Wind Energy Resource Atlas: Volume 11 - Hawaii and Pacific Islands Region

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WIND ENERGY RESOURCE ATLAS: Volume 11 -
Hawaii and Pacific Islands Region

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PREFACE

For the purpose of assessing the national wind resource, the United States and its possessions have been divided into twelve regions. For each region, wind resource assessments are presented in the form of an atlas. The atlases depict in graphic, tabular and narrative form the wind resource on a regional and state level. The information presented in the atlases will help guide homeowners, utilities and industry in decisions concerning the use of the wind as a source of energy. In this atlas, we divided the presentation into Hawaii (Chapter 3) and Pacific Islands (Chapter 4) since the state division is inappropriate.

This atlas of the wind energy resource is composed of introductory and background information, and assessments of the wind resource in each division of the region. Chapter 1 provides background on how the wind resource is assessed and on how the results of the assessment should be interpreted. Chapter 2 provides an introduction and outline to the descriptions of the wind resource for each division. Assessments for individual divisions are presented as separate chapters beginning with Chapter 3. This preface outlines the use and interpretation of the information found in the division chapters.

Much of the information in the division chapters is given in graphic or tabular form. The sequences for each chapter are similar, but some presentations used for Hawaii are inappropriate or impractical for presentation with the Pacific Islands. Hawaii chapter figure and tables are cited below and appropriate Pacific Islands figure and table numbers are included in brackets [].

Figures 3.1, 3.2 [4.1, 4.2] show the major geographical (mountains, rivers) and cultural (cities, towns) features in the division. This map can be used to orient the reader to the islands. Figure 3.3 portrays the topography of Hawaii in shaded relief. The shaded relief allows the reader to visualize the character of the terrain surrounding locations of special interest. Superimposed on Hawaii and Guam maps is a grid of dashed lines one-eighth degree (7.5') longitude by one-eighth degree (7.5') latitude. This grid is repeated on nearly all subsequent maps to give the reader an adequate frame of reference for locating the same feature on different maps. Samoa has one-half degree (30' longitude) by one-half degree (30' latitude) grids, while all other Pacific Islands groups have one degree longitude by one degree latitude grids.

Figure 3.4 is a map of the land-surface form. The information presented in Sections 1.6 and 1.8 indicates how the land-surface form is used to designate the terrain features considered to have a typical good exposure to the wind. Awareness of what constitutes well-exposed terrain features is crucial to the proper interpretation of the maps of wind power density.

Figures 3.5 and 3.6 [4.3] identify and locate wind data sites relevant to the assessment. All locations in each division for which the National Climatic Center (NCC) has wind data in its archives are shown and named in Figure 3.5 [4.3]. However, this assessment is based on a subset of NCC data augmented by data from other sources (see Sections 1.1 and 1.2). Figure 3.6 shows the location of all wind data sites used in the assessment. Sections 1.3 through 1.5 briefly describe the methods used to analyze the wind data and evaluate the wind power.

The wind energy resource for a division is illustrated using several maps. The wind power maps represent a careful synthesis of quantitative wind data guided by state-of-the-art concepts on air flow near the earth's surface. Section 1.6 describes how the analysis of the wind data is transformed into the map of annual average wind power density found in Figure 3.7 [4.4]. This map gives the annual average wind power density at typically-exposed sites. A discussion of the classes of wind power density in Section 1.7 gives the relationship between mean wind power density (watts/m^2) and mean wind speed (m/s or mph).

A certainty rating is used to provide a measure of the ability to objectively evaluate the wind resource in a grid cell. The certainty ratings are given in the maps of Figure 3.8 [4.5]. The degree of certainty with which the wind power can be estimated depends on the quality and quantity of wind data, the complexity of the terrain and concern over the variability of the wind resource over short distances. How these factors are combined to assign a certainty rating is discussed in Section 1.9.

The terrain feature with typical good exposure to the wind in a particular land-surface form provides a convenient and essential point on which to base the analyses of the wind resource shown in Figure 3.7 [4.4]. However, a substantial portion of the terrain may have poorer than typical exposure to the wind and will have a lower wind resource than shown on the wind power maps. The maps of Figure 3.9 provide an estimate of the percentage of area in each grid cell that may experience at least each of four different wind power classes. Section 1.10 discusses the assumptions underlying the evaluation of the areal distribution of the wind resource. The area of the island group estimated to experience a particular wind power class is given in Table 3.2 [4.2-4.7]. This table summarizes the contribution made by each grid cell to the areal distribution of wind power for the island group.

The annual average wind power density compresses into a single statistic time-varying trends on several time scales, *e.g.* annual, seasonal, monthly, and daily. In this atlas, the seasonal evolution of the geographical distribution of wind power is shown at the island group level. The maps of Figure 3.10 [4.6] give the average wind power density for winter, spring, summer, and autumn. The interpretation of the seasonal average wind power maps is identical to that for the annual average wind power map.

Additional information on the time variation and other characteristics of the wind resource in each division is presented for selected locations for which the National Climatic Center or the University of Hawaii placed 1-hourly or 3-hourly time-series data on magnetic tape. Descriptions of the characteristics of the wind resource presented for these stations are given in Section 2.2. The urge to consider information pertaining to one of these sites as representative of some other location must be tempered with the realization that wind characteristics are extremely site-dependent. The degree of correspondence between the wind characteristics at one site and those at another site depends on the similarity between the topographical setting of the sites, the weather patterns that affect the sites and the obstructions to the wind in the vicinity of the sites.

Table 3.3 [4.8] identifies the stations, and gives their location (see also Figures 3.5 and 3.6 [4.3]) and annual average wind speed and power density. Figure 3.11 [4.7]

shows how the yearly mean speed and power varied during the period of record. The monthly mean wind speed and power over the course of a year are shown in Figure 3.12 [4.8]. The hourly mean wind speed over the course of a day is shown in Figure 3.13 [4.9] with a separate curve for each season. Figures 3.12 [4.8] and 3.13 [4.9] indicate the time of year and time of day, respectively, the wind resource is available. Figure 3.11 [4.7], on the other hand, indicates the year-to-year variability that might be expected in the yearly mean resource.

The frequency of occurrence of winds from a particular direction and of winds with a particular speed is shown in Figures 3.14 [4.10] and 3.15 [4.11], respectively. The information on wind direction may be important in assessing the availability of the wind resource relative to surrounding terrain or nearby obstructions. However, it is also important to realize that the wind direction statistics are highly dependent on the location of the instrument site relative to obstructions and major terrain features, *e.g.* valleys, ridges, and mountain ranges.

Figures 3.16 [4.12] and 3.17 [4.13] portray speed and power frequency statistics in the form of speed and power exceedance curves, respectively. The fraction of the total period of record the speed equals or exceeds a given value is shown in Figure 3.16 [4.12]. The power exceedance curve in Figure 3.17 [4.13] gives the fraction of the period of record for which the power exceeds a given value.

As has been shown in the preceding discussion, the order of presentation of the wind resource in this atlas proceeds from an island group perspective in the first part of each division chapter, to individual station descriptions in the last part of the chapters. Attention given to Chapter 1 and Chapter 2 will make it possible for the reader to properly interpret the wind resource presentations.

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CHAPTER 1: REGIONAL WIND ENERGY RESOURCE ASSESSMENT

Rapid development of wind as a source of commercial electric power is the principal goal of the Federal Wind Energy Program. Utility planning, wind turbine manufacturing and marketing of wind energy conversion systems all depend on detailed wind resource assessments. This atlas of the Hawaiian and Pacific Islands' wind resources, a product of the Wind Characteristics Program Element of the Federal Wind Energy Program, represents a major source of information for meeting these various needs.

This wind energy resource atlas is one of twelve such atlases. The other atlases describe the potential wind resource in eleven other regions of the United States (see Figure 1.1). The wind resource in these regional assessments is depicted in considerably greater detail than that in existing national assessments (Reed, 1975; Coty, 1976; Garate, 1977; Elliot, 1977). Where possible, the Hawaiian and Pacific Islands atlas uses comparable data sets, analysis techniques, and presentation to ensure uniformity in assessment of the wind resource.

The Hawaii and the Pacific Islands region (see Figure 1.2) differs significantly from mainland regions. Though millions of square miles of ocean are included, land area is small. The State of Hawaii has 16,710 km² (6450 mi²) and a population of 1,000,000 (1980 estimate). The more than 2,200 Pacific Islands affiliated with the United States have a total land area of 2621 km² (1012 mi²) with a population of about 230,000. Table 1.1 lists the principal Pacific Island groups and their current political status. Some (*e.g.* Palau) are in political transition.

The Hawaii and Pacific Islands atlas contains two collections of wind resource data: one for Hawaii and one for the Pacific Islands. Pacific Islands groups are identified by traditional names. Presentations are equivalent to the state sections of the Northwest atlas (Elliott and Barchet, 1980).

The methods used to identify, screen, evaluate, and analyze the various types of data, and to produce the wind energy resource maps and graphs will be described

FIGURE 1.1. Geographic Divisions for Regional Wind Energy Assessments

TABLE 1.1. Current Divisions of Pacific Islands Affiliated with the United States.

Current Name	Island Chain	Political Status
Guam	Marianas	Commonwealth
Northern Marianas	Marianas	Commonwealth in 1981
Marshall Islands Government	Marshalls	Free Association
Federated States of Micronesia	Carolines	Free Association
1. Kosrae		
2. Ponape		
3. Truk		
4. Yap		
Palau	Carolines (Western)	Trust Territory
American Samoa	Samoa	Territory
Wake, Johnston, Midway		Military Control

only briefly. [For more detail, see Elliott and Barchet (1980).] However, this discussion should provide the reader with useful background information for interpreting the wind energy maps.

1.1 IDENTIFICATION OF WIND DATA SOURCES

The surface wind data on which this atlas has been based were obtained from several sources: the National Climatic Center (NCC), the U. S. Forestry Service, the University of Hawaii, and other government and private organizations. The National Climatic Center offers the largest collection of wind data. Surveys and indices of wind data archived at the NCC (Changery 1975, 1978; Changery *et al.*, 1977) were extremely helpful in locating available wind data. The *Index of Original Surface Weather Records*, published for each individual state by the NCC, provides additional information about stations at which measurements have been made.

The wind data available from the NCC may be in one or more of three formats: summarized, digitized and unsummarized. Initially, all data are in the unsummarized format—the original station weather records. For many stations, the collection of individual observations has been condensed into wind summaries. Changery *et al.* (1977) present examples of the various summary formats used and indices of the stations for which wind summaries are available. For still fewer stations (primarily airport stations), the NCC has put the original one- or three-hourly weather observations on magnetic tape to create a digitized time series of weather (and wind) observations. [TDF-14 (NCC 1975) describes the data on these tapes.] Table 1.2 indicates the number of stations with wind data in these various formats in Hawaii and the Pacific Islands.

The University of Hawaii is a repository for copies of unsummarized original weather records from a number of stations. We summarized these data.

Since much of the region is ocean, supplementary data were obtained from an extensive collection of ship wind observations available from the University of

TABLE 1.2. Stations with Wind Data in the Hawaii and Pacific Ocean Area in Assessment.

Source and Type	Screened	Retained
<i>HAWAII STATIONS</i>		
National Climatic Center		
Digitized	11	11
Summarized	9	7
Unsummarized	5	
Unsummarized ^(a)	16	14
Forest Service	11	6
University of Hawaii Research	33	26
Other		
Lawrence Livermore Lab	6	4
Hawaii Sugar Planters' Association	2	2
U. S. Military	1	1
<i>PACIFIC OCEAN STATIONS</i>		
National Climatic Center		
Digitized	16	16
Unsummarized	2	0
Unsummarized ^(a)	19	9

(a) Manuscript records previously obtained by the University of Hawaii were summarized by the contractor for selected periods (periods were normally 12-months and ranged from a few months up to 2 years).

Hawaii [Wyrski and Meyers (1975)]. Upper-level wind data were obtained from NCC summaries and from satellite-derived winds available at the University of Hawaii.

In contrast to the NCC data which are primarily from inhabited areas, U. S. Forestry Service data in the National Fire Weather Data Library (Furman and Brink, 1975) are from remote sites in mountainous and forested areas under the jurisdiction of the Federal Government (*i.e.*, national forests, national parks, Indian reservations, or Bureau of Land Management areas). Eleven stations with wind data are reported in the National Fire Weather Data Library for Hawaii (Marlatt, *et al.*, 1979). However, only one observation, at about 2 p.m., is digitized per day during the local fire weather season.

As part of state- and federally-sponsored wind energy research, the University of Hawaii Department of Meteorology established 23 wind monitoring sites and installed digital tape recording systems at 3 National Weather Service anemometers (Ramage *et al.*, 1979). Lawrence Livermore Laboratory established 4 digital stations on the north shore of Oahu (Shinn *et al.*, 1979). The University has also identified data sets used in agricultural research, air pollution analysis, site selection studies, and operation of astronomical observatories.

