Wind Energy Resource Atlas: Volume 8 - The Southern Rocky Mountain Region

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WIND ENERGY RESOURCE ATLAS:
Volume 8 - The Southern Rocky
Mountain 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.

This atlas of the wind energy resource is composed of introductory and background information, a regional summary of the wind resource, and assessments of the wind resource in each state 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. A description of the wind resource on a regional scale is then given in Chapter 2. The results of the wind energy assessments for each state are assembled in this chapter into an overview and summary of the various features of the regional wind energy resource. Chapter 3 provides an introduction and outline to the descriptions of the wind resource given for each state. Assessments for individual states are presented as separate chapters beginning with Chapter 4. The state wind energy resources are described in greater detail than is the regional wind energy resource, and features of selected stations are discussed. This preface outlines the use and interpretation of the information found in the state chapters.

Much of the information in the state chapters is given in graphic or tabular form. As is discussed in Section 3.1, the sequence of maps, tables, and graphs is the same in each state chapter. References to these figures and tables are made here with an asterisk (*) in place of the chapter number (e.g., Figure *.1, Table *.2). Similar maps and tables are found in Chapter 2 on the regional wind resource. References to the regional maps and tables are made in brackets, [].

Figure *.1 shows the major geographical (mountains, rivers) and cultural (cities, towns) features in the state [Figure 2.1]. This map can be used to orient the reader to the state. Figure *.2 portrays the topography of the state in shaded relief [Figure 2.2]. The shaded relief allows the reader to visualize the character of the terrain surrounding locations of special interest. Superimposed on these state maps (but not the regional maps) is a grid of dashed lines one-third degree (20') longitude by one-quarter degree (15') 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.

Figure *.3 is a map of the land-surface form [Figure 2.3]. 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 *.4 and *.5 identify and locate wind data sites relevant to the assessment. All locations in each state for which the National Climatic Center (NCC) has wind data in its archives are shown and named in Figure *.4. 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 *.5 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 state 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 *.6 [Figure 2.4]. 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 *.7. 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 reference point on which to base the analyses of the wind resource shown in Figure *.6. 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 *.8 provide an estimate of the percentage of area in each grid cell that may have 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 state estimated to have a particular wind power class is given in Table *.1 [Table 2.2]. This table summarizes the contribution made by each grid cell to the areal distribution of wind power for the state.

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 state level. The maps of Figure *.9 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. [For the region, Figure 2.5 shows only the season of maximum power.]

Additional information on the time variation and other characteristics of the wind resource in each state is presented for selected locations for which the National Climatic Center 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 3.2. 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 *.2 identifies the stations, and gives their location (see also Figures *.4 and *.5) and annual average wind speed and power density. Figure *.10 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 *.11. The hourly mean wind speed over the course of a day is shown in Figure *.12 with a separate curve for each season. Figures *.11 and *.12 indicate the variation by time of year and time of day, respectively, of the wind resource. Figure *.10, 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 *.13 and *.14, 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 *.15 and *.16 portray speed and power frequency statistics in the form of speed and power exceedance curves, respectively. The fraction of the total period of record during which the speed equals or exceeds a given value is shown in Figure *.15. The power exceedance curve in Figure *.16 gives the fraction of the total period of record during 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 a regional perspective in Chapter 2, to a state perspective in the first part of each state chapter, to individual station descriptions in the last part of the state chapters. Attention given to Chapter 1 and Chapter 3 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 wind resource in the Southern Rocky Mountain region, 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 the eighth of twelve such atlases that will be assembled. The other atlases will describe the potential wind resource in eleven other regions of the United States (see Figure 1.1). The spatial and temporal resolution of the wind resource in these regional assessments will be depicted in considerably greater detail than that in existing national assessments (Reed 1975, Coty 1976, Garate 1977, Elliott 1977). To produce the Southern Rocky Mountain atlas in a timely fashion, only existing relevant

data were used. The other atlases will use comparable data sets, analysis techniques and presentations to ensure the comparability of the wind resource assessments.

The Southern Rocky Mountain atlas assimilates five collections of wind resource data: one for the region and one for each of the four states that compose the Southern Rocky Mountain region (Arizona, Colorado, New Mexico, and Utah). At the state level, features of the climate, topography and wind resource are discussed in greater detail than is provided in the regional discussion, and the data locations on which the assessment is based are mapped. Variations, over several time scales, in the wind resource at selected stations in each state are shown on graphs of monthly average and inter-annual wind speed and power, and hourly average wind speed for each season. Other graphs present speed, direction, and duration frequencies of the wind at these locations.

The methods used to identify, screen, evaluate, and analyze the various types of

FIGURE 1.1. Geographic Divisions for Regional Wind Energy Assessments

data, and to produce the wind energy resource maps and graphs will only be described briefly. [For more detail see Elliott and Barchet (1980a), and Andersen and Freeman (1981).] However, this discussion will provide the reader with useful background information for interpreting the wind energy resource maps for the Southern Rocky Mountain region.

1.1 IDENTIFICATION OF WIND DATA SOURCES

The surface wind data on which this atlas is based were obtained from several sources: the National Climatic Center (NCC), the U.S. Forest Service, university research projects, proposed and operational nuclear and fossil-fueled power plant sites, DOE candidate wind turbine sites 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) are 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 wind data have been taken.

The wind data available from the NCC may be in one or more of three formats: summarized, digitized, and unsummarized. Initially, all wind data are in the unsummarized format consisting of 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.] In the remainder of this atlas, "digitized data" will refer to hourly averaged data in computer-accessible format, such as magnetic tape or computer cards. Table 1.1 indicates the number of stations with wind data in these various formats in the Southern Rocky Mountain region.

In contrast to the NCC data, which are primarily from inhabited areas, U.S. Forest 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). Two hundred and twenty-three stations with wind data are reported in the National Fire Weather Data Library for the Southern Rocky Mountain region (Marlatt et al. 1979). However, only one afternoon observation, at about 2 p.m., is digitized per day during the local fire weather season.

Wind data from 11 nuclear or fossil-fueled power plants or potential plant sites (Verholek 1977) were examined. Many other wind data sets collected by university research projects, state and local air pollution control agencies, or in support of environmental impact statements, have also been identified.

1.2 WIND DATA SCREENING

Table 1.1 indicates the quantity of wind data available in the Southern Rocky Mountain region and peripheral area. However, not all of these data need to, 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.

TABLE 1.1. Stations with Wind Data Screened for the Southern Rocky Mountain Region Wind Energy Resource Assessment

Source and Type	Screened	Retained
National Climatic Center		
Digitized	76	63
Summarized	46	33
Unsummarized	163	63
National Fire Weather Data Library	223	11
Nuclear and Fossil-Fueled Power Plant	11	11
University Research	19	19
Other	163	163

Wind data in summarized or digitized format were chosen over unsummarized data. When stations had both summarized and digitized data, the digitized data were used for selected stations to prepare a more extensive characterization of the wind resource.

Unsummarized data were used only when no

summarized or digitized data were available, and only if the data constituted a representative sample. Many of the NCC stations with unsummarized data were intermittently reporting stations, some of them having observations as infrequently as once or twice per month. A few of the NCC unsummarized data stations were omitted from the analysis because of poor anemometer exposure.

In areas with a high density of stations with wind summaries, those stations 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 were usually selected over other nearby stations. When more than one type of summary (see Changery et al. 1977) was available for a given station, 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 was chosen.

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 less than 24 hourly observations or 8 three-hourly observations per day, the values are only representative of the times of day for which the data were taken.

The four seasons are defined as:

- winter - December, January and February
- spring - March, April and May
- summer - June, July and August
- autumn - September, October and November.

The phrase "seasonal trends" refers to the change in monthly mean values over the course 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, wind power density was chosen over wind speed since the power density incorporates in a single number 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 unsummarized. 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 was calculated from:

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

where

n = the number of observations in the averaging period

ρ_i = the density (in kg/m³) computed from the station pressure and temperature at the i th observation time

V_i = the wind speed (in m/s) at the i th observation time.

For stations with wind summaries, $\bar{P}$ was calculated from:

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

where

$\bar{\rho}$ = the mean air density, approximated by using the National Advisory Committee for Aeronautics (NACA) standard atmosphere at station elevation

c = the number of wind speed classes

f_j = frequency of occurrence of wind in the j th class

V_j = median wind speed of the j th class.

In those cases for which unsummarized wind data were assessed, the seasonal and annual average speeds, $\bar{V}$, were estimated from a visual examination of one year's original weather records. The wind power density, $\bar{P}$, was then estimated by assuming that the speed frequency distribution followed a Rayleigh distribution. For a

wind speed frequency distribution that follows a Rayleigh distribution, wind power density is given by (Cliff 1977):

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

where

$\bar{\rho}$ = mean air density, approximated by using the NACA standard atmosphere at station elevation

$\bar{V}$ = mean wind speed for the period being analyzed.

It should be noted that the Rayleigh distribution is a good approximation of the natural distribution of windspeed for high windspeeds only. Cliff (1977) suggests a lower limit to $\bar{V}$ of 4.5 m/sec. At this mean speed, mean power density approximated by equation (3) is near 100 watts/m², or near the upper limit of the 10 meter class 1 wind power density category. Consequently, equation (3) provides a good approximation of wind power density for class 2 wind power density and higher. It should be noted, however, that the Rayleigh distribution has been found to be most accurate over simple terrain in neutral atmospheric conditions. Much of the terrain in the Southern Rocky Mountain region is very complex. For a comparison of actual vs Rayleigh wind speed distributions at various sites in the region, see Figures 4.14, 5.14, 6.14, and 7.14.

1.4.1 Vertical Adjustment

The anemometer height above the surface rarely was at either the 10-m or 50-m reference 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:

$$\frac{\bar{V}_r}{\bar{V}_a} = \left(\frac{Z_r}{Z_a} \right)^\alpha \quad \text{or} \quad \frac{\bar{P}_r}{\bar{P}_a} = \left(\frac{Z_r}{Z_a} \right)^{3\alpha} \quad (4)$$

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 was 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 from which conventional NCC data are available (Elliott 1979b).

1.4.2 Estimates for Mountainous Areas

The quantitative estimation of wind power over mountainous areas made use of the northern hemisphere upper-air wind climatologies for the 850, 700 and 500 mb constant pressure levels by Crutcher (1959). Since earlier studies had shown a strong correlation between mountaintop and free-air wind speeds (Wahl 1966), the free-air wind speed at mountain summit or ridge crest height was extrapolated (or interpolated) from the mean scalar speeds on the constant pressure surfaces. Estimates of the mountaintop wind speeds were made on a grid one-fourth degree latitude by one-third degree longitude. In each such cell of the grid over the mountains, the mean ridge crest or mountain summit elevation and appropriate constant pressure surface mean wind speeds were estimated. Linear extrapolation provided the mean free-air wind speed at the terrain elevation, and the application of a Rayleigh speed distribution gave the mean free-air wind power. The mean wind 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 considered to be lower limits for exposed ridge crests and mountain summits. Local terrain features in mountainous regions can enhance the wind power considerably. However, a major uncertainty in any 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).

1.5 QUALITATIVE WIND INDICATORS

Although more than 360 stations provided quantitative data used in the Southern Rocky Mountain regional wind resource assessment, these stations were not uniformly distributed. The station location figures for each state show many large areas in the Southern Rocky Mountain region that are devoid of any form of quantitative wind data suitable for this assessment, such as northeastern Arizona, western Utah, and eastern Colorado. To evaluate the distribution of the wind resource in data-sparse areas, qualitative indicators of the wind speed or power were used in the assessment.

The most widely used technique depended

on certain combinations of topographic and meteorological features (Elliott 1979a) that were associated with high or low wind speeds. Those features indicative of high mean wind speeds include:

- gaps, passes, and gorges in areas of frequent strong pressure gradients
- long valleys extending down from mountain ranges
- high elevation plains and plateaus
- exposed ridges and mountain summits in areas of strong upper-air winds.

Features that signal rather low mean wind speeds include:

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

1.6 WIND POWER MAPS

The production of mean wind power density maps, such as those presented for each state, depended on the coherent synthesis of several pieces of information. The goal of the synthesis process 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 expected to have good exposure to the wind (see Table 1.2). In contrast, locations in narrow valleys and canyons, downwind of hills and obstructions, or in forested or urban areas, are likely to have poor exposure. The wind power density shown on the maps in this atlas will not be representative of poorly exposed 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, it was necessary to become extremely familiar with the land-surface form and topography in the vicinity of every data site. Maps were prepared showing the locations of stations, the mean wind speed and mean wind power at the reference level, the character of anemometer exposure, and the land-surface form for each state. On these maps, areas with the appropriate combinations of topographic and meteorological features were identified. A great deal of attention was given to the orientation of topographic features with the prevailing wind directions. Only after all this information was assembled were the maps analyzed. The annual maps for each state were merged into a regional mosaic.

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 1.3 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. The definitions of the wind power density classes are repeated with the annual wind power map for the region and for each state as a convenience for the reader.

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%/1,000 m elevation (1%/1,000 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 the Southern Rocky Mountain region. Several characteristics are coded on this map:

- percentage of land area occupied by surfaces of gentle inclination (less than 8% slope)
- local relief, 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
- pattern of major crests, peaks, and escarpments.

The first three characteristics are used in the classification scheme (see Table 1.4); 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 gently sloping land is in the lowland. In areas of very little gentle slope (D) or very low relief and great smoothness (A1), the third designator is omitted.

For each land-surface form, the percentage of land area that is representative of well exposed, moderately exposed, and poorly exposed sites has been estimated. These percentages were determined subjectively as a function of the slope, local relief, and profile type. Table 1.2 gives the average percentage of land area that is designated as exposed terrain for the different classes of land-surface form. For simplicity, the percentages 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 Southern Rocky Mountain region. For example, the 30% for open hills is an average for C2 through C4. The average

percentage of land area that is designated as exposed terrain ranges from 92% on smooth plains to 2% 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 types of 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 geographic variability of the resource.

A certainty rating from 1 (low) to 4 (high) of the wind energy resource estimate was made for each cell of a one-quarter degree latitude by one-third degree longitude grid, on a state-by-state basis, 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. Forest 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 exists: <ul 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 topographic 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: <ul 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 A high-intermediate degree of certainty. One of the following conditions exists:
 - 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 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.

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 that are well exposed to the wind. Therefore, the map area designated as having a particular wind power class does not indicate the true land area having 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, the fraction of land area that would be favorably exposed to the winds, i.e., that would have the wind power density

indicated on the map, was estimated (see Table 1.2 for averages in various land-surface forms). Furthermore, to be able to establish a wind power density for the remaining area, it was also 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, such as isolated hills and ridges that rise above a nearly flat landscape, may even have a higher wind 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 wind power density was scaled to be 1) greater than, 2) equal to, 3) slightly less than, and 4) much less than the map value of wind power density. The factor by which the 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.

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

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 chapters on the state wind resources for threshold values of classes 2, 3, 4 and 5.

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

Both of these presentations of the areal distribution of the wind resource are highly dependent on the estimates used to

partition the land area into the four exposure categories, and on the scaling of the wind 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 are 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.

TABLE 1.2. Land-Surface Form Terrain Features Representative of Exposed Locations.

Land-Surface Form	Exposed Feature (Map Value)	Percentage Area ^(a)
Plains: A1,A2;B1,B2	Plains	92
Plains With Mountains: B4-6a,b	Plains (not shaded) ^(b) Ridge Crests and Mountain Summits (shaded)	68 10
Tablelands: B3-6c,d	Tablelands, uplands	79
Open Hills: C2-4	Hilltops and Uplands	30
Open Mountains: C5-6	Broad Valleys (not shaded) Ridge Crests and Mountain Summits (shaded)	80 9
Mountains: D5-6	Ridge Crests and Mountain Summits (shaded)	2

(a) Percentage represents an average over the land-surface forms found in the Southern Rocky Mountain region.

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

TABLE 1.3. 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 1.4. 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 0 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 on upland
- d >75% of gentle slope is on upland

CHAPTER 2: REGIONAL FEATURES

In this chapter, the geography, climate, and annual average and seasonal variations in the wind power are described for the Southern Rocky Mountain region. These features were considered for each state using the methods outlined in Chapter 1. Assessments for each state were combined to depict the wind energy resource potentially available in the Southern Rocky Mountain region. This regional assessment is summarized here. The description of the regional features is followed by discussions of areas of the Southern Rocky Mountain region that appear to have the greatest wind resource potential.

2.1 GEOGRAPHY AND TOPOGRAPHY

The Southern Rocky Mountain region, consisting of Arizona, Colorado, New Mexico and Utah, covers more than 1,000,000 km² (395,000 mi²) and had a total population of approximately 7,396,000 in 1977 (Statistical Abstracts, 100th edition, 1979), (see Table 2.1). Over 60% of the region's people reside in the metropolitan areas of Denver, Phoenix, Salt Lake City, Tucson, Albuquerque, and Colorado Springs. The remainder of the region's people live in agricultural, industrial, and resort communities distributed throughout the area.

TABLE 2.1 Land Area and Population of the Southern Rocky Mountain Region

State	Area (a)		Population in 1977	Population per km ² (mi ²) in 1977	
	km ²	(mi ²)			
Arizona	295,174	(113,909)	2,305,000	7.8	(20.2)
Colorado	270,136	(104,247)	2,625,000	9.7	(25.2)
New Mexico	315,275	(121,666)	1,196,000	3.8	(9.8)
Utah	220,044	(84,916)	1,270,000	5.8	(15.0)
Southern Rocky Mountain Region	1,100,629	(424,738)	7,396,000	6.7	(17.4)

(a) 1977 World Almanac

(b) Statistical Abstracts, 100th edition, 1979

Topography varies dramatically throughout the Southern Rocky Mountain region. The region is dissected by the Continental Divide which extends through central Colorado and western New Mexico, and is composed of five basic topographic areas, or types: (1) the high plains, (2) the Rocky Mountains, (3) the Colorado Plateau, (4) the Great Basin, and (5) the southwestern desert (see Figures 2.1, 2.2). The high plains area occupies roughly the eastern one-third of the states of Colorado and New Mexico, and most of its land area

is favorably exposed to strong winds. The Rocky Mountains, which extend from north to south through Colorado and New Mexico, are composed of numerous ranges that attain elevations in excess of 4,250 m (14,000 ft) and that are exposed to the strong upper-level westerly winds at ridge crest and mountain summit elevations. The Colorado Plateau occupies the area surrounding the Four Corners Area, and includes the Colorado River drainage of southern and eastern Utah, western Colorado, northwestern New Mexico and northeastern Arizona. The Great Basin area occupies western Utah and is composed of desert basins, playas and small mountain ranges. The last topographic type, the southwestern desert, includes the desert areas of southern New Mexico and southwestern Arizona. It must be noted that this general description of the topography is an oversimplification of the distribution of terrain types throughout the region. Many small mountain ranges, desert valleys, and plains are found within each of the above basic topographic areas.

2.2 CLIMATE

The climate of the Southern Rocky Mountain region varies from arid and semi-arid in the desert valleys and high plains, respectively, to subarctic and polar on the high mountain summits. In general, elevation is the greatest factor in determining the climatic conditions within any specific area. However, orientation with respect to mountain barriers and the pattern of synoptic-scale weather systems dictate the seasonal and spatial distribution of climate across the region.

The Southern Rocky Mountain region is primarily a mid-latitude continental region, isolated from the Pacific Ocean and the Gulf of Mexico by great distances. The dominant airmass type that affects the region is continental (either polar or tropical). However, periodic changes in the pattern of upper-level winds allow maritime (polar or tropical) airmasses to penetrate into the region. During periods of westerly winds, when moisture-laden Pacific storms penetrate the western United States, most maritime characteristics are lost as the moisture is deposited on mountain barriers in Washington, Oregon and California. What water remains is further depleted by the intermountain barriers in Nevada and Idaho, and the result is little or no precipitation in the Southern Rocky Mountain region. Generally, only the western slopes and summits of high mountainous areas receive appreciable precipi-

precipitation during Pacific airmass intrusions. In areas east of the Rocky Mountains, the contribution of water by Pacific airmasses is small. The effects of these modified Pacific maritime airmasses are limited to cloudy conditions, a general increase in surface winds, and moderating temperatures.

