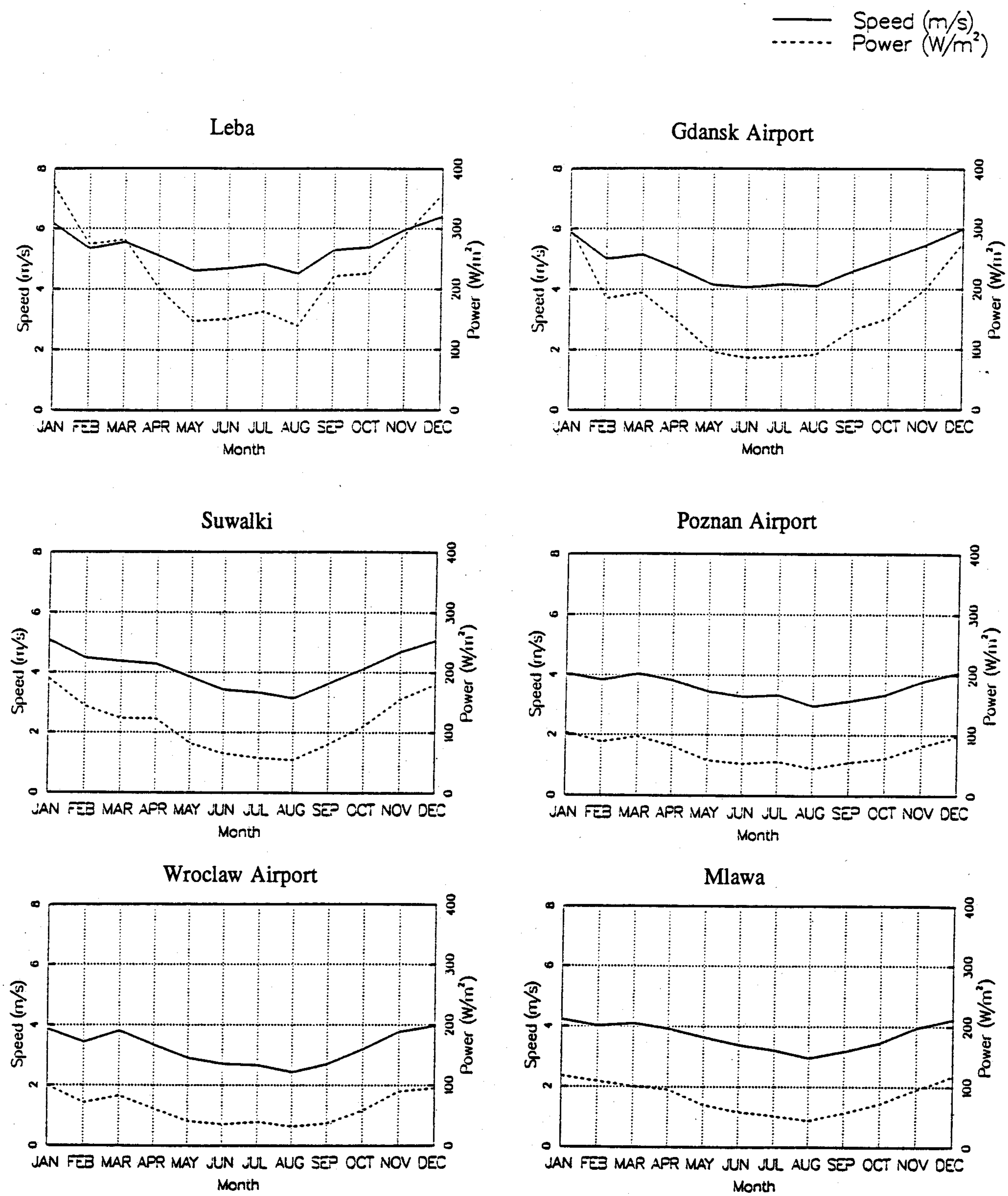


Figure 14. Wind Speed and Power by Month for Leba, Gdansk Airport, Suwalki, Poznan Airport, Mlawa, and Wroclaw Airport