1.2 WIND DATA SCREENING

Table 1.2 indicates the quantity of wind data available in Hawaii and the Pacific Islands. However, not all of these data need, or should, be used in a wind resource assessment. Screening procedures were developed to identify stations with the most useful data and to eliminate stations that would not significantly contribute information on the distribution of the wind resource.

We chose wind data in summarized or digitized format over unsunmarized data. When stations had both summarized and digitized data, we used the digitized data for selected stations to prepare a more extensive characterization of the wind resource.

In areas with many stations, we selected those appearing to have the best exposure to the wind, greatest number of daily observations, longest period of record, and longest period of unchanged anemometer height and location. When more than one type of summary (see Changery *et al.*, 1977) was available for a given station, we chose the summary covering the longest period of record with constant

anemometer height and location, with the greatest number of wind speed and direction classes, and with the highest frequency of daily observations.

1.3 TIME SCALES IN REGIONAL ASSESSMENTS

Several time scales are encountered in the following discussions of the wind resource: annual, seasonal, monthly, and diurnal. Annual mean values are generally based on an average of the one- or three-hourly observations of wind speed or power in the period of record; however, a complete calendar year's data (covering January 1 to December 31) is used for calculating individual yearly means. At stations with fewer than 24-hourly observations or 8 three-hourly observations per day, the values represent only the times of day at which the measurements were made.

The four seasons are:

N. Hemisphere	S. Hemisphere	Months
Winter	Summer	Dec, Jan, Feb
Spring	Autumn	Mar, Apr, May
Summer	Winter	Jun, Jul, Aug
Autumn	Spring	Sep, Oct, Nov

The phrase "seasonal trades" refers to the change in monthly mean values over the course of each of the four seasons.

Monthly mean values are based on as many hours of data as are available for that month in each year of the period of record.

The daily or diurnal cycles of variation in the hourly mean wind power or speed are referenced to local standard time on a 24-hour clock. Midnight is both 00 and 24.

1.4 EVALUATION OF WIND DATA

For the purpose of mapping the geographical variation of the wind resource, we chose wind power density over wind speed since the power density incorporates the combined effect of the distribution of wind speeds and the dependence of the power density on air density and on the cube of the wind speed. Quantitative wind data in three formats were evaluated for mean wind power density: digitized, summarized, and unsunmarized. The average wind power density $\bar{P}$ (watts/m²) in a vertical plane perpendicular to the wind direction for stations with one- or three-hourly digitized data is:

$$\bar{P} = \frac{1}{2n} \sum_{i=1}^n \rho_i V_i^3 \quad (1)$$

where

- n = the number of observations in the averaging period
- ρ_i = the density (in kg/m³) computed from the station pressure and temperature
- V_i = the wind speed (in m/s) at the i th observation time.

For stations with wind summaries, $\bar{P}$ is:

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

where

- $\bar{\rho}$ = the mean air density
- c = the number of wind speed classes
- f_j = frequency of occurrence of winds in the j th class
- V_j = the median wind speed of the j th class

1.4.1. Vertical Adjustment

With reference to the surface, anemometers were rarely at either the 10-m or 50-m levels chosen for the presentation of the wind resource. A power law was used to adjust the long-term mean wind speed or power density to the reference level:

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

where $\bar{V}_a, r$ and $\bar{P}_a, r$ = the mean wind speed or wind power density at heights Z_a, r (the anemometer and reference level, respectively).

α = the power law exponent.

An examination of long-term mean wind speeds at airport locations at which the anemometer height changed and at tower sites with multiple levels of anemometry indicates an $\alpha \sim 1/7$ to be widely applicable to low surface roughness and well-exposed sites (Elliott 1979b).

1.4.2 Estimates for Mountainous Areas

For quantitative estimation of wind power over mountains, we used tropical upper-air wind climatologies (Wiederanders, 1961), satellite-derived winds, NCC data summaries (on file at the University of Hawaii) and principles developed for the Northwest atlas and by the University of Hawaii. Major differences from previous atlases occur in Hawaii. The dominant weather system is the trade wind. Peak trade wind speeds occur at 600 m (2000 ft) and a strong temperature inversion overlies the trades at about 2200 m (7000 ft). For mountains above 1500 m (5000 ft), the trades are diverted around the barrier much as in channeled fluid flow. However, elongated low ranges such as Oahu's Koolau Range (900 m, 3000 ft) allow significant enhancement of open ocean winds as they pass the crest. For the Oahu ranges, we applied estimates from representative University of Hawaii wind stations to the mountain crests. For taller Hawaiian mountains and for those in the Pacific Islands (where the trade inversion is not as significant a factor), we used procedures as outlined in the Northwest atlas (Elliott and Barchet, 1980).

Since earlier studies indicated a strong correlation between mountaintop and free-air wind speeds (Wahl, 1966), the free-air wind at mountainous summit or ridge crest height was extrapolated (or interpolated) from the mean scalar speeds at the constant pressure surfaces. Linear extrapolation provided the mean free-air wind speed at the terrain elevation and application of a Rayleigh speed distribution gave the mean free-air wind power. The mean power at the 10-m and 50-m reference heights was taken to be one-third and two-thirds of the free-air value, respectively, to account for the frictional slowing of the wind near the surface.

These estimates are lower limits for exposed ridge crests and mountain summits. Local terrain features in these mountainous regions can enhance the wind power considerably. However, a major uncertainty in mountainous terrain is the representativeness of some of the data upon which the free-air estimates are based (*e.g.*, sheltering by nearby mountains can bias rawinsonde winds).

Wherever possible, these estimates were compared with surface data from ridge crests and mountain summits. Over some of the mountainous areas, the estimates were adjusted based on the location of the upper-air recording station and/or the surface data from ridge crests.

1.5 QUALITATIVE WIND INDICATORS

Although more than 120 stations provided quantitative data for the wind resource assessment, these stations are not uniformly distributed. The station location figures show that most NCC stations lie in coastal regions especially at airports. Fifty per cent of the land area in Hawaii is above 600 m (2000 ft) elevation. Several of the Pacific Islands (Ponape, Kosrae, Tutuila, several of the Marianas) are high islands with similar station location biases. In Hawaii, the University of Hawaii has supplemented NCC stations with special stations in known windy regions. Nevertheless, much of Hawaii has not been sampled.

To evaluate the distribution of the wind resource in data-sparse areas, three qualitative indicators of the wind speed or power were developed for possible use in the assessment.

The most widely-used technique depended on certain combinations of topographical and meteorological features (Elliott, 1979a) that were associated with high or low wind speeds. These features indicative of high mean wind speeds are:

- gaps, passes, and gorges in areas of frequent strong pressure gradients
- long valleys extending down from mountain ranges
- high elevation plains and plateaus
- plains and valleys with persistent strong downslope winds associated with strong pressure gradients
- exposed ridges and mountain summits in areas of strong upper-air winds
- exposed coastal sites in areas of
 - 1) strong upper-air winds, or
 - 2) strong thermal/pressure gradients

Features that signal rather low mean wind speeds are:

- valleys perpendicular to the prevailing winds aloft
- sheltered basins
- short and/or narrow valleys and canyons
- areas of high surface roughness, *e.g.* forested hilly terrain.

Areas in which the appropriate features occur were determined by examining topographic contour and shaded relief maps and synoptic and climatological maps of sea-level pressure

patterns and air flow. We used these features extensively for the Hawaiian Islands and Guam. The University of Hawaii wind assessment program developed these principles in 1975.

The removal and deposition of surface materials by the wind to form playas and sand dunes indicate strong winds from a nearly constant direction. Correlating characteristics of eolian features to long-term mean wind speeds has proven difficult (Marrs and Gaylord, 1979). However, eolian features aided in delineating the high wind energy region of northwest Molokai, Hawaii.

Evidence of persistent strong winds can also be found in wind-deformed vegetation. However, we avoided use of mean wind speeds deduced from extent and morphology of tree deformation (Hewson *et al.*, 1979) because salt deposition in a marine environment can also contribute significantly to tree deformation.

1.6 WIND POWER MAPS

The production of mean wind power density maps presented for each island group depended on the coherent synthesis of several pieces of information. The goal was to present wind power density values representative of sites well-exposed to the prevailing strong winds. Hilltops, ridge crests, mountain summits, large clearings and other locations free of local obstructions to the wind are well exposed (see Table 1.3). In contrast, locations in narrow valleys and canyons, downwind of hills and obstructions, or in forested or urban areas are poorly exposed. The wind power density shown on the maps in this atlas will not be representative of poorly-based locations. Estimates for ridge crests and summits (the shaded areas on the maps) are lower limits to the wind power expected at exposed sites. In such areas, local terrain features can enhance the wind power considerably (*e.g.* by a factor of 2 or 3). By specifying the type of wind exposure to which the map values of wind power pertain, we avoid the ambiguity that typical-location or average-for-the-terrain values might introduce. In this atlas, the terms wind energy, wind power, and wind power density are used synonymously.

To represent the wind resource at well-exposed sites, one must be familiar with the land-surface form and topography in the vicinity of every data site. We prepared maps showing the station location, the mean wind speed and mean wind power at the reference level, the character of anemometer exposure, and the land-surface form for each county and island group. On these maps, we identified areas with the appropriate combinations of topographical and meteorological features. We emphasized orientation of topographic features with respect to prevailing wind directions. Only after all this information was assembled did we analyze the maps.

1.7 WIND POWER DENSITY CLASSES

The analysis of wind power maps departs from conventional isopleth analyses by showing the boundaries of wind power density classes. Each wind power class represents the range of wind power densities likely to be encountered at exposed sites within an area designated as having that wind power class. Table 1.4 gives the power density limits for the wind power classes used in the atlas for the 10-m (33-ft) and 50-m (164 ft) reference levels.

Wind power density is proportional to the third moment of the wind speed distribution and to air density; therefore, a unique correspondence between power density and mean wind speed (the first moment of the speed distribution) does not exist. However, by specifying a Rayleigh wind speed distribution and a standard sea level air density (1.22 kg/m^3) a mean wind speed can be determined for each wind power class limit. The decrease of air density with elevation requires the mean Rayleigh speed to increase by about 3%/1000 m elevation (1%/1000 ft) to maintain the same power density. If the wind speed distribution is more sharply peaked than the Rayleigh distribution, the equivalent mean speed will be slightly higher than the value in Table 1.3. Conversely, a

broader distribution of wind speeds will slightly reduce the equivalent mean speed.

1.8 CLASSES OF LAND-SURFACE FORM

The physical characteristics of the land-surface form affect the number of wind turbines that can be sited in exposed places. For example, over 90% of the land area in a flat plain may be favorably exposed to the wind, whereas in mountainous terrain only the ridge crests and passes, which may be only a small percentage (<5%) of the land area, may represent exposed sites. The map of classes of land-surface form by Hammond (1964) provided information on the distribution of plains, tablelands, hills and mountains in Hawaii. Several characteristics are coded on this map:

- percentage of land area with gentle inclination (less than 8% slope)
- local relief, defined as the maximum difference in elevation within a unit square six miles across
- percentage of gently inclined surfaces that lie in the lower half of the local relief
- land area covered by sand, ice, and standing water

TABLE 1.3. Land Surface Form Terrain Features Representative of Exposed Locations.

Land-Surface Form	Exposed Feature (Map Value)	Percentage Area ^(a)
Plains: A1; B1, 2	Plains	93
Plains With Hills: A, B3a, b	Open Plains	79
Plains With Mountains: B4-6a, b	Plains (not shaded) ^(b)	67
	Ridge Crests and Mountain Summits (shaded)	10
Tablelands: B3-6c, d	Tablelands, Uplands	80
Open Hills: C2-4	Hilltops and Uplands	27
Open Mountains: C5-6	Broad Valleys (not shaded)	80
	Ridge Crests and Mountain Summits (shaded)	12
Hills: D3-4	Hilltops and Uplands	9
Mountains: D5-6	Ridge Crests and Mountain Summits (shaded)	3

(a) Percentage represents an average over the land-surface forms found in the Northwest region which we applied to Hawaii and the Pacific Islands.

(b) Shaded areas on the wind maps, emphasize that map values are estimates for ridge crests and mountain summit locations.

TABLE 1.4. Classes of Wind Power Density at 10 m and 50 m^(a)

Wind Power Class	10 m (33 ft)		50 m (164 ft)	
	Wind Power Density watts/m ²	Speed ^(b) m/s (mph)	Wind Power Density watts/m ²	Speed ^(b) m/s (mph)
	0	0	0	0
1	100	4.4(9.8)	200	5.6(12.5)
2	150	5.1(11.5)	300	6.4(14.3)
3	200	5.6(12.5)	400	7.0(15.7)
4	250	6.0(13.4)	500	7.5(16.8)
5	300	6.4(14.3)	600	8.0(17.9)
6	400	7.0(15.7)	800	8.8(19.7)
7	1000	9.4(21.1)	2000	11.9(26.6)

(a) Vertical extrapolation of wind speed based on the 1/7 power law.