During periods of strong northwesterly and northerly upper-level winds, continental airmasses that originate in northern Canada and on the Canadian prairies penetrate the region, bringing colder temperatures and dry conditions. Although these continental airmasses can affect areas as far south as Arizona and as far west as Utah, their effects are usually restricted to areas east of the Rocky Mountains. Because these cold air masses are typically shallow, westerly penetration over the Rocky Mountains is limited to only very strong intrusions.

During periods of southerly and southeasterly flow, moist maritime tropical air frequently moves up from the Gulf of Mexico and can penetrate all but the extreme northern portions of the region. This type of airmass provides most of the precipitation that falls in the lowland areas of the region. When southerly flow brings continental tropical airmasses from the Sonoran Desert and Mexican interior, very low humidities and warm conditions prevail over the region.

During the frequent periods of light upper-air winds, the air over the region takes on its own continental airmass characteristics. These basic characteristics are clear skies and dry conditions, locally-controlled wind flow (e.g. mountain-valley circulations), a large diurnal temperature range, nighttime formation of surface temperature inversions, and good vertical mixing of air during the day.

Coldest winters in the region occur on the Great Plains and in the intermountain areas of Colorado and eastern Utah. Intrusions of polar or arctic air into these areas brings bitter cold temperatures and very dry air. Farther south and west, the winters are comparatively warmer, partly because of the protection provided by the Rocky Mountains, and partly because of the greater solar insolation in more southerly locations. For most of the winter, the Great Basin and Colorado Plateau areas are occupied by a semi-permanent high pressure system, with its associated clear skies and light winds. During these periods, general air stagnation results, and local downslope drainage flow causes cold stable air to collect in most lowlands west of the Continental Divide. Because these conditions can persist for weeks at a time, this

buildup of cold stable air can result in western valleys having temperatures well below zero, while the higher surrounding terrain remains in the warmer Pacific air. Occasionally, strong mid-latitude cyclones from the Pacific move through the region, bringing significant amounts of snow to the mountains and strong winds to the entire region. These winds tend to scour out the stable air near the surface. However, unless the movement of storms through the region continues, stable surface conditions redevelop in a few days.

Southern New Mexico and Arizona have generally mild winters, with abundant sunshine and dry conditions. Daytime temperatures in southern Arizona are frequently over 20°C (68°F) at the same time that mountain and valley locations in Colorado are having temperatures well below zero.

Summers are cool and refreshing at high elevations in the region. Average daytime temperatures in the Rocky Mountains and in other mountainous areas of Utah, Arizona, and New Mexico, are generally near 20°C (68°F). Above 2,400 m (8,000 ft), nights are quite cool throughout the summer, while during the day bright sunshine makes the days comfortably warm. In the lowland areas of the region, summer daytime temperatures are quite warm. In the desert valleys and on the southern plains, afternoon daytime temperatures frequently exceed 38°C (100°F). Because of the very low relative humidity accompanying these high temperatures, hot days cause less discomfort here than they do in more humid areas. During the summer, frequent afternoon thunderstorms form over the region, bringing showers and cooling to scattered areas. On the eastern plains of Colorado and New Mexico, these thunderstorms frequently reach severe levels, spawning tornadoes, large hail, and heavy rains. In late summer, warm moist air moving up from the Gulf of Mexico provides the region with a monsoon season. During this period, widespread thunderstorms with heavy rains can persist for days at a time.

Annual precipitation varies from over 127 cm (50 in) on Wolf Creek Pass in the San Juan Mountains of Colorado, to less than 8 cm (3 in) at stations in the southwestern desert area of Arizona. In general, high mountain summits and ridge crests throughout most of the region receive most of their precipitation during the winter in the form of snow. Moist upper-level air that accompanies eastward-moving mid-latitude storm systems impinge upon the mountain slopes and are orographically lifted. This results in heavy snows on the western slopes and summits. The

snow pack runoff which develops in the spring supplies virtually all of the water for the lowland areas of the region.

Although the east slope of the Rocky Mountains and the high plains occasionally receive severe blizzards during the winter, most of the precipitation received in these areas comes during the spring and summer months in the form of showers from thunderstorms that form over the Rocky Mountains and move out onto the plains. The season of maximum rainfall in most of Arizona, New Mexico, and southern Utah is during the late summer, when moist air from the Gulf of Mexico moves into the region.

2.3 WIND POWER IN THE SOUTHERN ROCKY MOUNTAIN REGION

The annual average available wind power density for the Southern Rocky Mountain region is shown in Figure 2.4. The analyses of mean wind power apply to terrain features that are favorably exposed to the wind, such as mountain summits, ridge crests, hilltops, tablelands, and uplands (see Section 1.6 and Table 1.2). However, because of the complexity and high relief of most of the region, nearby terrain features may interact with the wind field to cause large spatial variability of the wind resource. In general, the high plains and broad basins have low relief and are thus well-exposed to the wind. In mountainous areas, the graphic display of Figure 2.4 delineates major valleys. The percentage of land area that is favorably exposed to the wind strongly depends on the land-surface form (see Section 1.8 and Table 1.2).

In the Southern Rocky Mountain region, the high wind resource areas (class 4 and greater) are confined to the high plains of eastern Colorado and New Mexico, and to ridge crests and mountain summits throughout the region. However, several additional areas were identified that may have borderline class 4 potential. These areas were linked to particular topographic features, referred to as wind corridors. A wind corridor is a passageway of lower elevation than the surrounding terrain through which winds are channeled and sometimes enhanced. However, only those gaps, passes, valleys, gorges or canyons in which the meteorological conditions cause higher relative wind speeds are referred to as wind corridors (Elliott 1979a). Two such wind corridors are found in the Rio Grande valley in northern New Mexico and in the Escalante-Sevier Desert area near Milford in southwestern Utah. Because the analysis of winds in these two particular areas was limited to one anemometer site each, there may be specific locations within each corridor that have higher wind speeds.

A brief description of the major (class 4 and greater) wind resource areas follows in Section 2.5. For more complete discussions of these wind resource areas, refer to the chapter on the state containing these areas.

2.3.1 Certainty Rating of the Wind Resource

Certainty ratings for the annual average wind power estimates were assigned to each grid cell, as described in Section 1.9. Maps of the certainty ratings for each state accompany the descriptions of that state's wind resource.

Certainty ratings throughout the Southern Rocky Mountain region range from low (1) to high (4). Highest certainty ratings were given to areas with representative long-term data and simple terrain. Because of the high relief of most of the Southern Rocky Mountain region, there are few areas that were given certainty ratings of 4. Such areas are found primarily near population centers where the most extensive data sets were taken, e.g. near Salt Lake City and in the Great Salt Lake Desert in Utah, in southern Arizona near Kingman, Phoenix, Tucson, Gila Bend, and Yuma, and in New Mexico near Farmington, Gallup, Deming, Albuquerque, Alamogordo, Las Vegas, and Roswell. Although the high plains of the eastern Southern Rocky Mountain region consist largely of relatively simple terrain, this area was not generally given certainty ratings of 4 because of the lack of data. There are no areas that have both high (class 4 or greater) annual average wind power and high (4) certainty ratings.

Except for ridge crest and mountain summit areas, much of the region was given certainty ratings of 3. In general, ratings of 3 were given to areas where representative data exist, but are for a short (<2 years) period of record, or are based on less than 24 observations per day. Areas in which no data were found, but which appear to have little variability in the wind resource, were assigned certainty ratings of 2, except for areas that contain complex terrain. Areas with no data and that are composed of complex terrain were given certainty ratings of 1. Large areas of these low certainty ratings are found in data-sparse areas such as the Colorado Plateau, the vicinity of the Grand Canyon, east-central and extreme southwestern Arizona (except for Yuma), the hilly areas bordering the White Mountains in eastern Arizona and the Gallo Mountains in western New Mexico, north-central New Mexico, and the hills of southeastern Colorado.

Although little year-round data from exposed ridge crests and mountain summits were found, these areas were given certainty ratings of 2 because upper-air wind data were used to approximate the annual average wind power.

2.3.2 Areal Distribution

Through the superposition of a grid one-third degree longitude by one-quarter degree latitude over the region, the areal distribution of wind power was computed as described in Section 1.10.

Of the 1,380 grid cells that constitute the Southern Rocky Mountain region, only 211, or about 15%, have exposed areas with class 4 or greater wind power. In addition, because much of this exposed terrain is on ridge crests and mountain summits, which are only a small part of the total land area in mountainous areas, the actual exposed land area in the region is only about 2.7% of the total land area (see Table 2.2). Most of this 2.7% is found on the plains of southeastern Colorado and northeastern New Mexico, near the high-wind areas of Kansas and the Oklahoma and Texas panhandles, and in extreme northeastern Colorado near the southern Wyoming wind corridor (see Elliott and Barchet, 1980b). In these areas, 80 to 96% of the total land area is estimated to have exposure to class 4 or greater wind power, while mountainous areas are estimated to have less than 10% of their total land area so exposed.

In contrast, the land area estimated to have low wind power exposure (class 1 and 2) is about 87% of the region's total land area, significantly larger than the 69% suggested by the annual wind power map of Figure 2.4. This difference is also a consequence of the fact that much of the region is composed of highly complex terrain.

Table 2.2 summarizes the results of the computation of the areal distribution for states in the Southern Rocky Mountain region. More detailed descriptions of the areal distribution within each state are found in the areal distribution sections of each state chapter.

2.4 SEASONAL VARIATIONS IN THE WIND RESOURCE

Throughout most of the Southern Rocky Mountain region, winter and spring are the seasons of maximum wind power (see Figure 2.5). Areas with a winter maximum are found primarily on the exposed mountain summits and ridge crests in the northern half of the region, and in exposed areas

near the Wyoming border in extreme northern Colorado and northeastern Utah. This is because mean upper-level winds (above 3,200 m, or 10,500 ft) in this part of the region are strongest during the winter (December, January and February). However, mean winter wind speeds are generally low in sheltered basins and mountain valleys. Cold air often fills these basins and valleys, creating a vertical temperature profile that remains stable for weeks at a time. Under these stable surface conditions, vertical mixing of the atmosphere is limited, and persistent low-level air stagnation occurs in the lowland areas, even though winds may be strong on nearby higher terrain.

A similar situation occurs on the eastern plains during the winter. Here, frequent strong winds occur that are associated with low pressure systems that develop on the lee side of the Rocky Mountains in the winter; however, the frequent intrusion of cold airmasses from the Canadian interior, as well as the frequent occurrence of nighttime low-level temperature inversions, produces a layer of stable air near the surface that frequently shields surface air from strong winds at higher levels. This results in lower average wind power in the winter than would otherwise be expected.

Areas of extreme northern Colorado and northeastern Utah that are close to the southern Wyoming wind corridor are less subject to such low-level stability episodes. These areas are generally more susceptible to high-speed westerly synoptic winds that are channeled across the Continental Divide. Consequently, periods of maximum wind power in these areas correspond to periods of maximum upper-level winds which are highest in the winter.

In spring, (March, April and May), upper-level winds remain relatively strong over most of the Southern Rocky Mountain region, although their strength decreases from March to May. Because solar insolation is greater in spring than in winter, vertical temperature profiles are less stable and more vertical mixing of the surface layer occurs, so that spring is the season of maximum wind power in most lowland areas. In addition, increasing temperature gradients between the northern portions of the Rocky Mountain region and the southern desert areas during spring provide a strong mechanism for the development of active large-scale circulation in the region. Frequent intense cyclones that develop in the lee of the Rocky Mountains and move across the plains also help to support the class 5-class 6 wind power areas in eastern Colorado and New Mexico.

Although winter is the season of maximum wind power on ridge crests and mountain summits in the northern half of the region, spring is the season of maximum wind power on ridge crests and mountain summits in the southern half of the region. In autumn and spring, upper-air wind speeds are about equal in the northern half of the region, while in the southern half the seasonal lag in the development of upper-air winds in autumn results in ridge crest and mountain summit wind power being greater in spring than in autumn.

During the summer, mean upper-air wind speeds are lowest (June, July and August) and ridge crests and mountain summits generally have only low to moderate wind power. Because of the weak synoptic pressure gradients, surface winds in lowland areas become dominated by local mountain-valley upslope-downslope circulation. In general, during summer, most stations in the region have a high diurnal variation in wind speed. During the day strong surface heating results in good vertical mixing of the lower atmosphere, linking surface winds with the winds aloft. At night this condition is reversed, with clear skies and low relative humidities causing strong radiational heat loss from the surface and the formation of a stable air layer near the ground. During the summer, frequent afternoon development of thunderstorms results in short periods (several hours) of strong surface winds. This mesoscale phenomenon is short-lived and affects only small areas at any one time.

In the autumn (September, October and November), upper-air wind speeds increase from September to November. In the northern half of the region, ridge crest and mountain summit wind power estimates are approximately the same in autumn as in spring. However, in the southern mountain regions, the seasonal lag in the development of upper-level winds in autumn, as discussed above, results in ridge crest and mountain summit wind power estimates being lower in autumn than in spring. Lowland areas throughout the region have lower wind speeds in autumn than in spring because of the more frequent occurrence of stable surface air, less vertical mixing, and weaker pressure gradient circulation.

Seasonal variations in atmospheric stability affect the variation of wind speed with height in the Southern Rocky Mountain region. For example, on the San Rafael Desert in eastern Utah, upper-air winds (e.g., at 3,000 m, or 10,000 ft) are strongest in the winter and lightest in the summer (see Figure 2.6). At the surface, however, the highest average wind speeds occur in the spring and summer, and are

lowest in the winter. This seasonal trend in mean wind profiles is typical of many of the valleys, basins, and plains in the Southern Rocky Mountain region.

2.5 MAJOR WIND RESOURCE AREAS

Major areas in the Southern Rocky Mountain region with high annual average wind power (class 4 and greater) are briefly described in this section. Many other isolated areas in the Southern Rocky Mountain region that could have class 4 annual average wind power were also identified; however, because of insufficient verifying data, class 4 wind power estimates were not made for these areas. For additional detail on these areas, as well as on the major areas of high wind power, refer to chapters on the state assessments. For the locations of place names mentioned in this section, refer to the individual state maps (e.g., Figures 4.1 and 4.4 for Arizona).

2.5.1 Eastern Plains of Colorado and New Mexico

An area of high annual average wind power is found on the high plains near the eastern borders of Colorado and northern New Mexico. Highest (class 5) annual average wind power within this area is centered near the extreme southeastern corner of Colorado and the northeastern corner of New Mexico. Strong northerly and southerly winds in this area are usually associated with the intense surface pressure gradients that are prevalent during the winter and spring. Plains areas farther west are within the sheltering influence of the Rocky Mountains and river drainages, and therefore generally have less wind power. Diurnal variations in wind speed are typically very low in this area, with maximum speeds usually occurring in mid-to-late afternoon.

2.5.2 Northern Colorado Plains

North of the South Platte River in northeastern Colorado, the elevation increases northward to the high plains of southeastern Wyoming and western Nebraska. The proximity of the sheltered South Platte River valley to the southern Wyoming wind corridor creates a steep gradient of annual average wind speed, and hence wind power, between these areas. The strong prevailing westerly winds, which blow uninterrupted through the large gap in the Continental Divide in southern Wyoming, appear to extend into northeastern Colorado and western Nebraska. Strongest winds in this area occur during the winter as a result of intense pressure gradients between the low pressure systems moving east across the

northern tier of states, and the semi-permanent high pressure system that occupies the Great Basin. Prevailing wind directions during strongest winds are generally westerly and northwesterly. Diurnal variations in wind speed are small on well-exposed sites in this area.

2.5.3 Exposed Mountain Ridges and Summits

Class 4 or higher annual average wind power is estimated for exposed mountain summits and ridge crests in Utah, Colorado, and New Mexico, except for lower elevation ranges in the Great Basin, on the Colorado Plateau, and in southern New Mexico. The map analyses represent lower limits to the wind resource for exposed terrain in these mountainous areas. Average wind speeds may

vary significantly from one ridge crest site to another, and are primarily influenced by the height and slope of the ridge, orientation to prevailing winds, and the proximity of other mountains and ridges. Winter is estimated to be the season of maximum wind power over mountain summits and ridge crests in Utah, Colorado and northern New Mexico, because mean upper-air wind speeds are highest over these areas during this season. However, spring appears to be the season of maximum wind power on the exposed mountainous areas of Arizona and southern New Mexico. In contrast to plains locations, maximum diurnal wind speeds may occur at night on many mountain summits and ridge crests, particularly if they are isolated.

FIGURE 2.1. Geographic Map of the Southern Rocky Mountain Region.

FIGURE 2.2. Topographic Map of the Southern Rocky Mountain Region.

FIGURE 2.3. Classes of Land-Surface Form in the Southern Rocky Mountain Region.

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 2.4. Annual Average Wind Power in the Southern Rocky Mountain Region

Classes of Wind Power Density at 10m and 50m (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 2.2 Areal Distribution of Wind Power Classes in the Southern Rockies

Power Class	Southern Rockies	Land Area (km ²) Equal or Exceeding Power Class			
		Arizona	Colorado	New Mexico	Utah
1	1,077,358	281,070	268,274	314,365	213,650
2	259,513	4,925	97,891	137,838	18,859
3	141,524	903	72,549	62,794	5,278
4	28,583	0	18,240	8,646	1,697
5	6,187	0	3,281	2,965	570
6	<200	0	<100	<100	<100
7	0	0	0	0	0

Power Class	Southern Rockies	Percentage Land Area Equal or Exceeding Power Class			
		Arizona	Colorado	New Mexico	Utah
1	100.0	100.0	100.0	100.0	100.0
2	24.1	1.8	36.5	43.9	8.8
3	13.1	0.3	27.0	20.0	2.5
4	2.7	0.0	6.8	2.8	0.8
5	0.6	0.0	1.2	0.9	0.3
6	<0.1	0.0	<0.1	<0.1	<0.1
7	0.0	0.0	0.0	0.0	0.0

FIGURE 2.5. Seasonal Maximum Wind Power in the Southern Rocky Mountain Region

FIGURE 2.6. Seasonal Variation in Wind Resource at Green River, Utah (Hoidale, Dayton, and Newman 1975)

CHAPTER 3: STATE FEATURES

The wind resource for each state is described in Chapters 4 through 7. The text of each description is followed by maps, graphs and tables that identify features of the geography and the wind power resource, and summarize the data collected from the observation stations. The sequence of maps, tables and graphs used to depict these features is presented in Table 3.1. In the state descriptions, these illustrations are presented so that related information is on facing pages and can be viewed simultaneously.

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 for each state are summarized here.

3.1 MAPS OF STATE FEATURES

The maps of cultural geography show the locations of major cities, rivers and terrain features for each state. The maps of shaded topographic relief are reproductions of the 1:500,000 scale U.S. Geological Survey maps. The land-surface form maps are reconstructions 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). The use of the land-surface form map was described in Section 1.8.

Two maps are used to show the locations of stations with wind data. The first map gives the locations and names of NCC stations with wind data in any form. The other map shows the locations of NCC, fire weather, and other data stations that were utilized in this assessment of the wind resource.

The map of annual average wind power is accompanied by maps of certainty rating of the estimated annual average wind power by grid cell, and 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. The certainty rating is based on the availability of wind data, the complexity of the terrain, and the inherent geographic variability of the wind resource (see Section 1.9). The maps of areal distribution give the percentage of actual land area in each cell that is estimated to have an annual average wind power class equal to or exceeding power classes 2, 3, 4, and 5 (see Section 1.10).

