WIND ENERGY RESOURCE ANALYSIS FOR EGYPT

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WIND ENERGY RESOURCE ANAYSIS FOR EGYPT

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LOUIS BERGER INTERNATIONAL, INC.
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Submitted by

BATTELLE, PACIFIC NORTHWEST LABORATORIES
Richland, Washington

Prepared by

D. L. Elliot
C. G. Holladay
D. S. Renne
M. N. Schwartz

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1.0 INTRODUCTION

The Government of Egypt (GOE) is undertaking to adjust internal energy prices to levels more in line with free market values. In connection with this action, the GOE, jointly with USAID/Cairo, is conducting a renewable energy field testing program in an effort to determine the feasibility of subsidizing conventional sources with renewable sources. Wind energy is one of the renewable energy resources that is being tested in this program.

A viable wind energy resource has long been recognized in certain regions of Egypt. Following World War II, water pumping windmills manufactured domestically were used extensively along the Mediterranean coastline. More recently, a network of small, battery-charging windmills has been installed at a number of communications towers. These experiences indicate that wind energy could provide electrical power to villages not connected with the electric grid that runs along the Nile River. Wind energy could also provide fresh water through desalination and save fuel in communities where diesel generators are currently the primary source of electricity.

An important step in the current field testing program is quantifying the extent of Egypt's wind resources using existing data. This report provides the beginning of that quantification. The information collected in this study will be used to assist planners in focusing on specific areas where wind energy use is practicable.

This wind resource assessment activity represents a continuation of two earlier studies performed for Egypt. The first study, performed by Dr. M. S. El Din Harb of the Meteorological Authority, Cairo, and reported in the Phase I final report (Hughes 1975), identified two main regions where wind energy might be used in Egypt: the Red Sea and the Mediterranean coastal areas. Dr. El Din Harb's study was based on an analysis of standard surface-weather observations in Egypt.

In the second study, eight stations were installed at various locations along the Mediterranean and Red Sea coastlines (Hughes 1979). Data were

acquired for periods of four to eleven months. The study concluded that although certain locations along the Mediterranean coast may be suitable for small wind machine applications, significant potential for wind energy utilization exists in areas along the Red Sea coast.

In a separate study, Dr. Atef Hassanein of the Aeronautical Institute, University of Cairo, used available Meteorological Authority data to estimate wind power for the country (Hassanein and Darwish 1984). This report confirmed the conclusions of the earlier studies, but also showed that portions of the Sinai Peninsula and the Western Desert have potentially viable wind resources.

In building upon the results of these previous studies, this assessment synthesizes the data from previous studies and supplements those data with data obtained for many additional locations and periods of record. In all, surface data were identified for 63 locations, with some locations having data records as far back as the late 1800's. An extensive screening process was applied to select the most useful surface data. In addition, climatological data on winds aloft, maps of pressure patterns, air flow, and topography were used in estimating the wind resource in many data-sparse areas.

Section 2 discusses the sources of data used in this assessment. Section 3 describes the methodology used to develop quantitative estimates of the wind resource. Section 4 presents the results of the assessment, with information on annual, seasonal, and diurnal distribution of the resource, and on our relative certainty of these estimates. Several key regions of the country, including the Red Sea and Mediterranean coasts, the Sinai Peninsula, and the Western Desert, are considered separately. Section 5 describes the climatological basis for the wind resources of Egypt for the separate regions. Section 6 summarizes the results of the assessment and makes recommendations for more accurately assessing the wind resource in Egypt with greater certainty, using existing as well as new data. In the appendix, monthly and diurnal plots of the wind resource for a number of stations throughout Egypt are presented.

2. SOURCES OF DATA

The data used in this assessment were obtained from various sources. As stated in the introduction, this assessment builds upon data collected in two earlier studies performed for Egypt (Hughes 1975, 1979), along with wind power estimates calculated by Dr. Atef Hassanein with data made available to him by the Egyptian Meteorological Authority. An additional major source of preliminary information was Battelle's "World-Wide Wind Energy Resource Assessment" (Elliott et al. 1981).

Other wind speed and wind power estimates came from a 1982 report entitled "Wind Energy in Egypt" by Dr. Amin Mobarak of Cairo University. The Egyptian Meteorological Authority (1976) report, "Climatological Data for the Study of Qattara Depression Project," contained wind speed frequency information useful for calculating wind power estimates. The Egyptian Electrical Authority (EEA) has provided more recent data from special measurement programs at Ras Ghareb, Zafarana, and East Oweinatt.

In addition to data from these sources, the United States' National Climatic Data Center provided several useful reports and data sets:

1. A report on the climatology and winds in the Red Sea area;

2. A publication, "Sailing Directions for the Red Sea" by the U.S. Naval Oceanographic office, containing wind summaries for various locations along the northern Red Sea;

3. Wind summaries for six coastal marine areas, drawn from many years of ships' observations. The centers of these marine areas, located in the Gulf of Suez, the Red Sea, and off the Mediterranean coast, are depicted in Figure 1. Included in the summaries are monthly statistics on the distribution of wind speeds by time of day and by direction.

4. Wind summaries containing wind speed frequency data for selected stations in Egypt.

Figure 1 shows the locations in Egypt and surrounding coastal areas where some type of wind data was available. To facilitate the identification

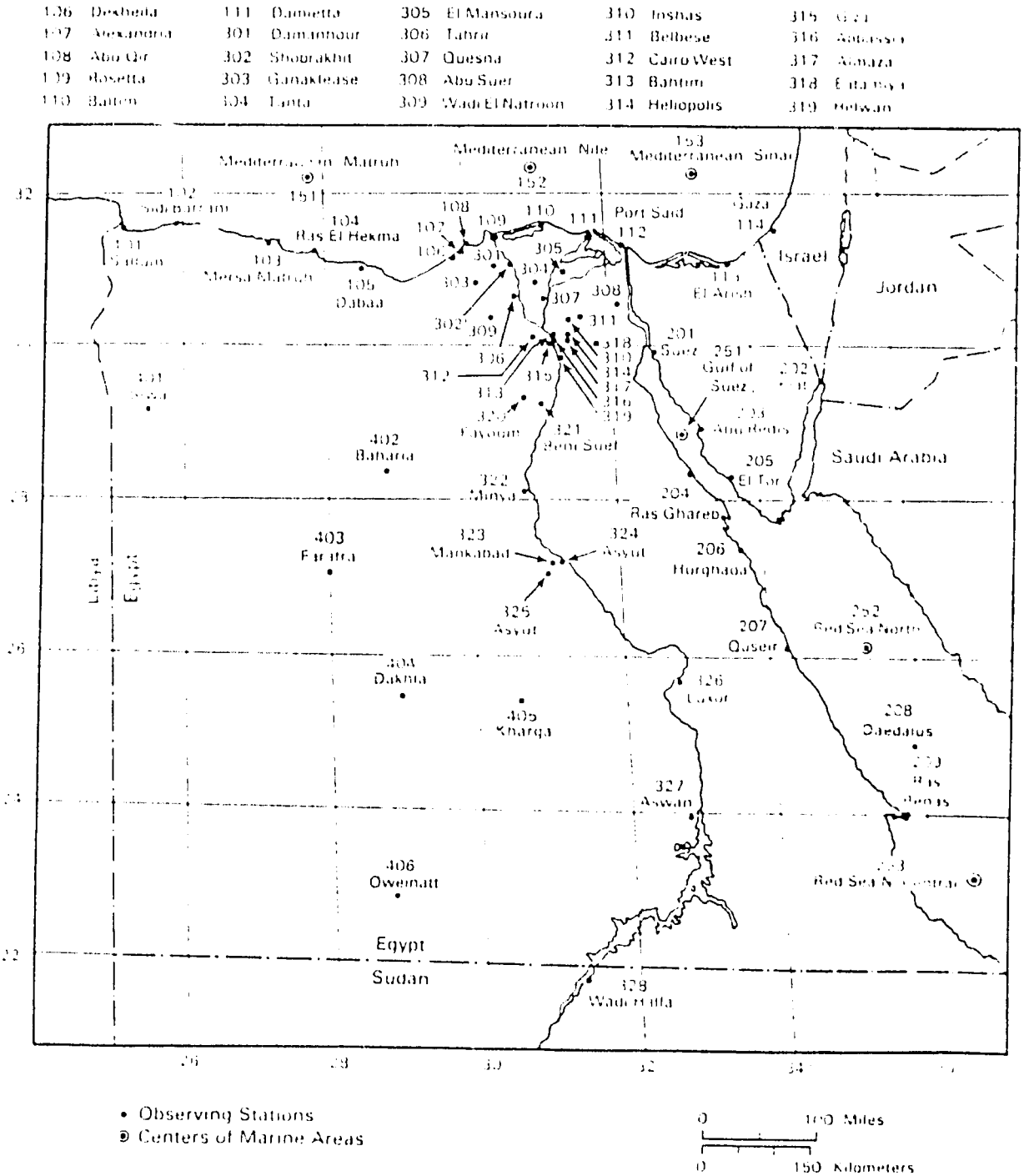


FIGURE 1. Map Showing All Observing Stations and Centers of Marine Areas for Which Surface Wind Data Were Identified and Evaluated.

of locations in Figure 1, Egypt was divided into four climatological regions: (1) Mediterranean, (2) Gulf of Suez and Red Sea, (3) Nile, and (4) Western Desert. Station numbers assigned here correspond to the region in which a station is located; for example, 100s are Mediterranean locations, 200s are Gulf of Suez or Red Sea locations, 300s are Nile locations, and 400s are Western Desert locations. Numbers within a region increase in going from west to east and from north to south.

Although upper-air data available for this assessment were very limited, one special data set was useful. Data from a one-year period of radar, wind and pilot balloon observations over Africa and southwest Asia have been collected, edited, and analyzed (Aspliden et al. 1973) to produce monthly and annual wind fields at standard levels, including 600 m above ground level.

Other sources of data and pertinent site information were not readily available for preparing this assessment but may become available later for an updated assessment. These sources will be considered further in Section 6.

3. METHODOLOGY

3.1 CHARACTERIZING THE WIND ENERGY POTENTIAL

The wind resource at a site is often described by the mean wind speed. However, a better way of estimating the wind resource is to use the wind power density value, if it is available. This value is proportional to the cube of the instantaneous or short-term (e.g., hourly or three-hourly) mean wind speed. In practice, it is computed from the wind speed frequency distribution of short-term mean wind speeds when wind data have been summarized in this form. The equation used is

$$\bar{P} = \frac{1}{2}\bar{\rho} \sum_{j=1}^{c} f_j v_j^3 \qquad (1)$$

where

$\bar{P}$ = mean wind power density (W/m^2) in a vertical plane perpendicular to the wind direction

$\bar{\rho}$ = mean air density (kg/m^3)

c = number of wind speed classes

f_j = frequency of occurrence of winds in the jth class

v_j = the median wind speed (m/s) of the jth class.

The mean air density was estimated by correcting standard air density for station elevation and was calculated by:

$$\bar{\rho} = 1.225 - (1.194 \times 10^{-4})Z \qquad (2)$$

where Z is the station elevation in meters.

For stations with wind data that included only monthly or annual mean speeds, the wind power density, $\bar{P}$, was estimated by assuming that the speed frequency distribution followed a Rayleigh distribution (Cliff 1977). Thus,

$$\bar{P} = 0.955\bar{\rho}\ \bar{V}^3 \qquad (3)$$

where $\bar{V}$ is the mean monthly or annual wind speed.

Since both the mean wind speed and mean wind power density generally increase with height, the wind resource assessment must be related to a particular reference height above ground level. However, sufficient information about actual anemometer heights was not available during preparation of this assessment. Because the most commonly recommended height for surface wind observations is 10 m, that height was assumed for all data used in the wind power density calculations.

The wind power class scale defined in Table 1 is used to describe the wind energy potential at a site or in an area. Each class represents a range of mean wind power density values or equivalent mean wind speeds at 10 m above ground at a well-exposed site.

TABLE 1. Classes of Wind Power Density at 10 m Above Ground

Wind Power Class	Wind Power Density (W/m^2)	Speed,[a] m/s (mph)
	0	0
1	100	4.4 (9.8)
2	150	5.1 (11.5)
3	200	5.6 (12.5)
4	250	6.0 (13.4)
5	300	6.4 (14.3)
6	400	7.0 (15.7)
7	1000	9.4 (21.1)

(a) Mean wind speed is based on Rayleigh speed distribution of equivalent mean wind power density. Wind speed is for standard sea-level conditions. To maintain the same power density, speed increases 3%/1000 m of elevation.

The relationship between the mean wind power density and the mean wind speed in Table 1 assumes a Rayleigh distribution of wind speeds and sea-level air density. The Rayleigh distribution is a special case of the Weibull

method with a shape factor equal to 2 (Hennessey 1977). The only information required to determine a Rayleigh distribution is mean wind speed. The decrease of air density occurring with increased altitude means that a higher mean wind speed is required to achieve a given wind power density at higher elevations. As a result, the mean speed must be about 3% higher than that shown in Table 1 for every 1,000 meters above sea level to obtain the same wind power density.

Areas where class 3 or greater power is estimated are suitable for many wind turbine applications. Areas having class 2 power are marginal for wind turbine applications, and class 1 areas are generally not suitable.

The wind power estimates in this assessment apply to areas free of local obstructions to the wind and to terrain features that are well exposed to the wind, such as open plains, plateaus, and hilltops. Within mountainous areas, wind resource estimates apply to exposed ridge crests and mountain summits.

3.2 WIND DATA SCREENING

In preparing this assessment, a large amount of wind data was considered. Not all of these data were used in the assessment. Screening procedures were developed to select stations with the most useful data and to eliminate stations that would contribute little information on the distribution of the wind resource.

In general, wind data summarized into wind speed frequency classes were preferred to data including only monthly or annual mean wind speeds. However, other important considerations were site exposure, anemometer height, periods of record, and the frequency of observation. When several sets of data covered different periods of record for the same or adjacent locations, site exposure was usually emphasized. Figure 2 shows ten stations in Egypt having more than one set of wind data. In evaluating the wind energy potential throughout the country, wind data from existing airports were compared with older data. For many stations, it was determined that the older anemometer locations had better exposures than the more recent locations. The data from the most exposed anemometer site at each location was used in this assessment. So, for instance, 50- to 80-year old data from Abu Qir were used in this assessment instead of more recent data from Alexandria because the Abu Qir site was better exposed.

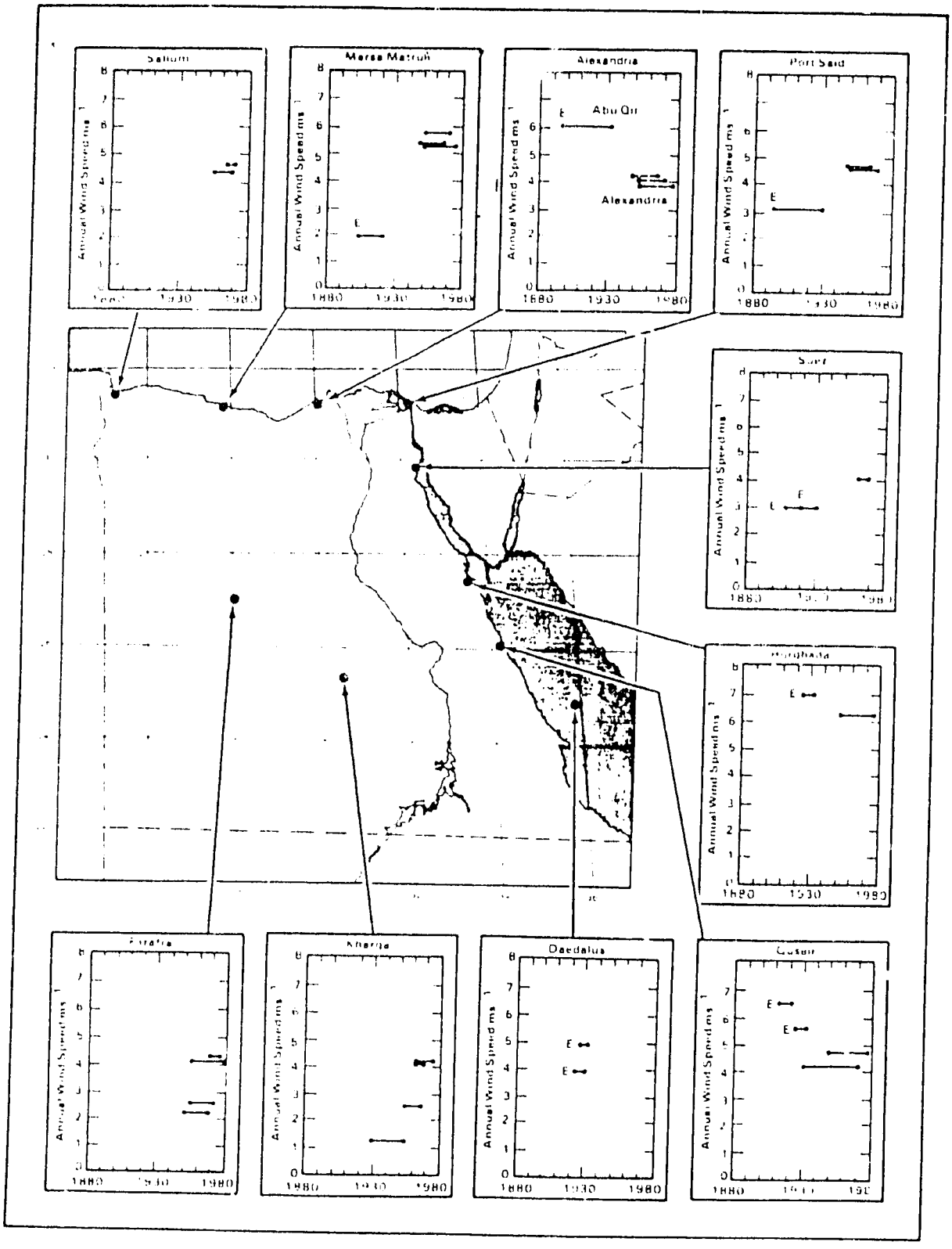


FIGURE 2. Stations in Egypt with More than One Set of Wind Data. For each data set, the annual average wind speed is plotted versus the period of record. E stands for estimated period of record.

The Quseir data gathered prior to 1920 were used instead of later data from Quseir for the same reason.

No vertical adjustment of any of these data was possible because sufficient information about anemometer heights was not available when this assessment was being prepared. In the mean power density calculations, all of the data were assumed to come from anemometers located 10 m above ground level.

3.2 USE OF METEOROLOGICAL AND TOPOGRAPHIC INDICATORS

In addition to surface wind data, climatological data on winds aloft and maps of pressure patterns, air flow, and topography (see Figure 3) were used to assess the geographical distribution of the wind resource and to estimate the wind resource in many data-sparse areas of Egypt. Information of this nature was also extensively applied in assessing the wind resource distribution throughout the United States (Pacific Northwest Laboratory 1980-1981). In the United States assessment, certain combinations of meteorological and topographical features (Elliott 1979) were used to qualitatively estimate the wind resource in many data-sparse areas. Many of these features were found to exist in Egypt and were used as qualitative indicators of the wind resource. These features are described below along with examples of areas in Egypt where they occur.

Features associated with high wind resource are:

- prominent mountain gaps, passes, and corridors in areas of frequent strong pressure gradients, e. g., the southern Gulf of Suez
- high plains and plateaus in areas of strong winds aloft, e.g., the Gilf Kebir Plateau
- exposed ridges and mountain summits in areas of strong upper-air winds, e.g., the Sinai Mountains
- exposed coastal sites in areas with strong winds aloft or strong thermal/pressure gradients, e. g., much of the Mediterranean and Red Sea coasts.