(b) 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 5%/5000 ft (3%/1000 m) of elevation.

- pattern of major crests, peaks, and escarpments.

The first three characteristics are used in the classification scheme (see Table 1.5); the latter two have been omitted from the maps presented here. A three-character code, for example B3a, designates each class of land-surface form. In this example, the "B" indicates that 50% to 80% of the area is occupied by gentle slopes; the "3" that the maximum local difference in elevation is 100 to 150 m (300 to 500 ft); and the "a" that more than 75% of the gentle sloping land is in the lowland. In areas of very little gentle slopes (D) or very low relief and great smoothness (A1), the third designator is omitted.

We assigned land form classifications to the Pacific Islands. For each land-surface form, we estimated the percentage of land area that is representative of well-exposed, moderately-exposed, and poorly-exposed sites. These percentages were determined subjectively as a function of the slope, local relief, and profile type. Table 1.3 gives the average percentage of land area designated as exposed terrain for the different classes of land-surface form. For simplicity, the percentage shown for each class of land-surface form have been averaged over the range of categories in local relief and profile type found in the Northwest. For example, the 27% for open hills is an average for C2 through C4. The average percentage of land area designated

TABLE 1.5. Scheme of Classification

Slope (1st item)

- A <80% of area gently sloping
- B 50 to 80% of area gently sloping
- C 20 to 50% of area gently sloping
- D >20% of area gently sloping

Local Relief (2nd item)

- 1 1 to 30 m (0 to 100 ft)
- 2 30 to 90 m (100 to 300 ft)
- 3 90 to 150 m (300 to 500 ft)
- 4 150 to 300 m (500 to 1000 ft)
- 5 300 to 900 m (1000 to 3000 ft)
- 6 900 to 1500 m (3000 to 5000 ft)

Profile Type (3rd item)

- a >75% of gentle slope is in lowland
- b 50 to 75% of gentle slope is in lowland
- c 50 to 75% of gentle slope is in upland
- d <75% of gentle slope is in upland

as exposed terrain ranges from 93% in smooth plains to 3% in mountainous areas where the exposed areas are usually the ridge crests and mountain summits.

1.9 CERTAINTY RATING

The analyses of wind power density at exposed sites shown on the wind power maps depend on the subjective integration of several factors: quantitative wind data, qualitative indicators of wind speed or power, the characteristics of exposed sites in various terrain and familiarity with the meteorology, climatology, and topography of the region. As a result, the degree of certainty with which the wind power class can be specified depends on:

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

We made a certainty rating from 1 (low) to 4 (high) of the wind energy resource estimate for each cell of a one-eighth degree latitude by one-eighth degree longitude grid for Hawaii and Guam by considering the influence of the above three factors on the certainty of the estimate of the wind power class for each cell. The definitions for the certainty ratings are adopted from those used by Voelker *et al.* (1979) in a resource assessment of U. S. Forestry Service tracts. The certainty ratings for the wind resource assessment are defined as follows:

Rating	Definition
1	The lowest degree of certainty. A combination of the following conditions exist: <ol style="list-style-type: none"> 1) No data in the vicinity of the cell. 2) Highly complex terrain. 3) Various meteorological and topographical indicators suggest a high level of variability of the resource within the cell.
2	A low-intermediate degree of certainty. One of the following conditions exists: <ol style="list-style-type: none"> 1) Little or no data in or near the cell, but the small variability of the resource and the low complexity of the terrain suggest that the wind resource differs insignificantly from the resource in nearby areas with data. 2) Limited data in the vicinity

Rating	Definition
	of the cell, but highly complex terrain or large mesoscale variability of the resource.
3	A high-intermediate degree of certainty. One of the following conditions exists: <ol style="list-style-type: none"> 1) Limited wind data in the vicinity of the cell, but the low complexity of terrain and the small mesoscale variability of the resource indicate little departure from the wind resource in nearby areas with data. 2) Considerable wind data but in moderately complex terrain and/or in areas where moderate variability of the resource is likely to occur.
4	The highest degree of certainty. Quantitative data at exposed sites in the vicinity of the cell can be confidently applied to exposed areas in the cell because of low terrain complexity and low spatial variability of the resource.

The assignment of a certainty rating requires subjective evaluation of the interaction of the factors involved.

1.10 AREAL DISTRIBUTION OF THE WIND RESOURCE

As noted above, the wind power density class values shown on the maps apply only to sites well-exposed to the wind. Therefore, the map area designated as having a particular wind power class does not indicate the true land area experiencing this wind power. Instead, there is a complicated and difficult-to-quantify relationship among the class of land-surface form, the land-surface area and the map value of wind power density. For each land surface form, we estimated the fraction of land area that would be favorably exposed to the winds, *i.e.*, have the wind power density indicated on the map (see Table 1.3 for averages in various land-surface forms). Furthermore, to be able to establish a wind power density for the remaining area, it was necessary to specify a factor by which the wind power shown on the map is reduced in the less-exposed areas. As an additional complication, some land-surface forms, isolated hills and ridges that rise above a nearly flat landscape may even experience a higher power density than the map indicates.

To accommodate these various situations, the land area represented by a given land-

surface form was divided into four exposure categories: 1) better exposure than typical for the terrain, 2) exposure typical for that land-surface form, 3) partially-sheltered exposure, and 4) very sheltered exposure. The partitioning of the land-surface forms into the four categories was based on the parameters used to classify the land-surface forms and on the experience of the authors and their co-workers with the terrain represented by the land-surface forms.

In order to adjust the wind power density from the map value to the various exposure categories, the power density was scaled to be 1) greater than, 2) equal to, 3) slightly less than, and 4) much less than the map value power density. The factor by which map value was adjusted to represent the wind power density in each category was determined by the magnitude of elevation relief given by the middle character of the land-surface form code. (The minimum power density allowed for a category was the median value of wind power density class 1.) The scaling factors for the wind power density were based on a conservative application of a power-law type vertical adjustment with the height change specified by the terrain relief code.

For Hawaii and Guam, in each cell of a grid one-eighth degree longitude by one-eighth degree latitude, we specified the land-surface form and the wind power class associated with a typically-exposed site in that land-surface form. By partitioning the area of the cell into four exposure categories and by scaling the wind power class to each category, we determined the contribution of that cell to the areal distribution.

A cell-by-cell representation of the areal distribution is given in a map that

indicates the percentage land area in a cell over which the wind power class equals or exceeds a threshold value. Four maps are shown in the chapter on Hawaii wind resources for threshold values of classes 2, 3, 4 and 5.

For the smaller Pacific Islands, we treated an individual island or island complex (such as Truk) as one cell. We have omitted maps indicating the percentage land area in an island over which the wind power class equals or exceeds a threshold value.

A summary table of the areal distribution that combines the contributions by each cell is provided for Hawaii and the Pacific Islands. For each power class, we determined the sum of the area contributed by each exposure category. Summing the area associated with each power class in each cell gives the area over which the power class exceeds a given value. The table gives the estimated land area (km²) and the percentage of land area associated with each power class.

Both of these presentations of the areal distribution of the wind resource depend highly on the estimates used to partition the land area into the four exposure categories and on the scaling of the power density for each category of exposure. Therefore, the areal distribution derived from the wind power and land-surface form maps must be considered only an approximation. The quantity and quality of wind data and topographic information required to make a highly accurate cell-by-cell appraisal of the wind resource goes far beyond the scope of this regional wind resource assessment. However, as wind information becomes available through new measurement programs or through the discovery and processing of existing data sets, the evaluation of the areal distribution of the wind resource can be improved on a cell-by-cell basis.

FIGURE 1.2. Geographic Map of the Hawaii and Pacific Islands Region.

Wind resource descriptions are presented in Chapter 3 (Hawaii) and Chapter 4 (Pacific Islands). The text of each description is followed by maps, graphs, and tables that identify features of the geography and the wind energy resource and summarize the data collected from the observation stations. The sequence of maps, tables and graphs used to depict these features for Hawaii is presented in Table 2.1. The Pacific Islands presentation differs from that for Hawaii.

TABLE 2.1. Maps, Tables and Graphs Used to Depict the Wind Resource for Hawaii

MAPS

State Map
Cultural Geography (4 maps)
Topographic Shaded Relief
Land-Surface Form (4 maps)
Legend to Land-Surface Form
NCC and University of Hawaii Station Locations (4 maps)
Location of Stations Used in Wind Assessment (4 maps)
Legend to Wind Power Classes
Table on Areal Distribution
Annual Average Wind Power (4 maps)
Legend for Certainty Rating
Certainty Rating (4 maps)
Areal Distribution (Class 2, 4 maps)
Areal Distribution (Class 3, 4 maps)
Areal Distribution (Class 4, 4 maps)
Areal Distribution (Class 5, 4 maps)
Seasonal Average Wind Power (winter, 4 maps)
Seasonal Average Wind Power (spring, 4 maps)
Seasonal Average Wind Power (summer, 4 maps)
Seasonal Average Wind Power (autumn, 4 maps)

GRAPHS

Summary Table of Selected Stations
Interannual Speed and Power
Monthly Speed and Power
Diurnal Speed
Directional Frequency
Speed Frequency
Speed Duration
Power Duration

To avoid repetition in the following chapters, the general format and content of the various maps, tables and graphs used to describe the wind resource are summarized here.

2.1 MAPS OF HAWAII FEATURES

Maps of cultural geography show the locations of major cities, towns, and terrain features for each county. The shaded topographic relief map is a reproduction of a 1:500,000 scale U. S. Geological Survey map. The land-surface form map is a reconstruction of portions of the map of classes of land-surface form by Hammond (1964); this is also available at a scale of 1:17,000,000 on Plate 62 in the *National Atlas of the United States*. We described the use of the land-surface form map in Section 1.8.

Two sets of maps show locations of stations with wind data. The first map gives the locations and names of the NCC and University of Hawaii stations with wind data in any form. The other map set shows the locations of NCC, University, fire weather and other stations utilized in this assessment of the wind resource.

The map of annual average wind power is accompanied by gridded maps of the certainty rating of the estimated annual average wind power by grid cell, and gridded map of the areal distribution of the wind resource by grid cell. The certainty rating, which ranges from 1 (low) to 4 (high), indicates the level of confidence in the estimates of the wind resource in each cell of the grid and is based on the availability of wind data, the complexity of the terrain, and the inherent geographical variability of the wind resource (see Section 1.9). The maps of areal distribution give the percentage of land area in each cell estimated to experience an annual wind power class equal to or exceeding power classes 2, 3, 4, and 5 (see Section 1.10).

We present maps of the average wind power for each season. The legend for the power classes is found with the annual average wind power map.

2.1.1 Maps of Pacific Islands Features

Pacific Islands presentation of maps differ from the Hawaii presentation in the following aspects:

- 1) Wind power maps are presented by island group—the groups are Guam, the Northern Marianas, Marshalls, Carolines, American Samoa, and the isolated islands of Midway, Wake, and Johnston.
- 2) No shaded topography or land-surface forms are shown.
- 3) Wind power maps are not isoplethted.

- 4) Wind power values are presented for the surrounding ocean areas using the Wyrski and Meyers (1975) ship wind data set. Ship winds were assumed to be at 15 m elevation and were adjusted by use of a one-seventh power law (see Section 1.4.1). Six years of data were averaged, then power was calculated using a Rayleigh distribution (see Section 1.4).
- 5) Areal distribution maps are not presented. We do present areal distribution in tabular form.

2.2 FEATURES OF SELECTED STATIONS

The analysis of the wind resource on a state and regional basis depends on information from individual stations. For those stations with one- or three-hourly data on NCC magnetic tapes, a very detailed presentation of the temporal variation and character of the wind resource can be obtained. Graphs portraying various features of the wind resource have been prepared for selected stations in each state and are presented in the state chapters. For each station presented, a brief description of the station's topographical setting and unique features is given in the text preceding the maps and graphs. The geographical area represented by a station varies, depending on the complexity of the local terrain and variability of the wind resource.

A table listing the stations for which graphs and summaries of the features of the wind resource are presented precedes the series of graphs. Height adjustments were made only to obtain estimates of the average wind speed and power at 10 m (33 ft) and 50 m (164 ft) given in this table. No attempt was made to adjust to a reference height any of the other wind characteristics (*e.g.*, diurnal wind speeds, frequency distributions of wind speed, wind direction, speed and power duration, etc.) presented in the graphs for selected stations. Caution should therefore be used in comparing and interpreting station plots.