Maps of the average wind power are presented for each season: winter (December, January, February); spring (March, April, May); summer (June, July, August); and autumn (September, October, November). The legend for the power classes is found with the annual average wind power map.

TABLE 3.1. Maps, Tables and Graphs Used to Depict the Wind Resource

Maps	
Left Hand	Right Hand
Cultural Geography	Topographic Shaded Relief
Land-Surface Form	Legend to Land-Surface Form
NCC Station Locations	Location of Stations Used in Wind Assessment
Annual Average Wind Power	Legend to Wind Power Classes and Table on Areal Distribution
Certainty Rating	Legend for Certainty Rating
Areal Distribution (Power Classes 2 & 3)	Areal Distribution (Power Classes 4 & 5)
Seasonal Average Wind Power (Winter, Summer)	Seasonal Average Wind Power (Spring, Autumn)
Graphs	
Summary Table of Selected Stations	Interannual Speed and Power
Monthly Speed and Power	Diurnal Speed
Directional Frequency	Speed Frequency
Speed Duration	Power Duration

3.2 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 topographic setting and unique features is given in the text preceding the maps and graphs. The geographic area represented by a station varies, depending on the complexity of the local terrain and variability of the wind resource.

A table that lists 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 and 50 m 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. Even though some stations had several periods of record, only one period of record with constant anemometer height was plotted. Usually, periods when the anemometer was located on a mast mounted 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 location, the anemometer height (Z) in m, and the annual average wind speed ($\bar{V}$) in m/s and wind power ($\bar{P}$) in watts/m². $\bar{V}$ and $\bar{P}$ 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 that 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 the elevation above ground level, not roof level; the "R" indicates an exposure type.
- G - indicates that the anemometer was located on a mast attached directly to the ground. Most anemometers at airport locations were 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% 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.

3.2.1 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). Changes in instrument exposure from local development and other factors can affect interannual variations in wind speed and power.

3.2.2 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 be representative of 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.

3.2.3 Diurnal Wind Speed by Season

The diurnal variation in wind speed according to season 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 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.

3.2.4 Directional Frequency and Average Speed

Graphs of the annual average frequency of occurrence of wind direction 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 within 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 when the wind is 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.

3.2.5 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 prior to 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 occurrence of observations in the calm and 2 m/s classes.

3.2.6 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.

ARIZONA

CHAPTER 4: ARIZONA

Arizona covers 295,174 km² (113,909 mi²) and had a population of 2,305,000 in 1977 (Statistical Abstracts, 100th edition, 1979). Its largest cities, Phoenix and Tucson, have a combined population of over 1.1 million (including suburbs) and are located in desert valleys in south-central and southern Arizona, respectively (see Figure 4.1). Most of the remaining population is evenly distributed throughout the state. Flagstaff, Prescott, and Winslow in the central mountain region, Yuma and Gila Bend in the southwestern desert, and numerous other smaller cities, provide a large spatial distribution of the state's population. Grand Canyon National Park, the Painted Desert, and several Indian reservations are located in Arizona. Indian reservations within the state comprise approximately one-third of the land area (World Almanac, 1977).

The state can be divided into three main topographical regions: (1) the northeastern high plateau area, with elevations averaging 1,500 to 2,100 m (5,000 to 7,000 ft); (2) the central mountain area running diagonally from the southeastern to the northwestern corners of the state, with maximum elevations between 2,700 m and 3,600 m (9,000 and 12,000 ft); (3) the southwestern third of the state, made up of isolated mountain ranges and desert valleys (Figures 4.2, 4.3). The northeastern plateau is composed of numerous dry washes and mesas. The Chuska Mountains, Black Mesa, and the Kaibito Plateau are a few of the topographic features of this area. The intermountain region extends from the White Mountains in eastern Arizona, which have a maximum elevation of 3,503 m (11,490 ft), across the Mogollon Rim to the San Francisco Peaks in north-central Arizona, with a maximum elevation of 3,863 m (12,670 ft). The desert valleys of southwestern Arizona are an extension of the Sonoran Desert of Mexico, with elevations as low as 30 m (100 feet) above sea level near the lower Colorado River.

The availability of wind data varies from area to area within the state. In northeastern and northwestern Arizona, and in the east-central mountains, data are extremely sparse. In the desert valley areas of southwestern and south-central Arizona, wind data are fairly abundant and adequately describe the wind resource on valley floors. In the mountainous regions of central and northern Arizona, most of the available data were taken at moderately sheltered locations that are unrepresentative of the wind resource at well-exposed locations.

All available National Climatic Center data in digitized, summarized and unsummarized form were used in the assessment (Figure 4.4). This data base was supplemented with summarized wind data from private sources in industry and research at an additional 31 locations. Fire weather data are reasonably abundant in mountainous areas, but these data were taken for only one time of day, around 1300 local time, during fire weather season. Only data from those fire weather stations that indicated greater than class 1 annual average wind power, and that had sufficient records, were considered in the analysis.

4.1 ANNUAL AVERAGE WIND POWER

The annual average wind power density in Arizona is shown in Figure 4.6. This analysis of mean wind power applies to terrain features that are favorably exposed to the wind, such as mountain summits, ridge crests, hilltops, and uplands (see Section 1.6). However, nearby terrain features may interact with the windfield to cause the windpower at some exposed sites to vary as much as ± 50 to $\pm 100\%$ from the assessment value. (See Wegley et al., 1980 for information on terrain features that may increase or reduce wind energy.) In forested or wooded areas, the assessment values are representative of large clearings, such as airports, with good exposure to prevailing strong winds. The percentage of land area that is favorably exposed to the wind strongly depends on the land-surface form (see Section 1.8). In mountainous regions, the graphic displays delineate major areas of high ridges and mountains.

The annual average wind power is estimated to be class 2 or greater on exposed ridge crests and mountain summits throughout the state. Mountain summit estimates were made using a combination of extrapolated mean free air velocities at average ridge crest elevations, based on upper-air climatology (Crutcher, 1959), and on an empirical correlation between mountain summit and free air wind speeds (Wahl, 1966; see Section 1.4.2). The class 2 annual average wind power estimates for the western and southern mountain areas below 2,100 m (7,000 ft) represent the wind power potential on top and on the windward side of well exposed ridge crests that are oriented perpendicular to prevailing winds. Ridge crest and mountain summit wind power estimates for the northern and eastern mountains are class 2 and 3. The large class 3 area in east-central Arizona represents annual average wind power on the

highest (greater than 9,000 ft, or 2,700 m) ridge crests and mountain summits. This area has a wide range of elevations and ridge crests and mountain summits at lower elevations may have less annual average wind power than that indicated in Figure 4.6.

Except for a class 2 wind corridor near Kingman in northwestern Arizona, and a class 2 zone on the elevated terrain surrounding the White Mountains in east-central Arizona, the rest of the state (excluding ridge crests) is estimated to have class 1 annual average wind power. Wind data from Winslow, Kingman Airport, Safford, and four fire weather lookouts show class 2 annual average wind power. Data from the remaining 70 wind stations analyzed show class 1. However, most of these 70 stations are located in areas under the influence of mountain-valley circulations, with less than ideal exposure to the winds aloft. For example, Winslow, Prescott, Payson, and Flagstaff were the primary data sources used to estimate the wind power potential for the northeastern plateau and central mountain region. Unfortunately, these stations are all under the influence of downslope nighttime drainage flow. This tends to fill the areas around these stations with stable air and shelters them from synoptic winds, especially during nighttime and early morning hours, and in the winter. It is possible that locations with better exposure on the mesas and bluffs throughout the northeastern and central areas of Arizona will have annual average wind power greater than that indicated in Figure 4.6. Wind corridors (regions of wind channeling and acceleration) that have not yet been identified will also have wind power potential higher than indicated.

4.1.1 Certainty Rating of the Wind Resource

Certainty ratings for the annual average wind power estimates for Arizona are shown in Figure 4.7. Highest (4) certainty ratings were given to grid cells that contain, or that are adjacent to grid cells that contain, sites with representative long-term data. These high certainty ratings were given primarily to highly-populated areas, where data are most abundant. Such areas are found in the vicinities of Phoenix, Tucson, Gila Bend, and Yuma. A certainty rating of 4 was also given to the small class 2 wind corridor near Kingman. Certainty ratings of 3 were generally given to grid cells with short-term data or data based on less than 24 observations per day. Areas with certainty ratings of 3 are scattered throughout the state, with concentrations in the large

portion of central Arizona that surrounds Prescott and the eastern part of the Coconino Plateau, in eastern Arizona north of the White Mountains, and in southeastern Arizona around Douglas.

Certainty ratings of 2 were given to grid cells that contain no data stations, but that are composed of simple terrain and for which the wind power estimate is considered to be reliable. Clusters of certainty ratings of 2 are found in extreme northwestern Arizona and in areas of ridge crest estimates where upper-air data were used to approximate the wind resource. Lowest (1) certainty ratings were given to areas of moderately to highly complex terrain with no data. These low certainty areas are found in the data-sparse areas of the Colorado Plateau in northeastern Arizona, the vicinity of the Grand Canyon, west-central Arizona, extreme south-central Arizona, and in the highly complex terrain to the west and south of the White Mountains in eastern Arizona.

4.1.2 Areal Distribution

The areal distribution of wind power in Arizona is illustrated in Figure 4.8 and tabulated in Table 4.1. Numbers represent the percentage of actual land area within each cell of the grid that is exposed to wind power that is equal to or exceeds some threshold value.

There is no class 4 or greater annual average wind power in Arizona, and areas with exposure to class 3 wind power amount to less than 1% of the total land area in the state. All of the class 3 wind power is found on scattered ridge crests in eastern and northern Arizona, where exposed land area amounts to 10% or less of the total land area (Figure 4.8, class 3).

Less than 2% of the land area in Arizona is estimated to have exposure to class 2 or greater wind power. Much of this is found in the small class 2 wind corridor near Kingman, where 75% of the land area is estimated to have class 2 exposure. The rest is found on isolated ridge crests throughout the state (Figure 4.8, class 2). About 98% of the land surface in Arizona is estimated to have class 1 wind power.

4.2 SEASONAL WIND POWER

Seasonal wind power maps for Arizona are shown in Figure 4.9. The season of maximum wind power is spring over most of the state, with the exception of the northern mountain summits and ridge crests, which have a winter-spring maximum. Winter is the season of minimum wind power for all areas of the state except ridge crests and

mountain summits in northern and central areas, which have minimum wind power in the summer and autumn.

4.2.1 Winter

During the winter the wind power is estimated to be class 1 for all of Arizona except for areas near the White Mountains in east-central Arizona, the small class 2 wind corridor near Kingman, and on ridge crests and mountain summits in the northern half of the state. These low wind power estimates are primarily the result of two factors. The first is the persistent occurrence of a high pressure system in southern Nevada and southwestern Utah which brings large-scale subsidence and general air stagnation to the surrounding region. The second is the high frequency (>85%) of surface-based temperature inversions that occur during the nighttime and morning hours as a result of strong surface cooling after sunset. Throughout the desert valleys and river drainages, local terrain influences on the wind flow pattern are usually in the form of mountain-valley circulations during winter months, when the prevailing winds are associated with stable air drainage down river valleys and mountain slopes. Examples of this are the prevailing easterly winds at Phoenix, southeasterly winds at Tucson, and, to a lesser degree, the southeasterly winds at Gila Bend.

Even though the winds aloft are strongest during the winter season, the wind power on exposed mountain summits and ridge crests in southern and southwestern Arizona is still estimated to be class 1. This estimate is based, in part, on data from the Mt. Hopkins observatory on Kitt Peak, at an elevation of 2,103 m (6,898 ft). Wind power on exposed ridge crests and mountain summits in the rest of the state is estimated to be class 2 or greater.

4.2.2 Spring

In the spring, exposed ridge crests in the central and northeastern parts of the state are estimated to have class 3 and class 4 wind power, based on the climatology of upper-air winds (Crutcher, 1959), as well as on data from surrounding stations.

Except for the ridge crest estimates mentioned above, the only areas estimated to have class 3 wind power are the class 3 wind corridor immediately northeast of Kingman, where prevailing southwesterly winds are channeled up the Sacramento Valley over the Kingman Gap and into the Hualpai Valley, and a class 3 area surrounding the White Mountains of east-

central Arizona. Ridge crest and mountain summit wind power estimates for southwestern Arizona are class 2, based on wind data from Mt. Hopkins observatory on Kitt Peak. The entire northern high plateau area, from the mountains east of Tucson and Phoenix northwest to Kingman and north across the Grand Canyon and the Kanab Plateau to the Utah border, is estimated to have at least class 2 wind power. However, data from Winslow and Safford suggest that some well-exposed mesa locations and tablelands in this area could have class 3 wind power.

As in winter, the desert valleys of southwestern Arizona are estimated to have Class 1 wind power.

4.2.3 Summer

In the summer, wind power is estimated to be class 1 throughout the state, except for the highest mountain summits and ridge crests which are estimated to have class 2 to class 3 wind power, and the class 2 wind corridor near Kingman.

During the daylight hours in summer, strong surface heating provides good vertical mixing of the lower atmosphere and creates moderate surface circulations in mountain-valley topography. However, after sunset, surface cooling frequently establishes a thermally stable layer of air at the ground that decouples surface winds from winds aloft and permits the development of either light downslope drainage winds or calm conditions. Wind power during afternoon hours (1100 to 1900 local time) averages approximately 60% higher than the 24-hour average wind power. In mountain-valley areas such as Flagstaff and Winslow, the afternoon wind power average is one to two classes higher than the 24-hour average.

4.2.4 Autumn

In autumn, the wind power is estimated to be nearly the same as in summer, with most of the state having class 1 wind power. All ridge crests and mountain summits are estimated to have class 2 wind power. It is possible that the highest summits of the White Mountains may have class 3 wind power, although this is not indicated in Figure 4.9.

Most of the stations analyzed had less wind power in autumn than in summer, a consequence of reduced surface heating (lower sun angle and shorter days) in the autumn, and therefore more stable surface conditions. In addition, the local circulations driven by the uneven heating of topography do not develop to the same intensity during autumn.

4.3 FEATURES OF SELECTED STATIONS

Table 4.2 gives the locations and annual wind speed and power density of thirteen stations in Arizona. Graphs of other features of the wind resource at these stations are shown in Figures 4.10 through 4.16. Five stations are located at elevations above 1,400 m (5,000 ft) in the mountain and plateau area that extends diagonally from the southeastern to the northwestern corner of the state. The remaining eight stations are located in the lowland desert valleys of southwestern Arizona.

Chandler/Williams AFB (Air Force Base) is located southeast of downtown Phoenix, midway between the Gila and Salt Rivers. Williams AFB, located approximately 10 miles east of Chandler, is representative of exposed sites in the basins of southeastern Arizona.

Flagstaff Airport, situated in the mountainous terrain northwest of the Mogollon Plateau near the base of San Francisco peaks, has an elevation of 2,133 m (7,000 ft). The airport site is located approximately 4 miles south of town on a well-exposed clearing that appears to have good exposure to prevailing southwesterly winds.

Fort Huachuca/Libby AAB (Army Air Base) is located approximately 30 km (18 mi) from the border of Mexico in southeastern Arizona. The station, located on an alluvial plain on the northeastern slope of the Huachuca Mountains, has moderately good exposure. However, because the station appears to be sheltered from southerly winds by the mountains, it is probable that wind power is higher in better-exposed locations in the area.

Gila Bend Airport appears to be representative of well-exposed stations in the southwestern desert of Arizona. Weak nighttime drainage flow from the Sauceda and Sand Tank Mountains, which rise 600 m (2,000 ft) above the Gila River nearby, produces a peak in the wind direction frequency distribution for south-southeast winds. However, it does not appear that surrounding terrain has much sheltering effect on the wind resource.

Payson Airport is located on Birch Mesa approximately 19 km (12 mi) southwest of the Mogollon Rim in the central mountains of Arizona. The terrain surrounding the airport is complex and forested, so that this site is most likely unrepresentative of well-exposed mountain locations in the area.

Three sites in the Phoenix area are included in Table 4.2. These are Skyharbor International Airport, Litchfield NAF (Naval Air Facility), and Luke AFB. The Phoenix Area is located in the Salt River basin in south-central Arizona and is a well documented, although poor, wind resource area. There are numerous locally well-exposed wind monitoring stations situated throughout the 4,150 km² (1,600 mi²) area surrounding downtown Phoenix. Average wind power is very consistent among these stations, although some differences exist in the prevailing wind directions. This is a result of channeling effects of the Agua Fria, Salt, and Gila river washes, which join just west of Phoenix.

Prescott Airport is located in west-central Arizona approximately 13 km (8 mi) northeast of the town of Prescott, on the southern shoulder of Chino Valley in the lee of the Bradshaw Mountains. The airport has moderate exposure to the prevailing south to southwesterly winds; however, because the surrounding terrain is complex and forested, it is probable that better-exposed locations on nearby higher terrain will have higher annual average wind power.

Two stations in the Tucson area are included in Table 4.2. These are Tucson International Airport and Davis-Monthan AFB. The Tucson area is located in the Santa Cruz Valley at an elevation of 730 m (2,400 ft), and is surrounded by mountain ranges. The normally dry Santa Cruz River runs approximately south to north along the west edge of the city. Prevailing winds in the area are in large part determined by the persistent mountain-valley circulation pattern that consists of downslope drainage winds from the south-southeast (down the Santa Cruz River) and upslope flow from the west (Frenzel, 1961). Data from the Tucson area is representative of desert valleys in southern Arizona.

Winslow Airport is situated on the southern edge of the Painted Desert, a few miles west of the Little Colorado River on the Colorado Plateau of northeastern Arizona. Data from this valley station frequently show prolonged periods during which unusually strong local temperature inversions trap cold dense air near the surface, decoupling surface winds from winds aloft (Brenner, 1980). During these periods, the Little Colorado River causes a light southeasterly drainage wind that provides some circulation. It is probable that sites at higher elevations surrounding the Winslow area will have appreciably more wind power than that at the Winslow Airport.

Yuma International Airport is located on the southern outskirts of Yuma on the south bank of the Colorado River in extreme southwestern Arizona. It appears that the airport is sheltered from northwesterly winds by the city. Sites situated on higher terrain nearby will probably have higher average wind power than that indicated by data from Yuma International Airport.

4.3.1. Interannual Wind Power and Speed

Ten stations have selected periods of record of ten years or more (Figure 4.10). Because of the low wind power resource for most of the state, which is primarily the result of generally light winds aloft and local circulations induced by the heating and cooling of steep terrain, the range of interannual variability of wind power is very low. The percentage interannual variability of wind speed is high because of the low magnitude of the mean speed. For example, at Phoenix, a 1 m/s increase in the annual mean speed represents an increase of nearly 50% over the long-term mean speed. Winslow, Flagstaff, and Tucson International Airport have the highest potential for interannual variability. There is good interstation agreement for the 1953 maximum at Flagstaff, Prescott, and to a lesser degree, at Winslow. Long-term trends of increasing or decreasing wind power should be treated with caution. For example, Phoenix/Luke AFB and Tucson International Airport both show a steady increase in wind power for the period from approximately 1952 to 1961 that is not evident in data from cognizant sites a few miles away.

4.3.2. Monthly Average Wind Power and Speed

All stations in Arizona have wind power maxima in the spring (Figure 4.11). This is a result of the strong thermal gradients that exist between the warm deserts of northern Mexico and southwestern Arizona, and the relatively cool mountain areas to the north. In addition, periodic penetration into Arizona of Pacific storms during the spring season reinforces pressure gradient flow. This is especially true at the northern plateau stations at Flagstaff, Prescott, Winslow, and the southern mountain station at Fort Huachuca. A secondary wind power maximum is present in July and early August for stations in the southwestern desert area (i.e., Yuma, and, to a lesser extent, Gila Bend). A secondary wind power maximum also appears in late autumn at Tucson International Airport (in the Santa Cruz River drainage) which is not evident in data from Tucson/Davis-Monthan AFB (on the outskirts of the Santa Cruz

River drainage). Indications are that the Santa Cruz River drainage winds are at their maximum at the surface in the fall, while greatest speeds at 300 m (1,000 ft) occur in January (Frenzel, 1961).