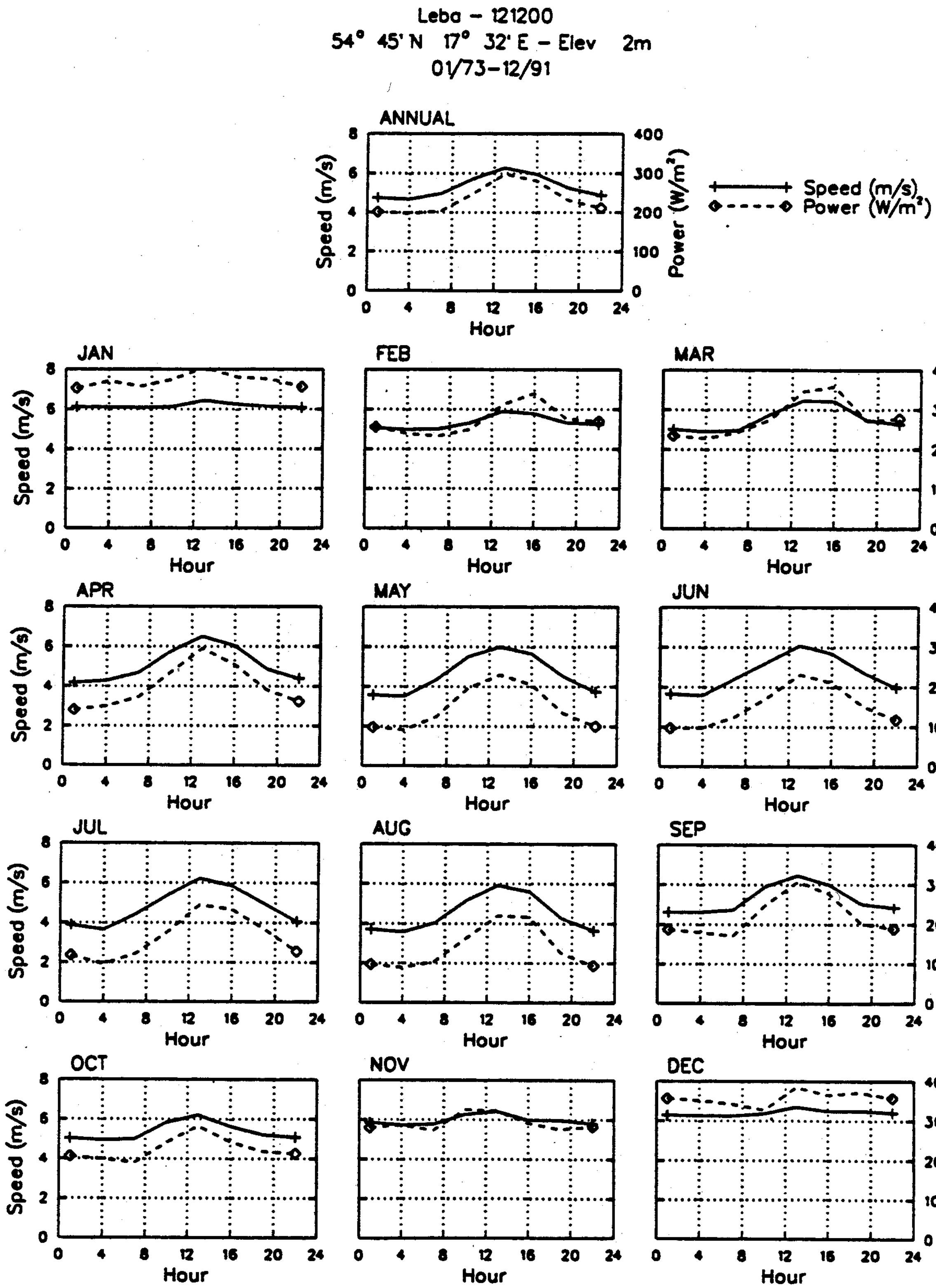


Figure 15. Wind Speed and Power by Hour for Leba

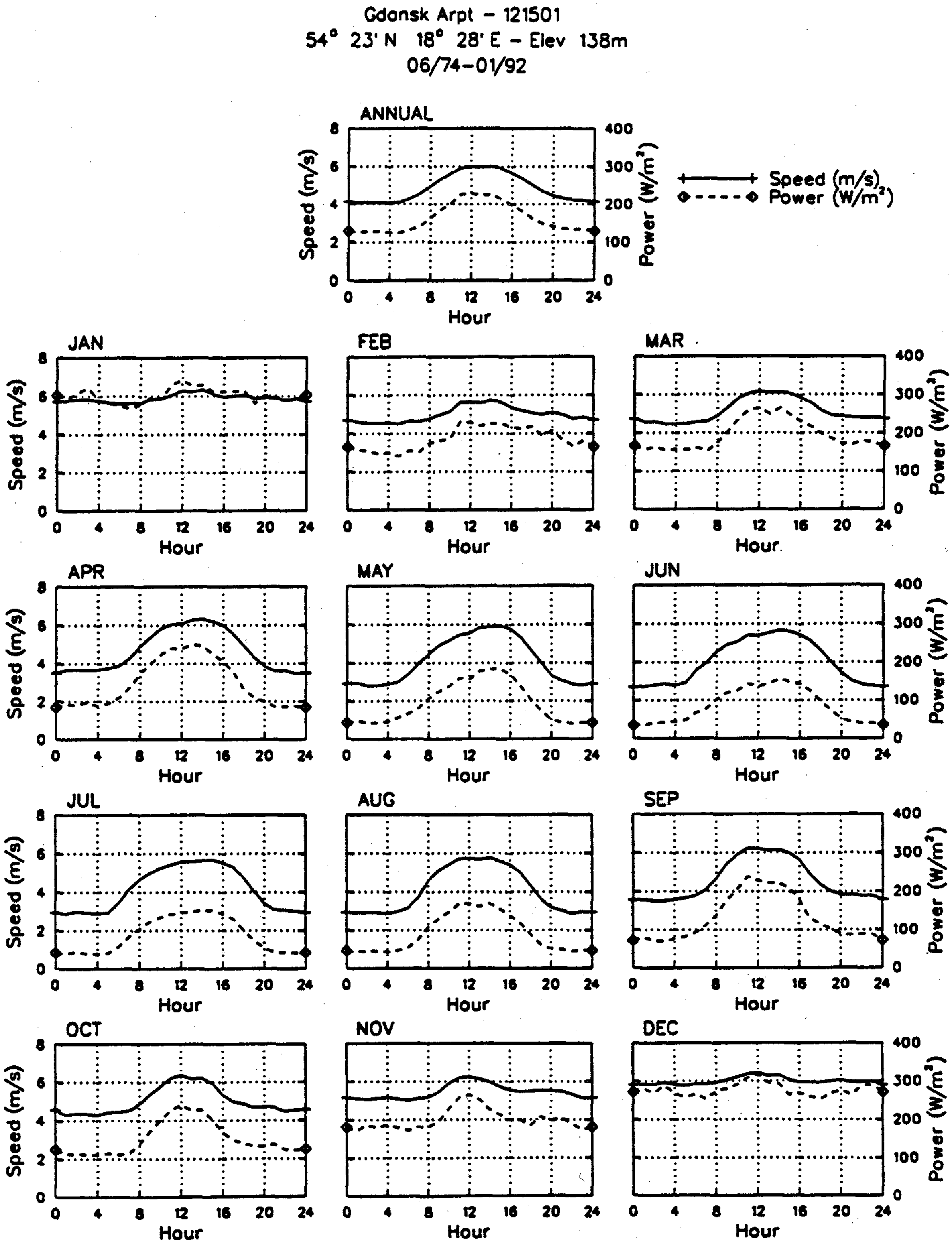


Figure 16. Wind Speed and Power by Hour for Gdansk Airport

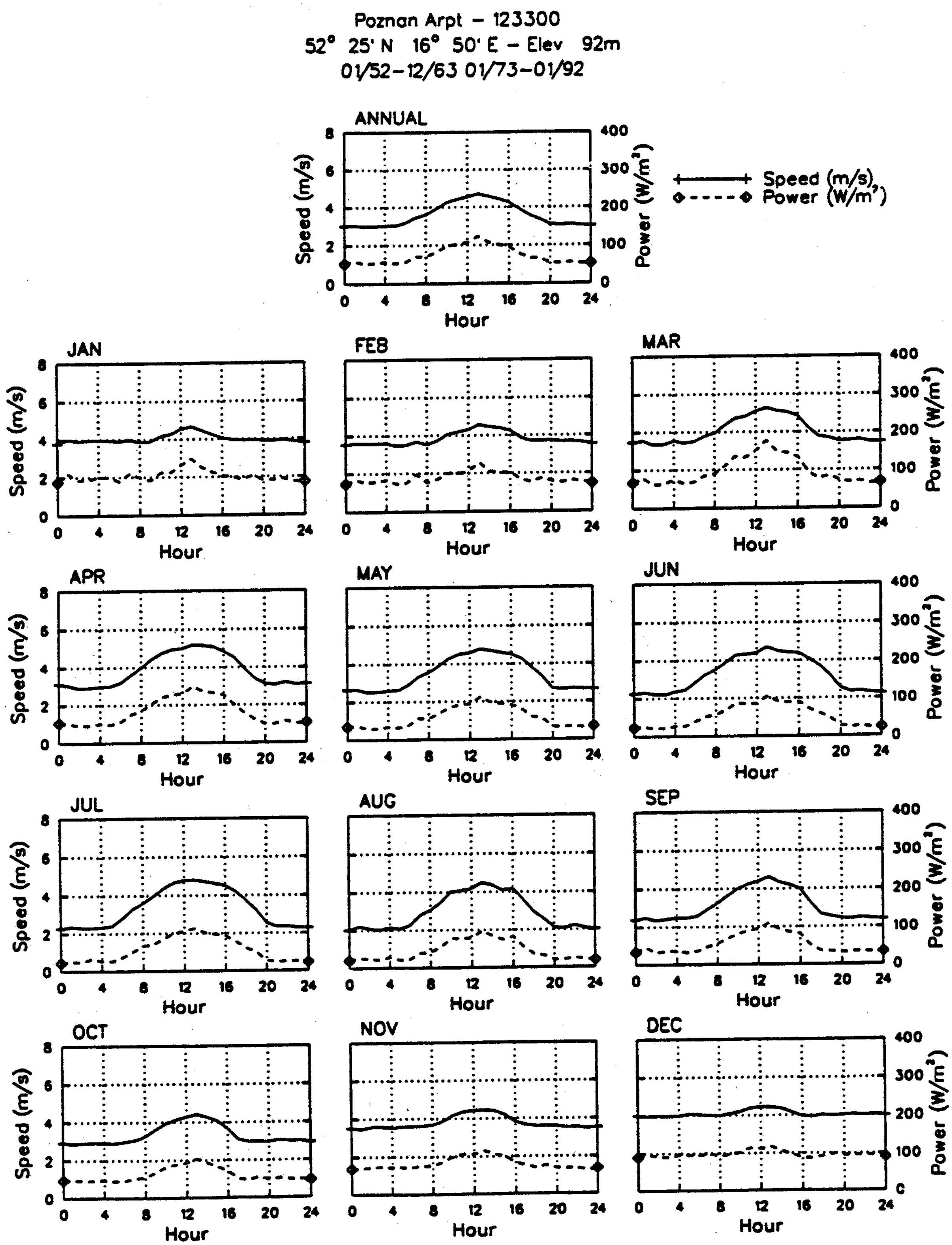


Figure 17. Wind Speed and Power by Hour for Poznan Airport

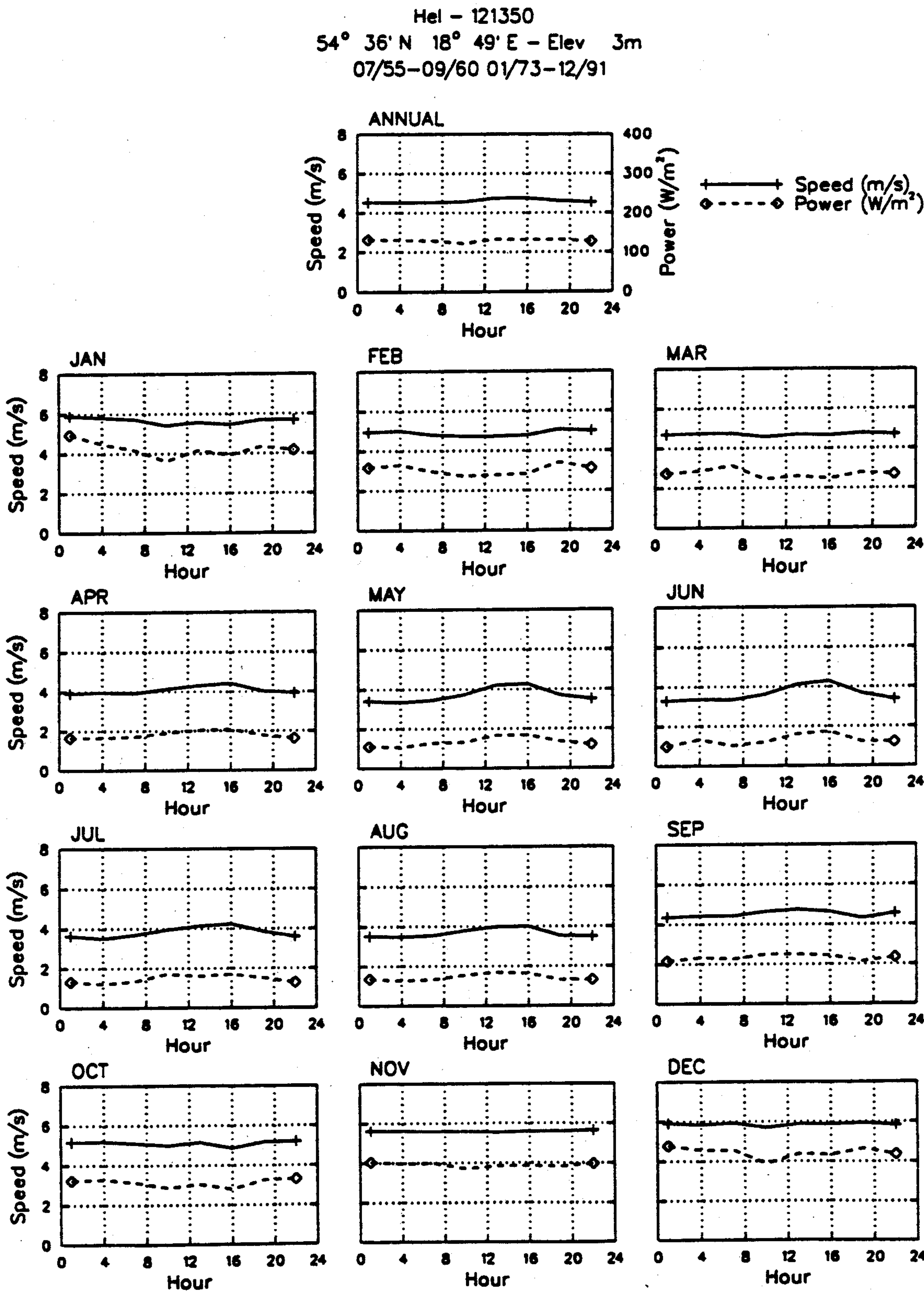


Figure 18. Wind Speed and Power by Hour for Hel

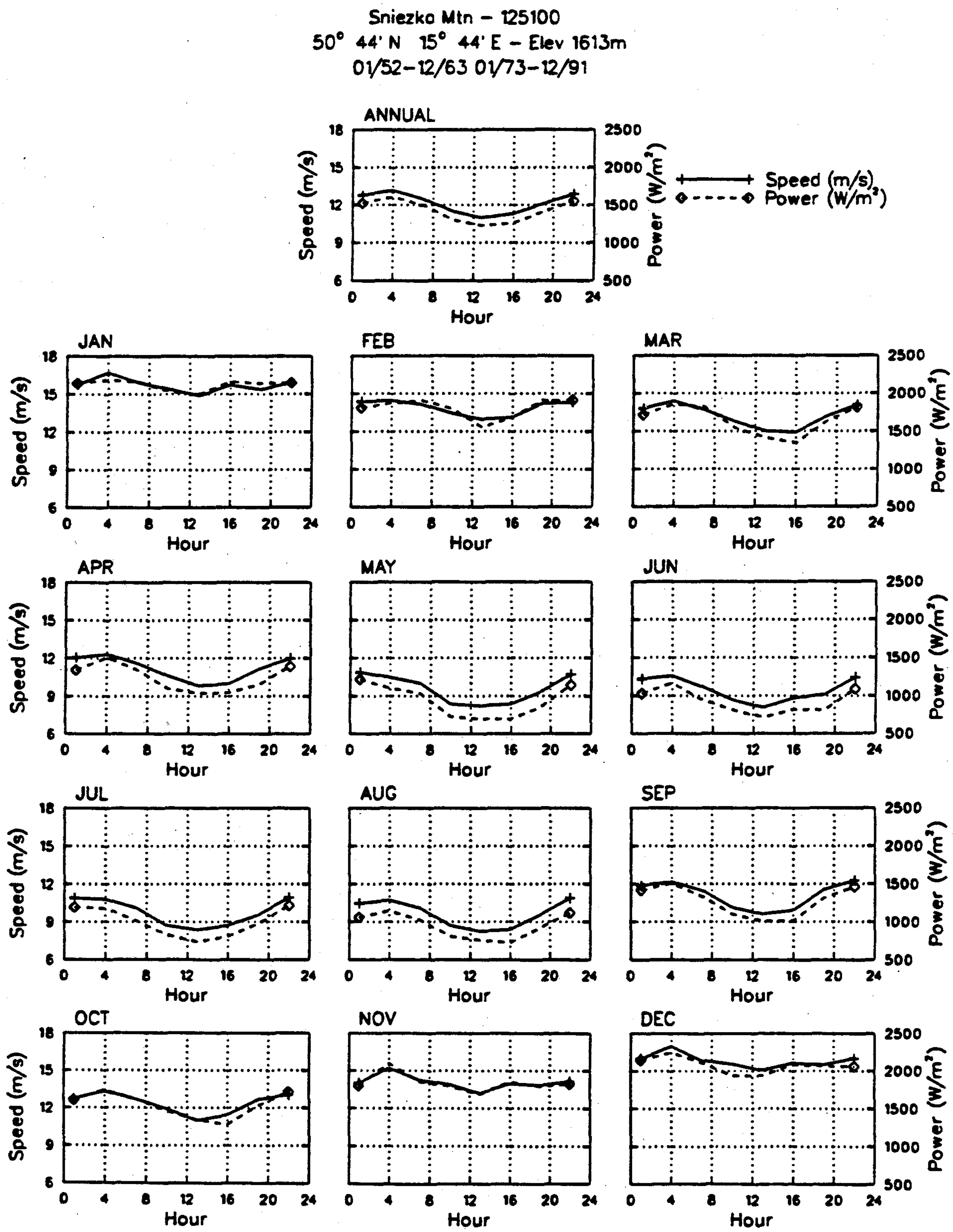


Figure 19. Wind Speed and Power by Hour for Sniezka Mountain

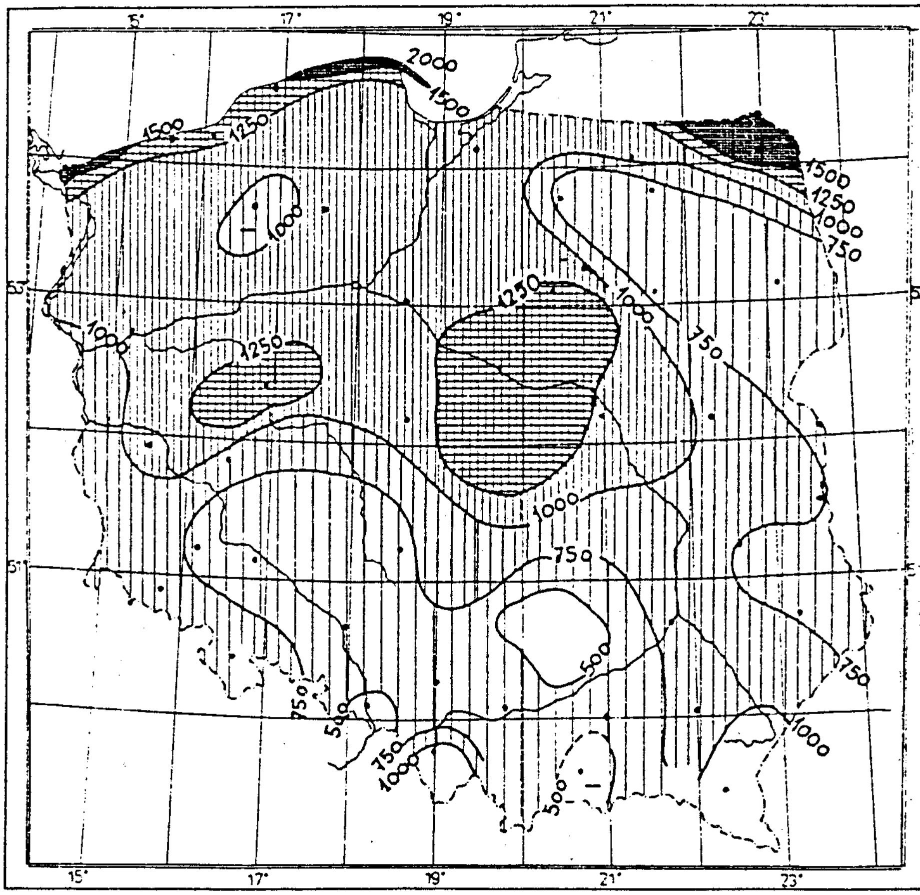


Figure 20. Wind Energy Map for 30 m Above Ground Level Produced by the Institute of Meteorology and Water Management (IMWM) (Lorenc 1991). Contours are in units of kWh/m^2.

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Appendix A

Definition of Power Law

Appendix A

Definition of Power Law

A power law adjusts the mean wind speed or wind power density to a reference height. The power law is

$$\frac{\overline{V}_r}{\overline{V}_a} = \left(\frac{Z_r}{Z_a}\right)^{\alpha} \quad \text{or} \quad \frac{\overline{P}_r}{\overline{P}_a} = \left(\frac{Z_r}{Z_a}\right)^{3\alpha}$$

where

$\overline{V}_{a,r}$ and $\overline{P}_{a,r}$ = the mean wind speed and power density at heights $Z_{a,r}$ (the anemometer and reference level respectively)
α = the power law exponent.