In the plots of interannual wind power and speed, the first line of each graph contains the station name and state. The second line contains the WBAN number. In all other plots, the first line on each station graph contains the station identification that corresponds to the name and location listed in the table and the month and year of the selected period of record. Only one period of record with constant anemometer height was plotted for most stations, even though some stations had several periods of record. However, if there was uncertainty as to which period

had better anemometer exposure or if two periods with similar exposure indicated substantially different wind characteristics, two periods of record were plotted. Usually, periods when the anemometer was located on a mast directly on the ground were preferred to periods when the anemometer was located on the roof of a building.

The second line of each station graph contains the WBAN number, the anemometer height (Z) in m and location, and the annual average wind speed (V) in m/s and wind power (P) in watts/m². V and P are adjusted to 10 m for the graphs of interannual and monthly average wind power and speed and are at anemometer height, Z, for all other graphs.

The coded information listed with the anemometer height is one of the following (Changery 1978):

- R - indicates the anemometer was located on the roof of a control tower, operations building, hangar or other similar structure. Normal mast heights were 2 to 4 m (6 to 12 ft) above roof line; however, many inner-city locations used considerably taller masts. The listed height is elevation above ground level, not roof level; the R indicates an exposure type.
- G - indicates the anemometer was located on a mast attached directly to the ground. Most anemometers at airport locations changed from a roof to ground exposure by the early 1960s.
- B - indicates a beacon tower exposure. For these locations, neither R nor G was considered satisfactory.
- UNK - indicates that documentation on instrument heights was not available.

If information on exposure was unavailable, no exposure code is given.

On a few station plots, an E follows the annual average wind power. If a pressure or temperature observation is missing, the wind power for that observation is computed using an air density based on station elevation. If the number of missing observations exceeds 25 per cent of the total, then an E is used to designate that the wind power is an estimated value.

Up to 18 graphs of the same type may appear on one page to allow for station-to-station comparison. The scale of each set of plots was determined by the maximum range of values found for all stations in the region.

2.2.1 Interannual Wind Power and Speed

The plots of interannual wind speed and power portray the variations of the yearly average over all periods of record. The beginning and ending of each period of record with constant anemometer height and location are designated by a "plus" symbol on the wind power curve and by a "diamond" symbol on the wind speed curve. If the anemometer height was unknown, a height of 10 m was assumed. Only yearly mean wind speeds based on 12 months' data (January through December) were plotted.

Year-to-year deviations from the long-term annual average may not be a reliable indicator of the deviations at nearby sites or areas (Elliott 1979b).

2.2.2 Monthly Average Wind Power and Speed

Graphs of the monthly average wind power and speed portray the monthly and seasonal trends of the wind. Stations with less than five years of observations may not show reliable seasonal trends. Also, stations in complex terrain may not represent the seasonal trends in nearby areas because of the influence of nearby terrain. Most of the station curves are within the 0 to 400 watts/m² range with the exception of some coastal stations.

2.2.3 Diurnal Wind Speed by Season

The diurnal variation in wind speed according to seasons is plotted on graphs containing four curves, one for each season. Local standard time (LST) is used with hour 24 as midnight and hour 1 as the beginning hour. For National Weather Service and Federal Aviation Administration stations, the diurnal curves are usually based on 24 observations daily for periods ending before 1965, and on 8 observations daily for periods ending after 1964. For Air Force stations, the diurnal curves are usually based on 24 observations daily regardless of the period. The diurnal curves for Navy stations are based on 24 observations daily for periods ending February 1972. The diurnal curves for University of Hawaii and LLL stations are based on 24 hourly averages computed from more frequent readings.

2.2.4 Directional Frequency and Average Speed

Graphs of the annual average frequency of occurrence show the percentage of time that the observed wind direction was from each of 16-point compass sectors and the average wind speed of all observations in each sector. Some stations show a definite bias toward 8-point compass observations. The coincidence of peaks in the two curves indicates that the highest wind speeds occur from the prevailing directions. Caution should be used in applying these data to other sites, because nearby terrain and obstructions strongly influence the wind directions. Some of the directional data presented may not be reliable or representative because of the anemometer location.

2.2.5 Annual Average Wind Speed Frequency

Graphs of the annual average frequency of observed wind speeds are shown in 1 m/s intervals about each whole m/s wind speed. Along with the observed distribution, a Rayleigh wind speed distribution based on the annual mean speed is shown. Some of the stations show pronounced peaks in the observed distribution; these peaks reflect observer bias toward certain wind speeds, such as 2, 5, and 8 m/s (5, 10 and 15 knots). This bias occurs more frequently in records from before 1960. Because many of the wind instruments used had a threshold velocity of about 1.5 m/s (3 knots), the frequency of observations in the 1 m/s class is often lower than the frequency of the calm and 2 m/s classes.

2.2.6 Annual Average Wind Speed and Power Duration

The percentage of time that a given wind speed or power is exceeded is shown in two sets of graphs. Abrupt changes in the slope of the duration curves for speed and power usually correspond to peaks in the speed frequency distribution caused by observer bias and instrument threshold velocity. Points are plotted at 1 m/s intervals for the speed duration curves. Points are plotted every 50 watts/m² up to 500 watts/m² and every 100 watts/m² up to 1,000 watts/m² in the power duration curves.

H A W A I I

CHAPTER 3: HAWAII

The Hawaiian Islands (Figure 3.1) cover an area of 16,710 km² (6450 mi²) and have a population of 1,000,000 (1980 estimate). The island of Hawaii comprises nearly two-thirds of the land area (Table 3.1). Over eighty per cent of the residents in the state live on the island of Oahu (Table 3.1). Major cities on the neighbor islands are Lihue, Kauai; Kahului, Wailuku, and Lahaina, Maui; and Hilo and Kailua-Kona, Hawaii (Figure 3.2).

These islands are the peaks of submarine volcanoes (see Figure 3.3). Local relief exceeds 900 m on most of the islands (Figure 3.4). Fifty per cent of the land area lies above 600 m (2000 ft) elevation and nearly fifty per cent lies within 8 km (5 miles) of the coastline.

Interaction of trade winds with Hawaiian topography produces variable microclimates. During trade wind conditions, insolation heating triggers mesoscale circulations which contribute to strong diurnal variations in winds, clouds, and precipitation. At Hilo at the windward foot of Mauna Loa (4172 m) the prevailing wind is west-southwest even though offshore it is east-northeast. Nocturnal drainage winds cause this feature. At Hilo, the highest rainfall frequency is at midnight while at Kealahou (600 m) on leeward Mauna Loa peak rainfall frequency is at 5:00 pm.

The maritime influence is seen in the annual variation of temperature. At Hilo, the difference between mean January and mean August temperatures is 5 °F (2.8 °C). At Mauna Loa Observatory (elev. 3400 m) the difference is 6 °F (3.3 °C). The mean temperature at Hilo is 74 °F (23 °C); at Mauna Loa, 44 °F (7 °C). At higher elevations, snow and ice are a problem during winter. In extreme cases, the ice-snow boundary has been as low as 2130 m (7000 ft). Mauna Loa and Mauna Kea are often snow-capped throughout the winter.

Annual precipitation varies from 75 to 125 cm (30 to 50 in.) at windward coasts, to over 1000 cm (400 in.) at crests on Kauai and Maui, to 25 cm (10 in.) or less on leeward coasts. On the higher mountains such as Mauna Loa, Mauna Kea, and Hualalai (2522 m) which lie above the trade wind inversion, rainfalls decrease with elevation above 1500 m. Most precipitation falls from orographic showers though thunderstorms occur a few times per year.

Significant weather systems other than the trade winds include winter cold fronts, "Kona" storms (or subtropical cyclones), and tropical cyclones. These systems produce heavy rains and locally strong winds. Their frequency is so low, however, as to preclude them as significant wind energy sources.

Wind data are fairly abundant in the coastal regions of all major islands (Figure 3.5) but are sparse in the mountainous regions. Wind power assessment programs within the state provide a significant number of additional stations. Of 11 fire weather stations, we retained 5 for use in the analysis (Figure 3.6).

3.1 ANNUAL AVERAGE WIND POWER

Interactions between prevailing trade winds and island topography determine the distribution of wind power. On all major islands (Figure 3.7) trades accelerate over coastal regions at the corners. The best examples are regions of class 6 or higher wind power on Oahu, Kauai, Molokai, and Hawaii. The rampart-like mountain crests of Oahu enhance prevailing winds to class 6. On other islands, circular mountain shapes and extreme elevations prevent the type of wind acceleration observed on the Oahu ranges.

The primary wind resources in Kauai County are on the southeast and northeast coasts of Kauai where trades accelerate

TABLE 3.1. Land Area and Maximum Elevation of Principal Hawaiian Islands

Island	Area		Peak Elevation		Population (1970)	Population per km ²
	km ²	mi ²	m	ft		
Hawaii	10453	4038	4206	13796	63468	6.1
Maui	1885	728	3056	10023	38691	20.5
Oahu	1573	608	1232	4040	630497	400.8
Kauai	1432	553	1598	5240	29524	20.6
Molokai	676	261	1515	4970	5261	7.8
Lanai	361	140	1027	3370	2204	6.1
Niihau	189	73	391	1281	237	1.3
Kahoolawe	116	45	450	1477	0	0

around the island barrier. The plain around and north of Lihue is class 3 becoming class 1 as trades stagnate at the base of Mount Waialeale. A ridge crest estimate for the central mountain is class 2 based on Lihue upper-air data and limited observations. Sea breezes dominate in the leeward regions, which are class 1.

Niihau lies partly in the wind shadow of Kauai. It has some relief (391 m) and some local high wind spots may exist. The island is privately owned and has a population of 237 (1970).

Oahu (Honolulu County) has over 80 per cent of the population and consumes 90 per cent of Hawaii's electric power. The long Koolau mountain rampart and shorter Waianae Range enhance trades to class 6 although the rugged topography, watershed value, and turbulent air flows over these ranges probably preclude practical application of wind power generation. The northeast (Kahuku) and southeast (Kokohead) tips of Oahu are class 7 with broad areas of class 4 or higher. Another class 4 region exists at Kaena Point on the northwest tip. Much of the area to the lee of the Koolaus and Waianaes is class 1. Trades return with some strength (class 3) near Pearl Harbor and accelerate slightly around the south tip of the Waianaes.

Maui County has 3 principal islands. Molokai is unique among the major Hawaiian Islands in that it lies almost parallel to the prevailing trades. Much of the northwest quadrant is class 4 or above, becoming class 7 at Ilio Point. The only significant eolian features are found in northwest Molokai. A narrow belt of class 4 lies on the southeast coast. The rugged eastern mountain is class 2.

Maui includes Haleakala (3056 m), which penetrates the trade wind layer. Strong winter westerlies are a major component in the class 3 rating for the summit. The primary wind resource lies in the central valley where trades accelerate between Haleakala and West Maui volcano existing as class 5 and 7 near Maalaea Bay. Secondary power resources exist at the extreme north (class 4) and southeast (class 3) tips.

Lanai lies partly in the wind shadow of West Maui. Nevertheless, deformed trees indicate that winds are slightly accelerated (class 4) over the northwest third of Lanai. This area is exposed to winds funneling through the Pailolo Channel between Maui and Molokai.

Kahoolawe is an unpopulated military bombing target. It lies to the lee of Haleakala and is considered as class 2.

Hawaii comprises 62.5 per cent of the total land area of the state. The island consists of five major mountains and the saddles between them. The tall volcanoes, Mauna Loa and Mauna Kea, provide a barrier to the trade winds, producing a stagnation which extends well upwind of Hilo. Trades diverted to the north of Mauna Kea accelerate through the Waimea saddle and over the Kohala Mountains, producing a significant wind power resource. Rugged topography on the windward side of the Kohalas reduces the impact of the strong winds but on the smooth uplands and mountain flanks and at Waimea wind turbines could easily provide 100 per cent of the island's electricity. A smaller resource exists at the south cape. The east rift of Kilauea volcano has few measured winds and the estimate of class 2 is intentionally conservative.

The sea breeze dominates leeward areas. These regions as well as much of the slopes of Mauna Loa and Mauna Kea are only class 1.

3.1.1 Certainty Rating of the Wind Resource

Certainty ratings of 4 are rare in Hawaii because the complex terrain creates strong mesoscale wind variability. In Kauai County (Figure 3.8) the certainty rating for the immediate vicinity of Lihue is 4. Certainty values are 1 for the central mountain, which is extremely eroded and undocumented. Wind power research efforts have concentrated on the southeast coast, which has a certainty rating of 3 as does the light wind area near Barking Sands. Niihau has a certainty rating of 1.

The coastal plains of Oahu near Honolulu Airport and Kaneohe have certainty ratings of 4. The Kahuku area (which has been intensively instrumented), the central saddle, and the coastal plains near Barbers Point have certainty ratings of 3. We have assigned ratings of 2 to the Oahu mountains because the University of Hawaii has established several monitoring stations in those areas. The extreme complexity of the mountain terrain precludes assigning a higher certainty rating.