The period of minimum wind power at most locations is in late August and September, when mountain-valley circulations and temperature gradients are weakest. Exceptions can be found at Winslow, Phoenix, Chandler, and at other sites where cold stable air collects in river basins during the winter. While downslope drainage flow at these sites is well established during winter periods, peak velocities associated with the drainage winds are above the surface and the air at the surface remains nearly stagnant, and wind power is at a minimum.

4.3.3 Diurnal Wind Speed by Season

Stations throughout Arizona generally show the highest wind speeds during the afternoon, particularly in spring and summer (Figure 4.12). Sites located at high elevations, such as Flagstaff, Fort Huachuca, Payson, and Winslow, have velocity maxima between approximately 1100 and 1800 local time during most of the year. These times are shifted ± 1 hour or so depending on the season. Stations that have well established diurnal mountain-valley circulations, such as Phoenix, Tucson, and Chandler, have maximum wind speeds between approximately 1300 and 1900 local time during the spring and summer. The 2 to 3 hour delay in establishment of upslope flow at these sites, as compared with mountain locations, is a consequence of the amount of surface heating required to overcome the downslope nighttime drainage pattern and reverse the wind field. In winter, mountain-valley circulation is extremely biased by downslope drainage winds. Maximum drainage winds during winter generally occur about an hour after sunrise when the downslope circulation is at a peak.

The largest diurnal variations occur in the spring when strong insolation provides good convective mixing and surface link-up with winds aloft in the daytime, while at night radiational cooling of the surface creates a stable surface air layer that decouples surface winds from winds aloft. In this case, minimum winds occur shortly after sunrise. This is exemplified by most Arizona stations in the spring and summer.

Diurnal variation of wind speed is the same for autumn and winter at most Arizona stations. At stations where established mountain drainage patterns control nighttime winds during the fall and winter, the period of minimum wind speed is shortly after sunset.

4.3.4 Directional Frequency and Average Speed

The directional frequency of the prevailing winds at stations throughout Arizona is highly dependent upon the nature of the surrounding terrain, because of the general absence of synoptic-scale pressure gradient winds (Figure 4.13). In general, the prevailing wind direction for strongest winds is west to southwest, but the most frequently occurring wind direction is usually associated with nighttime downslope drainage patterns. Phoenix/Skyharbor Airport, Phoenix/Litchfield Airport, Tucson International Airport, Chandler and, to a lesser degree, Gila Bend, all have prominent wind direction frequency maxima corresponding to the direction of downslope flow. In general, evaluation of wind direction frequency distributions and average speeds at any station in Arizona requires a clear understanding of local terrain influences.

4.3.5 Annual Average Wind Speed Frequency Distribution

The annual average wind speed frequency distributions for ten of the thirteen stations plotted (Figure 4.14) indicate that observer biases may be present in the data. Observer bias is apparent from the peaks at approximately 2 m/s (5 kts) and,

to a lesser degree, at approximately 5 m/s (10 kts) at Chandler, Payson, and Tucson/Davis-Monthan AFB. In addition, data from at least seven of the stations show a number of reported calms that unrealistically exceeds the number of reported wind speeds between zero and 2 mps.

Because these possible observer biases and low instrument threshold speeds distort the actual frequency distribution, the representativeness of the Rayleigh distribution is difficult to evaluate. In general, the distribution for the second period of record at Winslow and both periods of record at Yuma indicate reasonably good agreement with the Rayleigh distribution, although the threshold speed problem causes a noticeable departure at low wind speeds. However, observer errors or sensor limitations at low wind speeds probably do not significantly affect average wind power estimates.

4.3.6 Annual Average Wind Speed and Power Duration

The percentage of time that a given wind speed or power is exceeded is shown in Figures 4.15 and 4.16. 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, as discussed in Section 4.3.5.

FIGURE 4.1. Geographic Map of Arizona

FIGURE 4.2. Topographic Map of Arizona

FIGURE 4.3. Land-Surface Form Map for Arizona

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 4.4. NCC Station Locations in Arizona

FIGURE 4.5. Locations of Stations Used in Arizona Wind Assessment

FIGURE 4.6. Arizona Annual Average Wind Power

Classes of Wind Power Density at 10m and 50m (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 4.1. Areal Distribution (km²) of Wind Power Classes in Arizona

Power Class	Land Area	% Land Area	Cumulative Land Area	% Cumulative Land Area
1	276,145	98.3	281,070	100.0
2	4,022	1.4	4,925	1.8
3	903	0.3	903	0.3
4	0	0.0	0	0.0
5	0	0.0	0	0.0
6	0	0.0	0	0.0
7	0	0.0	0	0.0

FIGURE 4.7. Certainty Rating of Arizona Wind Resource

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 4.8. Areal Distribution of Wind Resource in Arizona (Power Classes 2 and 3); Percent of Land Area With or Exceeding Power Class Shown.

FIGURE 4.8 (Continued). Areal Distribution of Wind Resource in Arizona (Power Classes 4 and 5); Percent of Land Area With or Exceeding Power Class Shown.

FIGURE 4.9. Seasonal Average Wind Power in Arizona (Winter, Summer)

FIGURE 4.9. (Continued). Seasonal Average Wind Power in Arizona (Spring, Autumn)

TABLE 4.2. Arizona Stations with Graphs of the Wind Characteristics

Station	Station Name ^(a)	Lat N (deg, min)	Long W (deg, min)	Elevation (m)	Period of Record (month, year)	Anem. Height (m)	Annual Average Speed (m/s)			Annual Average Power (watts/m ²)		
							Anem Ht	At 10 m	At 50 m	Anem Ht	At 10 m	At 50 m
Chandler, Arizona	Williams AFB	33, 18	111, 40	412	5/53-3/56	14.6	2.5	2.4	3.0	32	27	54
Flagstaff, Arizona	Flagstaff Airport	35, 08	111, 40	2133	10/65-12/78	6.1	3.2	3.5	4.4	42	52	103
Fort Huachuca, Arizona	Libby AAB	31, 35	110, 20	1422	10/54-7/71	unk ^(c)	3.2	3.0	3.8	45	45	90
Gila Bend, Arizona	Gila Bend Airport	32, 53	112, 43	261	11/48-12/54	7.6	3.5	3.7	4.6	51	57	114
Payson, Arizona	Payson Airport	34, 14	111, 20	1497	1/49-2/51	6.1	2.3	2.5	3.1	20	25	49
Phoenix, Arizona	Skyharbor International Apt.	33, 26	112, 01	339	12/52-5/58	9.8	2.3	2.3	2.9	26	26	52
Phoenix, ^(b) Arizona	Litchfield NAF	33, 26	112, 22	292	3/55-1/63	13.7	2.4	2.3	2.9	28	24	49
Phoenix, Arizona	Luke AFB	33, 33	112, 22	331	5/53-3/59	9.1	2.1	2.2	2.7	26	27	54
Prescott, Arizona	Prescott Airport	34, 39	112, 26	1530	4/65-12/78	6.1	3.7	4.0	5.0	56	69	138
Tucson, Arizona	Tucson International Apt.	32, 07	110, 56	789	9/49-10/58 10/58-7/67	10.1 7.0	3.1 4.1	3.1 4.3	3.9 5.5	48 75	48 87	95 174
Tucson, Arizona	Davis-Monthan AFB	32, 11	110, 55	797	1/49-3/53	9.1	2.8	2.9	3.6	52	54	108
Winslow, Arizona	Winslow Airport	35, 01	110, 44	1488	8/51-2/59 2/59-12/78	11.3 6.1	3.7 3.9	3.6 4.2	4.6 5.3	84 90	80 111	159 222
Yuma, Arizona	Yuma International Airport	32, 40	114, 36	62	7/50-1/58 3/64-12/78	8.2 6.4	3.6 3.5	3.7 3.7	4.6 4.7	64 56	70 68	139 135

^(a) AFB - Air Force Base; AAB - Army Air Base; NAF - Naval Air Facility.

^(b) Station had less than 18 observations per day.

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

FIGURE 4.10. Interannual Wind Power and Speed for Arizona

— WIND POWER
 - - - WIND SPEED
 PNL-3195 WERA-8

LEFT ORDINATE - WATTS/M²
 RIGHT ORDINATE - M/S
 ABSCISSA - MONTH

V AND P ADJUSTED FROM Z TO 10 M BY 1/7 POWER LAW

FIGURE 4.11. Monthly Average Wind Power and Speed for Arizona

+---+ WINTER ♦---♦ SPRING
 ⊕---⊕ SUMMER ▣---▣ AUTUMN
 PNL-3195 WERA-8

ORDINATE - M/S
 ABSCISSA - HOUR

FIGURE 4.12. Diurnal Wind Speed by Season for Arizona

— PERCENT FREQUENCY LEFT ORDINATE - PERCENT
 - - - WIND SPEED RIGHT ORDINATE - M/S
 PNL-3195 WERA-8
 ABSCISSA - WIND DIRECTION

FIGURE 4.13. Directional Frequency and Average Wind Speed for Arizona

— ACTUAL DISTRIBUTION ORDINATE - PERCENT
 - - - RAYLEIGH DISTRIBUTION ABSCISSA - M/S
 PNL-3196 WERA-8

FIGURE 4.14. Annual Average Wind Speed Frequency for Arizona

ORDINATE - PERCENT
ABSCISSA - M/S
PNL-3195 WERA-8

FIGURE 4.15. Annual Average Wind Speed Duration for Arizona

ORDINATE - PERCENT
ABSCISSA - WATTS/M²
PNL-3195 WERA-8

FIGURE 4.16. Annual Average Wind Power Duration for Arizona

COLORADO

Colorado covers an area of 270,137 km² (104,247 mi²) and had a population of 2,625,000 in 1977 (Statistical Abstracts, 100th edition, 1979). Most of the residents live in the major cities on the eastern slope of the Rocky Mountains (see Figure 5.1). Recently, energy development and mining activities on the western slope of the Rockies have resulted in significant increases in the populations of western slope communities. The largest cities in Colorado are Denver, Boulder, and Colorado Springs on the eastern slope of the Rockies, and Grand Junction on the western slope.

The state of Colorado can be divided into two geographical regions, the Rocky Mountains and the eastern plains (see Figures 5.2 and 5.3). The Rocky Mountain range extends from north to south throughout the western half of the state and is composed of rugged mountains and steep valleys. Local elevations in the western valleys exceed 1,800 m (6,000 ft) and mountain summits with ridge elevations exceeding 4,000 m (13,000 ft) are common. The eastern foothills of the Rockies delineate the western border of the Great Plains. In this region the major population centers are immediately (within 20 miles) adjacent to the foothills of the Rockies. Elevations vary from approximately 1,600 m (5,280 ft) near the foothills to approximately 1,000 m (3,385 ft) in eastern Colorado near the Kansas border. Much of this area is agricultural, particularly the South Platte River and Arkansas River drainage basins.

Wind data are reasonably abundant on the eastern slope of the Rockies where the major towns and cities are located (see Figure 5.4). Data are generally sparse over the remainder of the state (Figure 5.5). Fire weather data are abundant in the mountainous regions, but these data generally consist of only one observation per day, at about 1400 local time, during the local fire weather season. Only fire weather data that indicated greater than class 1 annual average wind power and that had sufficient periods of record were used. The National Climatic Center data base used in the analysis was supplemented by wind data summaries from stations operated by utilities, mining companies and research agencies throughout the eastern plains and western valleys and mountains.

5.1 ANNUAL AVERAGE WIND POWER

The annual average available wind power density for Colorado is shown in Figure 5.6. Analyses of mean wind power

apply to terrain features that are favorably exposed to the wind, such as mountain summits, ridge crests, hilltops, and uplands (see Section 1.6). However, nearby terrain features may interact with the windfield to cause the wind power at some exposed sites to vary as much as ± 50 to 100% from the assessment value. (See Wegley et al., 1980 for information on terrain features that may increase or reduce wind energy.) In forested or wooded areas, the assessment values are representative of large clearings, such as airports, with good exposure to the prevailing strong winds. In mountainous regions, which constitute much of Colorado, the graphic displays (Figures 5.6 and 5.9) delineate major valleys such as the San Luis Valley in southwestern Colorado and the Colorado River drainage in western Colorado. The percentage of land area that is favorably exposed to the wind strongly depends on the land-surface form (see Section 1.8).

Throughout the valleys and drainage basins between the Utah border of western Colorado and the Continental Divide, annual average wind power is estimated to be generally class 1 (Figure 5.6). Exceptions to this occur in areas of extreme northern Colorado that are influenced by the southern Wyoming wind corridor (Elliott and Barchet, 1980b), and in the lower San Luis Valley.

In the mountainous areas of western Colorado, upland valleys are sheltered from the prevailing winds by steep valley walls. The large exposed basins of extreme western Colorado act as collection basins for cold air that flows downslope from the surrounding high terrain, creating a stable layer near the surface. A similar condition frequently exists during the fall, winter, and early spring, when strong subsidence inversions due to high pressure produce lengthy periods of air stagnation. When these stable surface conditions exist, the colder air near the ground decouples surface winds from synoptic pressure gradient winds aloft, resulting in low surface wind speeds.

High mountain summits and exposed ridges throughout the state are estimated to have class 3 or greater annual average wind power. The upper air climatology for this region shows a mean velocity gradient with westerly winds increasing in speed from the southwestern corner of the state to the northeastern corner. North of a line from Colorado Springs to Salt Lake City, Utah, data obtained at exposed mountain stations indicate that class 5 or greater annual average wind power can be expected on

exposed ridges above 3,000 m (10,000 ft). South of that line, annual average wind power can be expected to be class 5 or less at exposed summit locations. Data were obtained at several mountain summit locations that suggest the existence of terrain induced convergence zones, or wind compression areas, that can routinely increase annual average wind power well into the class 7 category. This is indicated by data from Pikes Peak and the Niwot Ridge Alpine Station. On the other hand, data from several well-exposed high mountain stations show annual average wind power values that are well below the ridge crest estimates. This variability illustrates the complex interaction between terrain exposure and orientation to prevailing wind directions as it affects the potential wind power in the high mountain climates of Colorado.

The area directly in the lee of the Continental Divide is sheltered by the continuous 4,000 m (13,000 ft) mountain barrier to the west. Annual average wind power in this region between elevations of 3,000 m (10,000 ft) near the base of the high ridges, and 1,700 m (5,500 ft) at the base of the foothills, is generally class 3 or less. Winds in this area are predominantly associated with the diurnal cycle of upslope and downslope flow which is persistent but gentle. An exception to this pattern is the occasional occurrence of strong downslope gradient winds known as "Chinook Winds".

Annual average wind power at the base of the Rocky Mountain foothills, in the area known as the east slope, is generally class 2 or less. This area is sheltered from weak to moderate westerly synoptic winds by the mountain barrier to the west and by cool stable air that collects in the river basins, as a result of either downslope flow of cool air from the mountains at night or radiational heat loss by the surface during winter months. In this area, a local upslope-downslope circulation persists as long as the general circulation pressure gradient is weak. However, under the influence of strong pressure gradients, very strong short-term (generally less than 24 hours) wind storms with average surface speeds exceeding 25 m/s (55 mph) and wind gusts to 50 m/s (110 mph) can occur. These winds make a substantial contribution to the annual average wind power in this area. For this reason, the useable wind resource is probably less than the available wind resource as shown in Figure 4.6.

North of the South Platte River valley in northeastern Colorado, a very strong north-south wind speed gradient exists

between the high plains of the southern Wyoming wind corridor and the lowlands of the South Platte River drainage. The northern Colorado Rockies form a barrier to strong westerly flow, causing westerly winds to be channeled through the southern Wyoming wind corridor as air flows over the Continental Divide (Elliott and Barchet, 1980b). East of this gap in the Continental Divide, there is a divergence zone in which the winds veer to a northwesterly direction and are reduced in magnitude as some of the air flows southeastward into the South Platte River drainage. In this area the annual average wind power decreases from class 4 on the Wyoming-Colorado border to class 1 near the South Platte River, approximately 35 miles south of the border.

South of the South Platte River drainage, on the higher terrain of the Palmer Ridge, annual average wind power is estimated to be class 3, although very few wind monitoring sites were identified. Data from several stations on the west side of this area indicate class 3 or greater annual average wind power. At Limon, near the eastern end of the Palmer Ridge, limited data from a sheltered location indicate a potential for class 3 wind power on exposed uplands and hilltops in the vicinity.

The Arkansas River valley creates a large perturbation of the east-west annual average wind power gradient and influences the wind resource up to 160 km (100 miles) east of the mountains. Annual average wind power in this river valley is estimated to be class 2, although higher values can be expected at well-exposed sites on either side of the river.

On the plains of eastern Colorado near the Kansas and Nebraska borders, annual average wind power is estimated to be class 4 or greater at well-exposed locations. Although a very limited number of stations were identified, digitized data from NCC stations at Goodland and Garden City, in western Kansas, show annual average wind power well within the class 4 category. Prevailing wind directions during peak wind speed periods on the high plains are either northerly or southerly.

5.1.1 Certainty Rating of the Wind Resource

Certainty ratings for the wind power estimates for Colorado are shown in Figure 5.7. The highest certainty rating given to any grid cell in Colorado was 3. These ratings (3) were given to grid cells that contain, or that are adjacent to grid cells that contain, sites with wind data.

Such areas are found mainly in eastern Colorado, e.g. near and north of Denver, and around Akron, Colorado Springs, and Pueblo. Areas with certainty ratings of 3 are also found in south-central Colorado near Alamosa in the San Luis valley, Grand Junction and Gunnison on the Colorado River drainage, and to the Dolores and Yampa River drainages in southwestern and northwestern Colorado respectively.

Highest (4) certainty ratings were not given to any grid cells in Colorado, primarily because sites with long-term data indicated annual average wind power that did not agree with the wind power category that was assigned to the general area on the basis of data from numerous other stations, as well as on the basis of terrain considerations. For example, three stations in the Denver area (Aurora/Buckley Field, Denver/Aurora NAS, and Denver/Stapleton International Airport) had long-term data that showed class 1 annual average wind power; however, these sites were located in relatively low-lying areas and were not considered truly representative of the surrounding higher areas to the north and south that are estimated to have class 2 and 3 annual average wind power. For another example, long-term data from Akron indicates class 4 annual average wind power (234 W/m^2); however, numerous other sites in the area indicated lower wind power, and the general area was estimated to have class 3 annual average wind power.

Certainty ratings of 2 were given to grid cells that have no data, but that are composed of relatively simple terrain, such as most of the eastern Colorado plains, and to grid cells that have data but in which the wind resource is expected to vary considerably, such as the area of north-eastern Colorado that borders Wyoming and that is influenced by the southern Wyoming wind corridor. Lowest (1) certainty ratings were given to grid cells that have no data and that are composed of terrain of moderate to high complexity. Areas with certainty ratings of 1 are found in low areas in northwestern Colorado that are close to the Wyoming border, to a large area in southeastern Colorado that has no data and that is composed of moderately complex (land-surface form B4c) terrain, and to grid cells on the eastern Colorado plains that have no data and that are traversed by the class 3-class 4 wind power boundary.

Much of Colorado is composed of mountainous areas and wind power estimates for these areas were based primarily on the

climatology of upper-air winds. These ridge crest and mountain summit wind power estimates were given a certainty rating of 2.