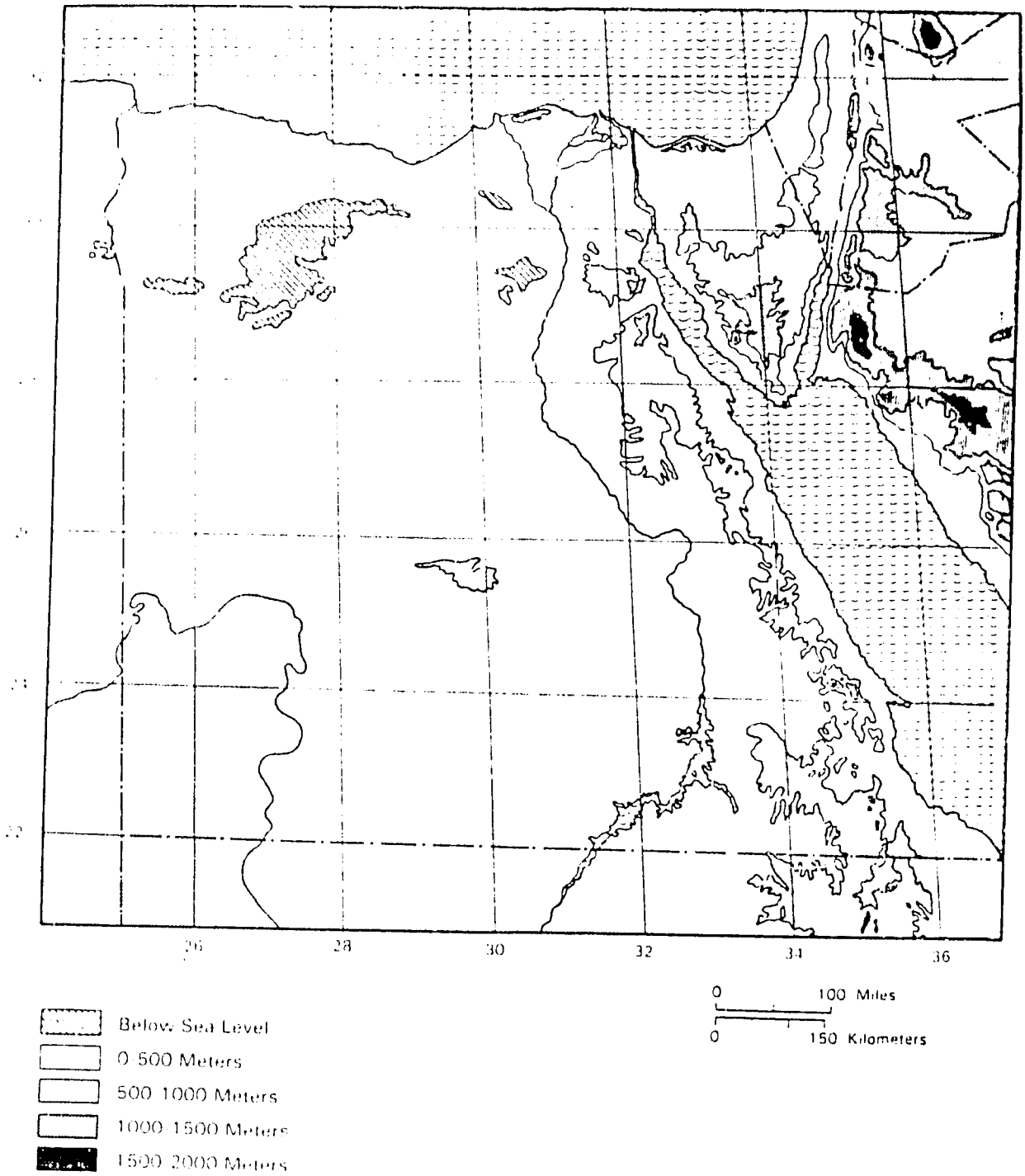


FIGURE 3. Topographical Map of Egypt and Surrounding Area

Features associated with low wind resource are:

- sheltered river valleys, e.g., much of the Nile River valley
- sheltered basins, e.g., the Qattara Depression and the various oases throughout the Western Desert
- areas of high surface roughness, e.g., built-up areas with numerous buildings, trees, etc., such as much of the Nile Delta area.

4.0 RESULTS

After the most useful wind data were identified, they were integrated with information about the topography and the synoptic scale wind and pressure patterns to estimate the annual, seasonal, monthly, and diurnal wind resource. The results are presented in this section. Refer to Figures 1 and 4 for locations of places mentioned in this section.

4.1 ANNUAL SUMMARIES

Figure 5 shows a map of the estimated distribution of the annual average wind energy resource in Egypt. As stated in Section 3.1, areas where class 3 or greater resource is estimated are suitable for many wind turbine applications. As Figure 5 shows, a large fraction of Egypt is estimated to have class 3 or greater wind resource. This fraction includes the Mediterranean coastal region, the Red Sea and Gulfs of Suez and Aqaba, the highlands of the Eastern Desert (i.e., the area east of the Nile River) and of the southern Sinai, and the southern part of the Western Desert (i.e., the area west of the Nile River). Annual wind resource in Egypt of class 4 or greater is found along the Mediterranean coast from Sallum to near Alexandria, along the Red Sea coast north of 24° north latitude, along the central and southern coasts of the Gulf of Suez, along the coast of the Gulf of Aqaba, and in the southwestern desert area. In addition, mountain summits and ridge crests in the southern Sinai and in the Eastern Desert are estimated to have class 4 or greater resource. Annual wind resource in Egypt of class 5 or greater is estimated along the Red Sea coast north of 26° north latitude and into the Gulf of Suez south of 29° north latitude, with class 6 or greater resource expected along the Red Sea coast north of Hurghada and into the Gulf of Suez to just north of Ras Ghareb on the west coast and El Tor on the east coast.

Local terrain features can cause the mean wind resource to vary considerably over short distances, especially in coastal, hilly, and mountainous terrain. Figure 5 identifies many areas estimated to have high wind resource, but it does not depict the local variability caused by local terrain features. Therefore, there may be local areas where the wind resource may be higher or lower than indicated on the map.

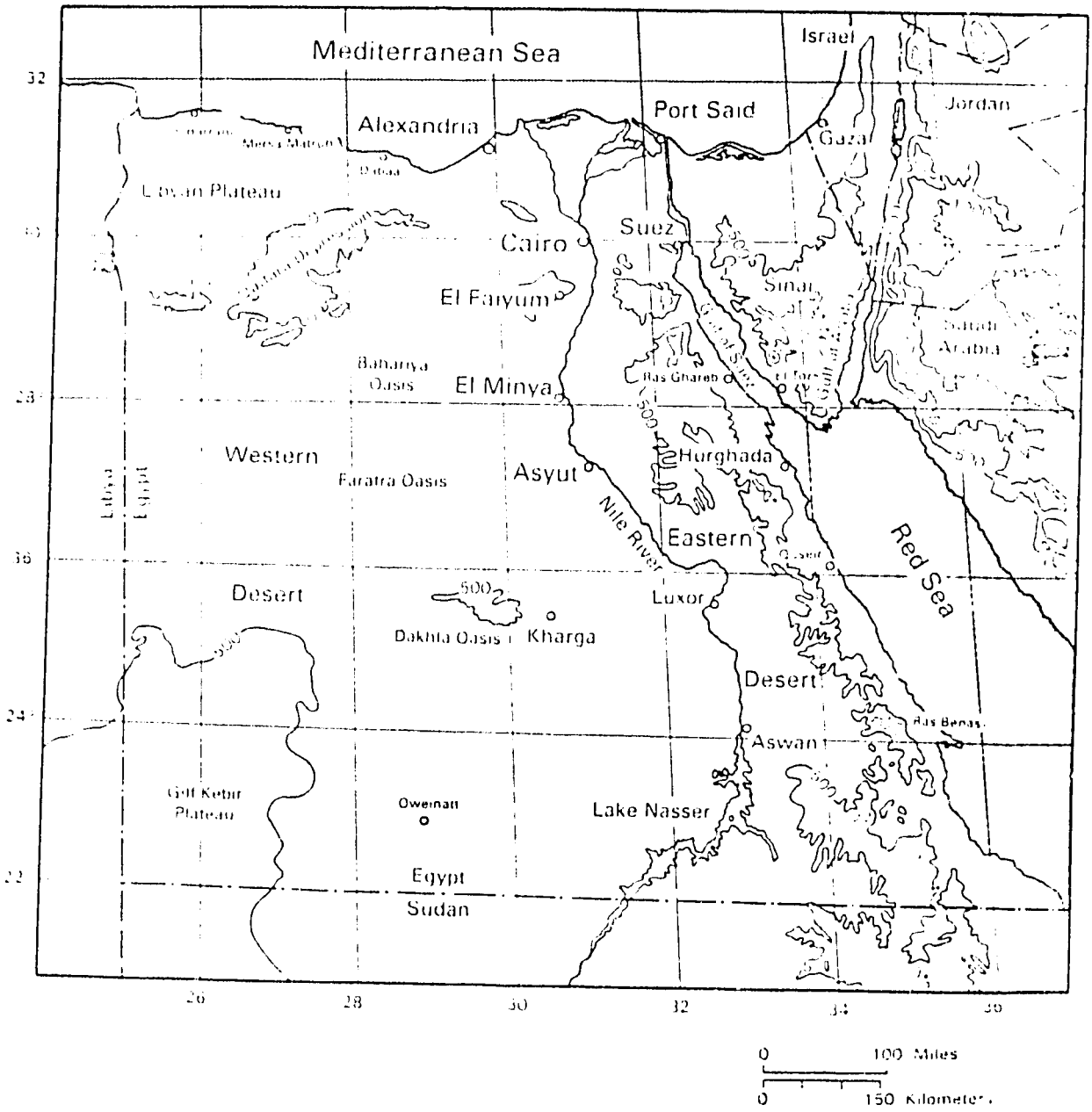
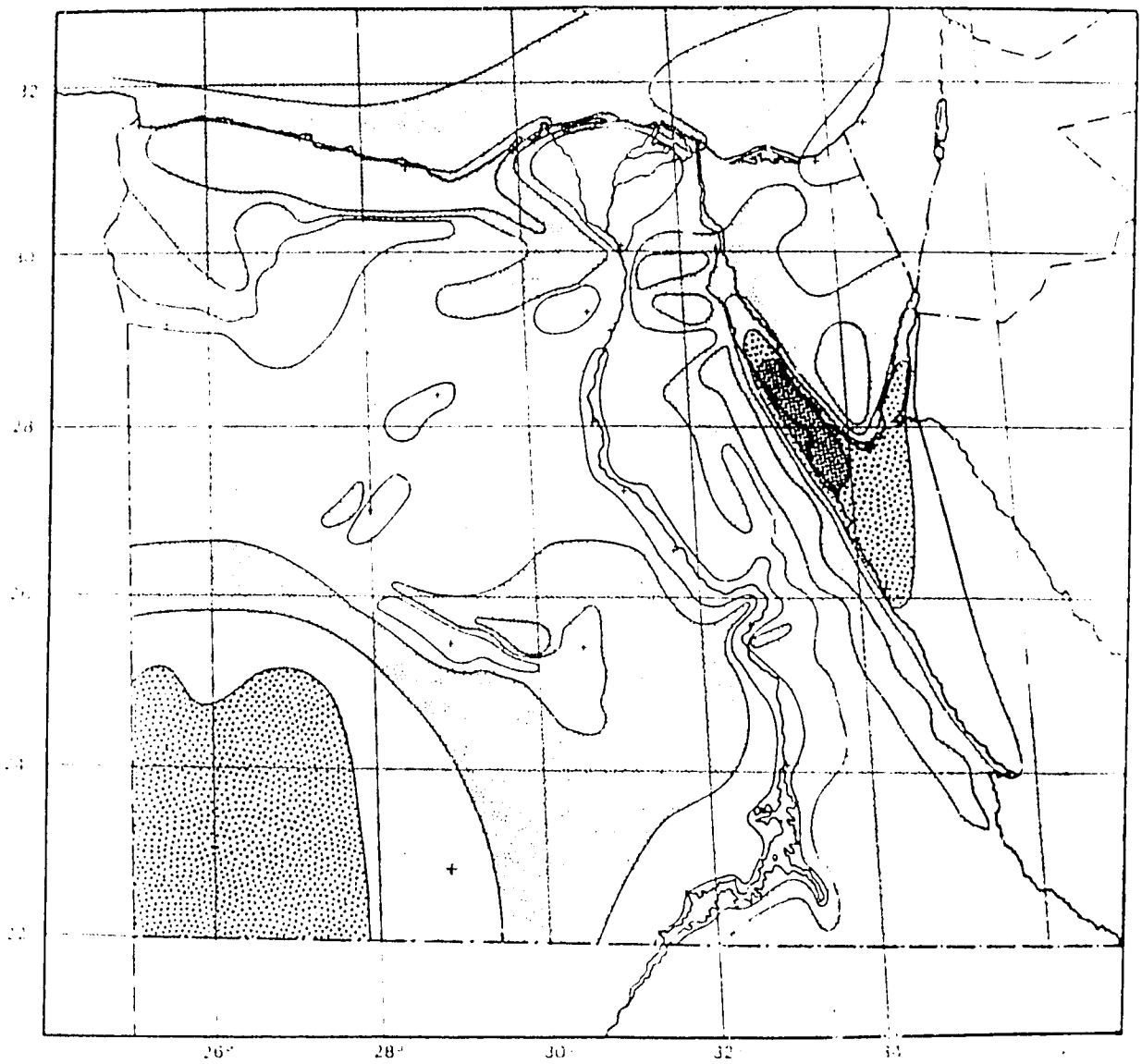
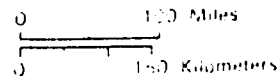


FIGURE 4. Map of Egypt Identifying Major Cities and Features





	Power Class	10 m Wind Power (W/m²)	10 m Speed (m/s)
	1	<100	<4.4
	2	100-150	4.4-5.1
	3	150-200	5.1-5.6
	4	200-250	5.6-6.0
	5	250-300	6.0-6.4
	6	300-400	6.4-7.0
	7	400-1000	7.0-9.4

FIGURE 5. Annual Average Wind Power Estimates for Areas of Egypt

4.1.1 Mediterranean

Figure 5 shows that class 4 is the highest estimated wind resource in the Mediterranean coastal region. Class 4 wind resource is estimated to extend from just east of Sallum to near Alexandria (Abu Qir) and inland as far as 80 km. (As stated in Section 3.2, we have used data from Abu Qir, an exposed coastal site northeast of Alexandria, to represent Alexandria rather than data from the Alexandria airport, which is in a more sheltered location). Existing data indicate that the area within 5 km of the coastline between Dabaa and Alexandria has slightly greater wind resource than the area to the west of Dabaa, even though both areas are shown in Figure 5 as having class 4 resource. For example, data indicate a strong class 4 or possibly even class 5 wind resource along coastal areas near Alexandria, where an annual wind power density of 249 W/m^2 is computed from the data; to the west of Dabaa, at Mersa Matruh, the wind power density is computed to be 209 W/m^2, indicating a lower but still class 4 resource. Further west, Sallum has a computed wind power density of 159 W/m^2, indicating a class 3 wind resource. To the east of Alexandria and along the Mediterranean coast to Port Said, Figure 5 shows that the wind resource is estimated to be class 3. The computed wind power density at Port Said is 149 W/m^2. To the east of Port Said, the annual wind resource is estimated to be class 2 or less.

Figure 5 shows that west of longitude 29° east, class 4 wind resource is estimated to extend as far as 80 km inland, whereas class 3 resource is estimated for the coastline and offshore. An estimated high summer wind resource inland, coupled with a winter wind resource that is estimated to be fairly uniform in the entire coastal region, indicate that the annual average wind resource is greater inland than it is within 5 km of the coastline and just offshore. For example, the data from Dabaa, located 15 km inland, indicate that class 4 to 5 wind power exists in the summer, while data from Ras El Hekma, located at the end of a cape that projects into the Mediterranean, indicate only class 1 power in the summer. There are no data available from further inland than 15 km from this part of the Mediterranean coastline. However, because the pressure gradient inland increases in the summer, the wind resource may continue to increase inland and may possibly be class 6 or greater in the summer at locations 30 to 50 km inland.

4.1.2 Red Sea Coast (including the Gulfs of Suez and Aqaba, the southern Sinai and the Eastern Desert)

Figure 5 shows that class 6 annual wind resource is estimated to occur along the Red Sea coast from Hurghada northward into the Gulf of Suez, to just north of Ras Ghareb on the western shore and to just offshore of El Tor on the eastern shore. This is the area of highest estimated annual wind energy potential in Egypt. Annual wind resource of at least class 5 is estimated along the Red Sea coast from Quseir northward into the Gulf of Suez south of 29° north latitude. One year of data from Ras Ghareb gives a computed wind power density of 332 W/m^2, or class 6 wind power; the computed annual wind power density at El Tor is 280 W/m^2, or class 5 wind resource.

Two different data sets were available for Hurghada; one set indicates class 5 wind power (283 W/m^2) and the other set indicates class 6 wind power (340 W/m^2). Because it was uncertain which of these data sets is most representative of Hurghada, we have shown the southern limit of the class 6 wind resource to be near Hurghada, as in Figure 5.

Data from Quseir indicate class 5 wind resource. Class 4 wind resource is estimated from Ras Benas northward to just south of Quseir and along the north-central coasts of the Gulf of Suez and the coast of the Gulf of Aqaba. Class 3 wind resource is estimated to occur south of Ras Benas and in the extreme northern parts of the Gulfs of Suez and Aqaba.

In the highlands of the Eastern Desert and the southern Sinai, class 4 wind resource is estimated for mountain summits and ridge crests, while class 3 wind resource is estimated for the remainder of the highlands. Since there were few surface data from this region, climatological information on winds aloft and topography of the Eastern Desert and southern Sinai were used in making these estimates.

4.1.3 The Nile Valley and Lower Egypt

Figure 5 shows that the estimated annual average wind resource in the Nile Valley and Lower Egypt is only class 1 or 2. The Nile Delta area has a greater concentration of stations with wind data than any other area of Egypt, as seen in Figure 1. The wind data from all stations in this area, except for Wadi

El Natroon, indicated only class 1 or 2 wind resources. The large numbers of buildings, trees, and other obstructions to the wind in this area reduce substantially the available wind resource at levels near the ground (i.e., 10 to 20 m above ground). The upland desert areas to the southwest and southeast of the Nile Delta are estimated to have class 3 to 4 wind resource potential.

Along the entire length of the Nile River valley, existing wind data indicate only class 1 or 2 wind resource. Wind speeds are reduced because of the relative lowness of the terrain and the large numbers of obstructions to the wind. However, class 3 or 4 wind resource may exist on some hills and upland areas near the Nile River, such as the upland areas near Luxor.

4.1.4 Western Desert and Inland Stations

Figure 5 shows that class 4 and 5 wind power resource is estimated for southwestern Egypt, including the Gilf Kebir Plateau. The only surface wind data from southwestern Egypt were from Oweinatt, and they were limited to daytime observations (0600-1800 LST) for a 10-month period. Analyzing these data and making an adjustment to account for somewhat lower nighttime wind speeds (as occur at other desert locations), we estimated class 4 wind resource for Oweinatt. Exposed areas in the Gilf Kebir Plateau are estimated to have class 5 or greater wind resource, based on an analysis of the climatology of winds aloft and the relatively high elevation of the plateau area. Similarly, class 4 wind resource is estimated for the high terrain area west of Kharga.