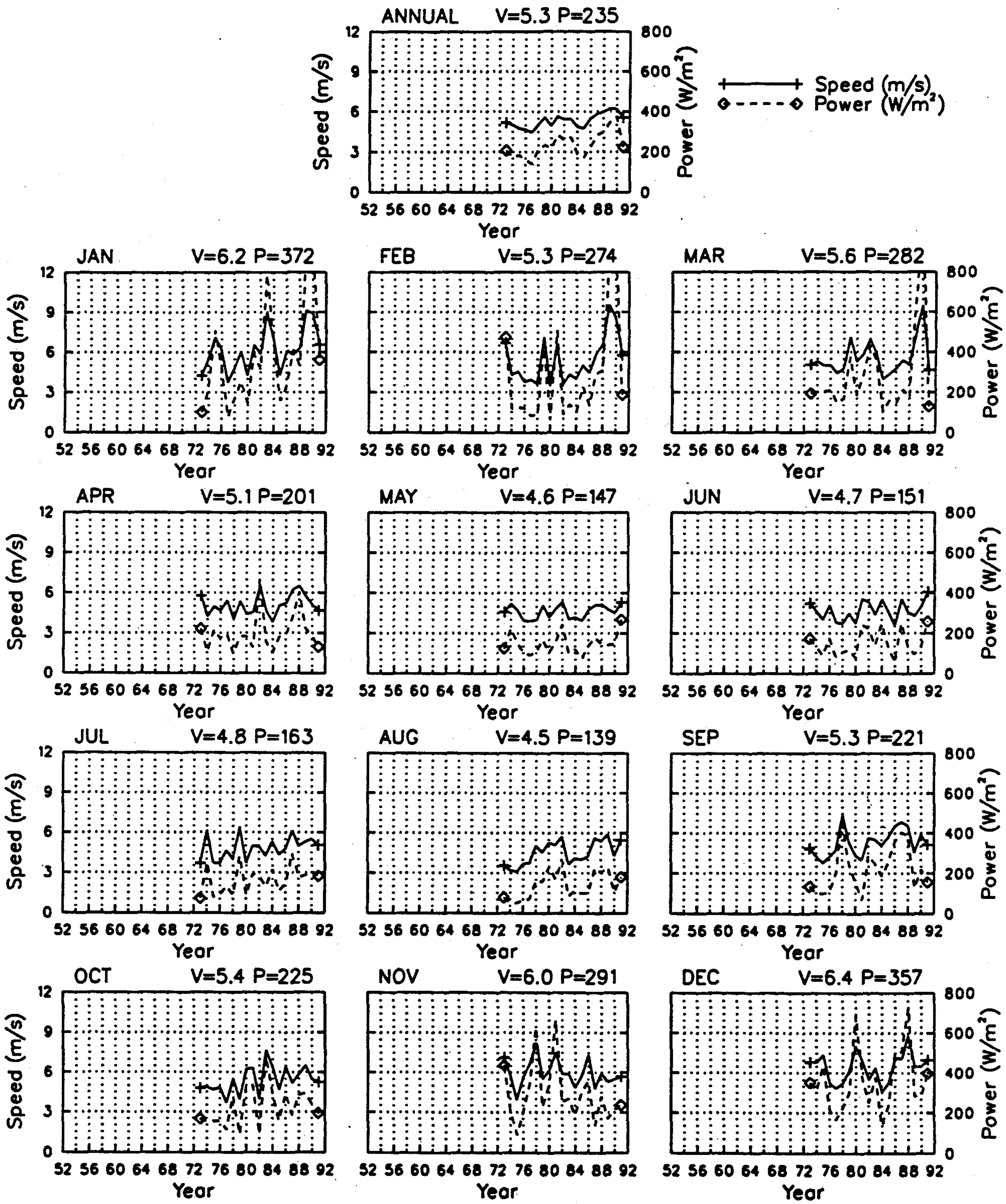
A power law exponent of 1/7 was used for exposed areas with low surface roughness in Poland.

Appendix B

Complete Set of Graphical Plots of Wind Characteristics Produced for Leba, Poland