5.1.2 Areal Distribution

The areal distribution of wind power in Colorado is illustrated in Figure 5.8 and tabulated in Table 5.1. Actual land area that is exposed to class 3 or greater wind power is about 27% of the total land area in the state (Table 5.1). Most of this is found in the plains area of eastern Colorado, as is apparent from Figure 5.8 (class 3). Except for eastern Colorado, class 3 or greater wind power is found only on exposed ridge crests and mountain summits, and exposed land surface area in these mountainous areas amounts to 10% or less of the total land area, and in most mountainous areas amounts to 2% or less. As shown in Table 5.1, it is estimated that there is more land-surface area exposed to class 3 wind power (20.2%) than is exposed to class 2 wind power (9.5%). This is because of the large amount of exposed area in eastern Colorado that is estimated to have class 3 annual average wind power.

Actual land area with exposure to class 4 or greater wind power constitutes less than 7% of the total land area of the state, and is found mainly on the plains of extreme eastern Colorado and in northern Colorado near the Wyoming border. In the latter area, it is estimated that 92% of the land area has class 4 exposure, a consequence of the proximity of this area to the southern Wyoming wind corridor.

Exposure to class 5 or greater wind power is found on about 1% of the total land area of the state. This exposed land is found primarily in extreme southeastern Colorado, near the high wind area of the Texas and Oklahoma panhandles and where it is estimated that 88% of the land surface area has exposure to class 5 or greater wind power, and on ridge crests and mountain summits of the central Colorado Rockies (Figure 5.8, class 5). In these mountainous areas, class 5 exposure is found on only about 2% of the total land area. The grid cell in north-central Colorado that shows 10% of land area with exposure to class 5 or greater wind power represents an area of Colorado that is part of the southern Wyoming wind corridor. Here, the terrain is less extreme than in most of the northern Colorado Rockies, and there is good exposure to westerly winds flowing over the Continental Divide.

5.2 SEASONAL WIND VARIATIONS

Wind power maps for each season are shown in Figure 5.9. Winter is the season of maximum wind power on the exposed ridges and summits of the Rocky Mountains, and along the northern border of Colorado adjacent to the Wyoming wind corridor. In the remainder of the state, maximum wind power occurs in the spring. Summer is the minimum wind power season throughout the state, although the average wind power is about the same in summer and fall for areas on the high plains of eastern Colorado.

5.2.1 Winter

In the winter average wind power is estimated to be class 5 to class 7 on exposed ridge crests and mountain summits throughout the high terrain areas of the state. This is a consequence of the southerly position of the polar front jet stream in this season, and the increased winds aloft associated with this phenomenon. Data from exposed mountain summits (above 3,500 m) such as Pikes Peak, Mines Peak near Berthoud Pass, and the Niwot Transect Alpine Station D1, show average wind power values near 1,200 W/m² (class 7) during the winter, yet data from nearby stations less than 500 m lower in elevation show average wind power that is less than 300 W/m² (class 4). In addition, analysis of the wind data collected at numerous ski areas throughout the state show extreme variability in the wind power resource at ridge top locations.

Average winter wind power is estimated to be class 1 throughout the valleys and basins of western Colorado, except for the central and southern portions of the San Luis Valley in south-central Colorado. Here, average winter wind power is estimated to be class 2. Wind data taken in the Yampa, Colorado, White and Gunnison river valleys show class 1 winter wind power, with prevailing wind directions that are oriented parallel to the valleys. The pattern of strong nighttime low-level temperature inversions, and periods of persistent air stagnation associated with the continental polar air mass which occupies the Great Basin to the west during the winter, contributes to the frequent calm conditions in the valleys and basin areas. Data from Eagle in west-central Colorado, for example, show a frequency of occurrence of calm conditions of 40% during the winter.

Average winter wind power in eastern Colorado increases from class 1 in the immediate lee of the Rocky Mountain foothills to class 4 on the high plains of

extreme eastern Colorado. The class 1 wind power area that comprises the South Platte and Poudre River drainage basins in north-eastern Colorado remains under a strong inversion during most of the winter, keeping all but the strongest gradient winds from reaching the surface. Higher average wind power near the Arkansas River is a consequence of the greater surface heating and link-up with gradient winds. The strong wind power gradient in north-eastern Colorado is a consequence of the proximity of the sheltered South Platte River basin to the class 6 southern Wyoming wind corridor.

5.2.2 Spring

In spring, eastern Colorado is estimated to have wind power that ranges from class 2 along the Rocky Mountain foothills to class 5 along the Kansas border. In early spring, areas near the foothills are periodically subject to very strong (>25 m/s) downslope westerly and north-westerly gradient winds of short duration (<24 hours); in late spring, nighttime radiation inversions are quickly dissipated by the warming sun. Because of this, average spring wind power in this area is estimated to be class 2 rather than class 1 as in winter. Because of the sheltering effect of the South Platte River valley, this area is estimated to have class 1 wind power. A strong northward wind power gradient exists, with spring wind power increasing to class 5 near the southern Wyoming wind corridor. (Also see Section 5.1).

On the eastern plains of Colorado the west-to-east wind power gradient from class 2 to class 5 is a result of increasing distance from the sheltering effects of the Rocky Mountains. In addition, midlatitude cyclones frequently develop during spring in the lee of the Colorado Rockies and intensify as they move out onto the plains. These developing low pressure systems frequently create strong northerly flow on the high plains. The prevailing north-south winds are also, in part, a consequence of the strong north-south temperature gradients that exist during this season.

In western Colorado, on the western slope of the Rockies, the persistent occurrence of nighttime radiation inversions keeps the valleys and basins at class 1, although well-exposed locations, such as the North Park area of extreme north-central Colorado, could easily have class 2 wind power. The central and southern portions of the San Luis Valley are estimated to have class 3 wind power.

The strong wind power gradients near the Wyoming border are a consequence of the proximity of these areas to the southern Wyoming wind corridor.

Ridge crests and mountain summits of the Rocky Mountains are estimated to have mostly class 4 or 5 wind power in the spring.

5.2.3 Summer

In summer, class 3 is the highest wind power anywhere in the state and is estimated to occur only on exposed ridge crests and mountain summits above 3,700 m (12,000 ft), and on the extreme eastern high plains. There is a possibility that there are well-exposed sites with class 4 wind power in the extreme southeastern corner of the state. During summer afternoons, steady southeast through southwest surface winds develop on the eastern plains and as a result, during periods from approximately 1100 through 1900 local time each day, wind power could be a class or more higher than the average summer estimate. This is indicated by NCC data taken at Dalhart, Texas, in the Texas Panhandle.

During the summer, winds aloft are light (<17 m/s at 700 mb), so that surface wind flow characteristics are largely determined by local topography. The persistent diurnal pattern of upslope-downslope winds affects most mountainous areas within the state.

5.2.4 Autumn

In autumn, wind power over mountainous areas generally increases from September to November as the winds aloft intensify. Over the plains and river basins, however, the increase in the upper winds is not felt very much at the surface. Because of restricted vertical mixing at night and relaxed pressure gradients during the day, wind power at the surface remains relatively low, and is not significantly greater than the summer wind power. The average upper-air wind speeds for autumn and spring are not significantly different, although the mid-latitude storm track is farther south in the spring. Average autumn wind power over the low-lying areas of the western slope of the Rockies, and throughout the eastern plains, is very similar to that in summer with the exception of areas near the Wyoming border in northeastern Colorado. Here, autumn wind power is higher, a result of the increased winds aloft and the proximity of this area to the southern Wyoming wind corridor. In general, all lowland areas in eastern Colorado have significantly less wind power

in autumn than they have in spring because of the absence of the strong north-south temperature gradient that exists in the spring. In spring the northern plains of Colorado frequently have temperatures near 0°C (32°F) while the plains of Texas have temperatures near 32°C (90°F). In autumn, temperatures in the two areas are very often within 5°C (10°F) of each other.

5.3 FEATURES OF SELECTED STATIONS

Table 5.2 gives the location and annual wind speed and power density of thirteen stations in Colorado. Ten of these stations are on the eastern slope and high plains areas east of the Continental Divide. Graphs of other features of the wind resource at these stations are shown in Figures 5.10 to 5.16.

Akron CAA (Civil Aeronautics Administration), located on the northeastern plains, appears to be representative of the best-exposed sites on the high plains of eastern Colorado, although the annual average wind power at this site is higher than at other nearby sites.

Alamosa Airport is located in the middle of the broad and flat San Luis Valley, between the San Juan Mountains to the west and Sangre de Cristo Mountains to the east. The site appears to have good exposure to prevailing southwest winds. However, average wind power figures for this site are based on 16 observations per day, during daytime hours, and should be modified downward. On numerous occasions in the winter, this station has reported the lowest nighttime temperatures in the nation, illustrating the pronounced effect of the cold alpine air that drains from the surrounding high mountains into the valley.

Aurora/Buckley Field is an Air National Guard station, formerly a naval air station, located in the eastern Denver area within the South Platte River drainage. Although located approximately 120 m (400 ft) higher than the Denver metropolitan area, the site is still somewhat sheltered from the southerly and southwesterly winds by higher terrain to the south.

Colorado Springs/Peterson Field is located near the base of Pikes Peak and Cheyenne Mountain. This eastern slope location is sheltered by very high ($>4,000$ m) terrain to the west and high terrain to the north. However, good exposure to prevailing south-southeasterly winds and strong downslope winds give this site some limited wind power potential. This site appears to be typical of the eastern slope of the Rockies.

Denver/Aurora NAS (Naval Air Station) is the former name of Aurora/Buckley Field, discussed previously. Data for the period of record from 8/50 through 3/59 agree favorably with data from Aurora/Buckley Field. The mean 10 m-adjusted wind speed for both periods of record is 3.7 m/s (8.3 mph).

Denver/Stapleton International Airport is situated on the eastern slope in the lee of the Rocky Mountains, approximately 25 km (15 mi) from the base of the Front Range. The airport is located on the southeastern bench of the South Platte River and winds at this site are influenced by the southerly stable air drainage pattern of the South Platte River that affects the entire Denver metropolitan area. Data from this site are generally representative of locations on the eastern slope, although locations in western and southeastern Denver may have higher average wind power because of their better-exposed locations away from and above the river.

Eagle County Airport is located by the Eagle River in west-central Colorado. Surrounded by the high mountains of the Rockies on the north and south, Eagle's prevailing wind directions are almost exclusively tied to a west-to-east, diurnal upslope-downslope flow pattern typical of the mountain valleys of Colorado. The airport is located approximately 6 km (4 mi) west of the town of Eagle, in an area where the river valley broadens significantly. Although prevailing winds are channeled by the valley orientation, calm conditions are prevalent in the fall and winter.

Fort Carson/Butts AFB (Air Force Base) is situated approximately 16 km (10 mi) south of Colorado Springs on the eastern slope of the central Colorado Rockies. Wind data from this site show a high frequency of north to south winds with class 3 annual average wind power. However, data for some of the period of record shown in Table 5.2 are based on less than 24 observations per day. High terrain to the west assists in channeling surface winds and provides a limited convergence area for the northeasterly and southeasterly prevailing winds common to the Front Range.

Grand Junction Airport is located in the Grand Valley at the confluence of the Colorado and Gunnison Rivers in western Colorado. The channeling influence of the Grand Valley on prevailing winds is typical of sheltered mountain valleys throughout the state, where low average wind power exists and where prevailing wind directions are parallel to canyon orientations.

La Junta Airport is located on the southeastern plains of Colorado, approximately 5 km (3 mi) north of the town of La Junta in the Arkansas River valley. Although the airport site, north of the river, is well exposed, it is still within the sheltering influence of the river drainage. In addition, prevailing southwesterly winds are probably influenced by the slightly (30 m) higher terrain 1/2 mile southwest of the site. Thus the average wind power at La Junta Airport is likely to be lower than that at well-exposed areas on the southeastern plains away from the river valley.

Pueblo Memorial Airport is located on the western edge of the southeastern plains of Colorado, approximately 8 km (5 mi) east-northeast of the town of Pueblo in the Arkansas River valley. The town and airport are within the sheltering influence of the Arkansas River valley and the average wind power at this site is probably lower than at sites on the uplands outside of the river drainage.

Trinidad/Los Animas County Airport is located 48 km (30 mi) east of the Culebra Range of the Sangre De Cristo Mountains near the southern border of Colorado. The airport is approximately 23 km (14 mi) northeast of the town of Trinidad on the southern steppe of the Purgatorie River, still within the influence of the river drainage. Surrounding terrain from the south through the northwest is more than 400 m (1,300 ft) above the valley floor and, although the higher terrain is several miles away, wind power is still reduced by its sheltering effect.

United States Air Force Academy, located approximately 18 km (11 mi) north of Colorado Springs, is at the base of the Front Range foothills. The site has good exposure to prevailing southerly winds but is sheltered from westerly flow. Annual average wind power at this site is consistent with that at Colorado Springs. Recent monitoring data taken approximately 11 km (7 mi) north-northeast of the Academy, on the Palmer Ridge, suggest the existence of a class 3 wind power area close by.

5.3.1 Interannual Wind Power and Speed

The interannual variability of wind power and speed is presented in Figure 5.10 for 13 stations in Colorado. Only 6 stations have periods of record that are longer than 10 years without anemometer change and 5 of these have data for the period from 1968 to 1978. However, interstation comparison of trends in the annual variability of the wind resource shows little correlation between stations for the same time periods.

The strong wind power gradients near the Wyoming border are a consequence of the proximity of these areas to the southern Wyoming wind corridor.

Ridge crests and mountain summits of the Rocky Mountains are estimated to have mostly class 4 or 5 wind power in the spring.

5.2.3 Summer

In summer, class 3 is the highest wind power anywhere in the state and is estimated to occur only on exposed ridge crests and mountain summits above 3,700 m (12,000 ft), and on the extreme eastern high plains. There is a possibility that there are well-exposed sites with class 4 wind power in the extreme southeastern corner of the state. During summer afternoons, steady southeast through southwest surface winds develop on the eastern plains and as a result, during periods from approximately 1100 through 1900 local time each day, wind power could be a class or more higher than the average summer estimate. This is indicated by NCC data taken at Dalhart, Texas, in the Texas Panhandle.

During the summer, winds aloft are light (<17 m/s at 700 mb), so that surface wind flow characteristics are largely determined by local topography. The persistent diurnal pattern of upslope-downslope winds affects most mountainous areas within the state.

5.2.4 Autumn

In autumn, wind power over mountainous areas generally increases from September to November as the winds aloft intensify. Over the plains and river basins, however, the increase in the upper winds is not felt very much at the surface. Because of restricted vertical mixing at night and relaxed pressure gradients during the day, wind power at the surface remains relatively low, and is not significantly greater than the summer wind power. The average upper-air wind speeds for autumn and spring are not significantly different, although the mid-latitude storm track is farther south in the spring. Average autumn wind power over the low-lying areas of the western slope of the Rockies, and throughout the eastern plains, is very similar to that in summer with the exception of areas near the Wyoming border in northeastern Colorado. Here, autumn wind power is higher, a result of the increased winds aloft and the proximity of this area to the southern Wyoming wind corridor. In general, all lowland areas in eastern Colorado have significantly less wind power

in autumn than they have in spring because of the absence of the strong north-south temperature gradient that exists in the spring. In spring the northern plains of Colorado frequently have temperatures near 0°C (32°F) while the plains of Texas have temperatures near 32°C (90°F). In autumn, temperatures in the two areas are very often within 5°C (10°F) of each other.

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Table 5.2 gives the location and annual wind speed and power density of thirteen stations in Colorado. Ten of these stations are on the eastern slope and high plains areas east of the Continental Divide. Graphs of other features of the wind resource at these stations are shown in Figures 5.10 to 5.16.

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Colorado Springs/Peterson Field is located near the base of Pikes Peak and Cheyenne Mountain. This eastern slope location is sheltered by very high (>4,000 m) terrain to the west and high terrain to the north. However, good exposure to prevailing south-southeasterly winds and strong downslope winds give this site some limited wind power potential. This site appears to be typical of the eastern slope of the Rockies.

Interannual variability of the wind power and speed appears to be highest on the eastern plains of Colorado, as is indicated by data from Akron CAA, and, to a lesser extent, by data from La Junta. In general, wind power on the high plains of Colorado is highly dependent upon the development of strong gradient winds that are associated with synoptic weather systems moving through the region. In years of frequent storminess, average wind power will be quite high in comparison to less active years.

Closer to the Rocky Mountain foothills of eastern Colorado, interannual wind power variability is also dependent upon the interannual variability of synoptic flow patterns. However, local terrain interaction with synoptic winds tends to dampen this variability. Interannual variability of the wind power resource is lowest in magnitude in mountain valleys where mountain-valley circulations dominate the flow. This is best illustrated at Eagle and Grand Junction, where indications are that small variations in the resource can be expected from year to year. However, percent changes of average wind power from year-to-year appear to be just as large as at higher wind power sites.

5.3.2 Monthly Average Wind Power and Speed

All stations show peak average wind power and speed during spring (Figure 5.11). Stations on the eastern plains at Akron, La Junta, and Trinidad have maximum wind power during March and April. The eastern slope and valley stations generally show maximum wind power to be nearly evenly distributed between March and June, although April appears to have slightly higher wind power in most cases. Secondary peaks in wind power during December are evident at Akron CAA, Denver/Stapleton Airport and at the U.S. Air Force Academy.

With the exception of Grand Junction and Eagle, all stations show minimum wind power in late summer and early autumn, during the transition from the predominantly summertime convectively-induced winds to the stronger winter-type synoptic winds. Minimum wind power at Grand Junction and Eagle occurs in December and January, a consequence of the persistence of cold stable air at the surface at these mountain valley locations.

Although minimum wind power generally occurs in late summer and early autumn, minimum wind speeds appear to occur in late autumn and early winter at many sites (e.g., Pueblo and Alamosa). The higher

mean wind power but lower mean wind speeds in late autumn can be attributed to the occasional occurrence of strong synoptically-driven winds which interrupt the light wind speed conditions that prevail during most of this period. The few hours of strong wind contribute significantly to the mean wind power, but are diluted by the high frequency of low wind speeds in the calculation of mean speed.

5.3.3 Diurnal Windspeed by Season

Diurnal trends vary throughout the state. Maximum diurnal variations occur during the spring and summer months (Figure 5.12). The magnitude of variation of wind speed between day and night is highest at stations that are typically under the influence of stable surface conditions at night and early morning, but that have no significant drainage flow. Stations with large diurnal variations include Alamosa, Eagle, Fort Carson, Pueblo, and the U.S. Air Force Academy. The remaining stations have relatively low diurnal variations in wind power for several reasons. At Akron and La Junta, both located on the eastern plains, strong pressure gradient winds, particularly during winter and spring, are not easily decoupled from the surface by the generally shallow layer of stable air at the surface. For a different reason, Aurora/Buckley Field, Stapleton International Airport, and Denver/Aurora NAS, as well as the west slope station at Grand Junction, all have low diurnal variation of wind power resource. This is because of the presence of a well developed nighttime downslope valley drainage flow that helps sustain the hourly mean wind velocity when nighttime stable conditions develop. At Grand Junction in fall and winter, for example, wind speeds during the nighttime drainage flow period actually exceed daytime wind speeds.

5.3.4 Directional Frequency and Average Speed

Except for areas of the eastern plains and at high mountain summit locations, prevailing surface wind directions in Colorado are strongly influenced by the terrain (Figure 5.13). At stations located in mountain valleys, the prevailing wind directions are strictly aligned with the valley orientation. At Eagle and Grand Junction the bimodal distribution of wind directions illustrates the up-valley and down-valley flow orientation. In general, wind speeds in upslope-downslope dominated circulations will be light. However, areas of higher wind velocity will occur when topographic constrictions to valley flow are present. In exposed areas (ridge

crests and mountain summits) of west-central Colorado, the prevailing wind direction is southwesterly in summer and northwesterly in winter, with westerly winds dominating during transition seasons.

Along the eastern slope of the Rockies and on the eastern plains of Colorado, the variation in the distributions of wind directions is greater. In general, the prevailing wind directions associated with synoptically-driven flow are northerly in winter and southerly in summer. Overlaid on these general wind patterns are upslope and downslope wind regimes in the Poudre, South Platte and Arkansas River drainage systems. At Denver, for example, persistent South Platte drainage winds are combined with synoptic southerly flow, resulting in a sharp peak in the wind distribution for southerly directions.