For the rest of the Western Desert, wind resource no greater than class 3 is estimated, with most of the area north of 26° north latitude having class 2 wind resource or less. Data from most of the major oases, including Dakhla, Farafra, Baharia and Siwa, indicate only class 1 wind power. Data from Kharga indicate class 2 wind resource.

4.2 SEASONAL PATTERNS

This section discusses the seasonal patterns of the wind resource in Egypt. The winter pattern described here extends from December to March, the summer pattern from June to September. The spring transition is April and May, and the autumn transition October and November. Figure 6 includes graphs of wind speed by month for selected stations. The map in the center

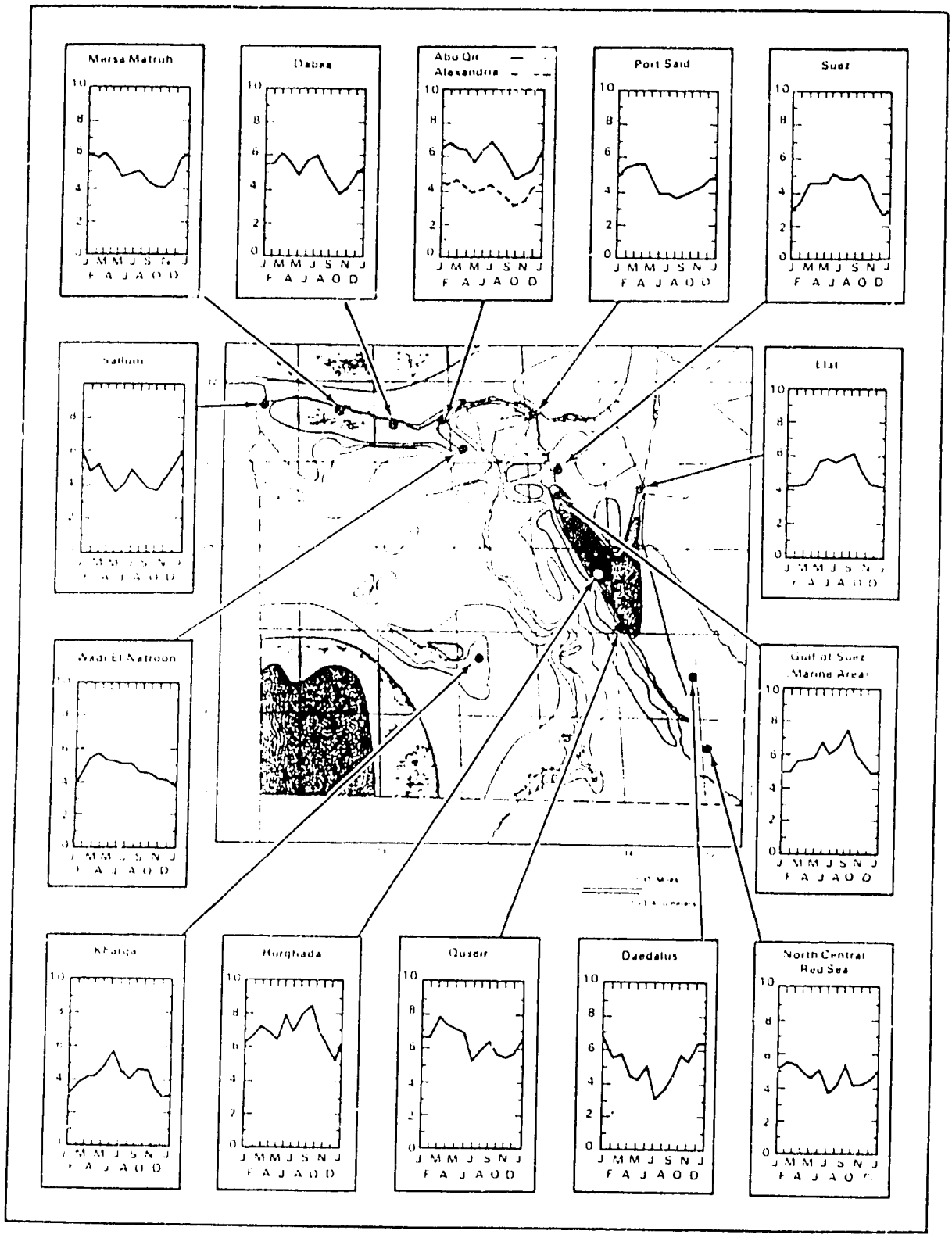


FIGURE 6. Mean Monthly Wind Speeds (m/s) for Selected Stations in Egypt. Map of Egypt in the center is the same annual average wind resource map as in Figure 5.

of Figure 6 is the annual average wind resource map (the same map as in Figure 5, reduced in size). Using the figure, one can readily associate the monthly or seasonal trends at a selected station with the relative magnitude and the estimated distribution of the annual average wind resource over an area about the station.

Moreover, this arrangement of station graphs allows one to conveniently compare the monthly or seasonal trends in wind resource at different locations throughout Egypt. For example, one can readily see the contrasting seasonal trends between the Mediterranean coast and the Gulf of Suez area and between the northern and central Red Sea areas (looking at the graphs for Hurghada and Daedalus). Many other monthly or seasonal trends can be compared using this figure, without losing perspective on the annual average wind resource distribution estimates.

The appendix includes additional figures showing monthly plots of wind speed and wind power density for selected stations for which the available data had been summarized into wind speed frequency classes.

4.2.1 Mediterranean

Winter

Winter is the season of maximum wind resource along the Mediterranean coast from Sallum to Alexandria, with class 5 wind resource estimated for exposed areas. East of Alexandria, the wind resource decreases to class 3 at Port Said and to class 1 at El Arish.

Spring

From Sallum eastward to Alexandria, April and May show a general decrease in wind resource from that of winter. Spring wind resources of class 3 or less occur from Sallum to Dabaa. A spring wind resource of class 4 is possible from Dabaa east to Port Said. Class 2 or lower spring wind resource is estimated from east of Port Said to El Arish. Inland, Wadi El Natroon reaches its maximum wind resource of class 5, lasting from March into April, decreasing to class 4 in May.

Summer

The summer wind resource varies considerably across the Mediterranean coastal region. From Dabaa westward to Sallum, the wind resource several kilometers inland is significantly greater than that at exposed coastal points. For example, data from Dabaa, located 15 km inland, indicate class 4 to 5 wind resource for the summer, while data from Ras El Hekma, located at the end of a cape that projects into the Mediterranean, indicate only class 1 resource in the summer. Offshore, ship data also indicate only class 1 wind resource in the summer. The higher wind resource inland is apparently due to greater pressure gradients onshore than offshore. Wind speeds may continue to increase with distances further inland, to about 30 to 50 km inland, but no data are known to exist from areas that far inland. At near coastal stations (such as Mersa Matruh and Sidi Barrani), the summer resource is class 2 to 3, which is greater than that at exposed coastal points (such as Ras El Hekma) but less than that at stations further inland (such as Dabaa).

From Dabaa eastward to Alexandria, the coastline wind resource in summer increases to class 4 to 5, as indicated by data from an exposed coastal site at Abu Qir. The data indicate that the wind resource decreases sharply from the coastline inland in the Nile Delta area. Offshore, data from ships indicate only class 1 wind resource. Apparently, maximum surface pressure gradients occur within a few kilometers of the coastline in the Alexandria area.

East of Alexandria to Port Said, the coastline wind resource in summer decreases to only class 2 or 1. Inland from the coast and also eastward along the coast to El Arish, the summer wind resource is estimated to be only class 1.

Autumn

The autumn transition is more abrupt than the spring transition. From the minimum wind resource in October, monthly wind resource increases gradually from October to December. Autumn wind resource of class 3 is estimated to occur along the Mediterranean from Sallum to Port Said. From Port Said eastward, the wind resource is estimated to be class 2 or lower.

4.2.2 Red Sea (including the Gulfs of Suez and Aqaba and the southern Sinai)

Winter

Winter is the season of maximum wind resource along the Red Sea coast south of Quseir. In contrast, winter is the season of minimum wind resource from Hurghada northward through the Gulf of Suez and in the Gulf of Aqaba.

Winter wind resources of class 3 to class 5 occur from approximately the north-central coast of the Gulf of Suez (29° north latitude) southward along the entire Red Sea coast to the Sudan. Thus, although the wind resource is not outstandingly high anywhere in this region in winter, all areas except the northern Gulfs of Suez and Aqaba have sufficient wind energy resource in winter for many wind turbine applications.

Wind resources of class 4 and 5 are estimated along the Red Sea coast from Hurghada south to Ras Benas. The area of highest wind resource (class 5) in winter is estimated to occur from south of Hurghada to south of Quseir (to about 25 north latitude). Class 3 wind resource is estimated for the Red Sea coast south of Ras Benas and north of Hurghada to Ras Ghareb. The northern Gulf of Suez and the Gulf of Aqaba are estimated to have class 2 or less wind resource in winter.

. From Quseir northward to the Gulf of Suez, the wind resource gradually increases from December to March. For example, winds at Quseir average 5.8 m/s in December, 6.8 m/s in January and February and reach their maximum monthly speed of 8.0 m/s in March.

Spring

The most significant spring trend is the increase of wind resource in the Gulfs of Suez and Aqaba and the decrease of wind resource along the Red Sea coast south of Quseir. Spring wind resources of class 3 and greater occur over the entire coastal areas of the Gulfs of Suez and Aqaba, the highlands of southern Sinai, and the Red Sea coastal areas north of Ras Benas. Spring wind resources as high as class 6 are estimated from Quseir northward to Ras Ghareb.

Summer

Summer is a season of contrasts in wind resource in the Red Sea region. North of Quseir (including the entire coastal areas of the Gulfs of Suez and Aqaba), summer is the season of maximum wind resource; south of Quseir to the Sudan, summer is a season of minimum wind resource.

Class 3 and greater wind resource is estimated to occur in summer over all areas from Quseir northward. Outstanding wind resource, class 7, occurs from Ras Ghareb and the central and southern coasts of the Gulf of Suez southward to Hurghada. At Suez on the extreme north end of the Gulf of Suez, wind resource reaches a seasonal maximum of class 4. Along the Gulf of Aqaba, wind resource reaches a seasonal maximum of class 5 to 6. The Quseir area has class 3 to 4 wind resource, but south of Quseir the wind resource decreases to class 2 or less.

Throughout the entire Red Sea region, including the Gulfs of Suez and Aqaba, the wind resource increases as the summer progresses from July to September. All locations show a summer minimum wind speed in July and a summer maximum wind speed in September. For example, at Hurghada, a station with class 6 to 7 summer resource, the monthly speeds vary from a minimum of 6.9 m/s in July to a maximum of 8.6 m/s in September. Further south at Daedalus, a station with only class 1 to 2 summer resource, the monthly speeds vary from a minimum of 3.0 m/s in July to 5.0 m/s in September.

Along the northern Red Sea (north of Quseir) and the Gulf coasts, the wind resource reaches a yearly maximum in September. In the area of highest wind resource, along the Gulf of Suez coast from Ras Ghareb to Hurghada, mean wind speeds in September exceed 8 m/s.

Autumn

Wind resource decreases abruptly through the autumn from its September maxima on the northern Red Sea and the Gulf coasts. The wind resource decreases more slowly from September to November in the area south of Quseir, than it does in the area north of Quseir. (Daedalus is the only station that shows a slight increase in wind speed from September to November.) Autumn

wind resources of class 6 or less are estimated from Quseir to Ras Ghareb. A class 3 wind resource is estimated for the remainder of the Red Sea and Gulfs of Suez and Aqaba.

4.2.3 Other Regions

Elsewhere in Egypt, either there are insufficient wind data available to estimate seasonal patterns of the wind resource or the pattern indicated by the data is class 1 or class 2 power, unsuitable for most wind turbine applications. An exception to this generalization is Kharga, where data indicate a summer maximum of class 3 wind resource.

4.3 DIURNAL PATTERNS

Few data were available for estimating the diurnal pattern of the wind resource. Data came from only twelve stations. The plots of these data for eleven stations are in the appendix. Except for the data from Ras Ghareb, the available data were summarized into a small number of wind frequency classes, with the result that wind speed and wind power density estimates tend to be higher than they would be if the data had been summarized into more classes. For Hurghada, which is not shown in the appendix, mean hourly wind speeds for each month were plotted in the report "Wind Energy in Egypt" by Mobarak (1982).

Some basic diurnal patterns are indicated. Data from five stations along the Mediterranean coast indicate that the highest wind speeds occur in the early afternoon, about 1400 LST, during the spring and summer. The highest wind speeds here ranged from 6 to 7.5 m/s, except at El Arish, where the maximum speed was 4.5 m/s. The highest wind power densities ranged from 300-500 W/m^2, or class 6 to class 7 wind power. The exception is El Arish, where the maximum wind density was only 100 W/m^2. The highest wind power densities occurred in the winter. The afternoon maximum in the wind resource along the Mediterranean is associated with increased vertical mixing due to daytime solar heating and increased thermal/pressure gradients along the coastal area. Afternoon winds are mostly onshore (sea breezes) during the warmer months.

Data from three stations on the Red Sea coast--Ras Ghareb, Hurghada, and Quseir--indicated that the highest diurnal wind speeds occurred during the morning, from 0800 to 1100 LST. Highest hourly speeds, averaged over the year, were 8.0 m/s at Hurghada and Ras Ghareb and 7.0 m/s at Quseir. The highest wind power densities were estimated to be 560 W/m^2 (class 7) at Ras Ghareb and 350 W/m^2 (class 6) at Quseir.

The cause of the early morning maxima is not clearly understood. However, the authors believe that these early morning maxima are most likely due to increased vertical mixing after sunrise. This mixing brings down strong nocturnal winds that persist into the morning. The height of these strong nocturnal winds is not known from available data, but it may be only a few hundred meters (less than 500 m) above ground, and wind speeds may decrease considerably at heights above 1000 m. It is known that the increase of surface wind speeds after sunrise is associated with a pronounced increase in the surface pressure. The increase may be as much as 1 to 2 mb, as indicated by diurnal pressure data from Hurghada. As vertical mixing increases through the morning, the low-level winds weaken considerably. By late morning and into the afternoon as solar heating increases, the strong winds become weaker as they are mixed through a considerably deeper layer. Surface pressures decrease significantly by late morning, and wind speeds decrease through late morning and afternoon. The low-level nocturnal winds begin to increase again during the evening after sunset. Surface wind speeds increase slightly during the evening and night hours, as these nocturnal low-level winds intensify. However, surface wind speeds at night increase at a much slower rate than the wind speeds a few hundred meters above ground. After sunrise and during the morning hours, surface wind speeds increase significantly as increased heating brings stronger wind aloft down to the surface.

We believe this nocturnal low-level wind maximum occurs not only over the Gulf of Suez and Red Sea areas but also over much of the Western and Eastern Deserts. The limited diurnal data from Oweinatt, an exposed site in southwestern Egypt, also indicate a morning wind speed maximum at the surface. Data from more sheltered locations in the Western and Eastern Deserts, such as locations in valleys and oases, indicate very low wind speeds during night and early morning hours. The relative lowness of these areas and the strong nighttime

stability that persists into morning delay any substantial mixing of winds aloft down to the surface until late morning and afternoon. Highest wind speeds in these areas do not occur until afternoon.

4.4 UNCERTAINTY IN THE ESTIMATES

The analysis of the wind resource at any particular site is based on the subjective integration of several factors: quantitative wind data, qualitative indicators of wind speed or power, the characteristics of exposed sites in various terrains, and familiarity with the meteorology, climatology, and topography of the region. As a result, the degree of certainty with which the wind power resource can be specified depends on

- the abundance and quality of wind data
- the complexity of terrain
- the geographical variability of the resource.

For this assessment, sufficient information was available to make a preliminary estimate of broad areas where high or low wind resource may exist. Additional quantitative data, when or if they become available, will be needed to achieve a high level of certainty. There are some areas of Egypt where it is likely that no quantitative data exist at this time and where only qualitative indicators of the wind resource can be analyzed. Thus, the certainty of the wind resource estimates in these areas will be less than that where good quantitative data are abundant.

5. CLIMATOLOGICAL BASIS FOR EGYPT'S WIND RESOURCES

5.1 MEDITERRANEAN

The annual wind speed distribution on the Mediterranean coast can be readily explained. The winter wind maximum is due to high wind speeds associated with the greater frequency of extra-tropical cyclones in winter. The month of maximum winter winds (January at Sallum, February and March further east) possibly differs because of the different storm tracks at this time of year. The July summer maximum is due to the land-sea breeze circulation. The contrast between the still relatively cool waters of the Mediterranean and the hot interior is greatest in July, and a strong north to northwest sea breeze is induced. Near the coastline, the summer maximum between Dabaa and Alexandria appears to be greater than that between Dabaa and Sallum. From Dabaa westward to Sallum, the summer wind resource is greater inland than at the coastline and offshore. This is because the maximum surface pressure gradients over this area are located inland rather than at the coastline. Further east, nearer Alexandria, it appears that maximum pressure gradients occur within a few kilometers of the coastline, and so the inland wind resource is less. Later in the year, as the Mediterranean warms and the thermal low in the interior weakens, the pressure gradient weakens and the wind decreases to its October minimum.

5.2 RED SEA

The sharp transition along the Red Sea coastline is not as easy to explain as the behavior of the winds along the Mediterranean. The prevailing wind throughout the year is northerly, with a semi-permanent high pressure area located to the north of the region.

Winter is the season of highest wind resource south of Quseir, but north of Quseir it is the season of lowest wind resource. In the winter, the high pressure area centers over northern Africa and extends into central Egypt and over the northern Red Sea and Gulf of Suez. As a result, pressure gradients are usually weak over the northern Red Sea and Gulf of Suez. This explains the winter minimum in the wind resource that exists over the northern Red Sea and the Gulfs of Suez and Aqaba. Pressure gradients increase to the south over

the central Red Sea off the coast of southern Egypt. This is why the wind resource is higher in winter along the Red Sea coast south of Quseir to Ras Benas than it is along the Red Sea coast north of Quseir and the Gulf of Suez. As the high pressure center moves north in the spring, the pressure gradient moves with it and so the wind resource increases in the northern Red Sea (north of Quseir) and the Gulfs of Suez and Aqaba but decreases south of Quseir.

During the summer, a trough of low pressure extends over southern Egypt. Therefore, pressure gradients are usually weak over southern Egypt, and the wind resource is at a minimum along the Red Sea coast south of Quseir. However, the wind resource increases dramatically north of Quseir from June through September, with a strong wind resource maximum in September.

The main factor causing this September maximum is the buildup of high pressure over the eastern Mediterranean in late summer. This increases the pressure gradient between the Mediterranean and the thermal low over Arabia, and thus increases the winds in the northern Red Sea and Gulf of Suez. The increase is augmented by a terrain-induced channeling effect through the Gulf of Suez. Where the Gulf of Suez widens into the Red Sea, the channeling effect decreases.

6.0 SUMMARY AND RECOMMENDATIONS

This assessment shows that a large portion of Egypt is estimated to have class 3 or greater annual wind resource, a resource suitable for most wind turbine applications. Areas that are estimated to have class 3 or greater wind resource include the Mediterranean coastal region, the Red Sea and Gulfs of Suez and Aqaba, the highlands of the Eastern Desert, the highlands of the southern Sinai, and the southern part of the Western Desert. The highest estimated annual wind resource, class 6 or greater, is expected to occur along the Red Sea coast, from north of Hurghada into the Gulf of Suez, to points just north of Ras Ghareb on the western shore and El Tor on the eastern shore.