Much of Maui County has complex terrain and/or no historic wind data. For these reasons, much of the county has certainty ratings of 1 and 2. Ratings of 3 are limited to the central valley of Maui, the summit of Haleakala, and the extreme eastern tip of Maui.

Terrain on the Big Island is the smoothest in the state. The immediate vicinities of Hilo Airport and Kona Airport have certainty ratings of 4. Much of the Kohala wind resource has a certainty rating of 3, as does much of the leeward Mauna Loa. Certainty ratings of 1 were assigned to the southeast

coastal areas where a wind resource may exist but is undocumented.

3.1.2 Areal Distribution

The areal distribution of wind power in Hawaii is illustrated in Figure 3.9. Although class 5 and higher wind power is predicted in 11.4 per cent of the grid cells, only 3.9 per cent of the land area is estimated to experience these power densities (see Table 3.2) because a low percentage of land area in mountainous terrain has the map value of wind power. Significant areas of each county appear in the maps of wind power class 5 or greater. Percentages of land area of class 2 or greater vary from 36.5 per cent for Oahu to 17.4 per cent for Hawaii. The Big Island provides 70 per cent of the class 1 area for the state. Every grid cell in the state has a significant fraction (10 to 100%) of area with only class 1 wind power because of local sheltering by surrounding higher terrain in mountainous regions or large-scale sheltering afforded by high mountains such as Mauna Loa and Mauna Kea.

3.2 SEASONAL WIND POWER

Wind power maps for each season are shown in Figure 3.10. The season for maximum wind power is summer over most of the state. The exceptions are at the summits of the high mountains of Maui and Hawaii. Autumn is the season of lowest wind power.

3.2.1 Winter

During winter, the trades, though prevalent, are less frequent though migratory anticyclones can produce strong trades for prolonged periods. Low pressure systems and intense cold fronts occasionally produce strong southwesterly and westerly winds. However, these systems do not occur often enough to alter the basic power density distributions. Wind power is greatest on coastal corners exposed to prevailing trades. The ridge crest estimate of class 5 for Oahu's mountains is probably low because the University of Hawaii measurements were made during exceptionally calm winters.

Winds aloft are stronger during winter and the observations show that the summits of Mauna Loa and Mauna Kea on Hawaii and Haleakala on Maui experience highest wind power densities in winter. Unfortunately, often these high power densities arise with winter storms which, in addition to damaging wind strengths (30 m/s or more), produce snow and icing. In rare instances, snow and ice have extended below 2130 m (7000 ft).

Elsewhere on Maui and Hawaii, power density patterns resemble the annual distributions. The Kohala and South Point areas of

the Big Island experience wind power of class 7 as does Ilio Point on northwest Molokai. Each county has some area of class 6.

3.2.2 Spring

In spring, trade wind frequencies increase and migratory anticyclones produce high speeds for prolonged periods. In the mountains of Oahu and along the upper slopes of Haleakala, Maui, spring is the season of maximum wind power. Elsewhere, spring is the season of a secondary maximum. Each county has regions with power estimates of class 6 or higher. On the island of Hawaii, the wind belt in the Kohalas extends southward as strong trades reach farther down the lee slope.

3.2.3 Summer

Summer is the season of maximum trade wind frequency and, in most regions, maximum wind power. Trade wind steadiness (defined as the ratio of resultant mean speed to mean wind speed) is typically 90 per cent. In each county, some region experiences class 7 wind power and significant sections class 6. The summer trade winds are probably the steadiest wind power source in the United States.

3.2.4 Autumn

Autumn is a transition period marked by a gradual weakening of the North Pacific anticyclone and the first southward advances of cold fronts. Winds are weaker throughout the state. Nevertheless, the Kahuku region of Oahu and the Kohala mountains of Hawaii continue to experience class 7 wind power. The most dramatic wind power decrease is in northeast Kauai, where Kilauea Point drops from a summer rating of class 7 to class 3. Even in this relatively weak wind season, regions of class 6 wind power densities exist in each county.

3.3 FEATURES OF SELECTED STATIONS

Table 3.3 gives the location and annual wind speed and power density of eighteen stations in Hawaii. Graphs of other features of the wind resource at these stations are shown in Figures 3.11 to 3.17. Seven of these are University of Hawaii or LLL stations and are located in known windy locations.

Barbers Point is on the Ewa plain of leeward Oahu.

Barking Sands, in southwestern Kauai, is sheltered from the prevailing trade winds. Sea breezes and land breezes dominate.

French Frigate Shoals, an atoll in the northwest Hawaiian Islands, has an unknown

anemometer height but provides useful information on wind characteristics other than speed.

Hilo, on the Big Island of Hawaii, lies in the stagnation created by massive Mauna Loa. Sea breezes and mountain drainage winds dominate.

Honolulu is well exposed to trade winds and winter storm winds.

Kaena Point lies on a cliff on the northwest tip of Oahu. It is well exposed to north and northwest winds but is moderately to poorly exposed to other directions.

Kahua Ranch is at 1170 meters on the windy northwest flank of the Kohala Mountains on the Big Island of Hawaii. The bulk of Mauna Kea to the south and the smooth Kohala slopes produce extreme speed enhancements.

Kahuku Hill, on the windswept northeast tip of Oahu, is well exposed to prevailing trades.

Kahului, Maui, at the entrance to the wind corridor of central Maui, is the windiest first-order weather station in Hawaii. West Maui mountain forces trades to shift to a more northerly direction.

Kaneohe Bay, on the east side of Oahu, is well exposed to trades and is subjected occasionally to extremely strong downslope southerly or westerly winds.

Kokohead, near the southeastern corner of Oahu, is a smooth cinder cone abreast the windy channel between Oahu and Molokai.

Lihue, located on the eastern coast of Kauai, is well exposed to trades and winter storm winds.

Molokai Airport lies at the eastern edge of the windy northwest Molokai wind region.

Port Allen, lies near the western end of the windy area along the southeastern coast of Kauai.

Puunene at the central portion of the central Maui valley experiences more northerly directions than Kahului.

Tantalus Tower is atop a cinder cone in the heavily-forested Koolau range of Oahu.

Waimea Airport, well exposed to trades funneled through the 800 m elevation saddle between Mauna Kea and the Kohala Mountains on the Big Island of Hawaii, is the windiest airport in the state.

Wahiawa/Wheeler Field sits in the saddle between the Koolau and Waianae ranges of Oahu. The Koolaus provide a shelter from most trade winds.

3.3.1 Interannual Wind Power and Speed

Six stations: Barbers Point, Hilo, Honolulu, Kahului, Kaneohe Bay, and Lihue, have selected periods of record of 10 years or more during which the anemometer was not moved. Interannual variations for similarly exposed stations may coincide. Mesoscale circulations at Hilo do not vary much in strength and Hilo's interannual variability is quite small. Ratios of highest to lowest annual wind power typically are below 2.0.

3.3.2 Monthly Average Wind Power and Speed

Most stations well exposed to trades show maximum wind power in July and a secondary maximum in the spring (March-April), when migratory anticyclones cause strong trades (Figure 3.12). Barking Sands, located in the lee of a high mountain, has higher wind power in the winter due to storm winds.

3.3.3 Diurnal Wind Speed by Season

Stations at low elevations generally have highest wind speeds in the afternoon, 1200 to 1500 local standard time (LST) (Figure 3.13). Amplitude of diurnal wind speed variations is lowest for stations at windward coasts, e.g., Lihue, Kaneohe Bay, Kokohead. Open ocean winds have almost no diurnal variation as seen at French Frigate Shoals. At elevations above 500 m the diurnal variation patterns differ from those near sea level. Both Tantalus Tower and Kahua Ranch have mid-day minima.

3.3.4 Directional Frequency and Average Speed

All stations except Barbers Point, Barking Sands and Hilo show maximum wind speed from prevailing trade winds (Figure 3.14). The prevailing direction at each station varies slightly due to topographic influences; for example, at Kahului, it is northeast, at Honolulu, east northeast.

At Barbers Point, trades prevail but significant speeds are from southeast through west. At Barking Sands, peak speeds are from south and north, both directions paralleling the coastline.

At Hilo, the trades produce highest speeds but do not dominate, the most frequent direction being southwest.

3.3.5 Annual Average Wind Speed Frequency Distribution

Because observer bias and low instrument threshold speeds so distort the observed frequency distribution (Figure 3.15), the representativeness of the Rayleigh speed distribution is hard to evaluate. Observer biases are obvious at Honolulu, Kahului, Lihue and Puunene, which have hourly observations. Data from stations such as Tantalus Tower and Waimea Airport are digitized six-minute integrated data. The goodness-of-fit

of the Rayleigh distribution is much better at these sites.

3.3.6 Annual Average Wind Speed and Power Duration

The percentage of time that a given wind speed or power is exceeded is shown in Figures 3.16 and 3.17. Abrupt changes in the slope of the duration curves correspond to peaks in the speed frequency distribution caused by observer bias and instrument threshold velocity.

FIGURE 3.1. Geographic Map of the Hawaiian Island Chain.

FIGURE 3.2. Geographic Map of Kauai County (Top) and Honolulu County (Bottom). Northwest Hawaiian Islands are part of Honolulu County but are excluded in this analysis.

FIGURE 3.2 (Continued). Geographic Map of Maui County (Top) and Hawaii County (Bottom).

FIGURE 3.3. Shaded Topographic Map of Hawaii.

LAND-SURFACE FORM LEGEND

PLAINS

A1	FLAT PLAINS
A2	SMOOTH PLAINS
B1	IRREGULAR PLAINS, SLIGHT RELIEF
B2	IRREGULAR PLAINS

TABLELANDS

B3c,d	TABLELANDS, MODERATE RELIEF
B4c,d	TABLELANDS, CONSIDERABLE RELIEF
B5c,d	TABLELANDS, HIGH RELIEF
B6c,d	TABLELANDS, VERY HIGH RELIEF

PLAINS WITH HILLS OR MOUNTAINS

A, B3a,b	PLAINS WITH HILLS
B4,a,b	PLAINS WITH HIGH HILLS
B5a,b	PLAINS WITH LOW MOUNTAINS
B6a,b	PLAINS WITH HIGH MOUNTAINS

SCHEME OF CLASSIFICATION

SLOPE (1st LETTER)

A	>80% OF AREA GENTLY SLOPING
B	50-80% OF AREA GENTLY SLOPING
C	20-50% OF AREA GENTLY SLOPING
D	<20% OF AREA GENTLY SLOPING

OPEN HILLS AND MOUNTAINS

C2	OPEN LOW HILLS
C3	OPEN HILLS
C4	OPEN HIGH HILLS
C5	OPEN LOW MOUNTAINS
C6	OPEN HIGH MOUNTAINS

LOCAL RELIEF (2nd LETTER)

1	0 TO 30m (1 TO 100 ft)
2	30 TO 90m (100 TO 300 ft)
3	90 TO 150m (300 TO 500 ft)
4	150 TO 300m (500 TO 1000 ft)
5	300 TO 900m (1000 TO 3000 ft)
6	900 TO 1500m (3000 TO 5000 ft)

HILLS AND MOUNTAINS

D3	HILLS
D4	HIGH HILLS
D5	LOW MOUNTAINS
D6	HIGH MOUNTAINS

PROFILE TYPE (3rd LETTER)

a	>75% OF GENTLE SLOPE IS IN LOWLAND
b	50-75% OF GENTLE SLOPE IS IN LOWLAND
c	50-75% OF GENTLE SLOPE IS ON UPLAND
d	>75% OF GENTLE SLOPE IS ON UPLAND

FIGURE 3.4. Classes of Land-Surface Form in Kauai County (Top) and Honolulu County (Bottom). Land-surface forms are based on the classification scheme of Hammond (1964).

FIGURE 3.4 (Continued). Classes of Land-Surface Form in Maui County (Top) and Hawaii County (Bottom).

FIGURE 3.5. NCC and University of Hawaii Station Locations in Kauai County (Top) and Honolulu County (Bottom).

FIGURE 3.6. Location of Stations used in Kauai County (Top) and Honolulu County (Bottom) Wind Assessments.

FIGURE 3.6 (Continued). Location of Stations used in Maui County (Top) and Hawaii County (Bottom) Wind Assessments.

FIGURE 3.7. Kauai County (Top) and Honolulu County (Bottom) Annual Average Wind Power. Numbers are wind power classes (see section 1.7).

FIGURE 3.7 (Continued). Maui County (Top) and Hawaii County (Bottom) Annual Average Wind Power.