SPEED AND POWER BY YEAR

Leba – 121200
54° 45' N 17° 32' E – Elev 2m
01/73–12/91

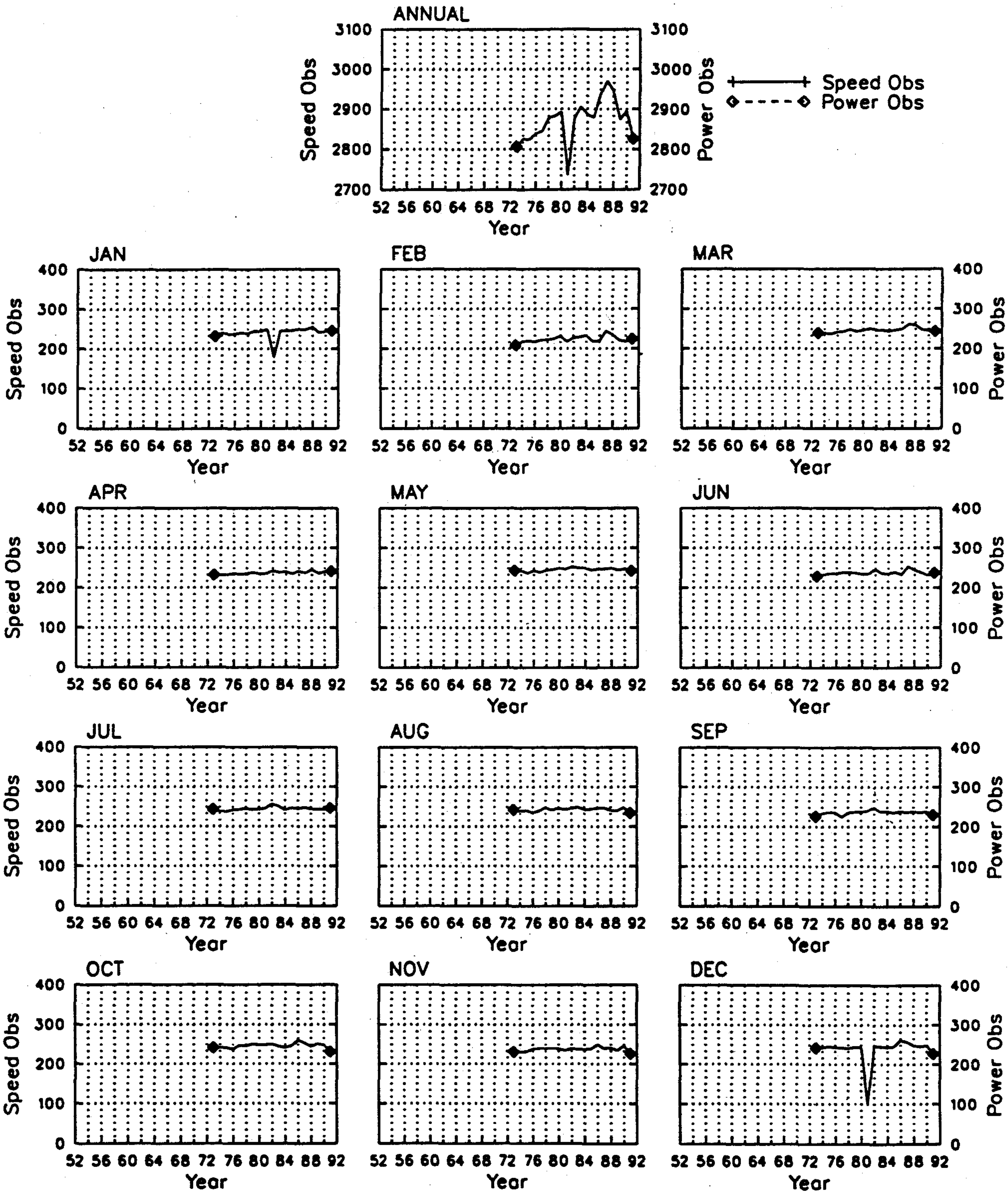


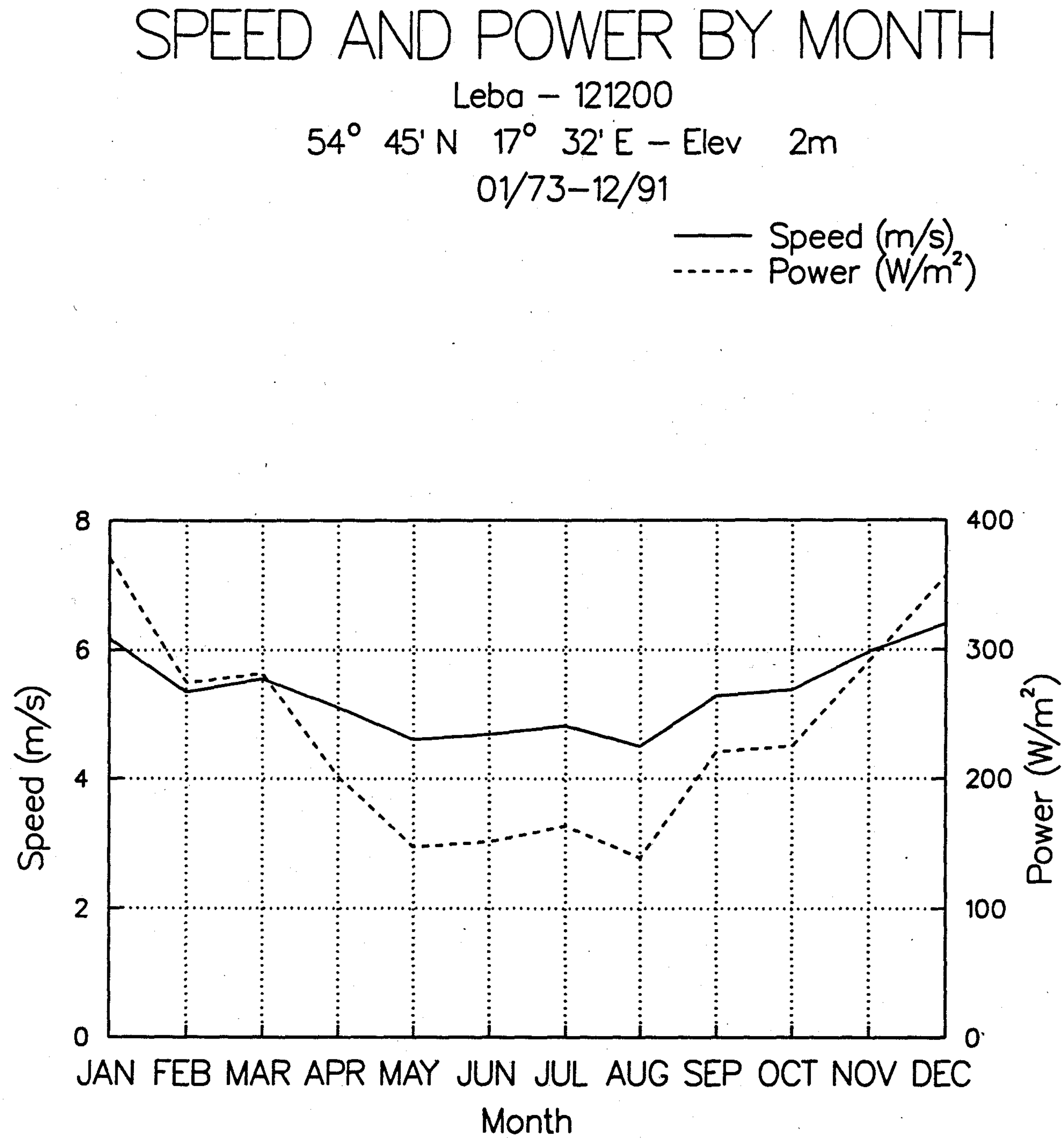
OBSERVATIONS BY YEAR

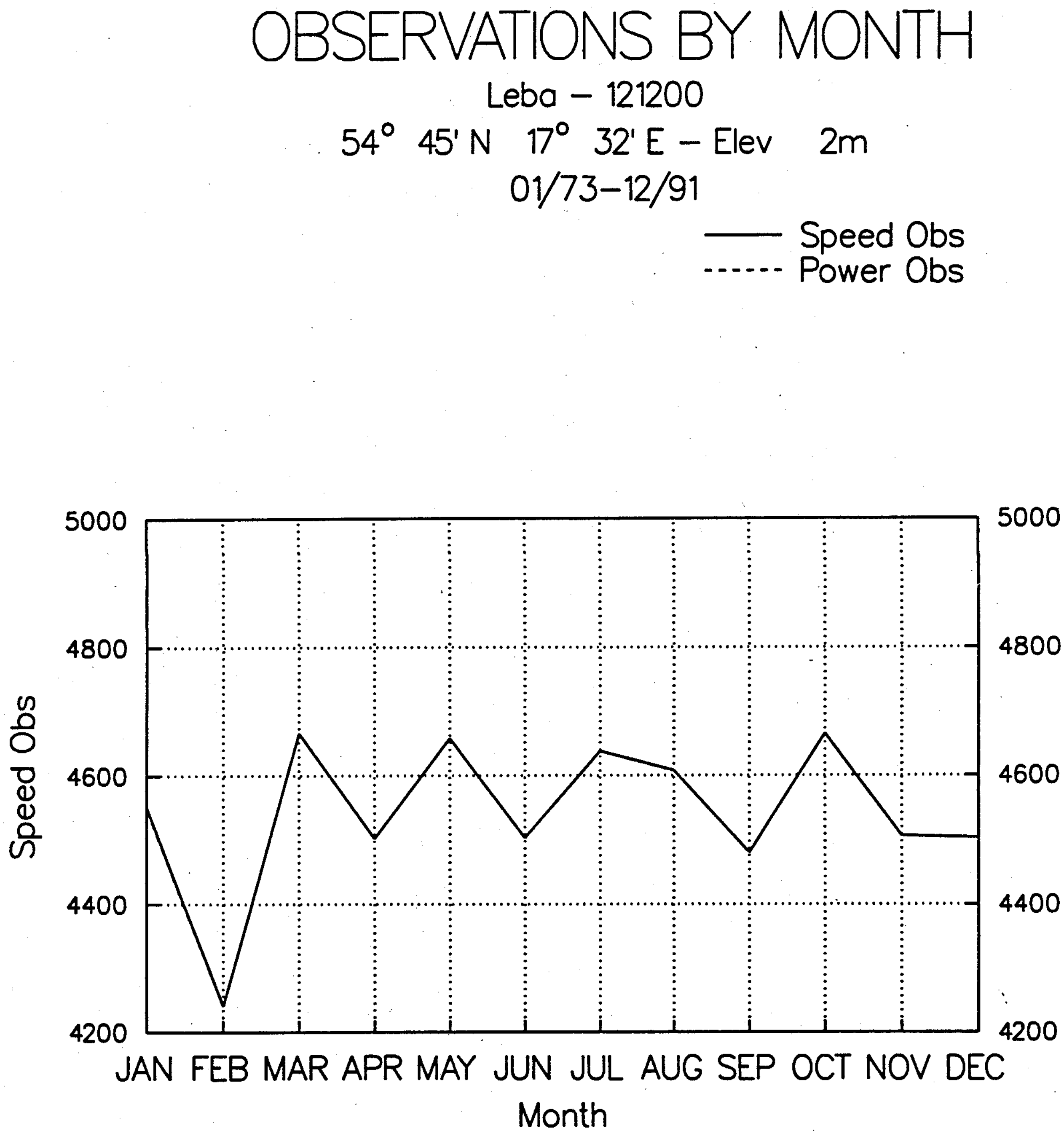
Leba – 121200

54° 45' N 17° 32' E – Elev 2m

01/73–12/91

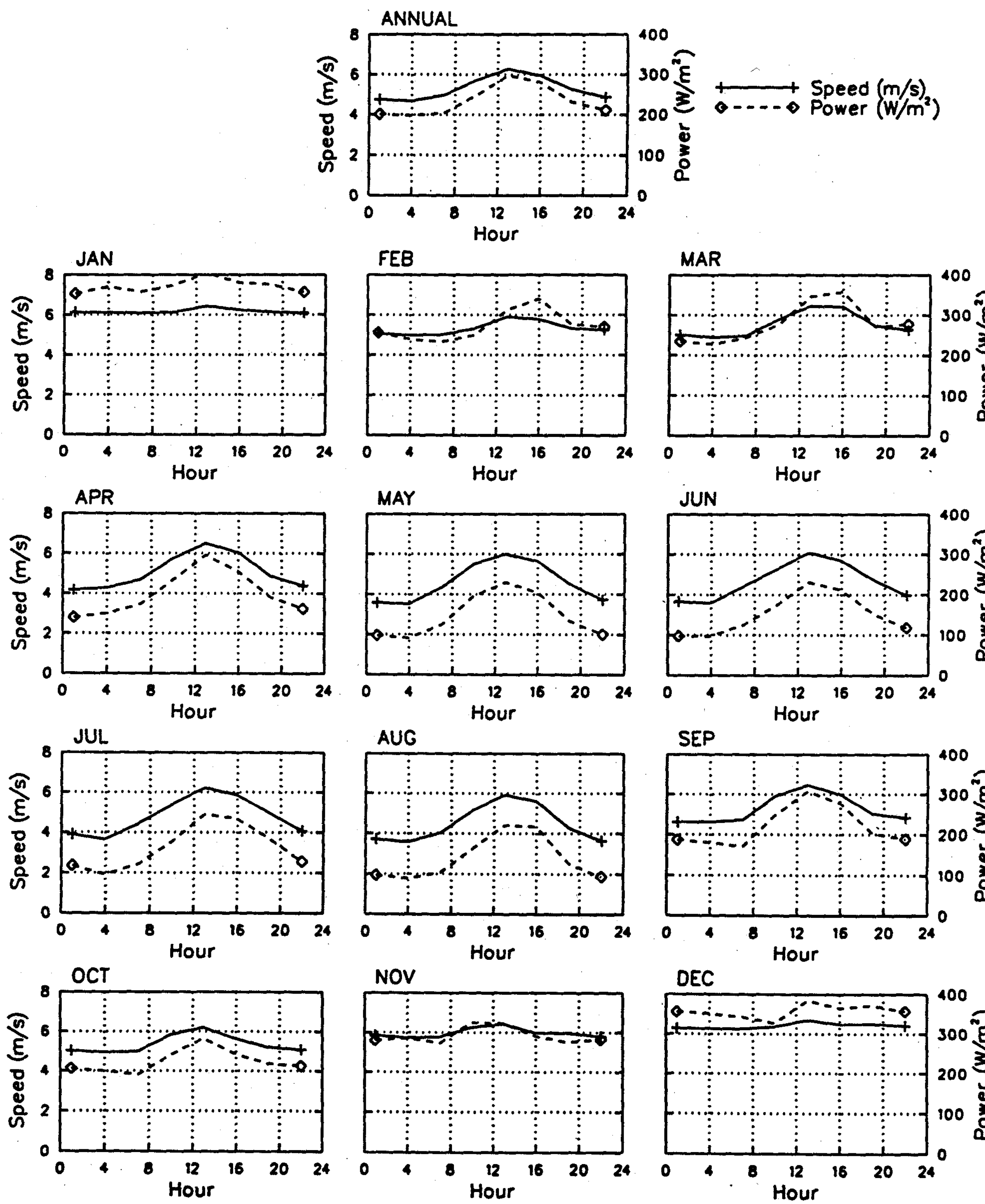



SPEED AND POWER BY MONTH
Leba - 121200
54° 45' N 17° 32' E - Elev 2m
01/73-12/91
Speed (m/s)
Power (W/m²)
8
6
4
2
0
400
300
200
100
0
Speed (m/s)
Power (W/m²)
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
Month


OBSERVATIONS BY MONTH
Leba – 121200
54° 45' N 17° 32' E – Elev 2m
01/73–12/91
Speed Obs
Power Obs
5000
4800
4600
4400
4200
Speed Obs
Power Obs
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC
Month