Additional data are needed to refine the wind resource estimates, because many areas had limited or no surface data. Any updated assessment should incorporate knowledge of the anemometer heights for all of the sites used in the assessment. The updated assessment would be further enhanced if the following information was available from all stations:

1. obstructions in the vicinity of the anemometer such as trees or buildings;
2. dates of any changes in anemometer height and location;
3. observation times (local standard time);
4. summaries of monthly and annual wind speed frequency distributions for periods when anemometer height and location were constant;
5. mean monthly temperature and station pressure for each station;
6. yearly mean wind speeds, and preferably wind speed frequency distributions, for each year of record; and
7. summaries of mean wind speed by hour of day for each station (annual and monthly).

Pattelle-Northwest is currently collecting wind information from six different locations along the Mediterranean coast, Gulf of Suez, and Red Sea (Figure 7) for the Egyptian Electrical Authority. This information could be incorporated in an updated assessment. Data from these stations will further define the high wind resource found along the Mediterranean coast and along the Red Sea and the Gulf of Suez. It would be useful to have additional data

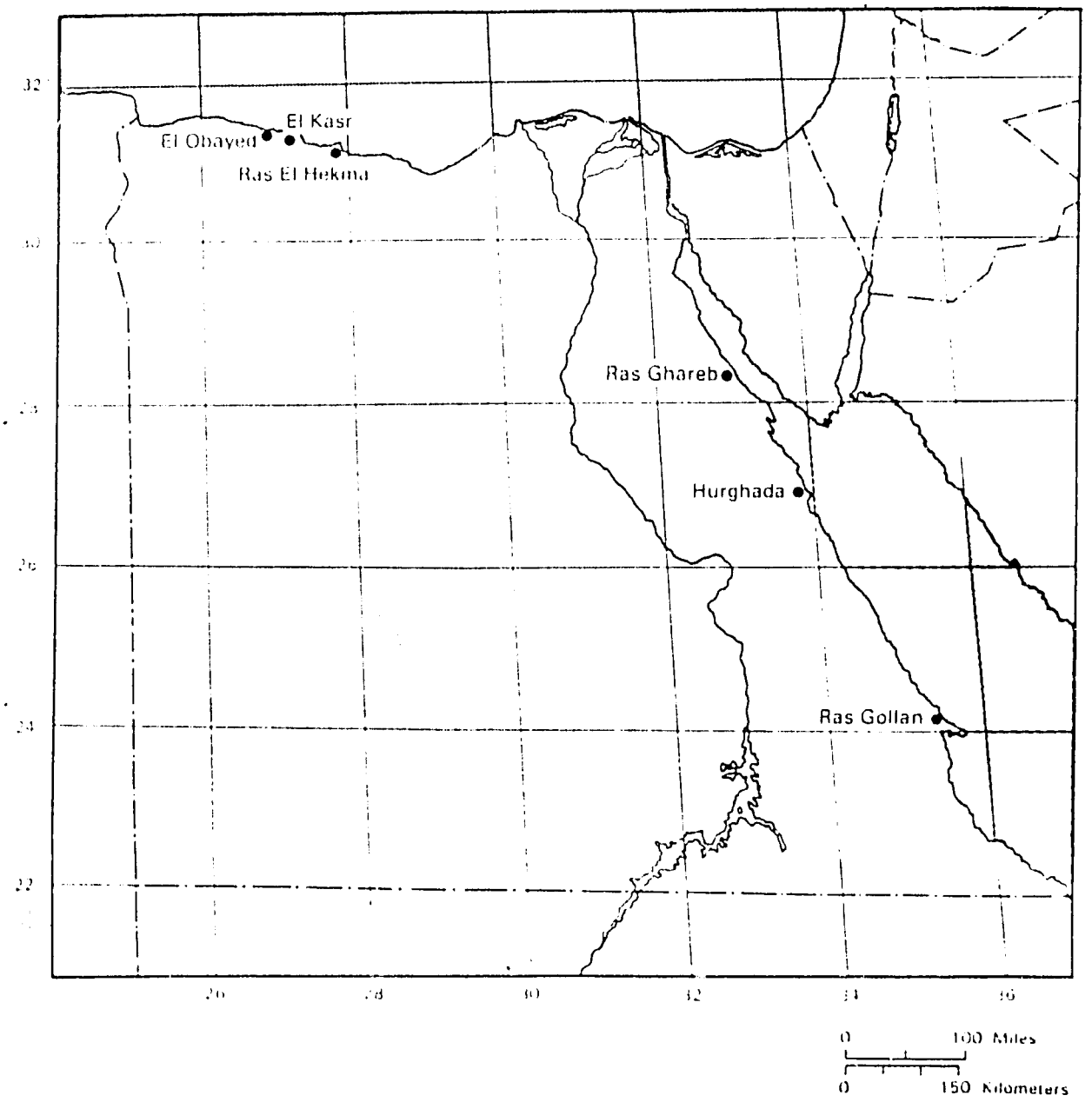


FIGURE 7. Locations Where Wind Information Collection is Being Monitored by Battelle.

from the Red Sea coast south of Hurghada, from the eastern and western shores of the Gulf of Suez, from the Mediterranean coast from Dabaa to Alexandria, from the Libyan Plateau (inland of the Mediterranean coast west of Dabaa), from southwestern Egypt including the Gilf Kebir Plateau and the Cweinatt area, from the southern Sinai, from the Gulf of Aqaba coast, from upland areas south of the Nile Delta (i.e., the class 3 and 4 areas near 30° north latitude in Figure 5), and from highland areas along the Nile River near Luxor.

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APPENDIX

DATA SUMMARIES FOR SELECTED STATIONS

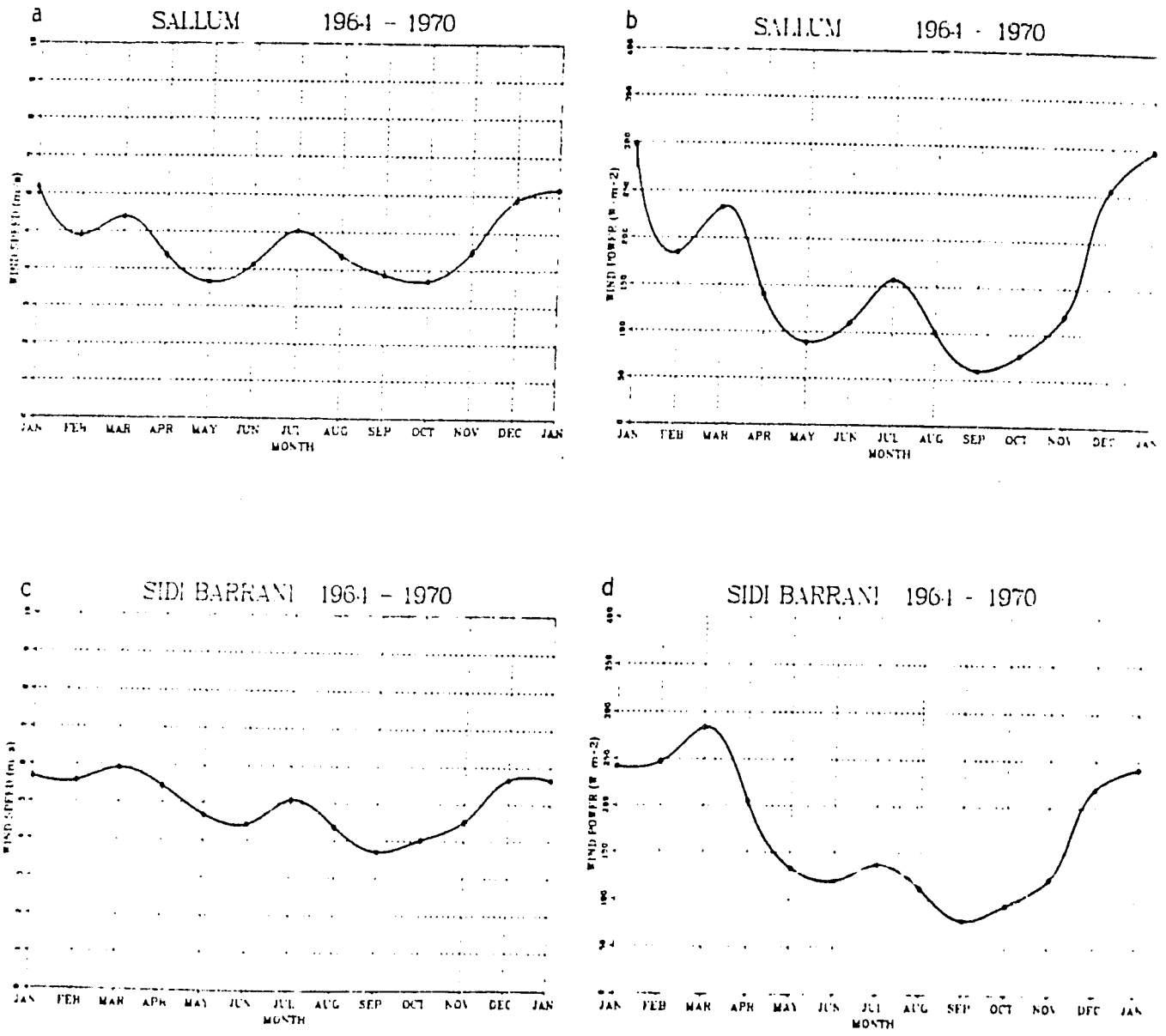

FIGURE A.1. Monthly Plots of a) Mean Wind Speed and b) Mean Wind Power Density for Sallum; Monthly Plots of c) Mean Wind Speed and d) Mean Wind Power Density for Sidi Barrani

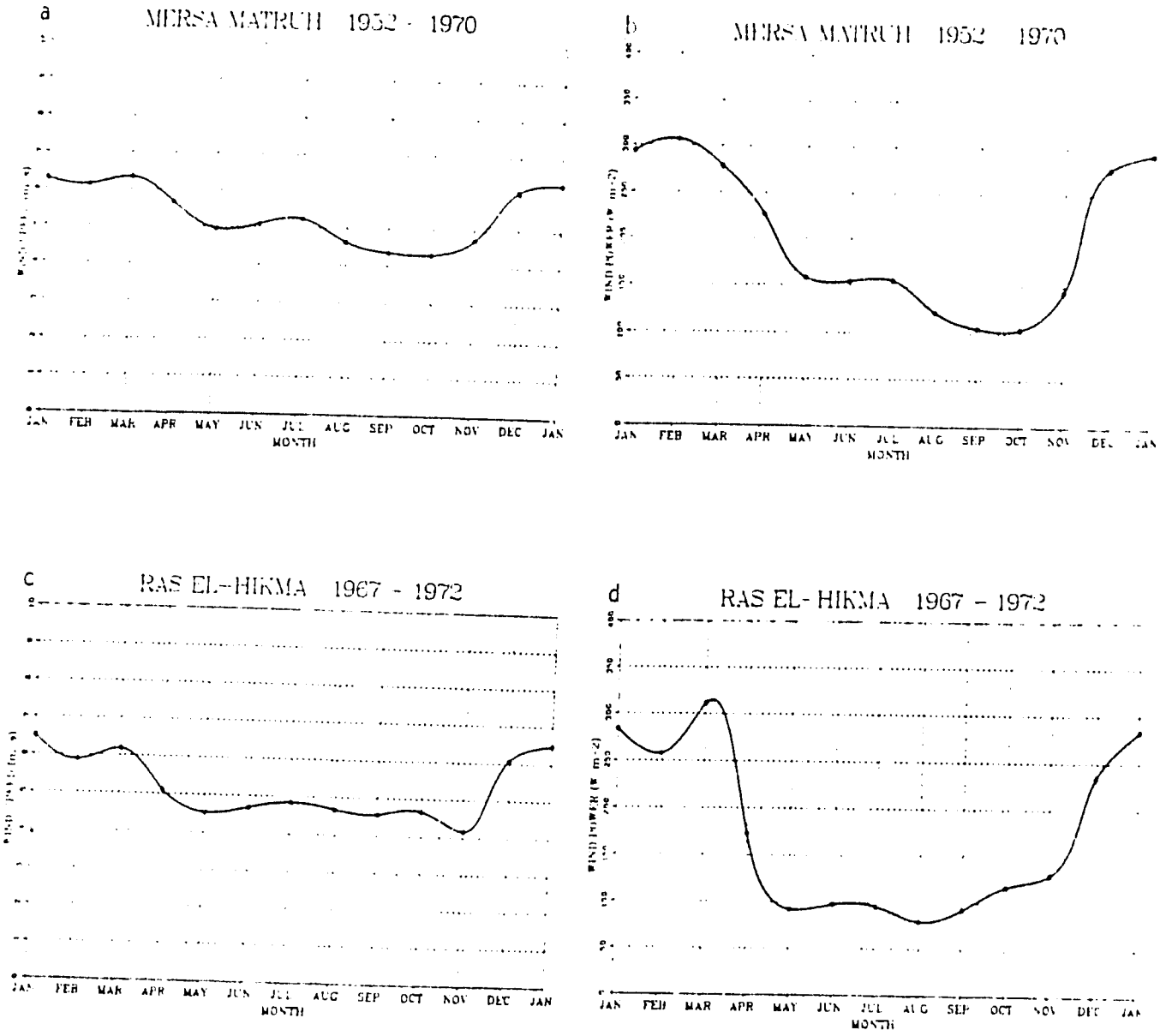

FIGURE A.2. Monthly Plots of a) Mean Wind Speed and b) Mean Wind Power Density for Mersa Matruh; Monthly Plots of c) Mean Wind Speed and d) Mean Wind Power Density for Ras El-Hikma

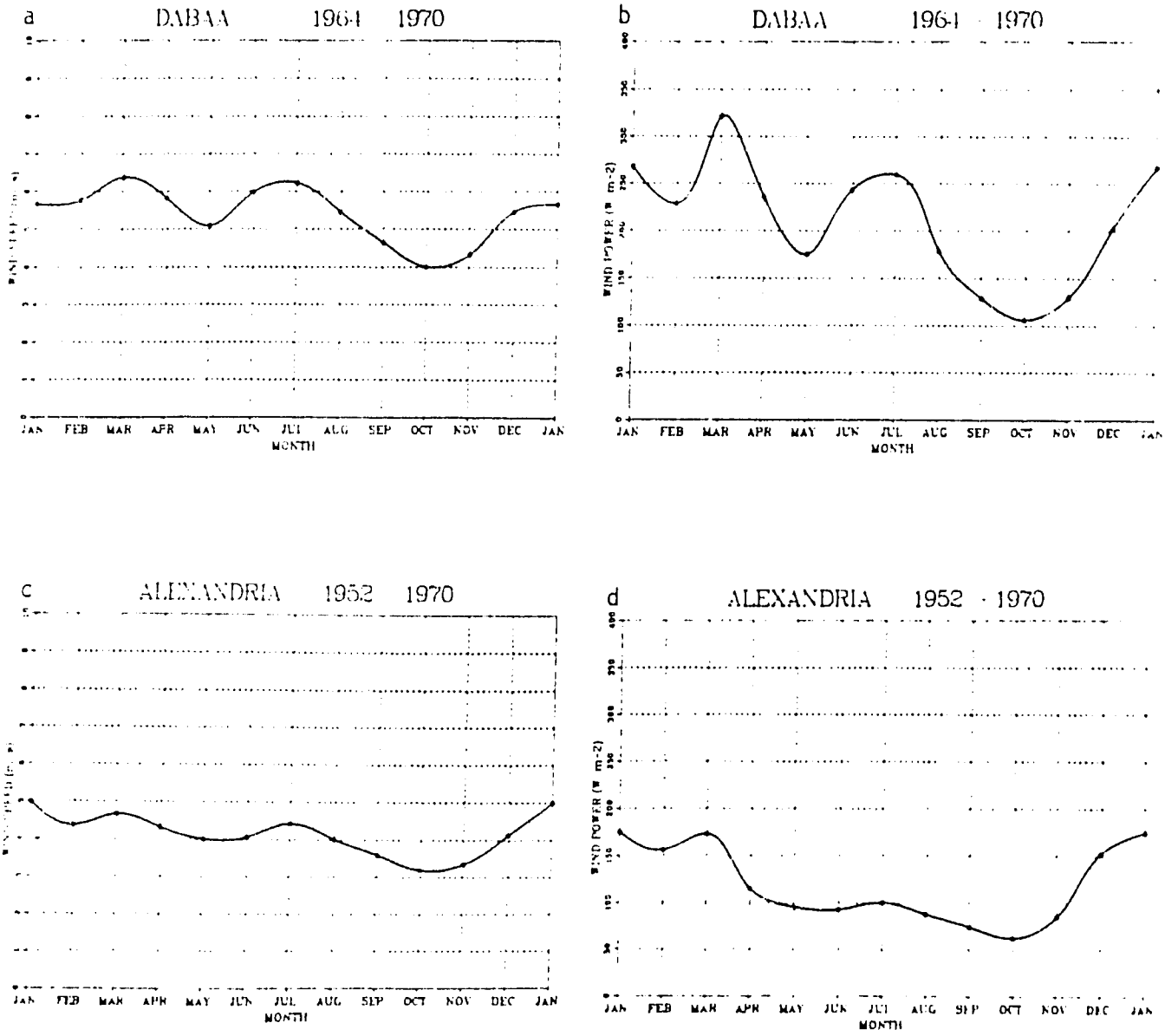

FIGURE A.3. Monthly Plots of a) Mean Wind Speed and b) Mean Wind Power Density for Dabaa; Monthly Plots of c) Mean Wind Speed and d) Mean Wind Power Density for Alexandria

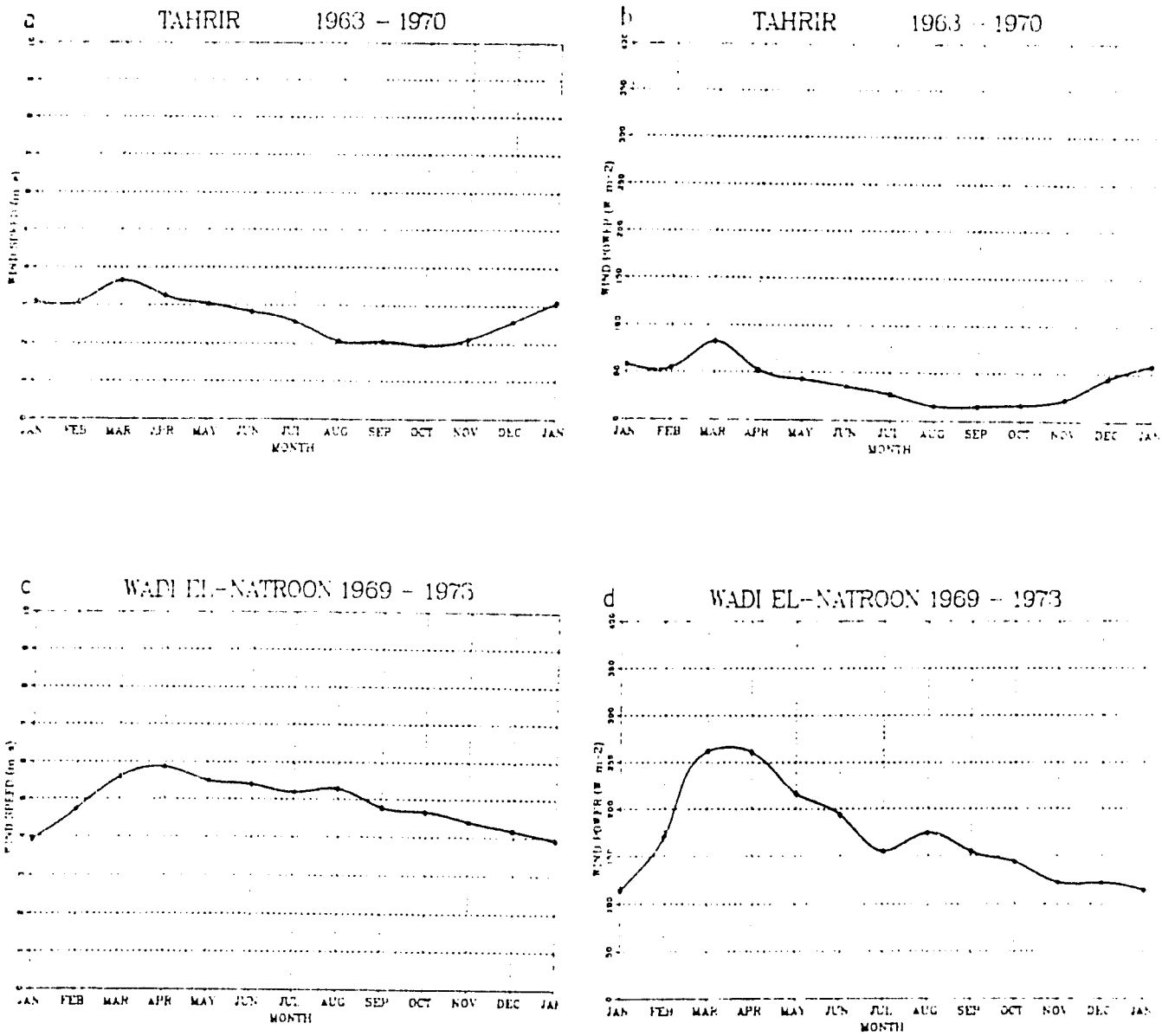

FIGURE A.4. Monthly Plots of a) Mean Wind Speed and b) Mean Wind Power Density for Tahrir; Monthly Plots of c) Mean Wind Speed and d) Mean Wind Power Density for Wadi El-Natroon