During late fall, winter, and early spring, strong westerly downslope winds frequently occur in eastern Colorado near the foothills of the Rockies, with accompanying speeds in excess of 40 m/s. These winds have historically caused widespread damage to the area; however, in general, they do not extend out into the eastern plains.

The eastern high plains area has wind patterns almost totally determined by synoptic pressure gradients. Frequently in winter, strong mid-latitude storms will develop into blizzards with accompanying strong northwesterly to northeasterly winds. These winds have been known to snap off telephone poles and, when combined with heavy snow, totally paralyze communities in the area.

5.3.5 Annual Average Wind Speed Frequency

Observer biases are seen at nearly all stations in Colorado at wind speeds of 2 and 5 m/s (5 and 10 knots) (Figure 5.14). Data from Aurora/Buckley Field, Colorado Springs, Denver/Stapleton Airport, and Pueblo, show very little observer bias. Wind speed frequency distributions at these stations are reasonably approximated by the Rayleigh distribution.

5.3.6 Annual Average Wind Speed and Power Duration

The percentage of time that a given wind speed or power is exceeded is shown in Figures 5.15 and 5.16. 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 5.1. Geographic Map of Colorado

FIGURE 5.2. Topographic Map of Colorado

FIGURE 5.3. Land-Surface Form Map for Colorado

LAND-SURFACE FORM LEGEND

PLAINS

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

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

OPEN HILLS AND MOUNTAINS

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

HILLS AND MOUNTAINS

D3	HILLS
D4	HIGH HILLS
D5	LOW MOUNTAINS
D6	HIGH MOUNTAINS

TABLELANDS

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

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

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)

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 5.4. NCC Station Locations in Colorado

FIGURE 5.5. Locations of Stations Used in Colorado Wind Assessment

FIGURE 5.6. Colorado Annual Average Wind Power

Classes of Wind Power Density at 10m and 50m (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 5.1. Areal Distribution (km²) of Wind Power Classes in Colorado

Power Class	Land Area	% Land Area	Cumulative Land Area	% Cumulative Land Area
1	170,383	63.5	268,274	100.0
2	25,341	9.5	97,891	36.5
3	54,309	20.2	72,549	27.0
4	14,959	5.6	18,240	6.8
5	3,210	1.2	3,281	1.2
6	<100	<0.1	<100	<0.1
7	0	0.0	0	0.0

FIGURE 5.7. Certainty Rating of Colorado Wind Resource

CERTAINTY RATING LEGEND

Rating	Definition
1	<p>The lowest degree of certainty. A combination of the following conditions exists:</p> <ul 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> <ul 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> <ul 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 5.8. Areal Distribution of Wind Resource in Colorado (Power Classes 2 and 3); Percent of Land Area With or Exceeding Power Class Shown. An asterisk denotes 100%.

FIGURE 5.8. (Continued). Areal Distribution of Wind Resource in Colorado (Power Classes 4 and 5); Percent of Land Area With or Exceeding Power Class Shown.

FIGURE 5.9. Seasonal Average Wind Power in Colorado (Winter, Summer)

FIGURE 5.9. (Continued). Seasonal Average Wind Power in Colorado (Spring, Autumn)

TABLE 5.2. Colorado Stations with Graphs of the Wind Characteristics

Station	Station Name (a)	Lat N (deg, min)	Long W (deg, min)	Elevation (m)	Period of Record (month, year)	Anem. Height (m)	Annual Average Speed (m/s)			Annual Average Power (watts/m ²)		
							Anem Ht	At 10 m	At 50 m	Anem Ht	At 10 m	At 50 m
Akron, Colorado	Akron CAA	40, 07	103, 10	1399	1/48-12/54	8.8	5.9	6.0	7.6	222	234	467
Alamosa, (b)	Alamosa Airport	37, 26	105, 51	2298	1/48-9/54	10.1	4.4	4.4	5.5	132	131	262
Aurora, Colorado	Buckley Field	39, 42	104, 45	1719	8/67-12/70	3.4	3.2	3.7	4.7	41	65	131
Colorado Springs, Colorado	Peterson Field	38, 49	104, 42	1887	2/58-12/64	6.7	4.5	4.8	6.0	95	112	225
Denver, (b,c)	Aurora NAS	39, 42	104, 45	1697	8/50-3/59	19.8	4.0	3.7	4.6	78	58	116
Denver, Colorado	Stapleton International Airport	39, 46	104, 53	1615	10/53-7/60	21.9	5.0	4.5	5.7	131	93	186
Eagle, Colorado	Eagle County Airport	39, 39	106, 55	1982	1/48-12/64	18.6	2.6	2.4	3.0	53	40	81
Fort Carson, (b)	Butts AFB	38, 41	104, 46	1782	9/66-12/70	2.4	3.8	4.6	5.8	83	151	303
Grand Junction, Colorado	Grand Junction Airport	39, 07	108, 32	1474	2/50-9/61	17.7	4.0	3.7	4.6	79	62	123
La Junta, Colorado	La Junta Airport	38, 03	103, 31	1278	8/50-6/55	12.2	4.0	3.9	4.9	106	97	194
Pueblo, Colorado	Pueblo Memorial Airport	38, 17	104, 31	1421	7/54-3/62 3/62-12/78	10.4 6.7	3.7 4.3	3.6 4.5	4.6 5.7	91 109	90 129	179 258
Trinidad, Colorado	Los Animas County Airport	37, 15	104, 20	1753	8/50-12/56	9.4	4.4	4.5	5.6	119	122	243
United States Air Force Academy, Colorado	USAF Academy	38, 58	104, 49	1995	11/67-12/70	unk ^(d)	4.4	4.4	5.5	101	101	201

(a) CAA - Civil Aeronautics Administration Facility; NAS - Naval Air Station; AFB - Air Force Base.

(b) Station had less than 18 observations per day.

(c) Winds from the north are considered to be unrepresentative.

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

FIGURE 5.10. Interannual Wind Power and Speed for Colorado

FIGURE 5.11. Monthly Average Wind Power and Speed for Colorado

FIGURE 5.12. Diurnal Wind Speed by Season for Colorado

— PERCENT FREQUENCY LEFT ORDINATE - PERCENT
 - - - WIND SPEED RIGHT ORDINATE - M/S
 PNL-3195 WERA-8
 ABSCISSA - WIND DIRECTION

FIGURE 5.13. Directional Frequency and Average Wind Speed for Colorado

— ACTUAL DISTRIBUTION ORDINATE - PERCENT
 - - - RAYLEIGH DISTRIBUTION ABSCISSA - M/S
 PNL-3195 WERA-8

FIGURE 5.14. Annual Average Wind Speed Frequency for Colorado

ORDINATE - PERCENT
ABSCISSA - M/S
PNL-3195 WERA-8

FIGURE 5.15. Annual Average Wind Speed Duration for Colorado

ORDINATE - PERCENT
ABSCISSA - WATTS/M²
PNL-3195 WERA-8

FIGURE 5.16. Annual Average Wind Power Duration for Colorado

NEW MEXICO

New Mexico covers an area of 315,275 km² (121,666 mi²). With a population of 1,196,000 in 1977, it is the least populated state in the Southern Rocky Mountain region (Statistical Abstracts, 100th edition, 1979). Almost one-third of the state's population resides in Bernalillo County, which includes the city of Albuquerque. The rest of the population is distributed throughout the river valleys and plains regions of the state (Figure 6.1). Some interesting features in the state include the Carlsbad Caverns National Park located in the southeastern corner of the state, the U.S. Defense Department's White Sands Missile Range, located in south central New Mexico, and numerous Indian reservations located throughout central and western New Mexico.

Geographically, New Mexico is in a transition zone that separates the High Plains region of the central United States from the deserts of the Southwest. Although the Continental Divide, which passes through the western portion, does not attain elevations comparable with those in Colorado, the numerous mountain ranges that compose the southernmost extension of the Rocky Mountains do rise to significant elevations. The river drainages west of the Continental Divide drain into the Gulf of California through the Colorado River system and the rivers east of the divide drain into the Gulf of Mexico through the Rio Grande system, with the exception of the extreme northeastern plains; this area drains to the Arkansas River system via the Canadian River. Climatic variability in New Mexico results from air mass intrusions from several climatic regions: the Gulf of California, the Gulf of Mexico, the arid southwestern desert, the Canadian prairies, and the semi-arid continental regions that surround the state. At times during winter and spring the northeastern New Mexico plains will have severe blizzard conditions as a result of the southward intrusion of cold Canadian air onto the Great Plains of Texas and Oklahoma. During late summer or early autumn, remnants of hurricanes coming up from either the Gulf of California or the Gulf of Mexico can significantly affect portions of southern New Mexico with thunderstorms and heavy rains.

The topography of the state consists mainly of plains, high plateaus or mesas, and numerous mountain ranges, canyons, valleys, and dry arroyos (Figures 6.2 and 6.3). Average elevation is about 1,750 m (5,700 ft). The lowest point, 860 m (2,817 ft), is near the New Mexico-Texas border in the Pecos River valley. The

highest point is Wheeler Peak in the Sangre De Cristo Mountains at an elevation of 4,013 m (13,161 ft). Because of the spatial distribution of terrain types, New Mexico was divided into three topographical areas for analysis: the eastern plains, the north-central and western valley-mountains, and the southern basin.

Wind data available from the National Climatic Center (NCC) are mostly from airport stations located near population centers along the major river drainages and on the eastern plains of New Mexico (Figure 6.4). Although NCC stations with summarized wind data are fairly well distributed throughout the state, the western portions of the state have limited available data. Where no year-round NCC data exist or where only unsystematized NCC data were available, an attempt was made to identify and acquire private sources of wind data to supplement the data base (Figure 6.5). Fire weather data are reasonably abundant in the mountainous regions, but these data generally consist of only one observation per day, at about 1400 local time. Only those fire weather stations that indicated greater than class 1 annual average wind power and that had periods of record of sufficient length were used.

6.1 ANNUAL AVERAGE WIND POWER

The annual average available wind power density for New Mexico is shown in Figure 6.6. Analyses of mean wind power apply to terrain features that are favorably exposed to the wind, such as mountain summits, ridge crests, hilltops, and uplands (see Section 1.6). However, nearby terrain features may interact with the wind field to cause the wind power at some exposed sites to vary as much as ± 50 to 100% from the assessment value. (See Wegley et al. 1980 for information on terrain features that may increase or reduce wind energy.) In forested or wooded areas, the assessment values are representative of large clearings, such as airports, with good exposure to the prevailing strong winds. The percentage of land area that is favorably exposed to the wind strongly depends on the land-surface form (see Section 1.8).

The annual average wind power map for New Mexico (Figure 6.6) shows class 3 or higher annual average wind power on the eastern plains, in the upper Rio Grande valley wind corridor (Santa Fe-Los Alamos area) and on high exposed mountain summits and ridge crests throughout the state.

Wind data from twelve stations on the eastern plains of New Mexico indicate that a very significant wind resource exists in this area. Class 5 annual average wind power is estimated for well-exposed sites in the extreme northeastern corner of the state. This estimate is based on wind data collected at Clayton, New Mexico; Dalhart and Amarillo, Texas; and Garden City, Kansas. Limited data from Clayton Municipal Airport show class 5 annual average wind power (280 W/m^2) at 10 meters for three years of record. However, wind data recently gathered at the Department of Energy's large wind turbine site nearby show annual average wind power to be more in the class 4 range. This difference is probably the result of the interannual variability of the wind resource that is typical of stations on the eastern plains of New Mexico. Several wind energy siting projects being conducted on high terrain 50 miles west of Clayton indicate that exposed stations in northeastern New Mexico have the potential for class 6 and higher annual average wind power (Barnett, 1980).

Except for class 3 ridge crest estimates and a class 3 wind corridor in the Rio Grande drainage near Santa Fe, annual average wind power in the north-central and western portions of New Mexico is estimated to be class 2 or less. Because much of the wind data that were used in this analysis were collected in sheltered valleys and basins, annual average wind power estimates made for this area may not be applicable to all sites. In mountain canyons with drainage flow, where terrain restrictions induce wind speed accelerations, annual average wind speeds may be enhanced. At Zuni, for example, the nighttime drainage winds can have sustained speeds that are equal to synoptic pressure gradient or upslope flow. This wind speed enhancement is also present in the White Rock Canyon of the San Luis Valley-Upper Rio Grande drainage system, near Santa Fe. The constriction of this canyon by the Sangre De Cristo and Jemez Mountains accelerates drainage winds that flow from the broad San Luis Valley.

Orientation of terrain with respect to prevailing synoptic winds can also enhance wind speeds, a phenomenon illustrated at Albuquerque Airport by the strong easterly winds that flow through the Tijeras Canyon, and at Santa Fe by the strong southeast-through-west winds that are enhanced by the terrain that slopes up to the airport from the west and south.

The San Juan Basin in northwestern New Mexico, although well exposed, is estimated to have class 1 annual average wind power.

This is a consequence of the frequent occurrence of nighttime radiation inversions or strong subsidence inversions that can persist for days during the winter. The resulting cold stable surface air in the basins and valleys in northwest, west, and central portions of the state decouples surface winds from winds aloft, resulting in low mean annual wind speeds and wind power.

Annual average wind power in the basins and broad valleys of southern New Mexico is estimated to be class 2 or lower. Although most of the data in southwestern New Mexico indicate borderline class 2 wind power, it was felt that these data are primarily from sheltered locations, not representative of well-exposed sites.

In the mountainous areas of the state, annual average wind power is estimated to be class 3 or greater. These ridge crest and mountain summit estimates are based on Crutcher's (1959) upper air climatology and on limited mountain top data. The upper air climatology for New Mexico shows a north-to-south increase of mean winds aloft. This increase may be the result of the absence in the south of significant upwind mountain barriers such as those that occur in northern New Mexico and southern Colorado. Ridge crest estimates for the southern mountains reflect this upper-level velocity gradient. Although ridge crest wind power was conservatively estimated to be class 4 and class 5 for exposed locations in the San Andres and Sacramento Mountains, respectively, recent wind turbine siting studies conducted on San Augustin Pass in the San Andres Mountains show class 7 annual average wind power (Barnett and Reynolds, 1980). Local terrain enhancement of prevailing winds appears to be responsible for these unusually high values (498 W/m^2 and 788 W/m^2 , respectively, at 10 m). The large class 3 area in southwestern New Mexico represents annual average wind power on the highest (greater than 9,000 ft, or 2,700 m) ridge crests and mountain summits. This area has a wide range of elevations and ridge crests and mountain summits at lower elevations may have less annual average wind power than that indicated in Figure 4.6.

6.1.1 Certainty Rating of the Wind Resource

Certainty ratings for the annual average wind power estimates for New Mexico are shown in Figure 5.7. Certainty ratings of 4 were given to grid cells that contain or that are adjacent to grid cells that contain sites with good long-term data.

Certainty ratings of 3 were given to grid cells that contain stations with short-term data or data based on less than 24 observations per day. These highest (3 and 4) certainty ratings are found in data-rich areas throughout the state, e.g. around Deming, Farmington, Albuquerque and Roswell. However, there are no areas that have both high (class 4 or greater) wind power and high (4) certainty ratings.

Certainty ratings of 2 were given to grid cells that contain no data stations, but that are composed of simple terrain. Such areas are found primarily on the plains of eastern New Mexico. Lowest (1) certainty ratings were given to grid cells that have no data and that are composed of terrain of moderate to high complexity. Such areas are found primarily in west-central New Mexico around the Gallo Mountains, and in northwestern New Mexico. (Also, see Section 2.3.1).

Although, very few year-round data were found from exposed sites in mountainous terrain, mountain summit and ridge crest estimates were given a certainty rating of 2 because upper-air wind data were used to approximate the wind power in these areas.

6.1.2 Areal Distribution

The areal distribution of wind power in New Mexico is illustrated in Figure 6.8 and tabulated in Table 6.1. Numbers represent the percentage of actual land area within each cell of the grid that is exposed to wind power that is equal to or exceeds some threshold value.

Less than 3% of the total land area of New Mexico has exposure to class 4 or higher wind power (Table 6.1). Ninety percent of this found in the relatively simple terrain of extreme northeastern New Mexico, which is estimated to have class 4 and 5 annual average wind power. The other 10% is found on ridge crests and mountain summits throughout the western two-thirds of the state. The grid cell in northeastern New Mexico that has 10% land area exposed to class 4 wind power represents Laughlin and Sierra Grande Peaks (Figure 6.8, class 4).

Most of the 20% of New Mexico land area that has exposure to class 3 or greater wind power is found on the plains of eastern New Mexico (Figure 6.8, class 3). Areas in western New Mexico typically have less than 10% of their land area with class 3 exposure, as opposed to 80 to 100% in eastern New Mexico.

6.2 SEASONAL WIND POWER

Wind power maps for each season are shown in Figure 6.9. The season of maximum wind power is generally spring in the plains, basins, valleys, and southern New Mexico ridge crests, and winter on mountain summits and ridge crests of northern New Mexico. Summer is the season of lowest wind power throughout most of the state, although in autumn and summer, ridge crests and mountain summits are estimated to have virtually the same average wind power.

6.2.1 Winter

The winter wind power analysis for New Mexico is identical to the annual wind power analysis except for mountain summit and ridge crest wind power estimates. Most of the eastern New Mexico plains are estimated to have class 3 or greater wind power. In eastern New Mexico, wind power increases from west to east, and a class 5 area exists in the northeastern corner of the state. This maximum wind power area is the result of strong pressure gradient winds associated with synoptic features that develop on the plains east of New Mexico. Frequently during winter months, cold continental air masses push southward into this area from central Canada, producing strong winds and blizzard conditions.

Although the mean velocity of the winds aloft is at a maximum in winter, seasonal wind power estimates for the lowland valleys and basins and for the western-most portion of the eastern plains are low. This is a consequence of the decoupling of the surface wind from the winds aloft by the formation of low-level temperature inversions. In sheltered areas throughout the state, the frequency of occurrence of nighttime surface-based inversions during winter exceeds 75% (Holzworth and Fisher, 1979); in deep mountain valleys the frequency is higher. Except for the San Luis Valley drainage corridor near Santa Fe, which is estimated to have class 3 wind power, winter wind power in the extreme western portion of the high plains (in the lee of the mountains), and in the southern basin, western plateau, and central valleys areas, is estimated to be class 2 or less. Nighttime downslope drainage winds occur in most valleys in New Mexico; at locations in the valleys where a constriction to flow exists, a significant amount of wind speed acceleration can occur.

During winter, mountain summits and exposed ridge crests are estimated to have class 4 or higher wind power throughout the state, except for a small class 3 portion

of the ridge crest area in southwestern New Mexico. These estimates are based on winds aloft, as well as on limited mountain-top data. Although maximum wind power in the northern mountains occurs in winter, maximum wind power in southern mountains occurs in both winter and spring, with values that are higher than those in the northern mountains.

6.2.2 Spring

Spring is the season of maximum wind power for most of New Mexico. Most of the exposed ridge crests in the mountainous areas of the state are estimated to have class 4 or greater seasonal wind power. Limited wind data from the San Andres Mountains indicate class 7 wind power ($1,316 \text{ W/m}^2$), although this is probably the result of very local terrain enhancement. The eastern plains area appears to have a wind power gradient that increases from class 4 in the west to class 6 in the east. The class 6 area in the extreme northeastern corner of the state is part of a high wind area centered in the panhandle areas of Texas and Oklahoma. Prevailing wind directions for spring are southwesterly in this area, although very strong north-northeasterly flow frequently accompanies storm development on the plains of Texas and Oklahoma.