SPEED AND POWER BY HOUR

Leba - 121200
54° 45' N 17° 32' E - Elev 2m
01/73-12/91

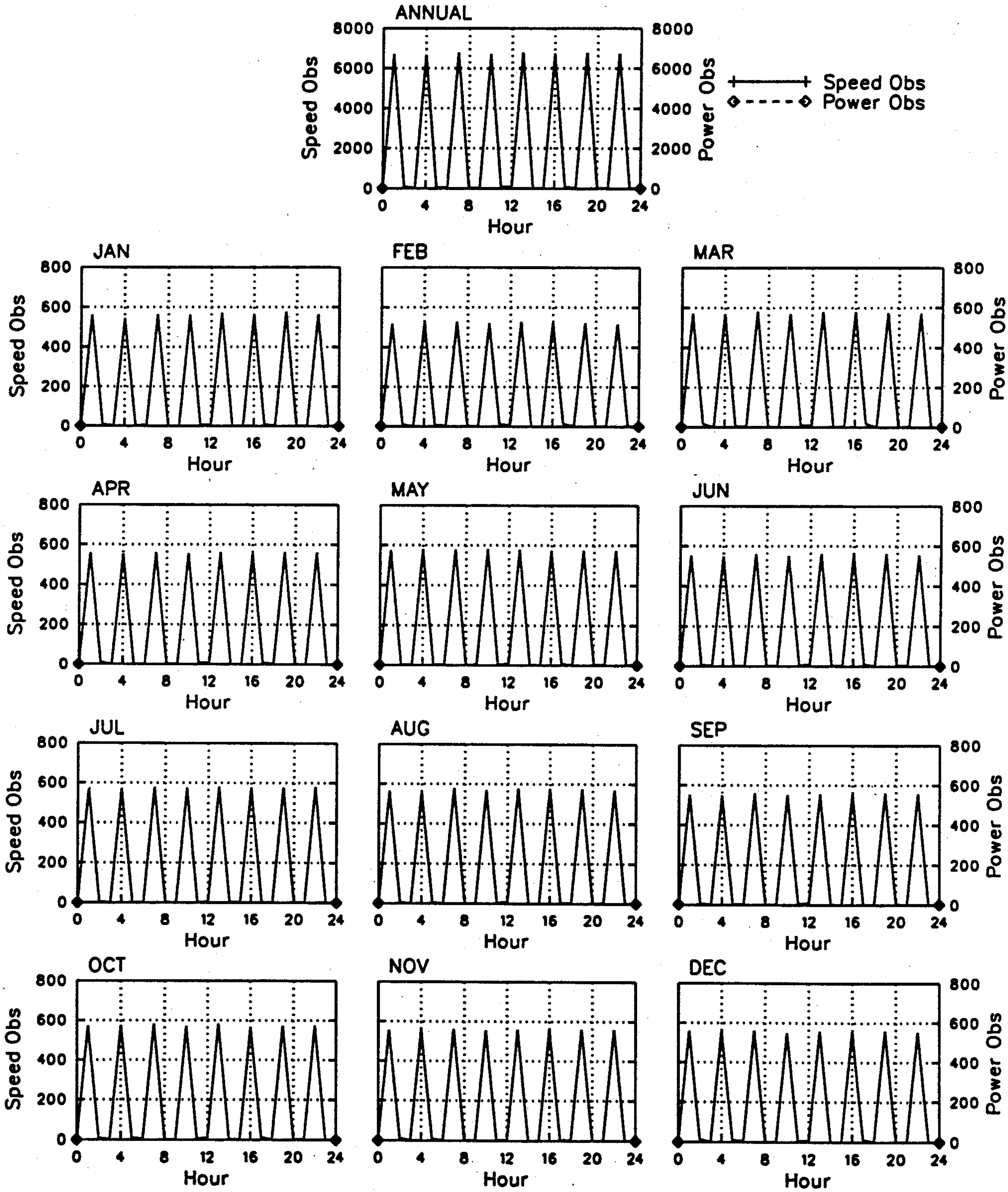


OBSERVATIONS BY HOUR

Leba – 121200

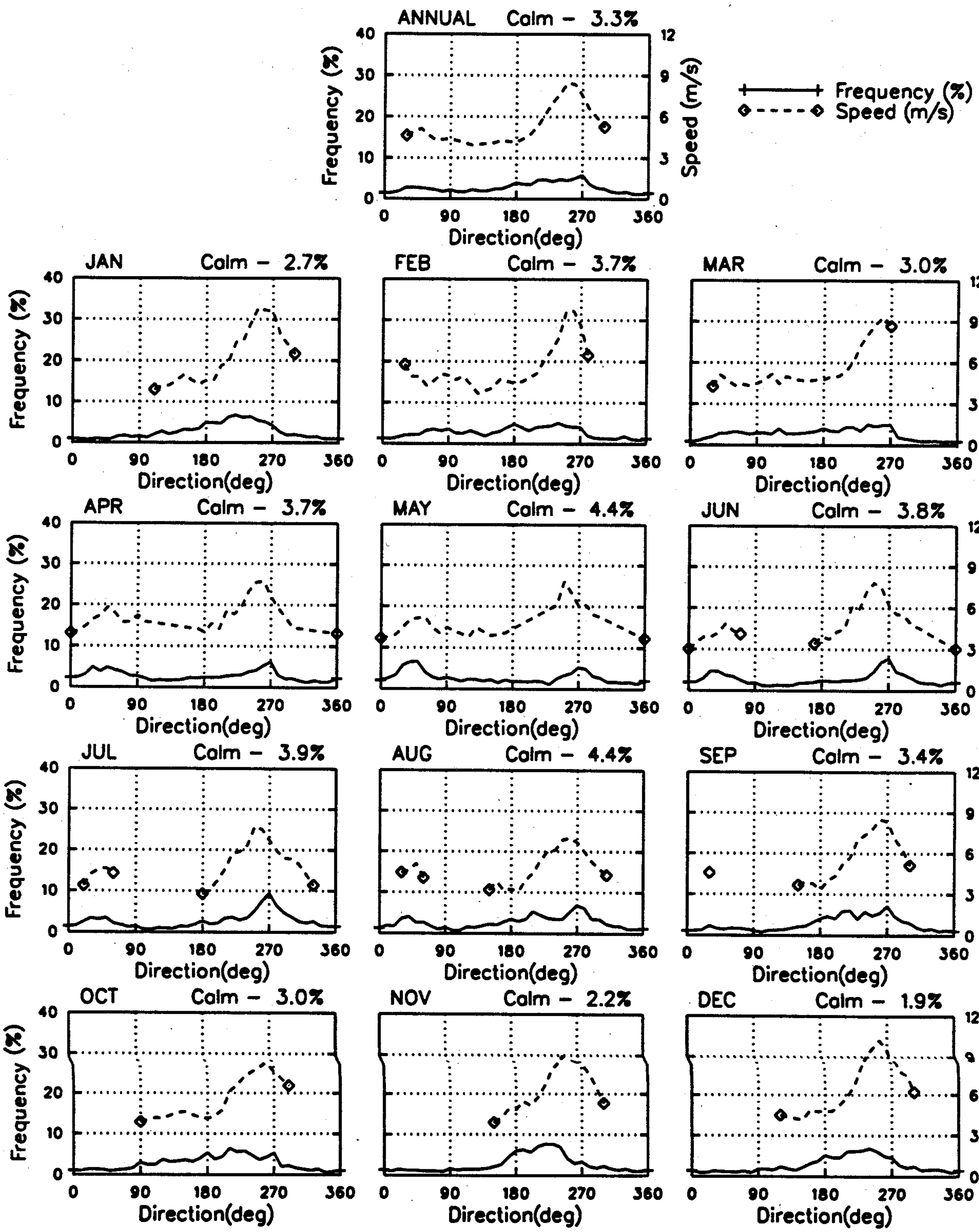
54° 45' N 17° 32' E – Elev 2m

01/73–12/91



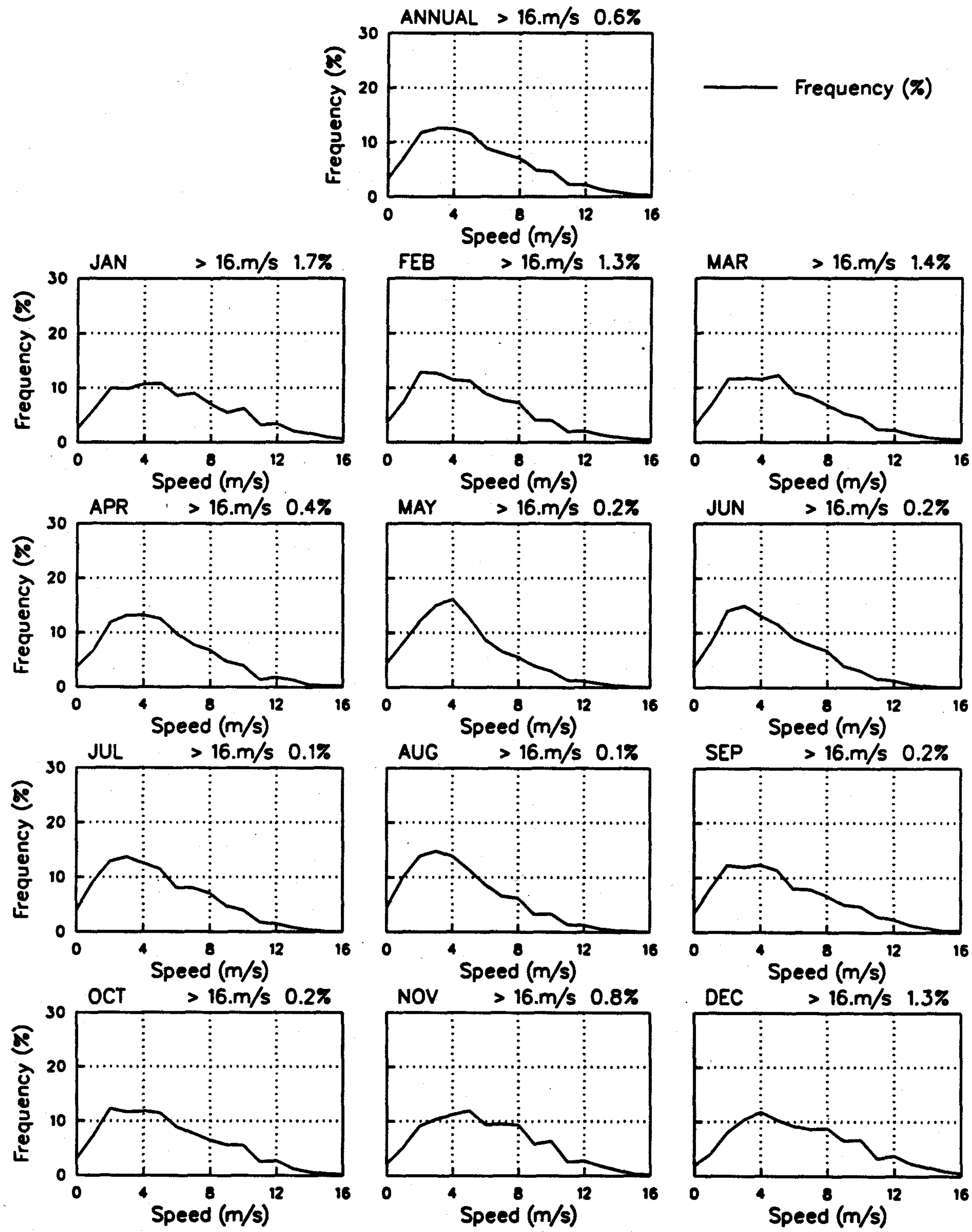
FREQUENCY AND SPEED BY DIRECTION

Leba – 121200
54° 45' N 17° 32' E – Elev 2m