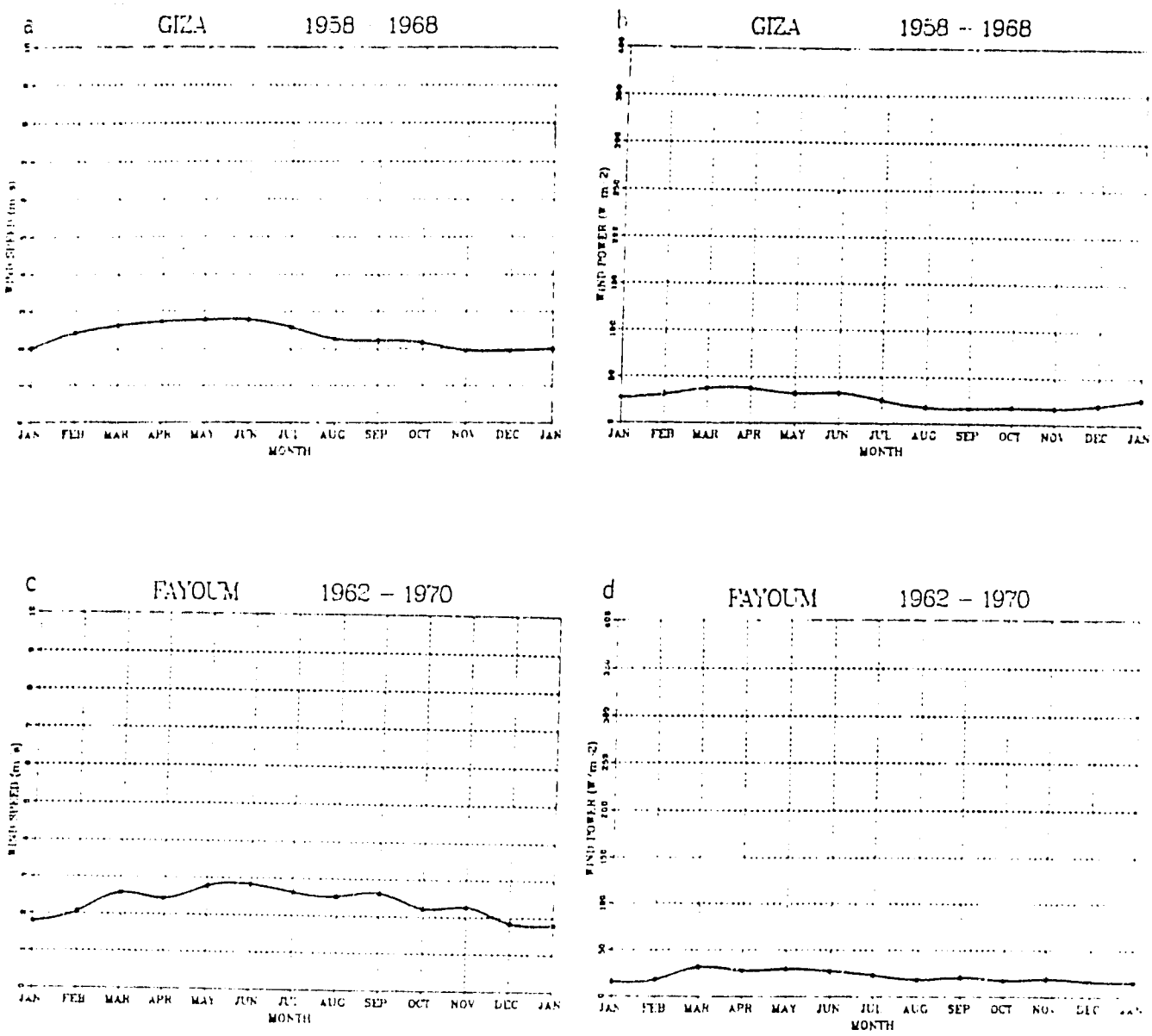

FIGURE A.5. Monthly Plots of a) Mean Wind Speed and b) Mean Wind Power Density for Giza; Monthly Plots of c) Mean Wind Speed and d) Mean wind Power Density for Fayoum

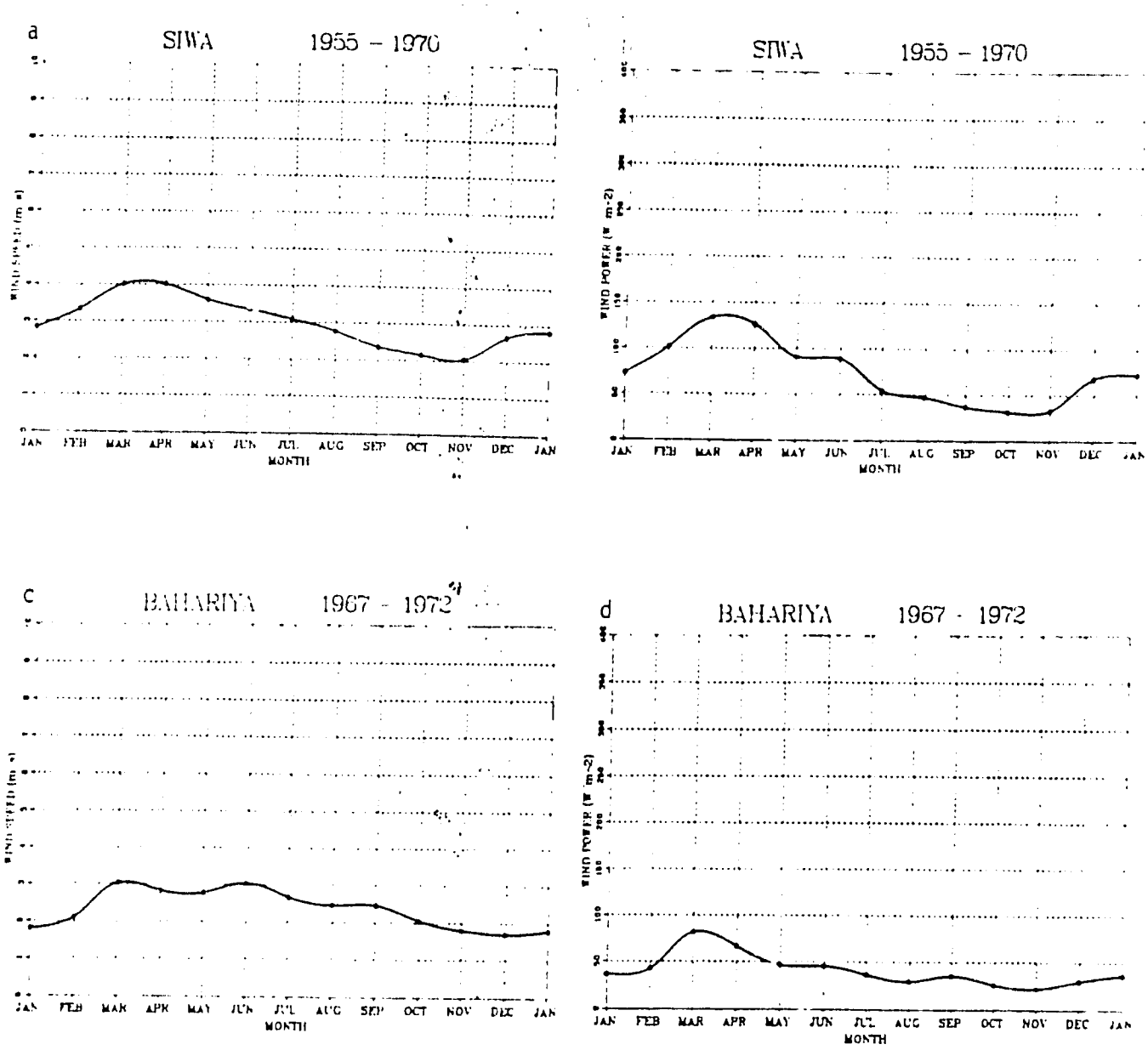

FIGURE A.6. Monthly Plots of a) Mean Wind Speed and b) Mean Wind Power Density for Siwa; Monthly Plots of c) Mean Wind Speed and d) Mean Wind Power Density for Bahariya

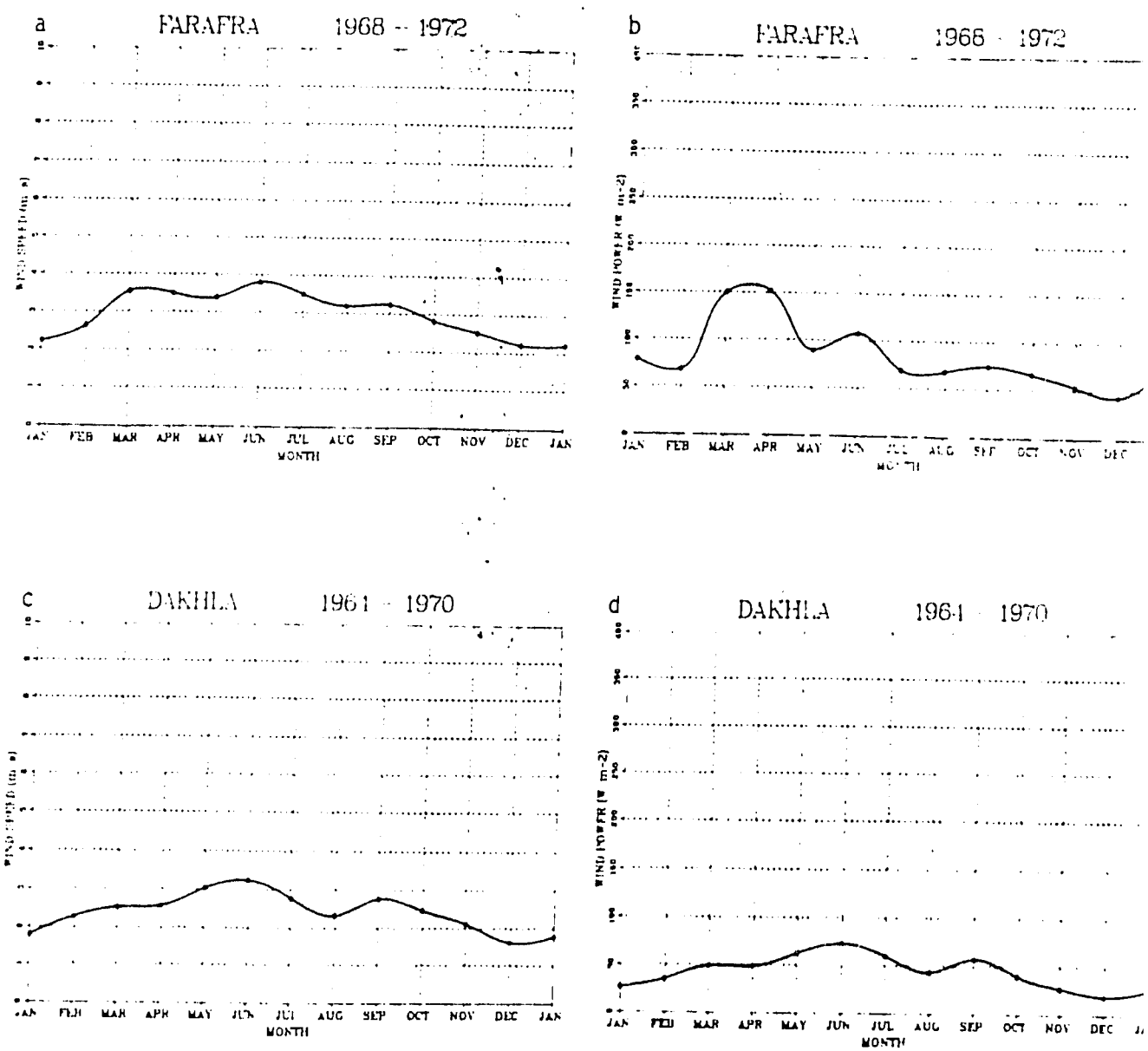

FIGURE A.7. Monthly Plots of a) Mean Wind Speed and b) Mean Wind Power Density for Farafra; Monthly Plots of c) Mean Wind Speed and d) Mean Wind Power Density for Dakhla

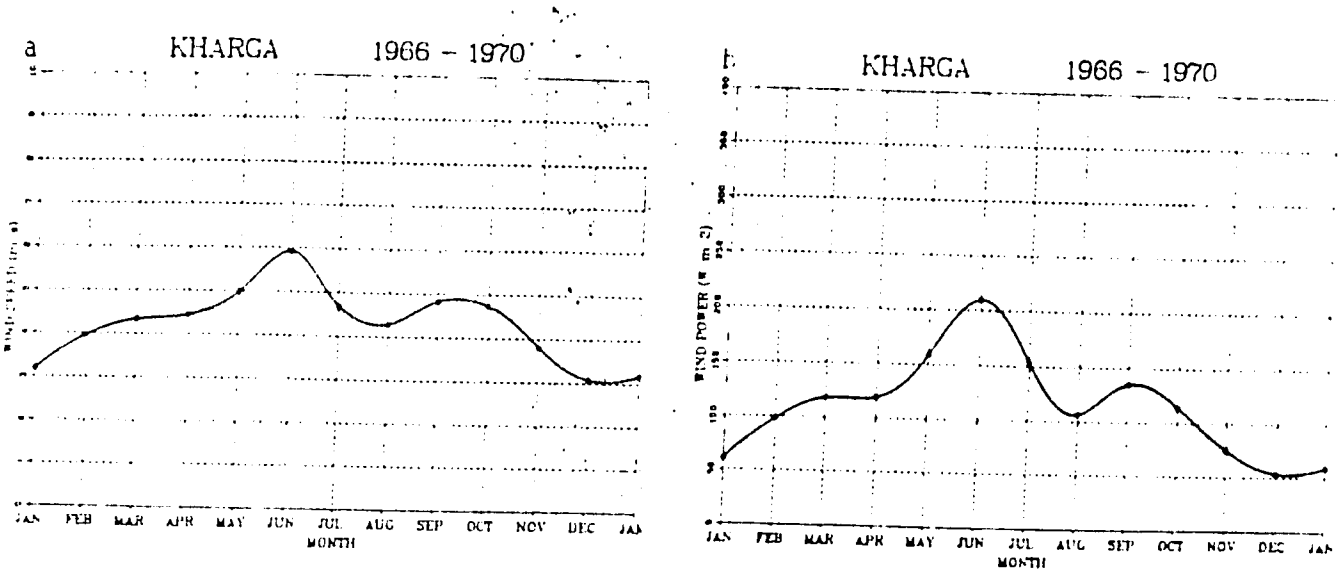

FIGURE A.8. Monthly Plots of a) Mean Wind Speed and b) Mean Wind Power Density for Kharga

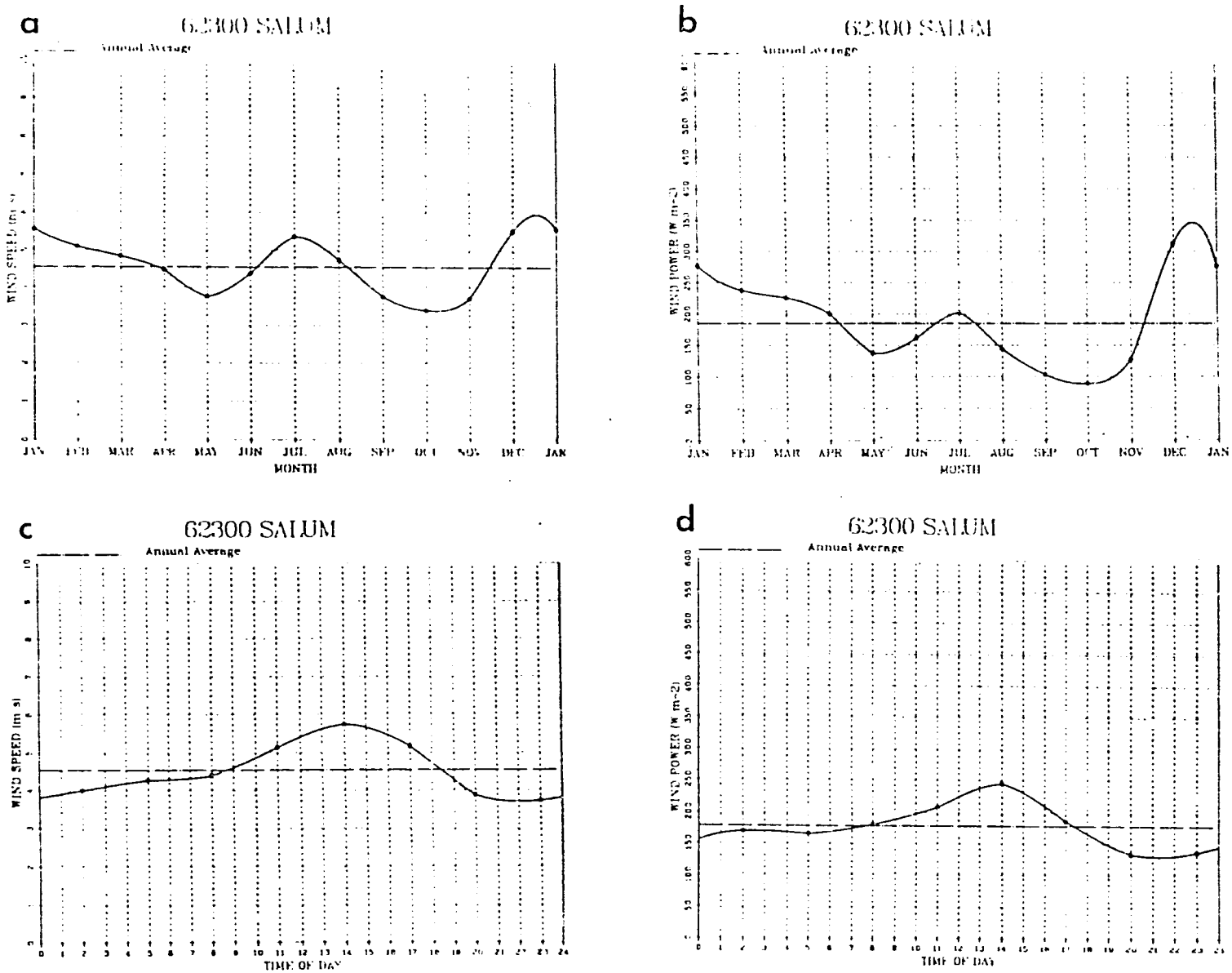

FIGURE A.9. Monthly Mean Wind a) Speed and b) Power Density; Diurnal Wind c) Speed and d) Power Density for Salum