Classes of Wind Power Density at 10 m and 50 m^(a)

Wind Power Class	10 m (33 ft)		50 m (164 ft)	
	Wind Power Density watts/m ²	Speed ^(b) m/s (mph)	Wind Power Density watts/m ²	Speed ^(b) m/s (mph)
	0	0	0	0
1	100	4.4 (9.8)	200	5.6 (12.5)
2	150	5.1 (11.5)	300	6.4 (14.3)
3	200	5.6 (12.5)	400	7.0 (15.7)
4	250	6.0 (13.4)	500	7.5 (16.8)
5	300	6.4 (14.3)	600	8.0 (17.9)
6	400	7.0 (15.7)	800	8.8 (19.7)
7	1000	9.4 (21.1)	2000	11.9 (26.6)

(a) Vertical extrapolation of wind speed based on the 1/7 power law.

(b) 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 5%/5000 ft (3%/1000 m) of elevation.

TABLE 3.2. Areal Distribution (km²) of Wind Power Classes in Hawaii

Power Class	Land Area	% Land Area	Cumulative Land Area	% Cumulative Land Area
1	12464	76.60	16272	100.00
2	1593	9.79	3808	23.40
3	735	4.52	2215	13.61
4	838	5.15	1480	9.09
5	176	1.08	642	3.94
6	301	1.85	466	2.80
7	164	1.01	164	1.01

CERTAINTY RATING LEGEND

Rating	Definition
1	<p>The lowest degree of certainty. A combination of the following conditions exists:</p> <ol style="list-style-type: none"> 1) No data exist in the vicinity of the cell. 2) The terrain is highly complex. 3) Various meteorological and topographical indicators suggest a high level of variability of the resource within the cell.
2	<p>A low-intermediate degree of certainty. One of the following conditions exists:</p> <ol style="list-style-type: none"> 1) Little or no data exist in or near the cell, but the small variability of the resource and the low complexity of the terrain suggest that the wind resource will not differ substantially from the resource in nearby areas with data. 2) Limited data exist in the vicinity of the cell, but the terrain is highly complex or the mesoscale variability of the resource is large.
3	<p>A high-intermediate degree of certainty. One of the following conditions exists:</p> <ol style="list-style-type: none"> 1) There are limited wind data in the vicinity of the cell, but the low complexity of terrain and the small mesoscale variability of the resource indicate little departure from the wind resource in nearby areas with data. 2) Considerable wind data exist but in moderately complex terrain and/or in areas where moderate variability of the resource is likely to occur.
4	<p>The highest degree of certainty. Quantitative data exist at exposed sites in the vicinity of the cell and can be confidently applied to exposed areas in the cell because of the low complexity of terrain and low spatial variability of the resource.</p>

FIGURE 3.8. Certainty Rating of Kauai County (Top) and Honolulu County (Bottom) Wind Resources. Ratings apply to 1/8° by 1/8° grid squares.

FIGURE 3.8 (Continued). Certainty Rating of Maui County (Top) and Hawaii County (Bottom) Wind Resources.

FIGURE 3.9. Areal Distribution of Wind Resource in Kaula County (Class 2--Top; Class 3--Bottom). Numbers indicate the percentage of land area within the grid square which has wind power class 2 (Top) (Class 3--Bottom) or greater.

FIGURE 3.9 (Continued). Areal Distribution of Wind Resource in Kauai County (Class 4--Top; Class 5--Bottom).

FIGURE 3.9 (Continued). Areal Distribution of Wind Resource in Honolulu County (Class 2--Top; Class 3--Bottom).

FIGURE 3.9 (Continued). Areal Distribution of Wind Resource in Honolulu County (Class 4--Top; Class 5--Bottom).

FIGURE 3.9 (Continued). Areal Distribution of Wind Resource in Maui County (Class 2--Top; Class 3--Bottom).

FIGURE 3.9 (Continued). Areal Distribution of Wind Resource in Maui County (Class 4--Top; Class 5--Bottom).

FIGURE 3.9 (Continued). Areal Distribution of Wind Resource in Hawaii County (Class 2--Top; Class 3--Bottom).

FIGURE 3.9 (Continued). Areal Distribution of Wind Resource in Hawaii County (Class 4--Top; Class 5--Bottom).

FIGURE 3.10. Seasonal Average Wind Power in Kauai County (Winter--Top; Spring--Bottom).

FIGURE 3.10 (Continued). Seasonal Average Wind Power in Kauai County (Summer--Top; Autumn--Bottom).

FIGURE 3.10 (Continued). Seasonal Average Wind Power in Honolulu County (Winter--Top; Spring--Bottom),

FIGURE 3.10 (Continued). Seasonal Average Wind Power in Honolulu County (Summer--Top; Autumn--Bottom).

FIGURE 3.10 (Continued). Seasonal Average Wind Power in Maui County (Summer--Top; Autumn--Bottom).

FIGURE 3.10 (Continued). Seasonal Average Wind Power in Maui County (Winter--Top; Spring--Bottom).

FIGURE 3.10 (Continued). Seasonal Average Wind Power in Hawaii County (Winter--Top; Spring--Bottom).

FIGURE 3.10 (Continued). Seasonal Average Wind Power in Hawaii County (Summer--Top; Autumn--Bottom).

TABLE 3.3. Hawaii Stations with Graphs of the Wind Characteristics

County	Station Name ^(a)	Latitude Degrees	Longitude Degrees	Elevation of Station, m	Period of Record Month/Year	Anemometer Height, m	Annual Average Wind Speed, m/s				Annual Average Wind Power, watts/m ²		
							At Anemometer Height, m	At 10 m	At 50 m		At Anemometer Height, m	At 10 m	At 50 m
Honolulu	Barbers Point NAS	21.32N	158.67W	15	04/59-02/72	3.7	3.5	4.0	5.1	50	77	153	
Kauai	Barking Sands Naval Facility	22.03N	159.78W	4	01/73-02/76	4.3	2.1	2.3	2.9	25	36	72	
NW Hawaii (Honolulu) ^(c)	French Frigate Shoals, NAS	23.78N	166.22W	2	04/45-04/48	Unk ^(b)	6.7	6.7	8.4	289	289	576	
Hawaii	Hilo Airport	19.72N	155.07W	10	06/66-12/78	6.4	2.9	3.1	3.9	27	33	65	
Honolulu	Honolulu Airport	21.33N	157.92W	5	07/66-12/78	7.6	5.4	5.6	7.0	149	167	334	
Honolulu	Kaena Point Tower, UH Site	21.57N	158.25W	384	06/75-11/79	9.1	5.9	5.9	7.4	231	233	464	
Hawaii	Kahua Ranch UH Site	20.13N	155.78W	1166	10/77-12/78	9.1	11.2	11.4	23.2	1507	1569	3127	
Honolulu	Kahuku Hill LLL Site	21.67N	158.00W	296	07/76-10/78	9.1	8.5	8.6	10.8	541	563	1123	
Maui	Kahului Airport	20.90N	156.43W	14	10/63-12/78	6.4	5.5	5.8	7.3	174	211	420	
Honolulu	Kaneohe Bay MCAS	21.45N	157.78W	3	05/68-12/78	4.0	4.5	5.1	6.4	93	138	276	
Honolulu	Koko Head UH Site	21.27N	157.70W	195	08/75-10/79	10.7	8.0	7.9	10.0	418	406	809	
Kauai	Lihue Airport	21.98N	159.35W	36	07/64-12/78	6.1	5.2	5.6	7.1	120	148	296	
Maui	Molokai Airport UH Site	21.32N	157.10W	139	07/77-12/79	6.1	5.6	6.0	7.7	170	210	419	
Kauai	Port Allen CAA	21.90N	159.60W	9	10/49-11/50	8.8	6.2	6.3	7.9	212	224	446	
Maui	Puunene, CAA	20.83N	156.47W	40	11/49-12/58	9.4	4.5	4.5	5.7	118	121	241	
Honolulu	Tantalus Tower UH Site	21.33N	157.82W	613	06/76-08/79	21.3	8.2	7.4	9.3	652	472	940	
Hawaii	Waimea Airport UH Site	20.00N	155.67W	814	10/77-01/80	6.1	7.4	7.9	10.0	417	515	1027	
Honolulu	Wahiawa Wheeler AFB	21.48N	158.02W	252	07/63-12/70	4.9	2.8	3.1	4.0	43	58	117	

^(a) NAS-Naval Air Station; UH-University of Hawaii; LLL-Lawrence Livermore Laboratory; MCAS-Marine Corps Air Station; CAA-Civil Aeronautics Administration Facility; AFB-Air Force Base.

^(b) Unk-Anemometer height is unknown. Height of 10m was assumed for estimating wind speed and power at 10 and 50 m.

^(c) The Hawaiian islands to the northwest of Kauai County are administered by various federal agencies and are usually considered to be a part of the City and County of Honolulu.

FIGURE 3.11. Interannual Wind Power and Speed for Hawaii. Note ranges of the ordinates vary with each station's wind strength.

FIGURE 3.12. Monthly Average Wind Power and Speed for Hawaii.

FIGURE 3.13. Diurnal Wind Speed by Season for Hawaii.

— PERCENT FREQUENCY LEFT ORDINATE - PERCENT
 - - - WIND SPEED RIGHT ORDINATE - M/S
 PNL-3195 WERA-11
 ABCISSA - WIND DIRECTION

FIGURE 3.14. Directional Frequency and Average Speed for Hawaii.

— ACTUAL DISTRIBUTION ORDINATE - PERCENT
 - - - RAYLEIGH DISTRIBUTION ABSCISSA - M/S
 PNL-3195 WERA-11

FIGURE 3.15. Annual Average Wind Speed Frequency for Hawaii.

ORDINATE - PERCENT
ABSCISSA - M/S
PNL-3195 WERA-11

FIGURE 3.16. Annual Average Wind Speed Duration for Hawaii.

ORDINATE - PERCENT
ABSCISSA - WATTS/M²
PNL-3195 WERA-11

FIGURE 3.17. Annual Average Wind Power Duration for Hawaii.

PACIFIC ISLANDS

CHAPTER 4: PACIFIC ISLANDS

The 2200 Pacific Islands affiliated with the United States (Figures 4.1 and 4.2) are set in millions of square kilometers of ocean. The land area is only 2621 km² (1012 mi²) and the population is approximately 230000. Table 4.1 lists the major island groups and estimated populations.

The islands are of two types: high islands and atolls. The former, which are less than 1000 m high, include the Northern Marianas, Guam, American Samoa, and several of the Carolines. Most of the islands are atolls, which may not rise more than 5 m above the ocean.

The climate in all regions is tropical. The Carolines and Marshalls lie within the area of the near equatorial convergence. Within this region, weather is dominated by light winds and humid, showery conditions. The eastern islands, Johnston, Midway and the Marshalls, lie under the influence of the trades generated by the Pacific anticyclone. The trades weaken in the western Pacific though migratory anticyclones during winter provide brisk northeasterlies.

Samoa experiences southern hemispheric trades during winter. In summer, a monsoonal trough develops eastward from Australia causing weak winds interrupted by tropical cyclones.

Tropical storms are major components of the climate of the Pacific Islands. Guam has

been hit by some of the most devastating typhoons on record. Tropical storms are primarily late summer and early fall features, but have occurred in all months.

Local influences on climate vary with island type. Atolls exert little influence on the prevailing air streams. Diurnal variations match those observed for the open oceans. High islands, especially in areas of light synoptic winds such as at Ponape, produce significant local effects on cloudiness and precipitation.

Wind data are sparse (Figure 4.3). Approximately half of the documented stations have questionable anemometer exposures or elevations due to the lack of adequate documentation. No organized wind measurement programs exist although some interest has been shown by groups in Guam, the Northern Marianas and Palau.

4.1 ANNUAL AVERAGE WIND POWER

Figure 4.4 is a map of ocean wind power classes based on the ship wind collection (Wyrski and Meyers, 1975) using 6 years of data (1965-1970) and a Rayleigh distribution. Data are based on 2° latitude by 10° longitude rectangles. Wind power densities are plotted for each island group (Figure 4.5). In all instances, open ocean wind power exceeds island values. This is true even for small atolls. Apparently, well-exposed sites are rare on small islands. Site descriptions

TABLE 4.1. Number of Islets, Areas, and Populations for Major Pacific Islands Groups.

Island or Group	Number of Islets	Land Area		Population
		km ²	mi ²	
Guam	4	572	221	94579
Northern Marianas	21	477	184	12256
Carolines				
1) Kosrae	5	109	42	3743
2) Ponape	163	344	133	17065
3) Truk	290	127	49	29208
4) Yap	149	119	46	7247
5) Palau	350	495	191	12525
Marshalls	1225	181	70	20206
American Samoa	6	197	76	31171
TOTAL	2213	2621	1012	228000

consistently mention adjacent stands of coconut palms.

We did not adjust island wind power values by use of ocean wind powers because of evidence known to us indicating that real wind speed reductions occur on atolls. We rather plotted ocean values along with island data for the readers.