01/73–12/91



FREQUENCY BY SPEED

Leba – 121200
54° 45' N 17° 32' E – Elev 2m
01/73–12/91

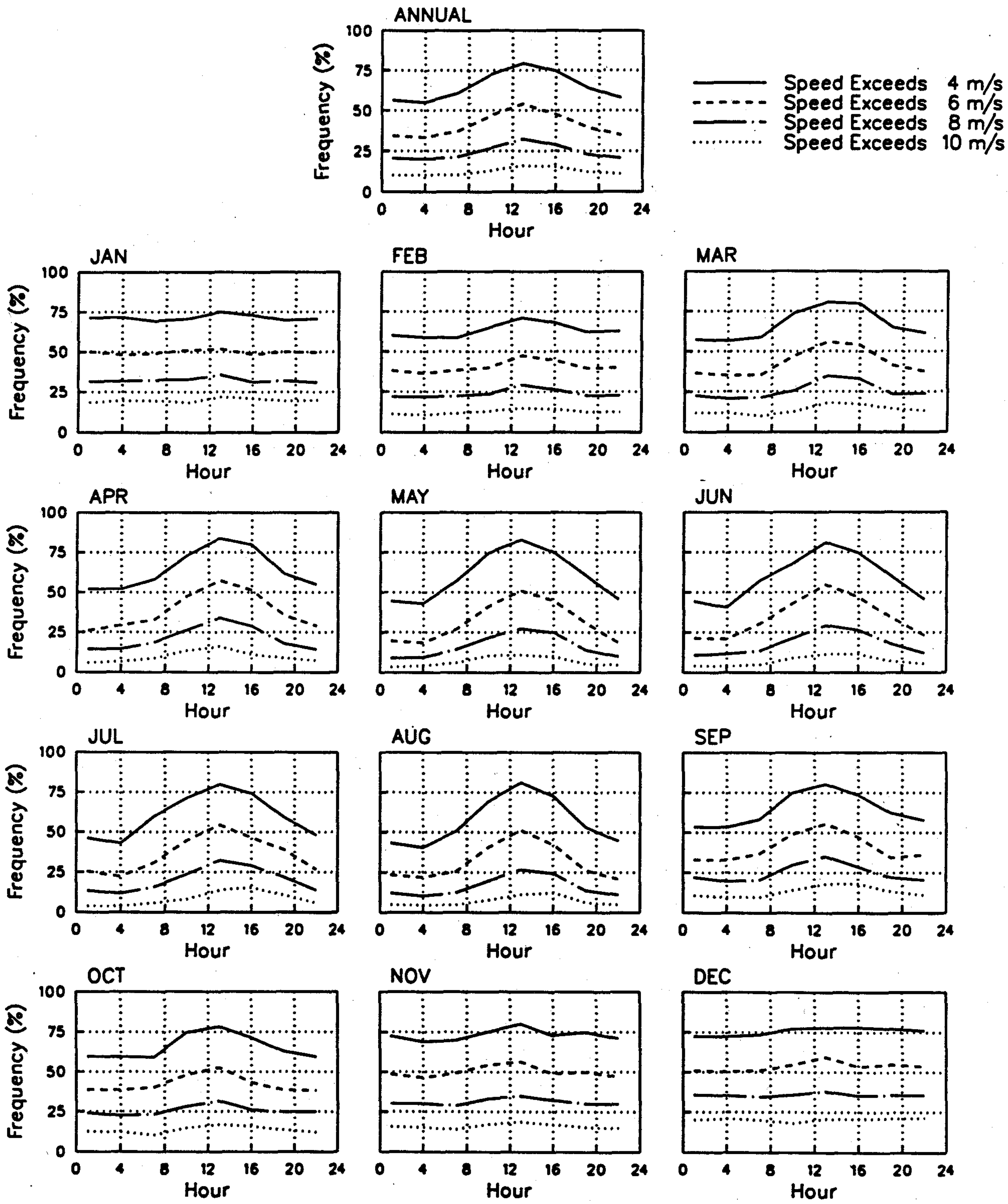


FREQUENCY SPEED EXCEEDS BY HOUR

Leba – 121200

54° 45' N 17° 32' E – Elev 2m

01/73–12/91

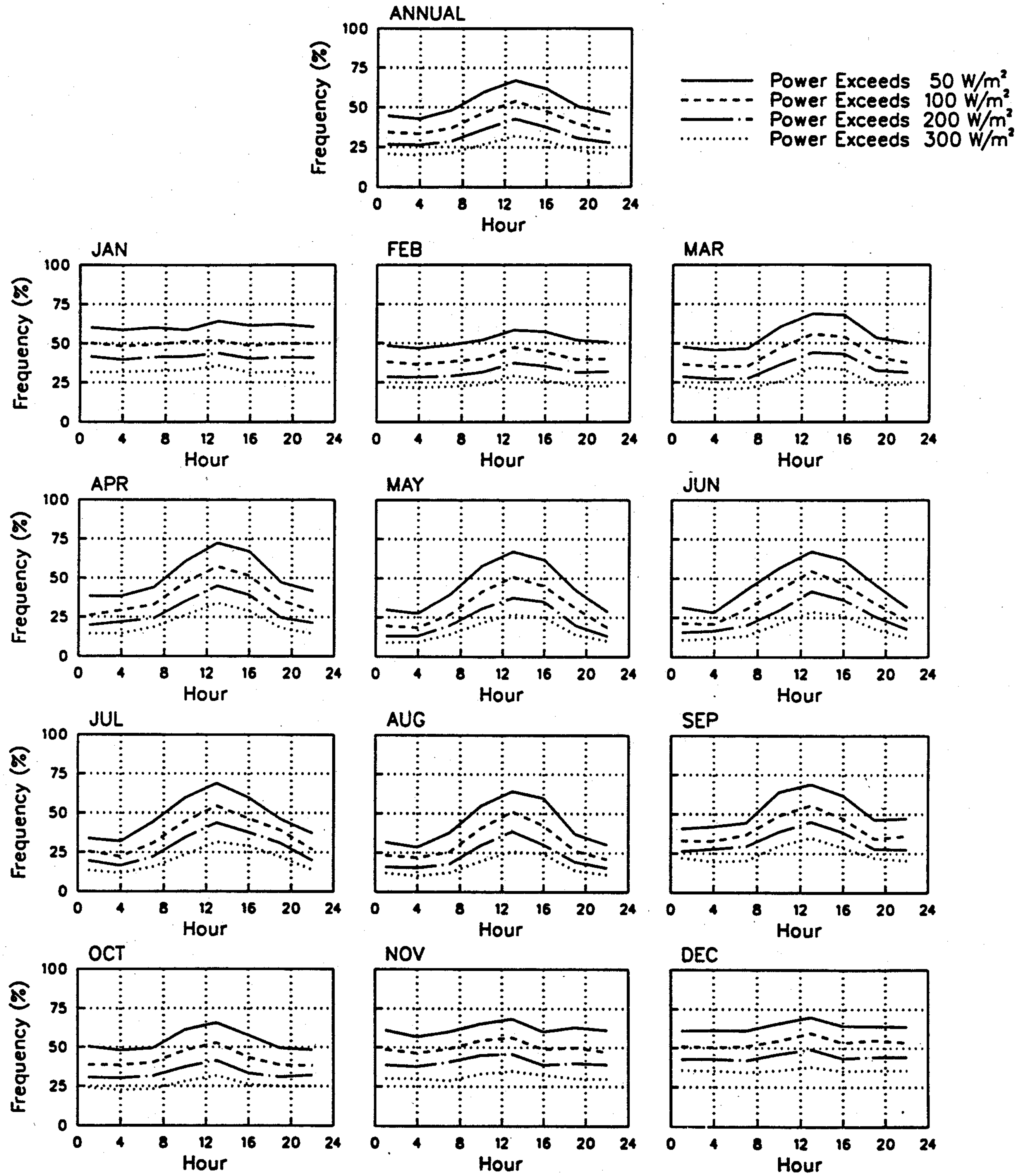


FREQUENCY POWER EXCEEDS BY HOUR

Leba – 121200

54° 45' N 17° 32' E – Elev 2m

01/73–12/91