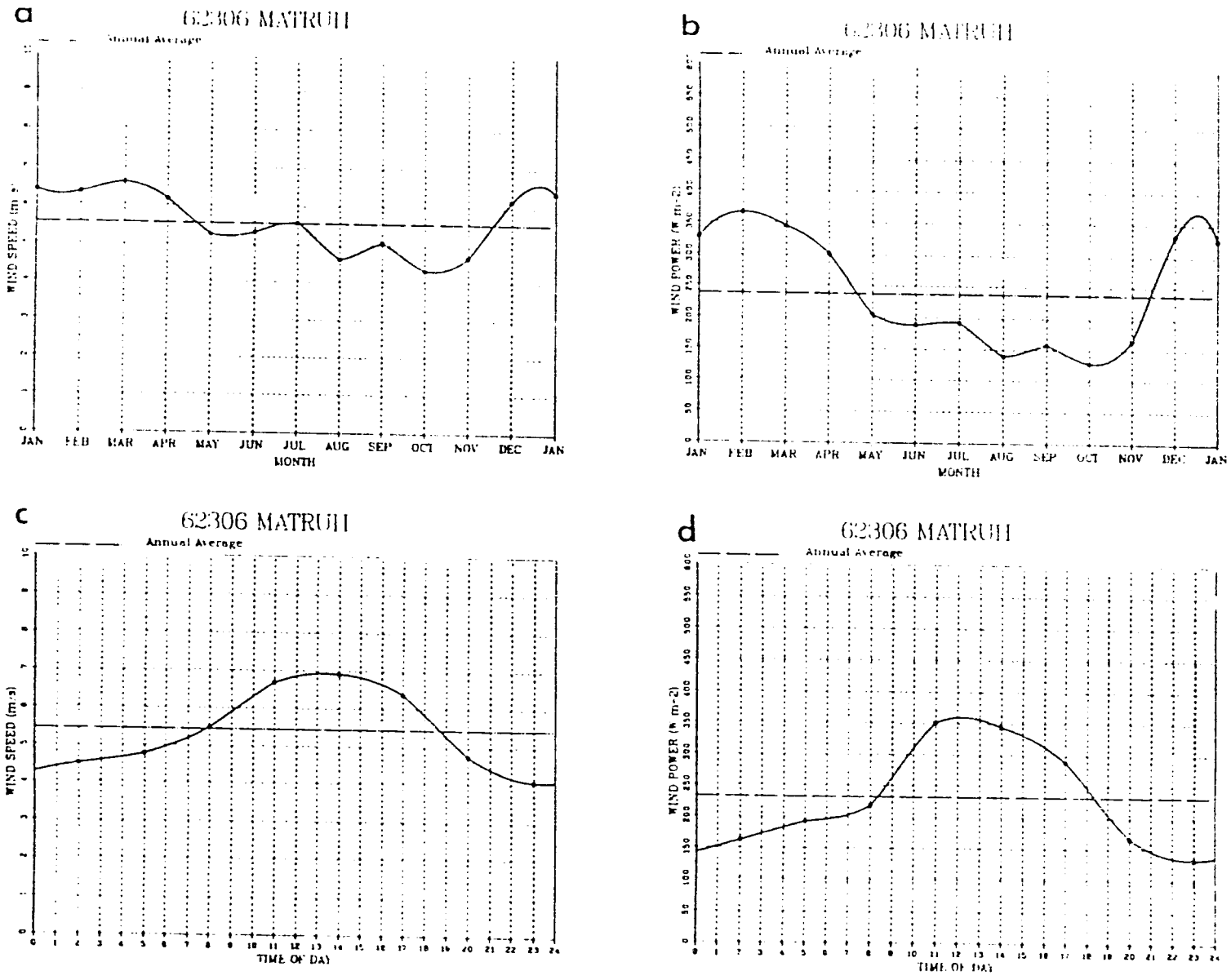

FIGURE A.10. Monthly Mean Wind a) Speed and b) Power Density; Diurnal Wind c) Speed and d) Power Density for Matruh

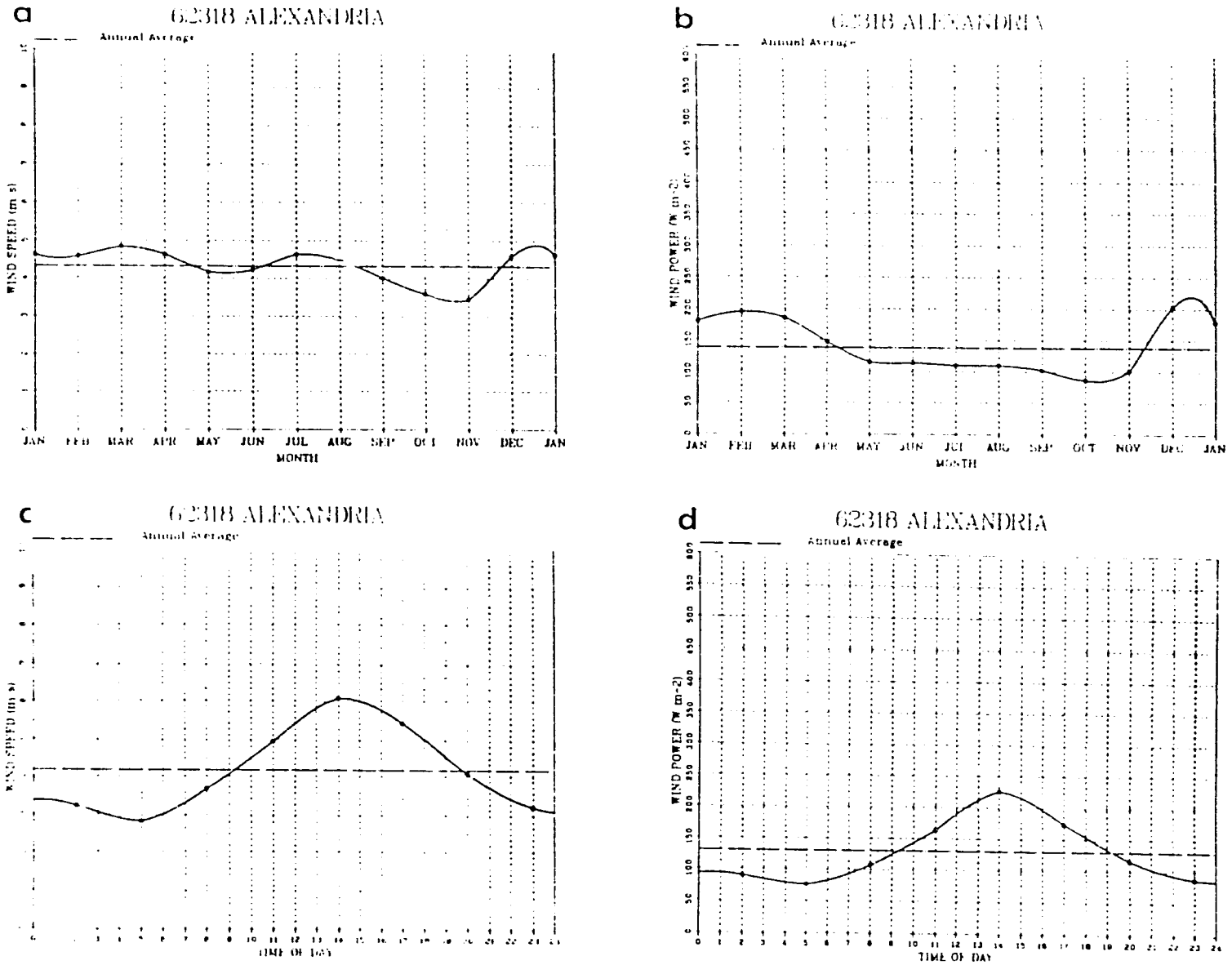

FIGURE A.11. Monthly Mean Wind a) Speed and b) Power Density; Diurnal Wind c) Speed and d) Power Density for Alexandria

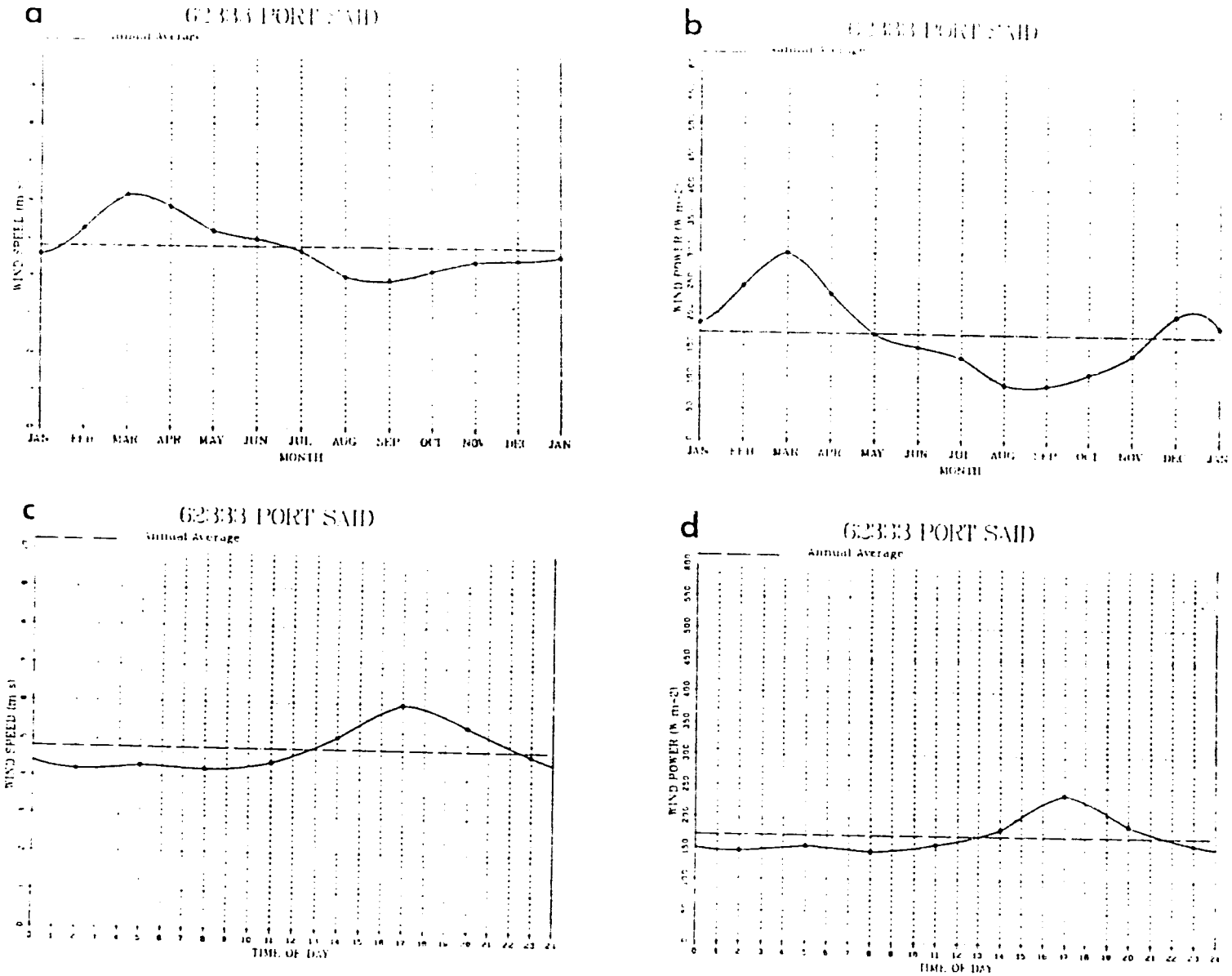

FIGURE A.12. Monthly Mean Wind a) Speed and b) Power Density; Diurnal Wind c) Speed and d) Power Density for Port Said

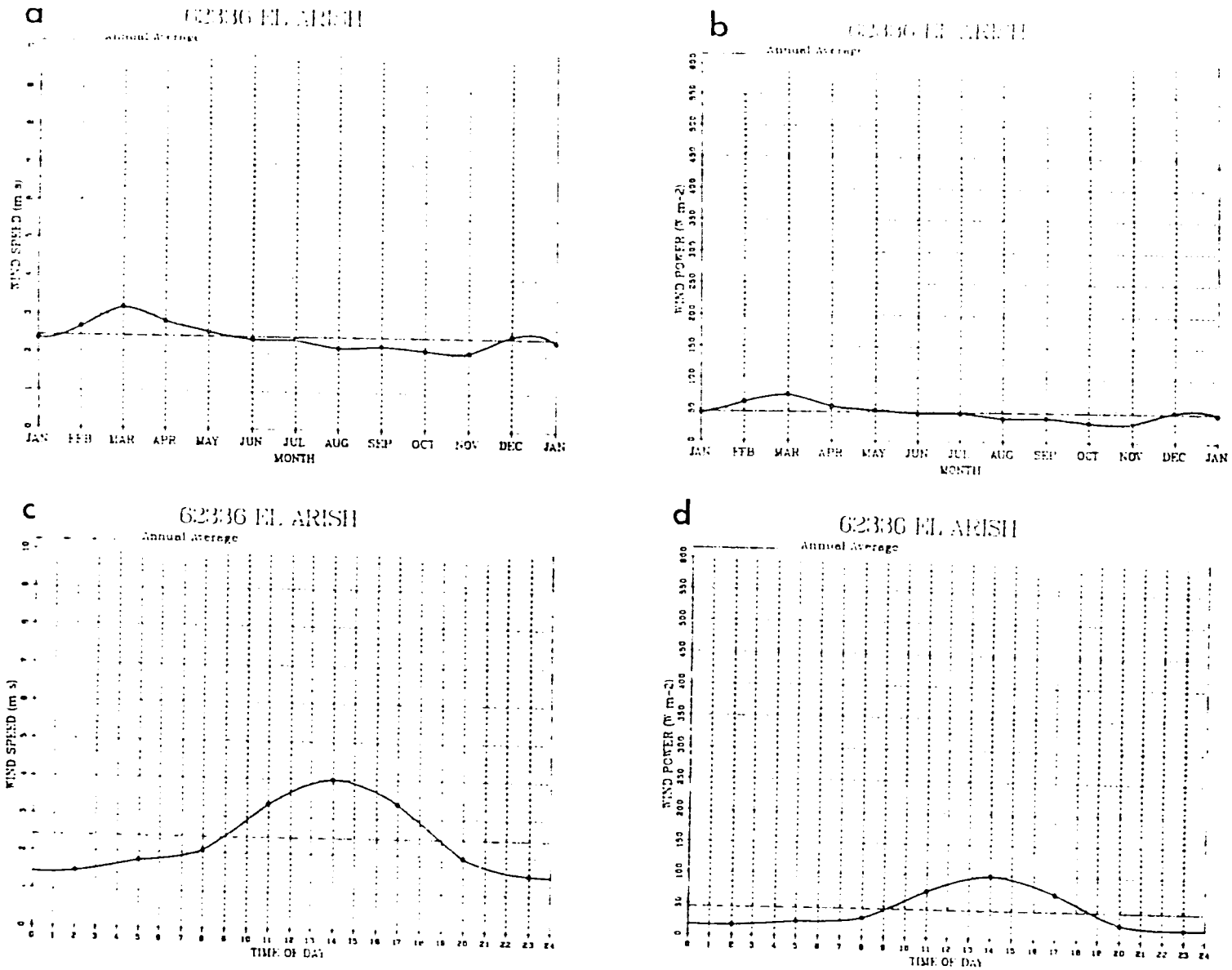

FIGURE A.13. Monthly Mean Wind a) Speed and b) Power Density; Diurnal Wind c) Speed and d) Power Density for El Arish

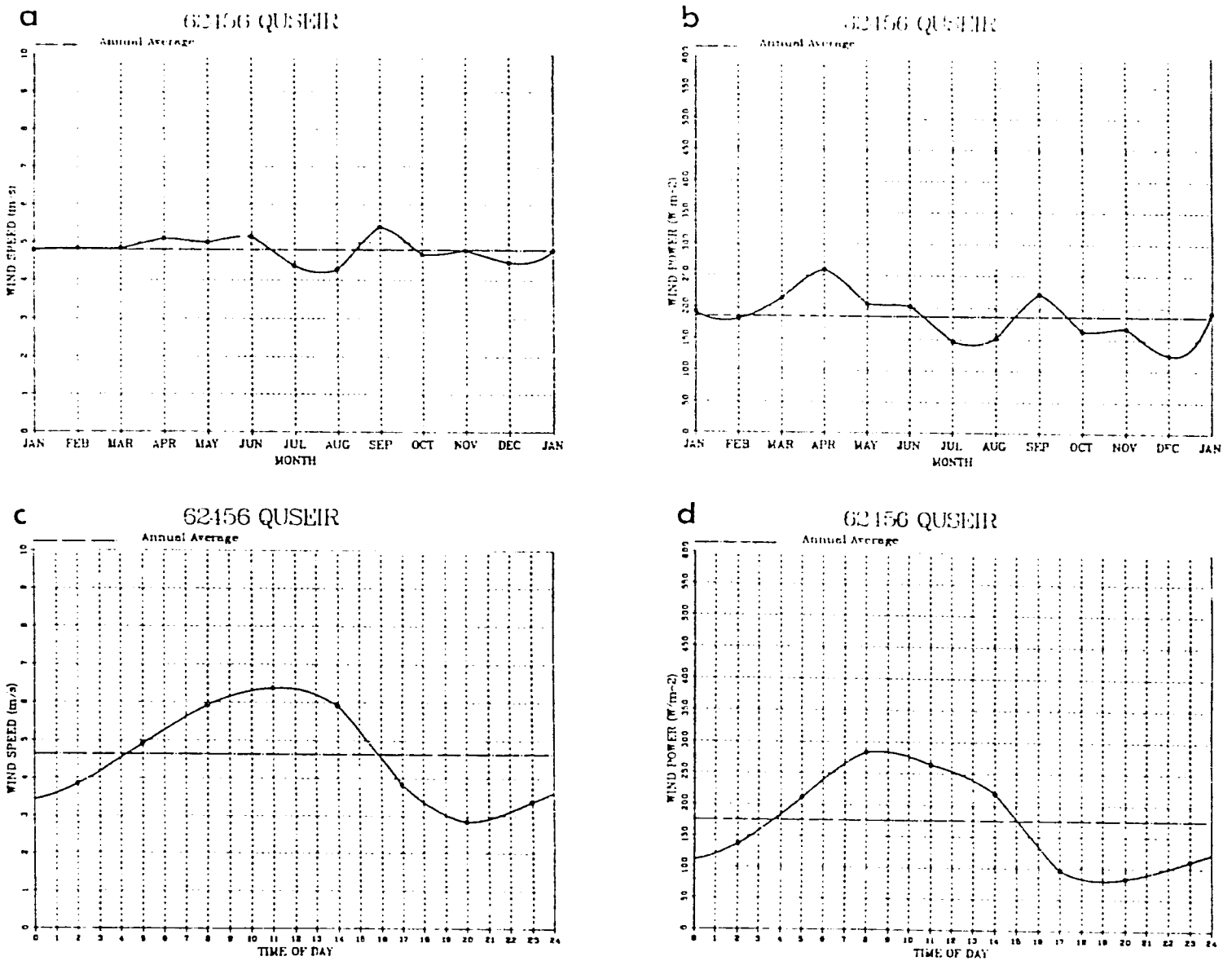

FIGURE A.14. Monthly Mean Wind a) Speed and b) Power Density; Diurnal Wind c) Speed and d) Power Density for Quseir