Wind power in the central valleys is estimated to be class 2, primarily because of sheltering by surrounding high terrain. The class 4 wind power area near Santa Fe represents exposed sites on the eastern shoulder of the White Rock Canyon, where prevailing westerly and southwesterly winds are accelerated by the west-facing, sloping terrain. Well-exposed areas of western New Mexico, and broad valleys of southwestern New Mexico, are estimated to have class 3 wind power. Again, isolated areas with sufficient terrain enhancement can have wind power that is one or two classes higher than those that are shown in Figure 6.9. Sheltered valleys in these areas can be expected to have wind power that is a class or two lower than indicated.

6.2.3 Summer

In the summer, most of the typically-exposed areas of central and western New Mexico are estimated to have class 1 wind power. Sites with sufficient terrain channeling or enhancement of prevailing winds, such as the area near Santa Fe, will probably have higher wind power than indicated. On the eastern plains, wind power is estimated to increase from class 1 in the western sections to class 3 in extreme northeastern New Mexico. However, class 6

and greater wind power has been estimated for Sierra Grande Mountain, 800 m (2,625 ft) above the New Mexico Plains (Barnett and Reynolds, 1980). This isolated peak is a nearly symmetrical mountain with unobstructed exposure to prevailing winds. Ridge crests and exposed mountain summits are estimated to have class 2 and class 3 wind power at most sites that are exposed to free-air winds.

6.2.4 Autumn

Wind power estimates for autumn are virtually the same as for summer, except for ridge crests that are exposed to the winds aloft and the upper Rio Grande valley near Santa Fe. In autumn, wind power at high, exposed mountainous areas generally increases from September to November as the upper-air wind speeds increase. Over the plains, basins, and broad valleys, the surface pressure gradient is still relatively gentle because of the absence of the strong north-south temperature gradient typical of winter and spring. The wind corridor at Santa Fe is estimated to have class 2 wind power, and the rest of central and western New Mexico is estimated to be class 1. The eastern plains area appears to have wind power that increases from class 2 on the western plains to class 4 in the northeastern corner of the state. Ridge crest and mountain summit estimates range from a class 2 and 3 in the south to class 4 on the Sangre de Cristo Mountains.

6.3 FEATURES OF SELECTED STATIONS

Table 6.2 gives the location and annual wind speed and power density for 25 stations in New Mexico. Graphs of other features of the wind resource at these stations are shown in Figures 6.10 to 6.16. Eleven of the stations are on the eastern plains, 8 are in the south-central and southwestern valleys and playas, and 6 stations are distributed throughout the northwestern quadrant of the state.

Acomita Airport is located in the Rio San Jose valley approximately 84 km (52 mi) west of Albuquerque. The valley orientation is east-west, providing good exposure to the prevailing westerly winds; however, the close proximity of the San Mateo Mountains to the north significantly shelters the site from northerly winds.

Alamogordo/Holloman AFB (Air Force Base) is situated in south-central New Mexico at the western base of the Sacramento Mountains in the Tularosa Valley. Data from this site shows low wind power, possibly because of sheltering by the high nearby terrain to the east and by the San Andres Mountains 56 km (35 mi) to the west.

Analysis of data from cognizant sites suggests that this effect extends throughout the Tularosa Valley.

Albuquerque International Airport, situated in the Rio Grande Valley, has moderately good exposure to strong easterly winds flowing through the narrow Tijeras Canyon (east of the Airport), which separates the Sandia and Manzanita Mountains. The effect of the Rio Grande valley on the wind flow is illustrated by the high frequency of moderate northerly drainage winds that flow down the valley.

Carlsbad Airport is located on the southeastern plains of New Mexico, approximately 16 km (10 mi) west of the Guadalupe Mountains in a well-exposed area. Wind power observed at Carlsbad is considerably higher than that at the nearby stations of Roswell and Hobbs, which are also located on the plains of southeastern New Mexico. An examination of the directional frequency and average wind speed plots suggests that a wind compression effect may exist as a result of the orientation of the Guadalupe Ridge.

Clayton Airport, located on the high plains of northeastern New Mexico, appears to have the highest wind power of any flat terrain station in the state. The winds at Clayton are typical of well-exposed sites located in the windy Texas-Oklahoma panhandle area.

Two sites near Clovis are included in Table 6.2 and Figures 6.10 through 6.16. Clovis/Cannon AFB is located just west of the city of Clovis; Clovis Airport borders the city on the northeast. These two stations appear to be representative of well-exposed sites on the eastern plains of New Mexico. Data from Clovis Airport is based on less than 18 observations per day, so that wind power at this station should probably be adjusted downward to account for low nighttime wind speeds.

Columbus/Hacienda Sur Luna Airport is located in extreme southwestern New Mexico, approximately 8 km (5 mi) from the Mexican border. The airport, 6 km (4 mi) north of Columbus, is located about 3 km (2 mi) east of the Tres Hermanas Mountains that rise to elevations approximately 300 m (1,000 ft) higher than the airport. Although the mountains to the west cover an area less than 200 km² (100 mi²), the prevailing westerly winds typical of well exposed-sites in the area are shifted to northwesterly at the airport. This suggests some sheltering effect.

El Morro CAA (Civil Aeronautics Administration), in west-central New Mexico, is situated on an open playa 11 km (7 mi) southwest of the Zuni Mountains. It is a moderately well-exposed site. However, because data for the plots in Figures 6.10 to 6.16 were based on less than one year of observations, interstation comparisons and detailed analyses of wind data were not performed.

Farmington Airport is located in northwestern New Mexico at the confluence of the La Plata, Animas, and San Juan rivers. The airport location is well-exposed on a plateau about 1 mile northwest of town. However, the airport is still well within the confines of the river valley, and a persistent deep stable layer frequently develops, resulting in a steady east-northeast drainage wind with a nearly constant speed of approximately 3 m/s (7 mph). Table 6.2 includes data for the period from 10/65 to 12/78, which are not shown in Figures 6.10 through 6.16. During this period, the anemometer was located on a ground mast at 6.7 m (22 ft) above ground. Consequently, this period of record may be more reliable than the period from 3/53 to 12/64, shown in Figures 6.10 through 6.16. During the earlier period, the anemometer was located on a rooftop (see Section 3.2).

Gallup Airport is located in a 16 km (10 mi) wide gap in the high plateau area of western New Mexico. Elevations rise to 150 m (500 ft) higher than the airport in all directions except southwest. Wind power on the surrounding plateau region is estimated to be higher than that observed at the airport.

Hobbs Airport is located in extreme southeastern New Mexico. It appears to be representative of well-exposed sites on the eastern plains of New Mexico.

Las Cruces/White Sands AF (Air Field) is located in southern New Mexico in the Rio Grande valley, just east of the Organ Mountains and across these mountains from the city of Las Cruces. The site appears to be sheltered by the mountains to the west. Nighttime wind speeds at this site are almost as great as daytime wind speeds. The high frequency of westerly winds seems to indicate a westerly drainage flow pattern.

Las Vegas Airport, in north-central New Mexico, is at a well-exposed location approximately 32 km (20 mi) east of the Santa Fe Mountains. The airport is situated on a plateau approximately 8 km (5 mi) northeast of Las Vegas.

Melrose Air Force Range is located on the eastern New Mexico plains, about 56 km (35 mi) southwest of Clovis. The site is representative of well-exposed plains sites and data from this site compare favorably with data from cognizant sites in the area. Data from this site shows wind power that is slightly higher than data from Clovis, probably a result of the absence of nighttime observations in the data set. The station had less than 12 observations per day for the period of record.

Otto CAA, located 32 km (20 mi) east of the Sandia Mountains in central New Mexico, has a high frequency of wind directions from the west through northwest.

Raton/Crews Airport, in northeastern New Mexico, is located 19 km (12 mi) south-southwest of Raton near the Canadian River. Although the airport is in close proximity to the higher terrain of the Sangre De Cristo steppe, the wind direction distribution and average annual wind power at this site closely resembles the data from other northeastern plains sites. Because of the surrounding complex terrain, wind power on exposed ridges and mesas nearby (e.g., Raton Pass, located approximately 25 km, or 15 mi, north of Crews Airport) is estimated to be 1 or 2 classes higher than that observed at the airport.

The Roswell area is located on the high plains of southeastern New Mexico, approximately 13 km (8 mi) west of the Pecos River. Three sites near Roswell were used in the wind power analysis. Roswell WBAS (Weather Bureau Airport Station) was located at the old airport, near or within the present Roswell city limits. Walker AFB and Roswell FAA (Federal Aviation Administration) are located at nearly the same location, south of Roswell on the old site of Walker AFB. Wind data from Walker AFB and Roswell FAA show significantly lower wind power than data from Roswell WBAS, and considerably lower than data from other cities on the southeastern New Mexico plains (e.g., Carlsbad and Hobbs). It is possible that there are better exposed sites in the area, with higher wind power more typical of well-exposed regions of the eastern plains region.

Santa Fe Airport, in north-central New Mexico, is located approximately 14 km (9 mi) southwest of Santa Fe on the exposed eastern shoulder of the Rio Grande valley wind corridor. The airport is approximately 335 m (1,100 ft) above the valley floor to the west. Wind characteristics at the airport location indicate the presence of a moderately strong upslope-downslope valley wind.

There appears to be some terrain enhancement of synoptic westerly winds at Santa Fe Airport, a result of the gradual increase in elevation east of the Rio Grande. Although the Rio Grande valley wind corridor is the only drainage channel for the large San Luis Valley of southern Colorado and northern New Mexico, the wind power may vary dramatically throughout the area around Santa Fe because of the complex topography.

Silver City/Grant County Airport, in southwestern New Mexico, is located in a reasonably well exposed area 23 km (14 mi) southeast of the town of Silver City. The town is situated in a sheltered area a few miles from the Continental Divide. Because the wind power estimates for this station were based on daytime observations only, it is expected that well-exposed sites in this area will have lower wind power than that indicated by the airport data.

Truth or Consequences Airport is situated on a wide-open flat area on the west side of the Rio Grande in southwestern New Mexico. Data from this site is representative of well-exposed sites in the wide southern Rio Grande valley.

Tucumcari Airport, although located on the eastern edge of moderately complex terrain in eastern New Mexico, is still representative of well-exposed sites on the eastern plains of New Mexico. It can be anticipated that some of the isolated mesas and buttes surrounding the area may have somewhat higher wind power potential than that estimated for this site.

Zuni/Black Rock Airport, in extreme western New Mexico, is located near the exit for drainage flow from the Zuni Mountains. The strong bimodal wind direction distribution and twice-a-day wind velocity maxima, at approximately 0500 and 1500 local time, suggest strong channeling of upslope-downslope valley flow and a well established nighttime drainage wind pattern. It appears that a slight sheltering effect exists at the airport for synoptic winds from the north or south.

6.3.1 Interannual Wind Power and Speed

Six stations have selected periods of record of ten years or more during which the anemometer was not moved (Figure 6.10), and five additional stations have combined periods of record of ten years or more during which anemometer height changes were made. Of these eleven stations, eight had high wind power years in which the annual average wind power was more than double that in the lowest wind power year. Some

of this variability may be a consequence of the strong dependency of wind power climatology on the mid-latitude storm track and synoptic pressure gradient patterns which vary from year to year. This is especially true for stations on the eastern New Mexico plains which are less influenced by local terrain (e.g., drainage flow patterns) than are stations in mountainous areas.

Interstation comparison of interannual trends of wind power and speed was performed by topographic areas because of the varied terrain. Among stations in the western mountain areas and in the Rio Grande valley, there is little correlation for years of low and high wind power. The northeastern plains stations at Raton, Las Vegas, and Tucumcari all show a maximum wind power period from 1950 to 1952 and minimum wind power in 1949 and 1961. However, data for other years at these stations do not show much correlation.

6.3.2 Monthly Average Wind Power and Speed

Spring is the season of maximum wind power and speed at all stations (Figure 6.11). Clayton shows a strong secondary speed maximum in January, as well. The lowest mean wind speeds occur during the late summer and early fall for all stations in the state. At many of the valley locations, low mean wind speeds persist into early winter, a result of strong temperature inversions and cold stable surface air in the river valleys. Santa Fe and Zuni, on the other hand, have sufficiently strong valley drainage flow to maintain relatively high mean wind speeds during late fall.

6.3.3 Diurnal Wind Speed By Season

Diurnal trends in wind speed vary throughout the state according to geographic location and complexity of terrain (Figure 6.12). Maximum diurnal variations occur in the spring when moderate nighttime low-level temperature inversions decouple surface winds from the stronger pressure gradient winds aloft, yet strong daytime heating quickly decays these inversions and links surface winds to upper-air winds. Diurnal variations are generally lowest in autumn and winter. Maximum winds generally occur in the afternoon between approximately 1200 and 1800 local time during the spring, and between about 1300 and 1900 local time during the summer. Minimum wind speeds for most sites in the state occur just after sunrise.

Exceptions to these generalizations occur at a few stations (e.g., Clayton,

Clovis, and Hobbs) where bimodal peaks occur in spring and summer at about 0900 and 1600 local time, and at stations that are located in mountain valleys and canyons. At Zuni, for example, during autumn and winter, a secondary velocity maximum occurs just after sunrise with a magnitude that is equal to the afternoon maximum. This morning maximum is the result of strong downslope drainage flow into the valley which begins shortly after sunset and increases throughout the night. Santa Fe is another example of a station having strong downslope drainage winds, except that the maximum morning winds occur a few hours after sunrise. The Rio Grande valley at Santa Fe airport, near the White Rock Canyon, is the only drainage path for stable air flowing out of the broad San Luis Valley, located about 25 km (15 mi) upstream. The 2 hour delay in the morning maximum wind at the airport may be a result of the obstruction to morning sunlight, and a consequent delay of surface heating at the valley floor, by the Sangre de Cristo Mountains to the east.

Stations located in broad valleys and eastern plains locations all show relatively constant minimum mean wind velocities during the nighttime hours and a steady wind velocity increase beginning an hour or so after sunrise. The velocity generally peaks between approximately 1400 and 1600, depending on the season.

No data were obtained in New Mexico that could indicate the diurnal variation of the wind resource at exposed ridge crests and mountain summits; however, limited mountain top data in Colorado indicate that wind velocity maxima occur in the late evening and that minima occur shortly after sunrise.

6.3.4 Directional Frequency and Average Speed

Although the prevailing surface wind directions throughout much of New Mexico are strongly influenced by the terrain, 15 stations out of 25 that were analyzed indicate that the prevailing wind direction during periods of strongest wind is mostly south-southwest through west-southwest (Figure 6.13). Variations in this pattern exist on the eastern plains of New Mexico where strong pressure gradient winds from the west-northwest through north-northeast occur during the passage of mid-latitude cyclones through northern New Mexico in winter and spring. These winds are responsible for a significant portion of the available wind power on the plains of eastern New Mexico during these seasons.

In the western and central intermountain areas, prevailing wind directions are highly dependent upon local topography. Stations located in river valleys such as Zuni, Farmington, Socorro, El Morro, and, to a lesser extent, Santa Fe, all have bimodal wind direction frequency distributions with directional peaks that correspond to the terrain orientation. This illustrates the effect of upslope-downslope valley winds. If a constriction to the air flow exists in the valleys, both the synoptic and drainage winds may be accelerated at the point of constriction, resulting in an increase in the mean speed. At Albuquerque airport, for example, the high wind velocities associated with easterly flow are probably due to enhancement of synoptic winds by the nearby Tijeras Canyon.

At exposed ridge crests and mountain summit locations, directional frequency is generally determined by the winds aloft.

6.3.5 Annual Average Wind Speed Frequency Distribution

Observer bias is apparent from peaks at 2, 5, and/or 8 m/s (5, 10, 15 kts) for 19

of the 24 stations analyzed (Figures 6.14). This can be seen by a comparison of data from the two Clovis sites. Data from Cannon AFB during the from period 12/51 to 3/55 indicate severe bias toward the 5 m/s (10 kts) speed bin, while data from Clovis Airport for the period from 7/60 to 10/69 do not.

Comparison of different periods of record at Roswell also illustrates observer or instrument bias in recording calm conditions. At Roswell WBAS for the period 5/51 to 7/60, almost no calms were recorded, yet records from the other two Roswell stations (Walker AFB and Roswell FAA) both have significantly more calms than does Roswell WBAS.

6.3.6 Annual Average Wind Speed and Power Duration

The percentage of time that a given wind speed or power is exceeded is shown in Figures 6.15 and 6.16. 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 6.1. Geographic Map of New Mexico

FIGURE 6.2. Topographic Map of New Mexico

FIGURE 6.3. Land-Surface Form Map for New Mexico

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 6.4. NCC Station Locations in New Mexico

FIGURE 6.5. Locations of Stations Used in New Mexico Wind Assessment

FIGURE 6.6. New Mexico Annual Average Wind Power

Classes of Wind Power Density at 10m and 50m (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 6.1. Areal Distribution (km²) of Wind Power Classes in New Mexico

Power Class	Land Area	% Land Area	Cumulative Land Area	% Cumulative Land Area
1	176,527	56.2	314,365	100.0
2	75,044	23.9	137,838	43.9
3	54,148	17.2	62,794	20.0
4	5,681	1.8	8,646	2.8
5	2,925	0.9	2,965	0.9
6	<100	<0.1	<100	<0.1
7	0	0.0	0	0.0

FIGURE 6.7. Certainty Rating of New Mexico Wind Resource

CERTAINTY RATING LEGEND

Rating	Definition
1	<p>The lowest degree of certainty. A combination of the following conditions exists:</p> <ul 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> <ul 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> <ul 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 6.8. Areal Distribution of Wind Resource in New Mexico (Power Classes 2 and 3); Percent of Land Area With or Exceeding Power Class Shown. An asterisk denotes 100%.

FIGURE 6.8 (Continued). Areal Distribution of Wind Resource in New Mexico (Power Classes 4 and 5); Percent of Land Area With or Exceeding Power Class Shown.