Guam is the only Pacific island outside of the Hawaiian chain with more than one wind station (Figure 4.3). Scientists on Guam made a series of spot measurements in the southern mountains during July and August 1976. Our analyses of these special data indicated that some enhancement occurs in Guam's mountains. The degree of enhancement was considerably less than in Hawaii due in part to the absence of a strong trade wind inversion. We concluded that the PNL ridge crest procedures were applicable for Guam. Average annual wind power density is class 2 over much of the island. Andersen AFB, on the plateau on what should be a windy island corner, is only class 2. Sheltered leeward locations such as Agana and Orote are class 1. Wind power estimates for the southern mountains indicate some class 3 areas probably exist. Tropical cyclones produce much of Guam's high winds and constitute a threat to wind energy systems. Detailed analysis of air flow over Guam during tropical cyclone passages should be undertaken before siting any large WECS.

The Marshall Islands lie in a belt of strong ocean winds and possess the best wind power potential of the major Pacific Islands groups. Ship wind power densities reach class 7 in the northern Marshalls but only class 4 in the south. With the exception of Enewetak and Kwajalein, island wind power densities differ drastically from the ship values. Enewetak's anemometer height is unknown. However, its estimated power density is probably inflated since in earlier years Pacific Islands anemometers were usually located higher than the 10 m assumed in our computations.

The Caroline group lies in a region of weaker ocean winds. The near-equatorial convergence migrating back and forth during the year accounts for weak winds, especially in the south. The islands lie well away from the major winter or summer trade wind belts. We employed ridge crest procedures to estimate power densities for Ponape and Kosrae, each of which is more than 600 m high. Since some wind power potential exists in the northern atolls such as Ulithi (class 3), we examined the Ulithi record in detail. Significant wind power occurs with cold air outbreaks from the Asian winter monsoon (trade winds) and with tropical storm

passages north of the chain (west or southwesterly winds).

The Northern Marianas, which extend 700 km in a nearly north-south line, are volcanic peaks, some with considerable relief [e.g. Asuncion reaches 891 m (2923 ft) in a surface area of 7.3 km² (2.8 mi²)]. Seven of the 14 islands were uninhabited in 1970. Wind power densities are similar to those of Guam. Ridge crest estimates for islands higher than 610 m (2000 ft) were based on interpolation of 850 mb winds from Guam and Iwo Jima (24°27'N, 141°20'E). Ship winds indicate power densities of class 5 to class 6 in surrounding waters.

American Samoa consists of 6 high islands. The main island, Tutuila, contains the only NCC station, Pago Pago. Surface and upper-level winds are light. We compared radiosonde winds with satellite-derived low-level winds in producing ridge-crest estimates (class 1) for the mountainous Manu'a Islands. Samoa seems to have little wind power potential.

We grouped Midway, Wake, and Johnston Islands for convenience even though they are widely separated. Each is a low coral island with negligible relief and little vegetation. The military is the prime tenant either directly as at Midway or via civilian contractors as at Johnston. The data on Midway indicate only class 2 power. However, ship data show class 6 power for the ocean area. Thus, exposed sites on Midway may have higher power than that estimated from the island data. Wind storms, which occasionally reach the main Hawaiian Islands to the southeast, contribute significantly to Midway's high winds.

At Johnston Atoll, 1500 km south-south-east of Midway, trades prevail throughout the year, yielding power density of class 5. Wake Island also has class 5 though most of the power comes from winter and spring migratory high pressure systems. Due to their remoteness and small populations, Wake and Johnston are ideal locations for wind energy development.

4.1.1 Certainty Rating of the Wind Resource

The wind power estimates for Guam have ratings that range from 3 in the windward and northern plateaus to 2 in leeward coasts and unmonitored coastal regions, and 1 in the rugged southern mountains (Figure 4.6). We based certainty ratings in the Marshalls upon documented history of anemometer exposures; terrain complexity is not a problem on atolls. Majuro and Kwajalein have wind power certainty ratings of 4; Jaluit and Utirik 3, and remaining anemometers 2. We assigned a certainty

rating of 2 to the wind power estimate at Enewetak because of the dubious anemometer height.

Anemometer exposure problems plague the Carolines and the Northern Marianas. Certainty ratings in both chains were considered as 3 for well-exposed and 2 for questionably exposed sites. The discrepancy between ocean- and land-based power estimates precluded the assignment of certainty ratings as high as 4. American Samoa has few surface wind observations and complex terrain but the weight of evidence from radiosondes and satellite-derived winds led us to assign a certainty rating of 2.

Wind observations at Midway, Johnston, and Wake Islands agree with synoptic climatology. In each location, anemometer exposures are good and terrain complexity is non-existent. We assigned certainty ratings of 4 to each wind power estimate.

4.1.2 Areal Distribution

The areal distribution of wind power in the Pacific Islands is shown in Tables 4.2 through 4.7. The southern mountains of Guam supply 90 per cent of the surface area of class 3 or higher power density (Table 4.2). The PNL procedures predict a 7 km² area of class 5 power density.

The Marshalls have no significant relief. Therefore, each island has one power density class. Twenty-nine per cent of the land area has class 4 or higher power density (Table 4.3). Several of the Carolines (*e.g.* Ponape, Kosrae) have significant relief. We estimate less than 5 per cent of the land area to be above class 1 power density (Table 4.4).

The Northern Marianas (Table 4.5) have considerably less percentage land area of class 3 or higher than does Guam. This is probably an artifact of the differing degrees of resolution attainable in the respective analyses. We expect that Saipan, Tinian and other southern islands have similar areal distribution of wind power density to Guam.

American Samoa has 47.5 per cent area estimated at greater than class 1 (Table 4.6), though nothing above class 3. The detached islands (Table 4.7) have one power density class per island.

4.2 SEASONAL WIND POWER

Wind power maps for each season are shown in Figure 4.7. The season of maximum wind power is winter over much of the region. Winter in American Samoa is June through August.

4.2.1 Winter

Cold air outbreaks from the Asian winter monsoon produce strong winter trade winds over the western North Pacific. The Marshalls, northern Carolines and Northern Marianas are exposed to ocean winds of power class 7. The southern mountains of Guam experience class 4 power density. In the Marshalls, wind power density at Kwajalein reaches class 6 and even poorly-exposed stations attain class 3. Ocean winds diminish from class 7 power density north of the Carolines to class 4 and 3 to the north. At Ulithi Atoll, winds produce a seasonal power peak at class 5. Brisk winds blow over the mountain crests of Ponape and Kosrae. Winds at Rota in the Northern Marianas approach open ocean power densities (class 6 versus class 7). We consider the power on windward Saipan as equal to windward Guam. Ridge crest estimates in the northern islands exceed those at Guam.

In American Samoa, winter trade winds produce higher power densities at Pago Pago than in the mountains. This is probably due to the differing data sources we employed for Samoa's mountains and lowlands. Ocean winds provide class 4 power densities. Each of the detached islands experiences maximum wind power in winter though the sources differ. Winter storms are important at Midway whereas trade winds produce the power at Johnston and Wake.

4.2.2 Spring

Open ocean winds diminish from winter peaks throughout the major island groups. On Guam, wind power decreases on the leeward coast but increases in the north and central regions. The area of class 3 or higher wind power densities is actually greater than for winter. In the Marshalls, a class 5 power density at Kwajalein compares favorably with class 6 ocean winds. The best locations in the Carolines are Ulithi at class 4 and the mountains of Ponape (class 5) and Kosrae (class 4). Exposed locations in the Northern Marianas experience class 3 power densities and ridge-crest estimates for higher islands are class 4.

In American Samoa, surface winds are weaker than in winter but upper-level winds are slightly stronger, yielding the maximum ridge-crest estimate for the Manu'a Islands. At Johnston and Wake Islands, power densities remain at class 6. At Midway, wind energy is two classes less than the winter maximum.

4.2.3 Summer

Power densities on Guam are class 1 except for a ridge crest power density of

class 2 in the southern mountains. The near-equatorial trough dominates weather over the Carolines and southern and central Marshalls. Ship winds indicate some useful power may still exist in the northern Marshalls. The Northern Marianas, like Guam, experience light winds. The monsoonal trough of northern Australia extends eastward over Samoa. Trade winds reach Johnston Island producing power densities of class 5. At Wake Island, wind power is much less than during spring.

4.2.4 Autumn

The weakened winds of summer persist into autumn. The light winds at Guam and the Northern Marianas are occasionally interrupted by tropical storms, which may contribute to the class 6 wind power densities over the oceans surrounding the Marianas. Nukuoro in the Carolines reports wind power densities of class 2 even though ocean winds indicate class 1 power density. At Johnston Island, autumn trades account for power density of class 4; at Wake Island, power density increases to class 5 after the class 3 minimum of summer. Winds at Midway remain light.

4.3 FEATURES OF SELECTED STATIONS

Table 4.8 gives the location and annual wind speed and power density of sixteen stations among the Pacific Islands. Graphs of other features of the wind resources at these stations are shown in Figure 4.8 to 4.14. Four of these are on one island, Guam. Many of these stations may not be well exposed to the winds.

CAROLINES

Koror lies southwest of mountainous Babelthup Island. It has a reported good local exposure though may be sheltered from the brisk winter northerly winds.

Ponape lies at the base of an 800 m mountain. The site is somewhat sheltered from the prevailing easterly trade winds.

Truk, in the central Carolines, is located on a high island in a complex of 98 islets. The airport is moderately exposed to trade winds. A 370 m mountain lies to the southeast.

Yap Island is the largest of a complex of fourteen islands. The airport lies in the heavily-vegetated southwest side of the island.

Guam has four stations. Agana lies in the leeward central portion, Andersen AFB on the plateau to the northeast, Orote on an extreme leeward location, and Taguac leeward of Andersen.

NORTHERN MARIANAS

Saipan is on the leeward side of a low mountainous island.

MARSHALLS

Enewetak, in the western portion of the Marshalls, has a questionable anemometer height but provides useful wind characteristics.

Kwajalein Atoll has similar wind characteristics to Enewetak and a known anemometer height.

Majuro Atoll, one of the Marshalls like Enewetak and Kwajalein, lies farther south away from strong trades.

SAMOA

Pago Pago is the only available station in American Samoa. It is centrally located on the main island, Tutuila.

JOHNSTON

Johnston Island is an atoll located in the belt of strong open ocean trades.

MIDWAY

Midway Island is actually an extreme northwest member of the Hawaiian group.

WAKE

Wake Island is an isolated atoll well exposed to all winds.

4.3.1 Interannual Wind Power and Speed

Five stations: Guam (Agana), Koror, Kwajalein, Midway, and Wake, have selected periods of record of 10 years or more during which the anemometer was not moved. The stations are spread over such a vast area that interannual variations are not easily compared. Ratios of highest to lowest annual wind power are generally less than 2.0 except for Wake Island (Figure 4.8), which had extremely light winds in 1964, the first year of record.

4.3.2 Monthly Average Wind Power and Speed

Almost all stations show maximum wind power in winter or spring (Figure 4.9). Most Pacific Islands are well west of the summer trade wind belt of the eastern Pacific. Migratory systems moving east from the Asian winter monsoon are the primary source of wind power. Johnston Island lies in the main trade wind belt of the year and shows little month-to-month wind power variation.

4.3.3 Diurnal Wind Speed by Season

These graphs demonstrate the differing characteristics of diurnal variations at islands with high mountains (Guam, Koror, Tutuila, Ponape, Saipan, Truk, and Yap) as compared to low islands (Enewetak, Johnston, Kwajalein, Majuro, Midway, and Wake Island) (Figure 4.10). Low islands show virtually no diurnal variation. High islands show typical afternoon wind speed maxima produced by heating and turbulent mixing.

4.3.4 Directional Frequency and Average Speed

Trade winds are the dominant feature at all stations (Figure 4.11). At most west Pacific stations, the less frequent westerly and southwesterly winds are often strong. A primary source of these winds are tropical disturbances, which are generated in the western Pacific throughout the year. They are especially important at Guam where they may intensify to typhoon strength. The Marshalls (Enewetak, Kwajalein, and Majuro)

lie east of the storm belt although they may rarely be affected by typhoons.

4.3.5 Annual Average Wind Speed Frequency Distribution

Because observer bias and low instrument threshold speeds so distort the observed frequency distribution (Figure 4.12), the representativeness of the Rayleigh speed distribution is hard to evaluate. Observer biases are apparent at every station. Anemometer threshold problems are evident at Koror and Yap, which are in light wind regimes.

4.3.6 Annual Average Wind Speed Power Duration

The percentage of time that a given wind speed or power is exceeded is shown in Figures 4.13 and 4.14. Abrupt changes in the slope of the duration curves correspond to peaks in the speed frequency distribution caused by observer bias and instrument threshold velocity.

FIGURE 4.1. Geographic Map of the Pacific Islands Region.