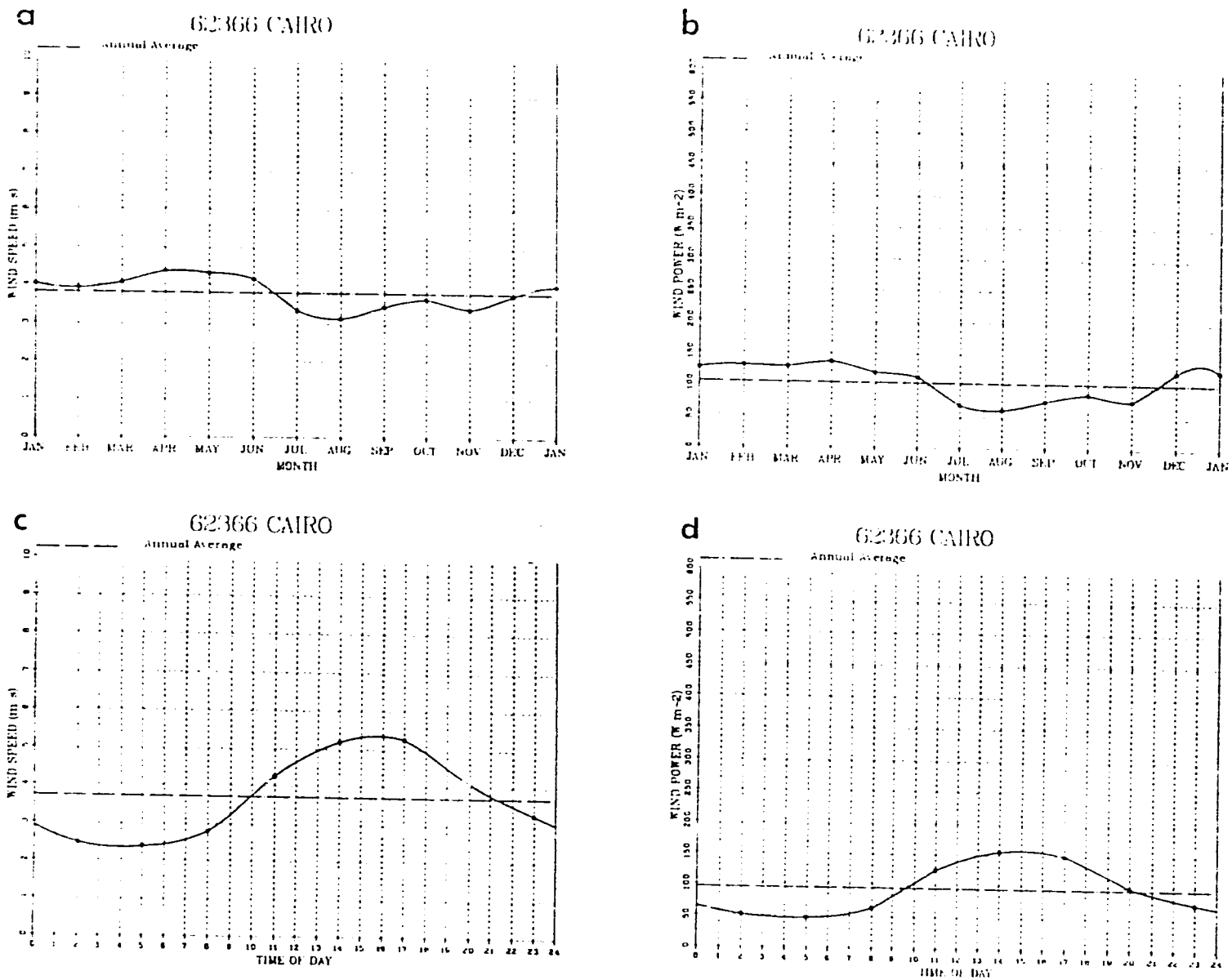

FIGURE A.15. Monthly Mean Wind a) Speed and b) Power Density; Diurnal Wind c) Speed and d) Power Density for Cairo

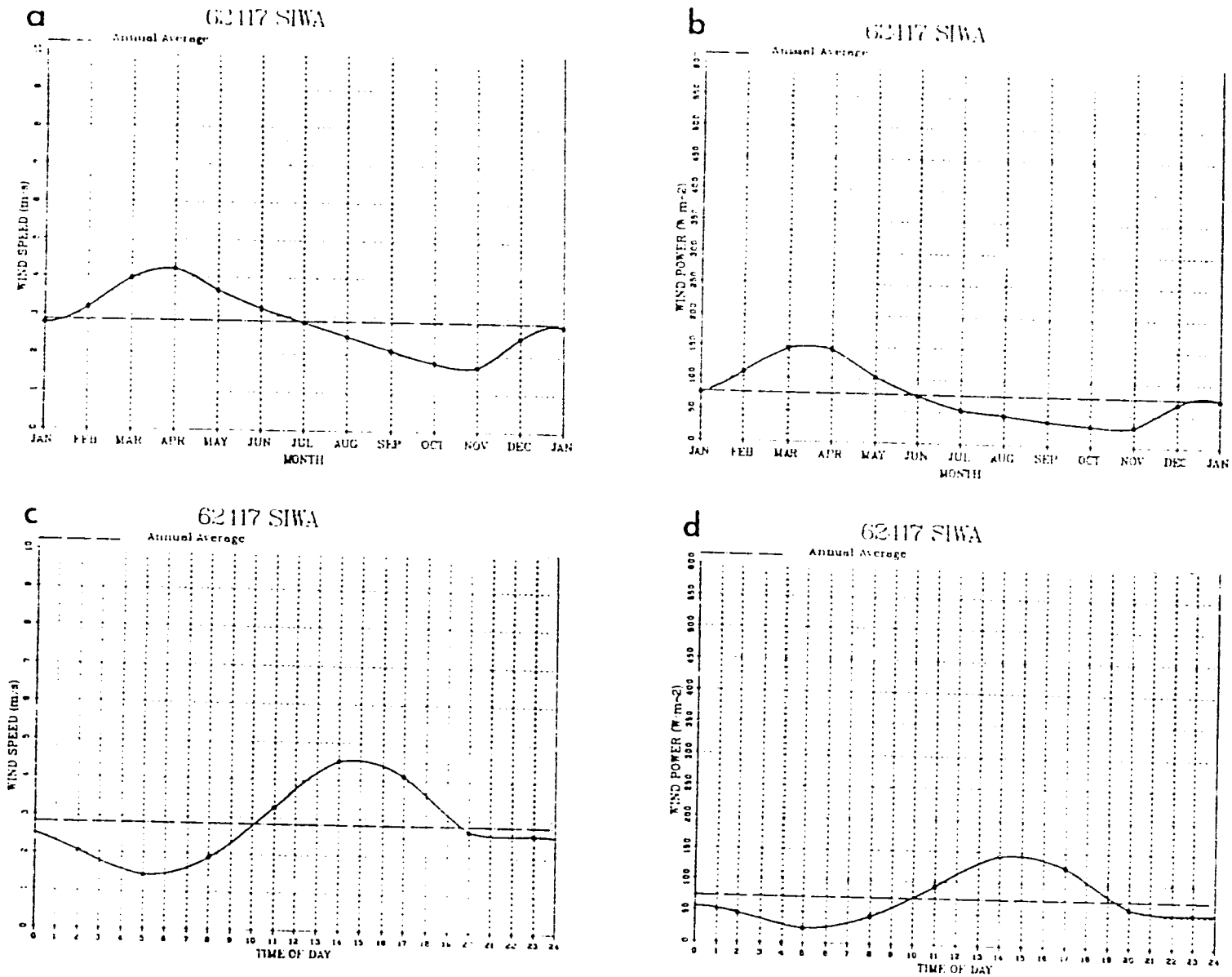

FIGURE A.16. Monthly Mean Wind a) Speed and b) Power Density; Diurnal Wind c) Speed and d) Power Density for Siwa

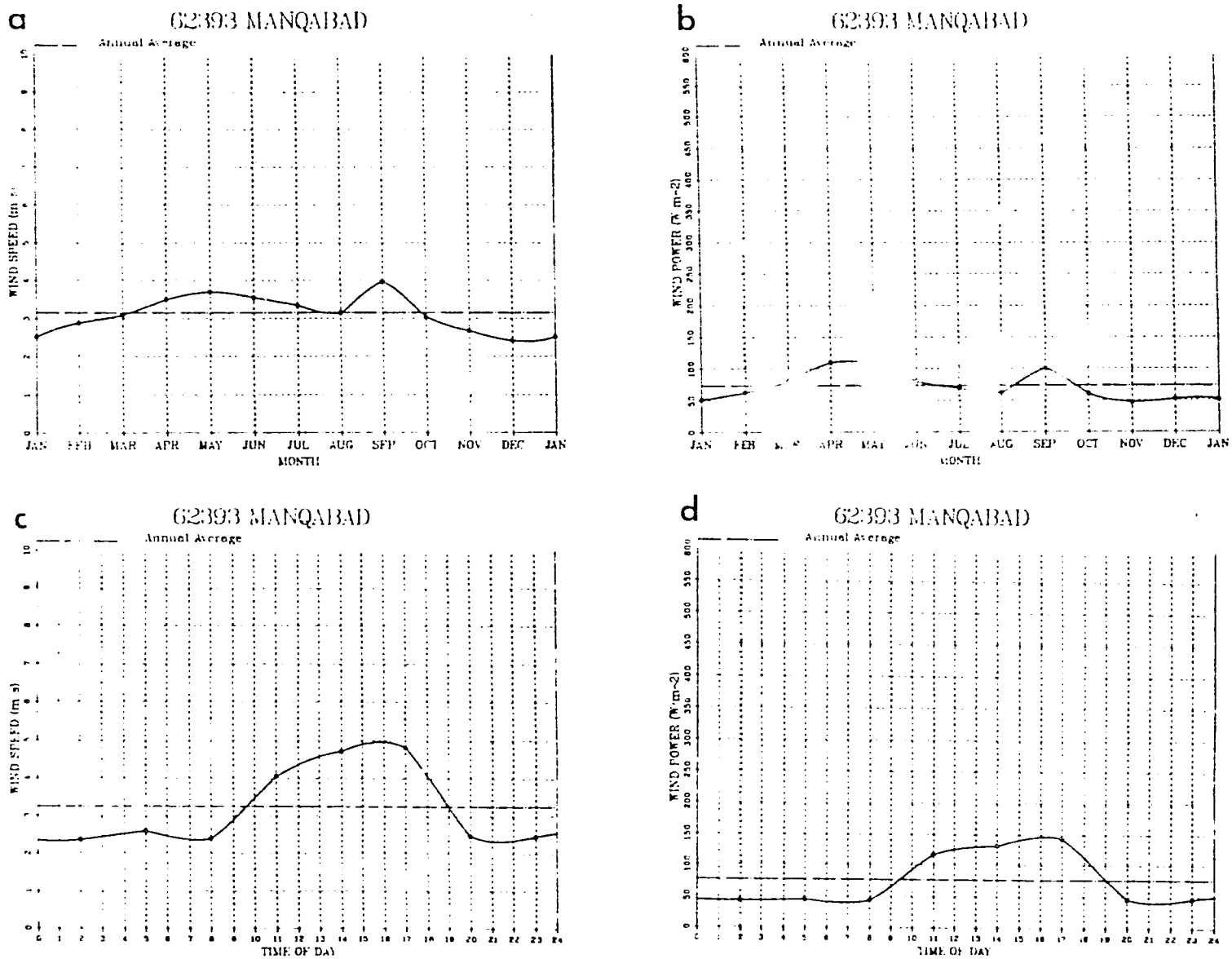

FIGURE A.17. Monthly Mean Wind a) Speed and b) Power Density; Diurnal Wind c) Speed and d) Power Density for Manqabad

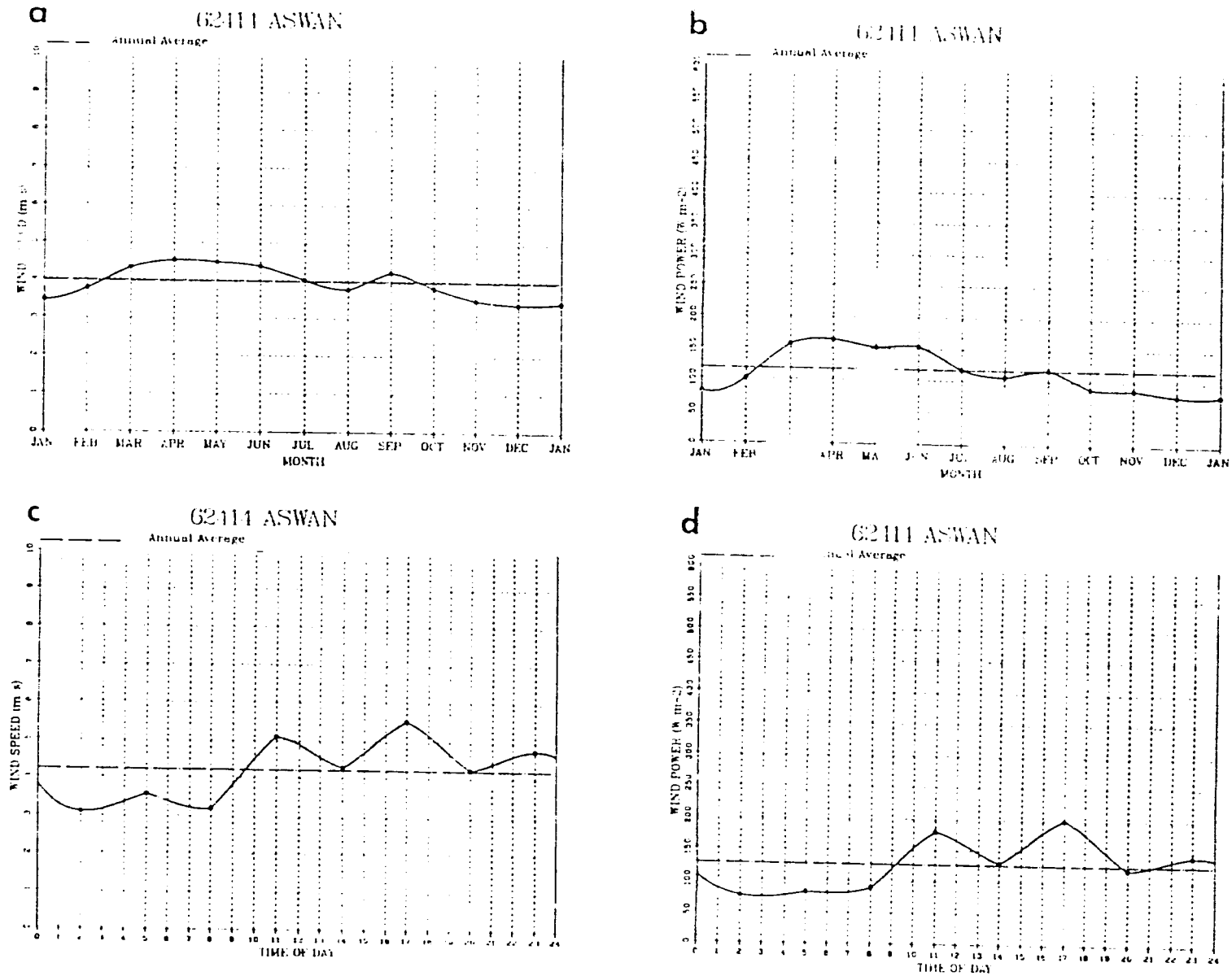

FIGURE A.18. Monthly Mean Wind a) Speed and b) Power Density; Diurnal Wind c) Speed and d) Power Density for Aswan

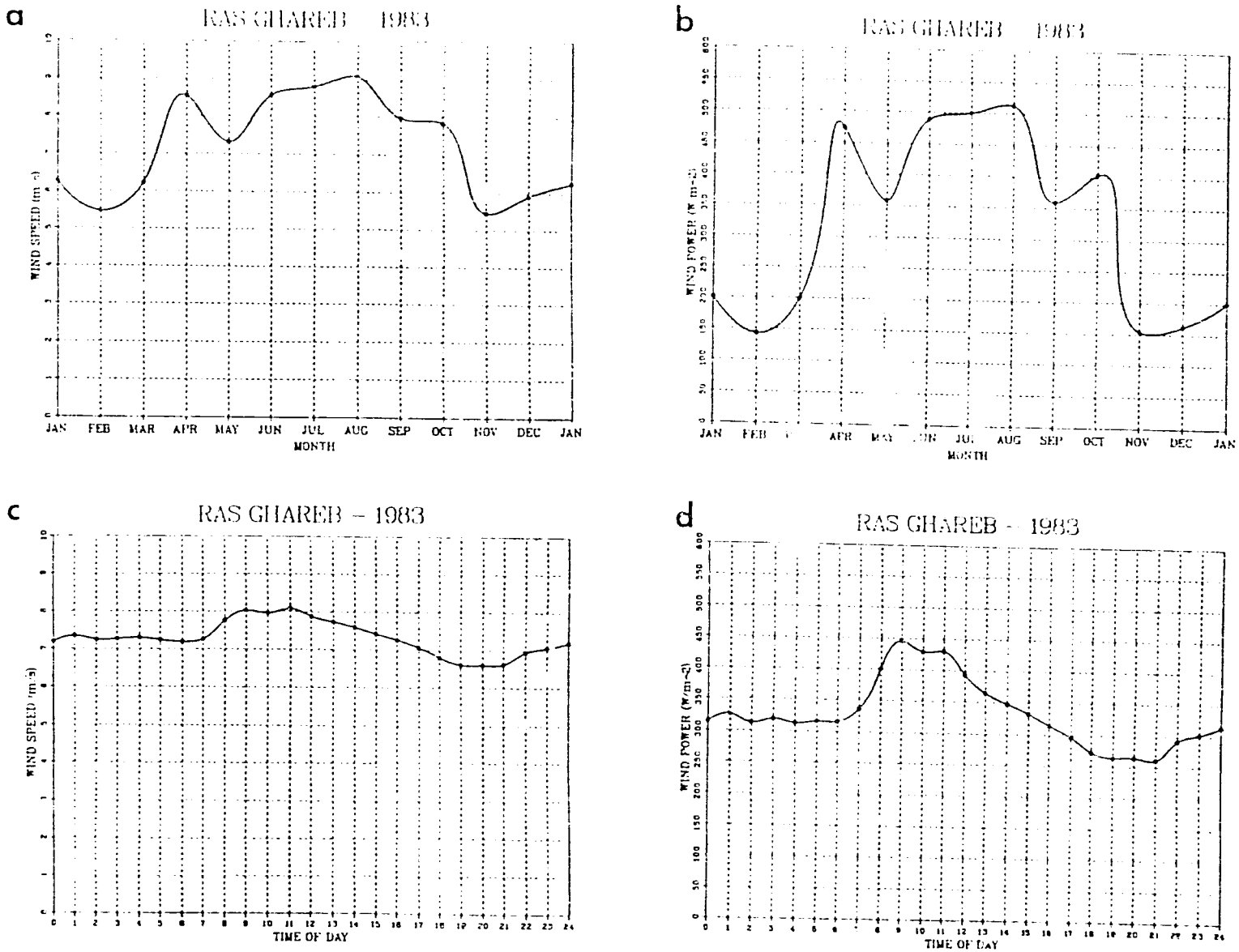

FIGURE A.19. Monthly Mean Wind a) Speed and b) Power Density; Diurnal Wind c) Speed and d) Power Density for Ras Ghareb