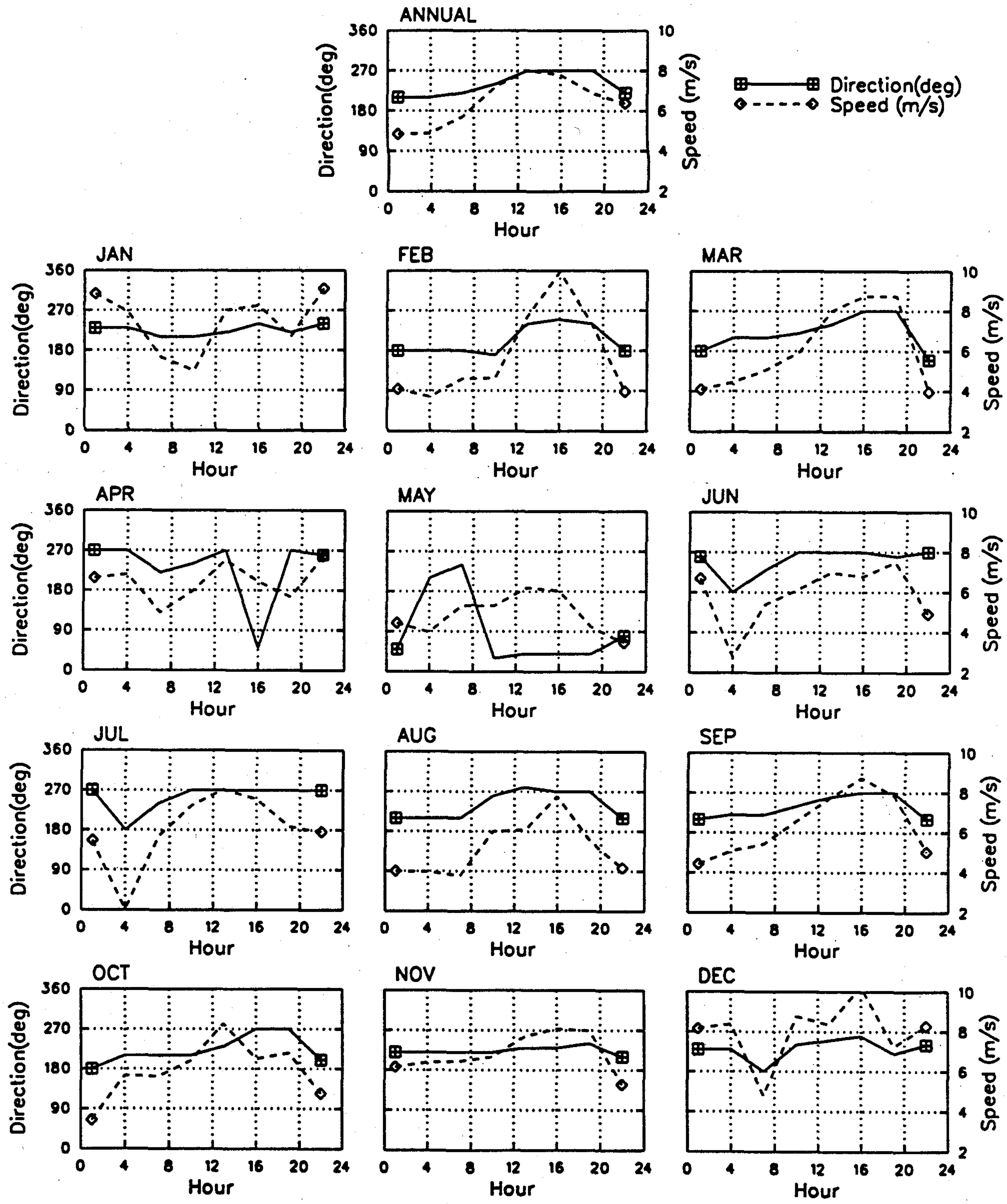


PREVAILING DIRECTION & SPEED BY HOUR

Leba – 121200

54° 45' N 17° 32' E – Elev 2m

01/73–12/91

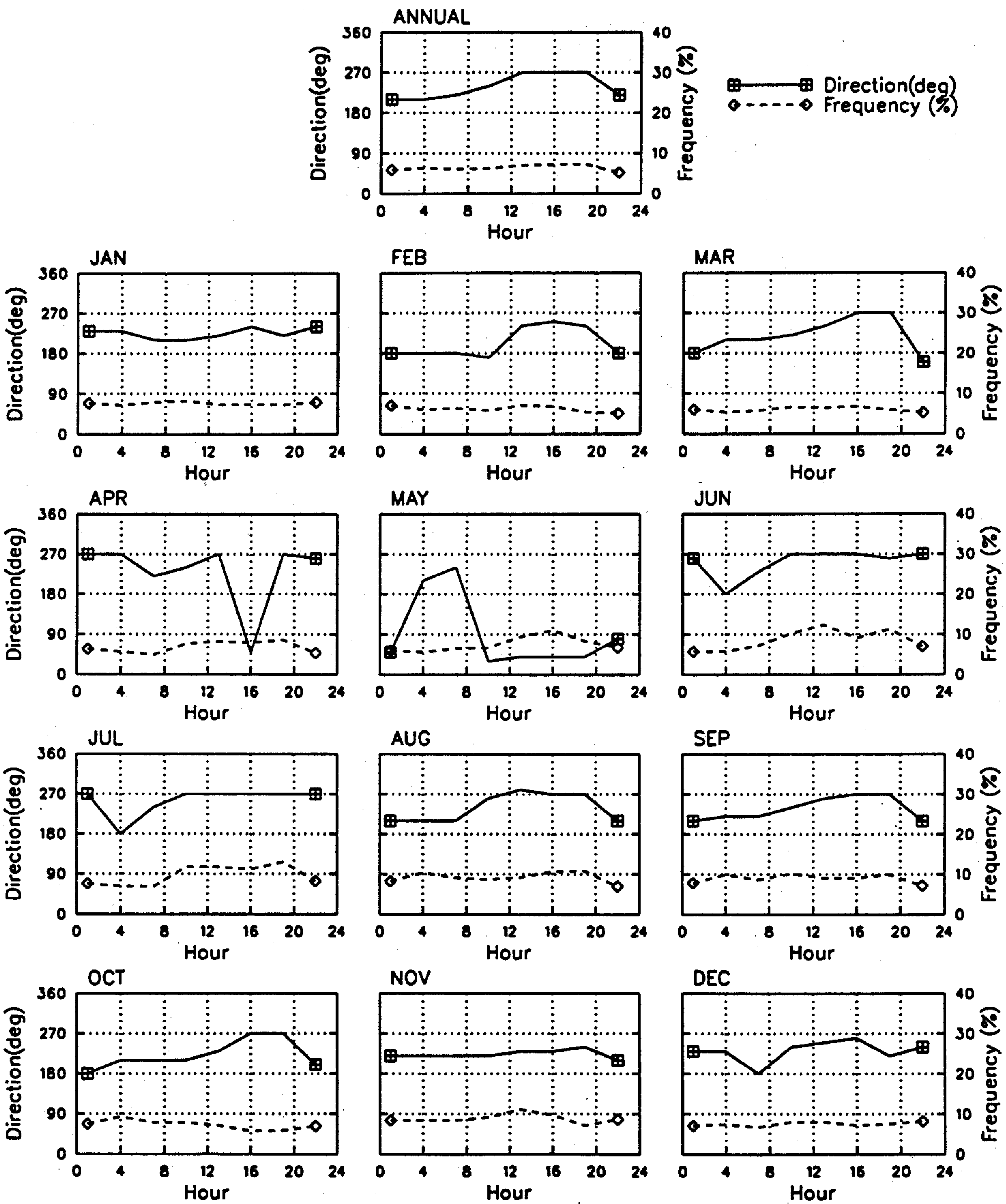


PREVAILING DIRECTION & FREQUENCY BY HOUR

Lebo - 121200

54° 45' N 17° 32' E - Elev 2m

01/73-12/91



PRESSURE BY MONTH

Leba – 121200

54° 45' N 17° 32' E – Elev 2m

01/73–12/91