FIGURE 4.2. GEOGRAPHIC MAP OF THE CAROLINE ISLANDS (TOP) AND AMERICAN SAMOA (BOTTOM)

FIGURE 4.2 (CONTINUED). GEOGRAPHIC MAP OF GUAM (TOP) AND THE MARSHALL ISLANDS (BOTTOM)

FIGURE 4.2 (Continued). Geographic Map
of the Northern Marianas.

FIGURE 4.3. NCC Station Locations in the Pacific Islands (except Guam).

FIGURE 4.3 (Continued). NCC Station
Locations in Guam.

FIGURE 4.4. Annual Average Wind Power over the Open Ocean. Numbers are wind power classes (see Section 1.7).

Classes of Wind Power Density at 10 m and 50 m^(a)

Wind Power Class	10 m (33 ft)		50 m (164 ft)	
	Wind Power Density watts/m ²	Speed ^(b) m/s (mph)	Wind Power Density watts/m ²	Speed ^(b) m/s (mph)
	0	0	0	0
1	100	4.4 (9.8)	200	5.6 (12.5)
2	150	5.1 (11.5)	300	6.4 (14.3)
3	200	5.6 (12.5)	400	7.0 (15.7)
4	250	6.0 (13.4)	500	7.5 (16.8)
5	300	6.4 (14.3)	600	8.0 (17.9)
6	400	7.0 (15.7)	800	8.8 (19.7)
7	1000	9.4 (21.1)	2000	11.9 (26.6)

(a) Vertical extrapolation of wind speed based on the 1/7 power law.

(b) 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 5%/5000 ft (3%/1000 m) of elevation.

FIGURE 4.5. Annual Average Wind Power for Guam (Top) and the Marshall Islands (Bottom). Slanted characters denote ocean wind power (see Fig. 4.4). Numbers are wind power class (see Section 1.7).

FIGURE 4.5 (Continued). Northern Marianas Average Annual Wind Power. Ocean wind power is denoted by slanted characters. () indicates ridge crest value for mountainous island.

FIGURE 4.5 (Continued). Caroline Islands Annual Average Wind Power. Ocean wind power is denoted by slanted characters. () indicates ridge crest value for mountainous island.

FIGURE 4.5 (Continued). American Samoa Annual Average Wind Power. Ocean wind power is denoted by slanted characters. () indicates ridge crest value for mountainous island.

FIGURE 4.5 (Continued). Average Annual Wind Power for Wake (Top Left), Midway (Top Right) and Johnston Island. Slanted characters denote ocean wind power.

CERTAINTY RATING LEGEND

Rating	Definition
1	<p>The lowest degree of certainty. A combination of the following conditions exists:</p> <ol style="list-style-type: none"> 1) No data exist in the vicinity of the cell. 2) The terrain is highly complex. 3) Various meteorological and topographical indicators suggest a high level of variability of the resource within the cell.
2	<p>A low-intermediate degree of certainty. One of the following conditions exists:</p> <ol style="list-style-type: none"> 1) Little or no data exist in or near the cell, but the small variability of the resource and the low complexity of the terrain suggest that the wind resource will not differ substantially from the resource in nearby areas with data. 2) Limited data exist in the vicinity of the cell, but the terrain is highly complex or the mesoscale variability of the resource is large.
3	<p>A high-intermediate degree of certainty. One of the following conditions exists:</p> <ol style="list-style-type: none"> 1) There are limited wind data in the vicinity of the cell, but the low complexity of terrain and the small mesoscale variability of the resource indicate little departure from the wind resource in nearby areas with data. 2) Considerable wind data exist but in moderately complex terrain and/or in areas where moderate variability of the resource is likely to occur.
4	<p>The highest degree of certainty. Quantitative data exist at exposed sites in the vicinity of the cell and can be confidently applied to exposed areas in the cell because of the low complexity of terrain and low spatial variability of the resource.</p>

FIGURE 4.6 (Continued). Certainty Rating of Pacific Islands Wind Resource. Ratings apply to individual anemometer locations.

FIGURE 4.6. Certainty Rating of Guam Wind Resource. Ratings apply to 1/8° by 1/8° grid squares.

TABLE 4.2. Areal Distribution (km²) of Wind Power Classes in Guam

Power Class	Land Area	% Land Area	Cumulative Land Area	% Cumulative Land Area
1	152	29	519	100
2	265	51	368	70.8
3	95	18.4	102	19.7
4	0	0	7	1.37
5	7	1.37	7	1.37
6	0	0	0	0
7	0	0	0	0

TABLE 4.3. Areal Distribution (km²) of Wind Power Classes in the Marshall Islands

Power Class	Land Area	% Land Area	Cumulative Land Area	% Cumulative Land Area
1	37	20	186	100
2	95	51	149	80
3	1	0.5	55	29.3
4	20	10.5	54	28.8
5	19	10.18	34	18.27
6	6	3.22	15	8.09
7	9	4.87	9	4.87

TABLE 4.4. Areal Distribution (km²) of Wind Power Classes in the Caroline Islands

Power Class	Land Area	% Land Area	Cumulative Land Area	% Cumulative Land Area
1	1142	95.65	1194	100
2	0	0.01	52	4.35
3	52	4.34	52	4.34
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0

TABLE 4.5. Areal Distribution (km²) of Wind Power Classes in the Northern Marianas.

Power Class	Land Area	% Land Area	Cumulative Land Area	% Cumulative Land Area
1	295	62.07	475	100.00
2	168	35.31	180	37.93
3	12	2.61	12	2.61
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0

TABLE 4.6. Areal Distribution (km²) of Wind Power Classes in American Samoa

Power Class	Land Area	% Land Area	Cumulative Land Area	% Cumulative Land Area
1	97	52.46	184	100.0
2	81	43.88	88	47.54
3	7	3.66	7	3.66
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0

TABLE 4.7. Areal Distribution (km²) of Wind Power Classes in Midway, Johnston, and Wake Islands

Power Class	Land Area	% Land Area	Cumulative Land Area	% Cumulative Land Area
1	0	0	14	100
2	5	37.7	14	100
3	0	0	9	62.3
4	0	0	9	62.3
5	9	62.3	9	62.3
6	0	0	0	0
7	0	0	0	0

FIGURE 4.7. Seasonal Average Wind Power for Guam (Winter--Top; Spring--Bottom).

RIDGE CREST ESTIMATE

RIDGE CREST ESTIMATE

FIGURE 4.7 (Continued). Seasonal Average Wind Power for Guam (Summer--Top; Autumn--Bottom).

FIGURE 4.7 (Continued). Seasonal Average Wind Power for the Marshall Islands (Winter--Top; Spring--Bottom). Slanted characters denote ocean wind power values.

FIGURE 4.7 (Continued). Seasonal Average Wind Power for the Marshall Islands (Summer--Top; Autumn--Bottom). Slanted characters denote ocean wind power values.

FIGURE 4.7 (Continued). Seasonal Average Wind Power for the Caroline Islands (Winter--Top; Spring--Bottom). Slanted characters denote ocean wind power values. () indicates ridge crest estimate.

FIGURE 4.7 (Continued). Seasonal Average Wind Power for the Caroline Islands (Summer--Top; Autumn--Bottom). Slanted characters denote ocean wind power values. () indicates ridge crest estimate,

FIGURE 4.7 (Continued). Seasonal Average Wind Power for the Northern Marianas (Winter--Left; Spring--Right). Slanted characters denote ocean wind power values. () indicates ridge crest estimate.

FIGURE 4.7 (Continued). Seasonal Average Wind Power for the Northern Marianas (Summer--Left; Autumn--Right). Slanted characters denote ocean wind power values, () indicates ridge crest estimate.

FIGURE 4.7 (Continued). Seasonal Average Wind Power for American Samoa (Winter--Top; Spring--Bottom). Slanted characters denote ocean wind power values. () indicates ridge crest estimate.

FIGURE 4.7 (Continued). Seasonal Average Wind Power for American Samoa (Summer--Top; Autumn--Bottom). Slanted characters denote ocean wind power values. () denotes ridge crest estimate.

FIGURE 4.7 (Continued). Seasonal Average Wind Power for Wake, Midway and Johnston Islands (Winter). Slanted characters denote ocean wind power values.

FIGURE 4.7 (Continued). Seasonal Average Wind Power for Wake, Midway, and Johnston Islands (Spring). Slanted characters denote ocean wind power values.

FIGURE 4.7 (Continued). Seasonal Average Wind Power for Wake, Midway, and Johnston Islands (Summer). Slanted characters denote ocean wind power values.

FIGURE 4.7 (Continued). Seasonal Average Wind Power for Wake, Midway, and Johnston Islands (Autumn). Slanted characters denote ocean wind power values.

TABLE 4.8. Pacific Island Stations with Graphs of the Wind Characteristics

Island Group	Station Name ^(a)	Latitude Degrees	Longitude Degrees	Elevation of Station, m	Period of Record Month/Year	Anemometer Height, m	Annual Average Wind Speed, m/s			Annual Average Wind Power, watts/m ²		
							At Anemometer Height, m	At 10 m	At 50 m	At Anemometer Height, m	At 10 m	At 50 m
Marshall	Enewetak AAF	11.35N	162.35E	5	09/50-12/59	Unk ^(b)	7.9	7.9	9.9	405	405	809
Guam	Agana NAS	13.50N	148.60E	77	01/61-12/78	7.9	3.8	4.0	5.0	69	76	152
Guam	Andersen AFB	13.58N	144.92E	162	02/61-11/68	Unk ^(b)	4.9	4.9	6.2	121	121	241
Guam	Orote AAF	13.43N	144.63E	30	06/45-05/48	Unk ^(b)	3.4	3.4	4.3	55	55	110
Guam	Taguac WSMO	13.55N	144.83E	111	01/73-12/78	9.8	4.9	4.9	6.2	111	112	224
Detached	Johnston Atoll Airfield	16.73N	169.52W	3	03/63-12/70	6.4	6.3	7.2	9.1	232	281	560
Caroline	Koror Airport	7.33N	134.48E	30	09/59-11/73	14.0	3.3	3.1	3.9	43	37	74
Marshall	Kwajalein Airfield	8.73N	167.73E	3	07/60-06/69	7.6	6.0	6.3	7.9	201	226	450
Marshall	Majuro Airport	7.08N	171.38E	2	01/66-01/73	6.1	4.6	4.9	6.2	94	116	232
Detached	Midway Island NAS	23.20N	177.38W	10	01/61-12/71	21.6	5.3	4.8	6.0	176	126	252
Samoa	Pago Pago Airport	14.33S	170.72W	5	10/72-12/78	8.5	4.8	4.9	6.2	123	132	262
Caroline	Ponape Airport	6.97N	158.22E	38	01/65-03/73	9.8	3.3	3.3	4.2	39	39	79
Mariana	Saipan NF	15.22N	145.73E	152	12/57-06/62	21.3	3.6	3.2	4.1	67	48	97
Caroline	Truk Airport	7.47N	151.25E	2	01/65-12/78	7.0	4.4	4.6	5.8	85	99	197
Detached	Wake Island Airfield	21.90N	159.60E	5	07/63-12/78	6.4	6.3	6.7	8.5	224	271	541
Caroline	Yap Airport	9.48N	138.08E	14	07/70-12/78	6.1	3.6	3.9	4.9	50	62	123

^(a) AAF-Army Air Field; NAS-Naval Air Station; AFB-Air Force Base; WSMO-Weather Service Meteorological Observatory; NF-Naval Facility.

^(b) Unk-Anemometer height is unknown. Height of 10 m was assumed for estimating wind speed and power at 10 m and 50m.

FIGURE 4.8. Interannual Wind Power and Speed for Pacific Islands. Note ranges of the ordinates vary with each station's wind strength.

FIGURE 4.9. Monthly Average Wind Power and Speed for Pacific Islands.

FIGURE 4.10. Diurnal Wind Speed by Season for Pacific Islands.

— PERCENT FREQUENCY LEFT ORDINATE - PERCENT
 - - - WIND SPEED RIGHT ORDINATE - M/S
 PNL-3195 WERA-11
 ABSISSA - WIND DIRECTION

FIGURE 4.11. Directional Frequency and Average Speed for Pacific Islands.

— ACTUAL DISTRIBUTION ORDINATE - PERCENT
 - - - RAYLEIGH DISTRIBUTION ABSCISSA - M/S
 PNL-3195 WERA-11

FIGURE 4.12. Annual Average Wind Speed Frequency for Pacific Islands.

ORDINATE - PERCENT

ABSCISSA - M/S

PNL-3195 WERA-11

FIGURE 4.13. Annual Average Wind Speed Duration for Pacific Islands.

ORDINATE - PERCENT
ABSCISSA - WATTS/M²
PNL-3195 WERA-11

FIGURE 4.14. Annual Average Wind Power Duration for Pacific Islands.

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