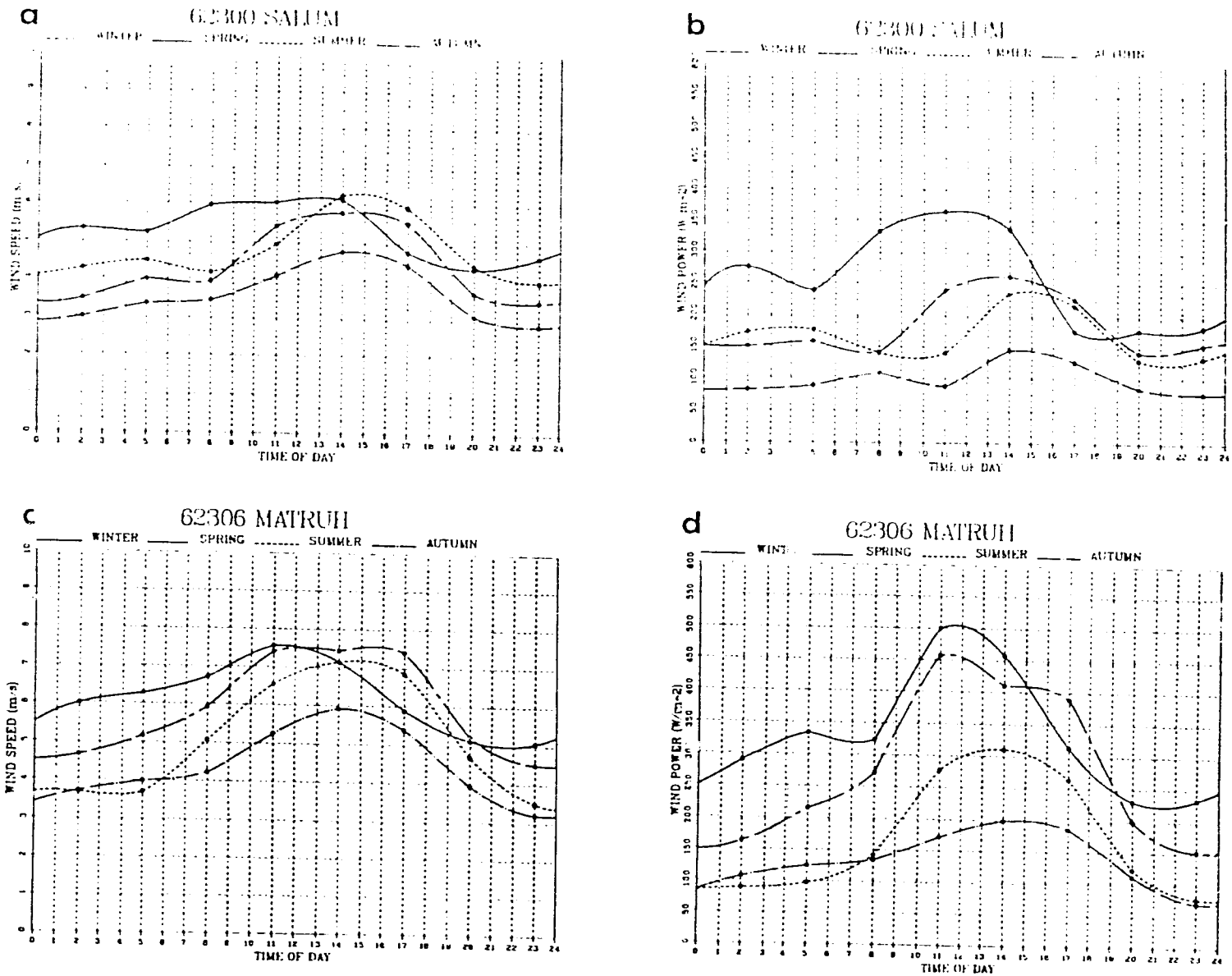

FIGURE A.20. Diurnal Wind a) Speed and b) Power Density by Season for Salum; Diurnal Wind c) Speed and d) Power Density by Season for Matruh

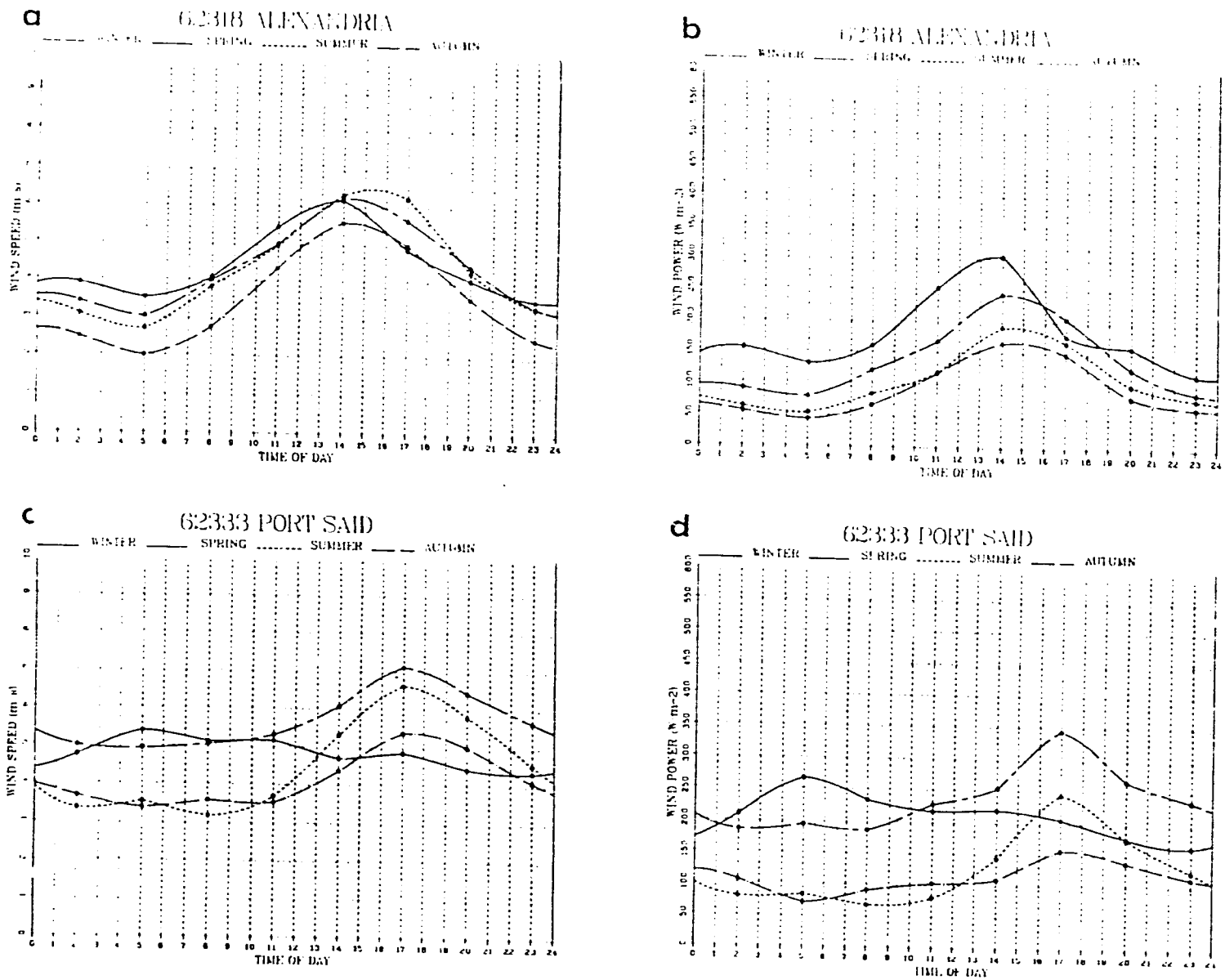

FIGURE A.21. Diurnal Wind a) Speed and b) Power Density by Season for Alexandria; Diurnal Wind c) Speed and d) Power Density by Season for Port Said

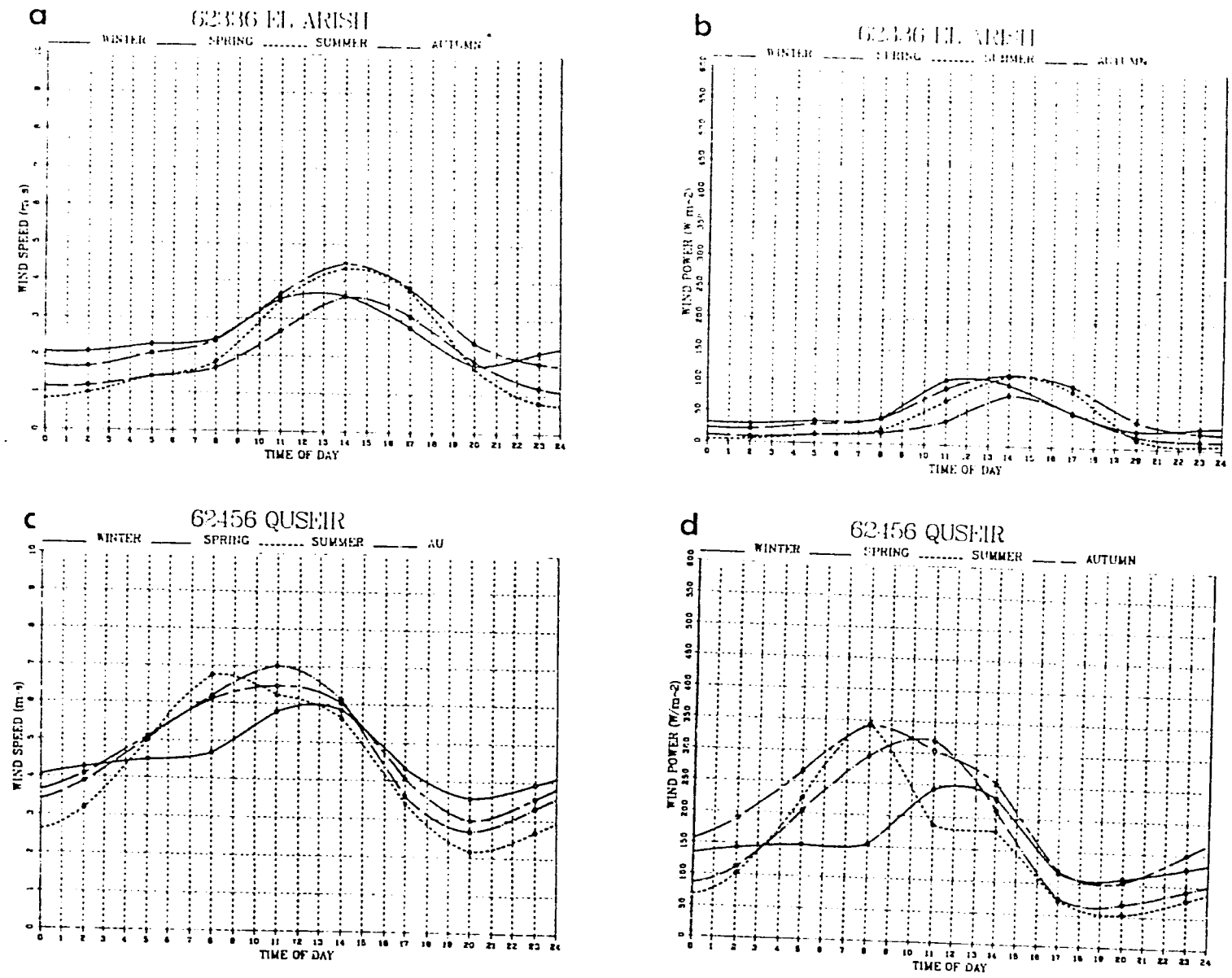

FIGURE A.22. Diurnal Wind a) Speed and b) Power Density by Season for El Arish; Diurnal Wind c) Speed and d) Power Density by Season for Quseir

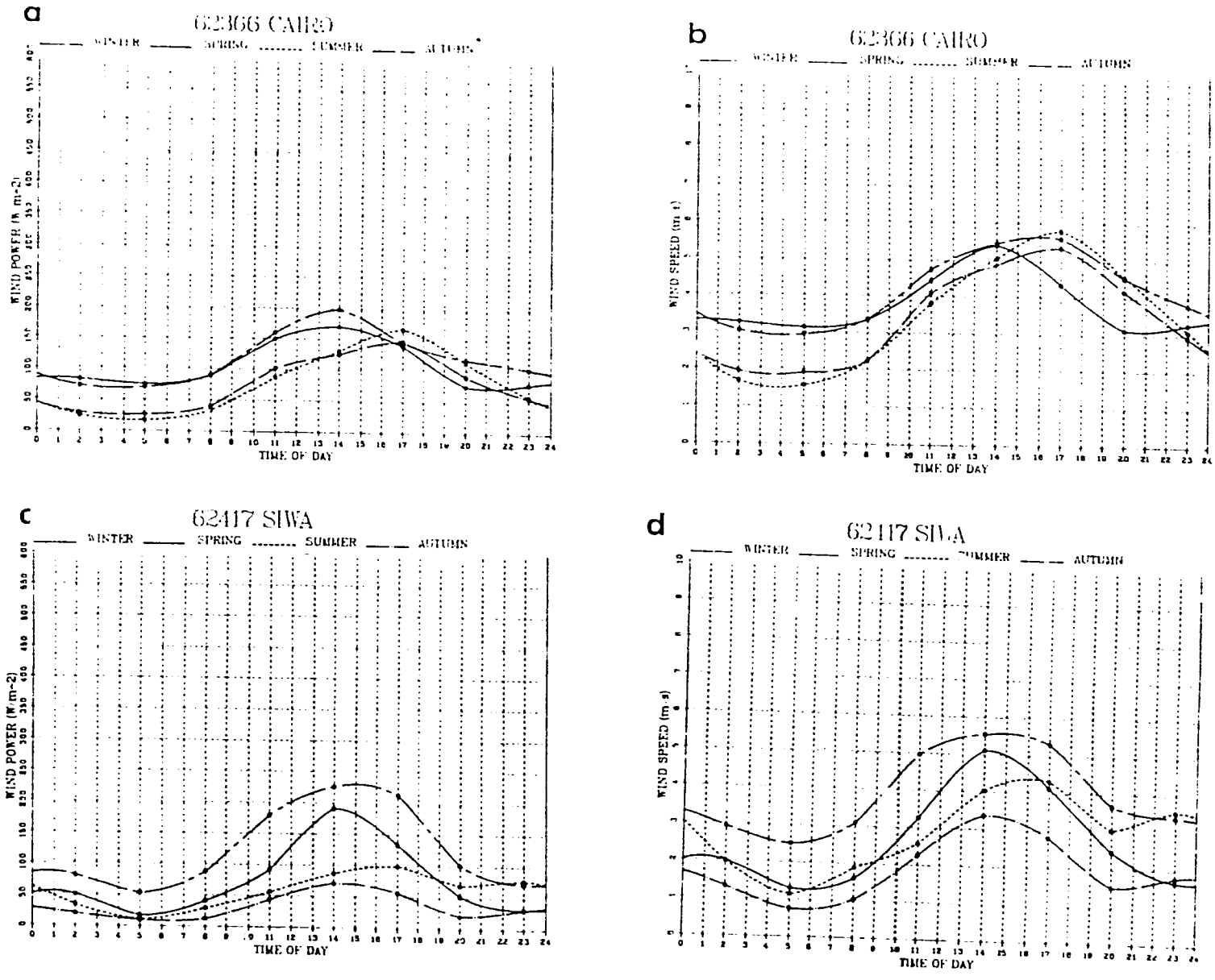

FIGURE A.23. Diurnal Wind a) Speed and b) Power Density by Season for Cairo; Diurnal Wind c) Speed and d) Power Density by Season for Siwa

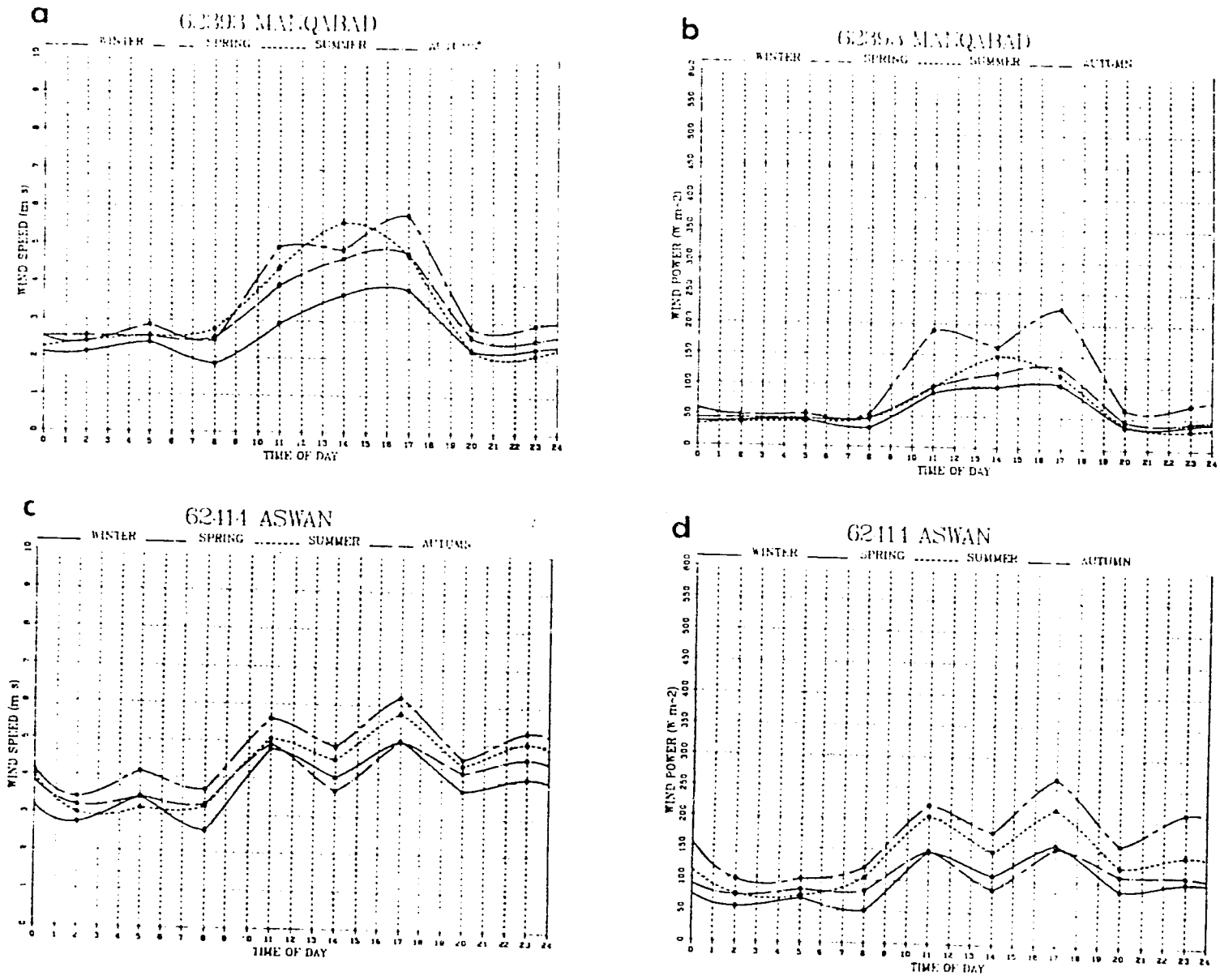

FIGURE A.24. Diurnal Wind a) Speed and b) Power Density by Season for Manqabad; Diurnal Wind c) Speed and d) Power Density by Season for Aswan