FIGURE 6.9. Seasonal Average Wind Power in New Mexico (Winter, Summer)

FIGURE 6.9 (Continued). Seasonal Average Wind Power in New Mexico (Spring, Autumn)

TABLE 6.2. New Mexico Stations with Graphs of the Wind Characteristics

Station	Station Name ^(a)	Lat N (deg, min)	Long W (deg, min)	Elevation (m)	Period of Record (month, year)	Anem. Height (m)	Annual Average Speed (m/s)			Annual Average Power (watts/m ²)		
							Anem Ht	At 10 m	At 50 m	Anem Ht	At 10 m	At 50 m
Acoma, New Mexico	Acoma Airport	35, 03	107, 43	2006	7/48-4/53	8.5	4.5	4.6	5.8	91	97	194
Alamogordo, New Mexico	Holloman AFB	32, 51	106, 05	1241	5/55-3/58	4.0	2.8	3.2	4.0	38	57	113
Albuquerque, New Mexico	Albuquerque International Airport	35, 03	106, 37	1620	3/60-12/64	7.0	3.6	3.8	4.7	65	76	151
					3/65-12/78	7.0	4.2	4.1	5.2	92	85	170
Carlsbad, New Mexico	Carlsbad Airport	32, 20	104, 16	990	7/48-12/54	15.2	5.3	5.0	6.3	231	193	384
Clayton, New Mexico	Clayton Airport	36, 27	103, 09	1515	7/48-9/51	9.1	6.5	6.6	8.2	269	280	557
Clovis, New Mexico	Cannon AFB	34, 23	103, 19	1305	12/51-3/55	27.4	5.7	5.0	6.3	201	130	260
Clovis, ^(b) New Mexico	Clovis Airport	34, 25	103, 05	1284	7/60-10/69	4.0	4.3	4.9	6.2	106	158	314
Columbus, New Mexico	Hacienda Sur Luna Airport	31, 49	107, 33	1229	7/48-12/54	8.5	3.9	4.0	5.0	94	101	201
El Morro, ^(c) New Mexico	El Morro CAA	35, 01	108, 24	2170	7/48-2/49	8.5	2.8 ^(c)	2.9 ^(c)	3.7 ^(c)	47 ^(c)	50 ^(c)	100 ^(c)
Farmington, New Mexico	Farmington Airport	36, 45	108, 14	1677	3/53-12/64	10.1 ^(d)	3.2 ^(d)	3.2 ^(d)	4.0 ^(d)	54 ^(d)	54 ^(d)	107 ^(d)
					10/65-12/78		3.7 ^(d)	3.9 ^(d)	4.9 ^(d)	75 ^(d)	89 ^(d)	177 ^(d)
Gallup, New Mexico	Gallup Airport	35, 31	108, 47	1971	1/73-12/78	6.1	3.1	3.3	4.1	66	82	163
Hobbs, New Mexico	Hobbs Airport	32, 41	103, 12	1123	7/48-12/54	10.7	5.4	5.3	6.7	168	163	326
Las Cruces, New Mexico	White Sands AF	32, 22	106, 29	1292	9/57-12/62	4.6	2.8	3.1	3.9	66	92	184
Las Vegas, New Mexico	Las Vegas Airport	35, 39	105, 09	2092	7/48-12/64	7.9	5.0	5.1	6.4	152	168	335
Melrose, ^(e) New Mexico	Melrose Air Force Range	34, 18	103, 48	1326	7/63-11/68	18.3	5.9	5.4	6.8	214	165	329
Otto, New Mexico	Otto CAA	35, 05	106, 01	1900	7/48-12/54	8.2	3.3	3.4	4.3	76	82	165
Raton, New Mexico	Crews Airport	36, 45	104, 30	1945	7/48-8/53	8.5	4.2	4.3	5.4	143	151	303
Roswell, New Mexico	Roswell WBAS (city)	33, 24	104, 32	1106	5/51-7/60	15.8	5.0	4.7	5.9	180	148	295
Roswell, New Mexico	Walker AFB	33, 18	104, 32	1110	4/57-3/63	4.6	3.5	4.0	5.0	76	106	212
Roswell, New Mexico	Roswell FAA	33, 19	104, 32	1113	1/73-12/78	6.7	4.0	4.2	5.3	77	91	182
Santa Fe, New Mexico	Santa Fe Airport	35, 37	106, 05	1934	7/48-12/54	8.5	5.1	5.3	6.6	148	158	316
Silver City, ^(b) New Mexico	Grant County Airport	32, 38	108, 10	1639	5/60-8/68	6.1	5.0	5.4	6.7	122	150	301
Truth or Consequences, New Mexico	Truth or Consequences Airport	33, 14	107, 16	1471	6/50-12/64	7.3	4.4	4.6	5.9	113	129	258
Tucumcari, New Mexico	Tucumcari Airport	35, 11	103, 36	1237	1/49-9/59	9.8	5.3	5.3	6.7	167	168	336
Zuni, New Mexico	Black Rock Airport	35, 06	108, 48	1965	2/49-10/58	7.6	4.2	4.3	5.4	88	98	197

(a) AFB - Air Force Base; CAA - Civil Aeronautics Administration; AF - Air Field; WBAS - Weather Bureau Airport Station; FAA - Federal Aviation Administration

(b) Station had less than 18 observations per day.

(c) Station had less than one year of digitized records.

(d) Station data for this period not included in graphs, Figures 6.10 through 6.16.

(e) Station had less than 12 observations per day.

FIGURE 6.10. Interannual Wind Power and Speed for New Mexico

FIGURE 6.10 (Continued). Interannual Wind Power and Speed for New Mexico

FIGURE 6.11. Monthly Average Wind Power and Speed for New Mexico

FIGURE 6.11 (Continued). Monthly Average Wind Power and Speed for New Mexico

FIGURE 6.12. Diurnal Wind Speed by Season for New Mexico

FIGURE 6.12 (Continued). Diurnal Wind Speed by Season for New Mexico

— PERCENT FREQUENCY LEFT ORDINATE — PERCENT
 - - - WIND SPEED RIGHT ORDINATE — M/S
 PNL-3195 WERA-8
 ABSCISSA — WIND DIRECTION

FIGURE 6.13. Directional Frequency and Average Wind Speed for New Mexico

— PERCENT FREQUENCY LEFT ORDINATE - PERCENT
 - - - WIND SPEED RIGHT ORDINATE - M/S
 PNL-3195 WERA-8
 ABSCISSA - WIND DIRECTION

FIGURE 6.13 (Continued). Directional Frequency and Average Wind Speed for New Mexico

— ACTUAL DISTRIBUTION ORDINATE - PERCENT
 - - - RAYLEIGH DISTRIBUTION ABSCISSA - M/S
 PNL-3195 WERA-8

FIGURE 6.14. Annual Average Wind Speed Frequency for New Mexico

— ACTUAL DISTRIBUTION ORDINATE — PERCENT
 ----- RAYLEIGH DISTRIBUTION ABSCISSA — M/S
 PNL-3195 WERA-8

FIGURE 6.14 (Continued). Annual Average Wind Speed Frequency for New Mexico

ORDINATE - PERCENT

ABSCISSA - M/S

PNL-3195 WERA-8

FIGURE 6.15. Annual Average Wind Speed Duration for New Mexico

ORDINATE - PERCENT

ABSCISSA - M/S

PNL-3195 WERA-8

FIGURE 6.15 (Continued). Annual Average Wind Speed Duration for New Mexico

ORDINATE - PERCENT
 ABSCISSA - WATTS/M²
 PNL-3195 WERA-8

FIGURE 6.16. Annual Average Wind Power Duration for New Mexico

ORDINATE - PERCENT
ABSCISSA - WATTS/M²
PNL-3195 WERA-8

MELROSE RANGE NM 07/63-11/68
93064 Z=18.3 R, V= 5.9, P= 214E

OTTO NM 07/48-12/54
23056 Z= 8.2 G, V= 3.3, P= 76

RATON/CREWS NM 07/48-08/53
23052 Z= 8.5 R, V= 4.2, P= 142

ROSWELL NM 05/51-07/60
23043 Z=15.8 R, V= 5.0, P= 180

ROSWELL/WALK. NM 04/57-03/63
23009 Z= 4.6 G, V= 3.5, P= 76E

ROSWELL NM 01/73-12/78
23009 Z= 6.7 G, V= 4.0, P= 77

SANTA FE NM 07/48-12/54
23049 Z= 8.5 R, V= 5.1, P= 148

SILVER CITY NM 05/60-08/68
93063 Z= 6.1 G, V= 5.0, P= 122

TRUTH OR CON. NM 06/50-12/64
93045 Z= 7.3 R, V= 4.4, P= 113

TUCUMCARI NM 01/49-09/59
23048 Z= 9.8 R, V= 5.3, P= 187

ZUNI NM 02/49-10/58
93044 Z= 7.6 R, V= 4.2, P= 88

FIGURE 6.16 (Continued). Annual Average Wind Power Duration for New Mexico

UTAH

Utah covers an area of 220,044 km² (84,916 mi²) and had a population in 1977 of 1,270,000 (Statistical Abstracts, 100th edition, 1979). The population is mostly urban, with about 705,000 residents living in the Salt Lake City-Ogden metropolitan area (See Figure 7.1). The remainder of the population is distributed in the valleys and basins throughout the state. The Great Salt Lake, Lake Powell, Utah Lake, and the Utah portion of Bear Lake are the largest bodies of water in the state, with a combined area of more than 5,200 km² (2,000 mi²). The popular vacation sites of Zion, Bryce Canyon, Capitol Reef, Canyonlands, and Arches National Parks, and the Glen Canyon National Recreation Area, are located in the southern and southeastern portions of the state.

Topographic features in Utah are extremely varied. Most of the region is composed of mountainous terrain (Figures 7.2, 7.3). (The Indian translation for Utah is "high in the mountains".) The major mountain ranges are the Wasatch Range (average ridge crest elevation approximately 3,000 m, or 10,000 ft), which extends from north to south in central Utah, and the Uinta Mountains (summit elevations above 4,000 m, or 13,000 ft), which extend from east to west through northeastern Utah. Numerous smaller mountain ranges scattered throughout the state also attain significant elevations. For example, the Tushar Mountains in southwestern Utah, the Abajo Mountains in southeastern Utah, the Deep Creek Range in western Utah, and the Stansbury Mountains in west-central Utah, all attain elevations above 3,350 m (11,000 ft). In addition to the numerous mountain ranges, Utah has virtually every type of elevated terrain type, including plateaus, benches, cliffs, mesas, terraces, folds, and reefs. These land forms are located in the southern and eastern areas of the state and attain elevations exceeding 2,700 m (9,000 ft).

Except for a few mountain ranges, the northwestern quadrant of the state is occupied by the Great Salt Lake and Great Salt Lake Desert, which is the bottom of the Great Basin, the largest closed basin in North America.

The topography of west-central Utah alternates between desert valleys and small mountain ranges. The major topographic features in this area are the Escalante and Sevier Deserts.

Practically all of eastern Utah is drained by the Colorado River and its

principal tributary within the state, the Green River. This area is composed of desert canyons, confined mountain valleys, basins, and plateaus. Significant topographic features in eastern Utah include the Uinta Basin, the Uinta Mountains and Tavaputs Plateau, the San Rafael Desert in southeastern Utah, and the Grand Valley, which extends into Utah from Colorado and which contains the Colorado River.

The density of wind data is low throughout most of Utah, with the exception of the Great Salt Lake Basin area (Figures 7.4, 7.5). Throughout the rest of the state, NCC wind recording stations have been limited to sites in the desert valleys, although some private monitoring has supplemented the data base in other locations. Areas in which data are most scarce include most of the high-elevation terrain throughout the state, the Uinta Basin, the western and south-central valleys, and the southeastern part of the state. There are 48 fire weather stations in the state, but data from these stations are limited to one observation per day, usually in the early afternoon, during the local fire weather season. Only seven of these sites indicated higher than class 1 annual average wind power.

7.1 ANNUAL AVERAGE WIND POWER

The annual average available wind power density for Utah is shown in Figure 7.6. Analyses of mean wind power apply to terrain features that are favorably exposed to the wind, such as mountain summits, ridge crests, hilltops, and uplands (see Section 1.6). However, nearby terrain features may interact with the windfield to cause the wind power at some exposed sites to vary as much as ± 50 to 100% from the assessed value. (See Wegley et al. 1980 for information on terrain features that may increase or reduce wind energy). In forested or wooded areas, the assessment values are representative of large clearings, such as airports, with good exposure to the prevailing strong winds. In mountainous area, which comprise much of Utah, the graphic displays of Figures 7.6 and 7.9 delineate major high mountain ridges and valleys. The percentage of land area that is favorably exposed to the wind strongly depends on the land-surface form (see Section 1.8).

The wind power resource is highest in the northern mountain regions of the state (Figure 7.6). Annual average wind power was estimated to be class 5 and 6 for ridge crests and mountain summit locations in the Uinta and Wasatch Mountains. Lower eleva-

tion ridge crest and summit locations in the smaller ranges near the northern border of Utah are estimated to have class 4 and 5 annual average wind power, primarily because of their exposure to the strong westerly winds aloft. Southern mountain areas of Utah received lower wind power estimates of class 3 and 4, even though ridge crests and mountain summit elevations in these areas are comparable to those in northern locations. This is because of the reduced strength and the more southwesterly prevailing direction of winds aloft in this part of the state. Ridge crests and mountain summits of less extensive mountain ranges, primarily in the Great Salt Lake Basin and in eastern and southern Utah, were estimated to have class 2 and 3 annual average wind power.

A wind corridor is located in the Escalante and Sevier Desert areas of southwestern Utah. This wind corridor was identified on the basis of data from Cedar City, Milford, and Delta, and includes the area from the vicinity of Cedar City north to Delta. In this general region, prevailing southwesterly winds are channeled by the central and western mountains through the Escalante and Sevier Desert valleys. Here, annual average wind power is estimated to be class 2. This channeling effect is greatest at Milford, where the valley narrows into a class 3 wind power corridor. It is probable that there are other wind corridors similar to the Escalante-Sevier Desert corridor in western Utah, although no data were acquired to substantiate this. For example, the Snake Valley area near Trout Creek in western Utah has orientation and terrain similar to that near Milford, and is likely to have higher annual average wind power than that shown in Figure 7.6.

Except for areas in extreme northeastern Utah that are influenced by the southern Wyoming wind corridor (Elliott and Barchet 1980b), the rest of the state is estimated to have class 1 annual average wind power. In general, this is a consequence of the high frequency of occurrence (>80%) of nighttime surface-based temperature inversions in the lowland areas (Holzworth and Fisher 1979), and the weak surface pressure gradients that are common in the state. The almost nightly formation of a stable air layer at the surface acts to shelter surface winds from winds aloft, resulting in either calm conditions or weak downslope drainage winds. In the Great Salt Lake Basin, for example, the surrounding mountains cool faster than do the valleys at night. This results in the drainage of cooler air from the mountain

slopes through the canyons and into the basin. The basin acts as a collection area, or sink, for this stable air, and the result is general air stagnation throughout the lake area.

Although not well-documented by existing data, stable air drainage through the numerous narrow canyons on the west slope of the Wasatch Range in the Salt Lake City-Ogden area can be very strong. This phenomenon, in addition to synoptic easterly winds and moderate upslope flow during the day, could result in canyon locations having annual average wind power that is a class or two higher than that indicated by Figure 7.6.

The Uinta Basin and the Green River-Colorado River drainages of eastern Utah were also estimated to have class 1 annual average wind power because of this frequent presence of stable air at the surface. In addition, the sheltering effect of surrounding higher terrain in this region reduces the wind resource. During winter, air stagnation episodes in these areas persist for weeks at a time, resulting in fog and low temperatures.

Annual average wind power estimates for eastern and southeastern Utah are based on limited data from stations located in lowland areas that may not be representative of sites at locations with better exposure. The terrain is very complicated in this area and ridge crests and exposed bluffs, mesas, reefs, swells, etc., are too numerous to isolate. However, data collected for two years at a well-exposed station (Red Sea Flat), approximately 27 km (17 mi) southwest of Moab in the Canyonlands National Park, indicate a potential for class 2 annual average wind power at well-exposed locations in southeastern Utah. It should also be noted that data from this site showed very high interannual variability. Wind data taken in spring and summer of 1978 at this Canyonlands site showed less than one-half the mean wind velocity that was shown by data taken in spring and summer of 1979.

7.1.1 Certainty Rating of the Wind Resource

Certainty ratings for the annual average wind power estimates for Utah are shown in Figure 7.7. In general, highest (4) certainty ratings were given to grid cells that contain, or that are adjacent to grid cells that contain, sites with long-term representative wind data. Such areas are found primarily in the data-rich areas along the Wasatch Front near Ogden and Salt Lake City, and in the western portion of

the Great Salt Lake Desert. Certainty ratings of 3 were given to grid cells that contain sites with data for shorter periods of record, or that are based on less than 24 observations per day. Areas with certainty ratings of 3 are found throughout Utah. Largest concentrations of these certainty ratings are found in the Great Salt Lake Desert, in the vicinity of the lower Escalante-Sevier Desert wind corridor, and in the San Rafael Desert of southeastern Utah.

Certainty ratings of 2 were given to grid cells that have no data, but are composed of simple terrain and are expected to have low variability of the wind resource, such as the upper Escalante-Sevier Desert wind corridor and east-central Utah. Lowest (1) certainty ratings were given to grid cells that have no data and that are composed of complex terrain. Clusters of certainty ratings of 1 are found in data-sparse areas of west-central Utah, in the complex terrain in the recreational areas of southeastern Utah, and on the Tavaputs Plateau in northwestern Utah.

Although no year-round data were found that were representative of exposed ridge crests and mountain tops in Utah, annual average wind power estimates in these areas were given a certainty of rating of 2 because upper-air wind data were used to approximate the wind resource.

7.1.2 Areal Distribution

The areal distribution of wind power in Utah is illustrated in Figure 7.8 and tabulated in Table 7.1. Although wind power class 4 or greater was assigned to 52 of the 296 grid cells in Utah, or 18%, the actual land surface area that is exposed to class 4 or greater wind power is estimated to be only about 0.8% of the total land area of the state (Table 7.1). This is a consequence of the fact that all of the class 4 or greater wind power is found on exposed ridge crests and mountain summits. In high relief terrain of this type, exposed land area is only 2 to 8% of the total land area, as shown in Figure 7.8 (classes 4 and 5).

Areas with exposure to class 3 annual average wind power amount to about 1.7% of the total land area of the state (Table 7.1). Roughly half of this is found in the Escalante-Sevier Desert wind corridor, where 100% of the land area is estimated to be exposed to class 3 wind power (Figure 7.8, class 3). The other half is distributed throughout the high, well-exposed areas of the state.

The effect of the high relief of most of the state is evident from the amount of land area that has exposure to class 1 wind power, 91.2%, as opposed to the amount of land area that has exposure to all higher wind power classes, 8.8% (Table 7.1). If an estimate of the land area with only class 1 wind power was made strictly on the basis of the percentage of grid cells assigned class 1 wind power, ignoring topography, these numbers would be 65% and 35% respectively.

7.2 SEASONAL WIND POWER

Average wind power maps of Utah for each season are shown in Figure 7.9. The season of maximum wind power is spring for lowland areas of the state. The seasons of maximum wind power on exposed ridge crests and mountain summits are winter for the higher ranges of northern Utah, and winter and spring for mountains in eastern and southeastern Utah. Summer is the season of minimum wind power on all ridge crests and mountaintops. Lowland areas throughout the state have minimum wind power in winter and autumn, a consequence of the frequent presence of stable surface air.

7.2.1 Winter

Winds aloft are strongest over Utah during the winter season; consequently, wind power on ridge crests and mountain summits throughout the state is estimated to be highest during this season (Westbrook 1980). The Uinta and Wasatch Mountains are estimated to have class 6 and 7 winter wind power as a result of these strong west-northwesterly winds. Mean wind speeds aloft decrease from north to the south, and exposed plateaus and mountain areas in south-central and southwestern Utah are estimated to have class 5 and 6 wind power. These estimates, as well as the class 3 and 4 estimates for exposed mountain areas in eastern and southeastern Utah, are based on upper-wind climatologies (Crutcher 1959, Westbrook 1980, Hoidale et al. 1975).

There are basically two synoptic weather patterns that influence Utah's winds in winter. The first occurs during periods of strong westerly or northwesterly flow aloft, when Pacific storms penetrate the intermountain regions of the western U.S., bringing winter snows and strong winds to much of the area. As these storms pass to the north or south of Utah, pressure gradient winds become the dominant surface flow feature. The winter wind power resource in Utah is highly dependent upon the frequency of occurrence of these winter storms. The second pattern occurs when the

Great Basin area is occupied by a nearly stationary high pressure system, with accompanying light winds, stable surface conditions, and general air stagnation. This is the most frequently occurring synoptic condition during winter and can persist for weeks at a time. When this condition is present, surface winds in low valleys and basins become dominated by local air drainage and thermally-driven weak upslope flow. Because of this frequent condition, winter wind power is estimated to be class 1 for nearly all lowland areas of Utah. In the narrow canyons east of Salt Lake City, Ogden, and Provo, downslope stable air drainage from the Wasatch Mountains is strongest during winter, so that wind power in these canyons may be one or two classes higher than that indicated by Figure 7.9.

The Escalante-Sevier Desert wind corridor is estimated to have class 2 wind power in winter, although it is expected that there will be high variability from year to year. Wind power in the portion of this corridor near Milford is estimated to be class 3. However, data from this area are based mostly on daytime observations; it is anticipated that the inclusion of nighttime wind data would indicate winter wind power that is on the borderline between class 2 and class 3.

7.2.2 Spring

In the spring, wind power on exposed ridge crests and mountain summits of the state is estimated to be class 5 and class 6 in the higher northern mountains; class 4 and 5 in the southern mountains; and class 3 and 4 in the less extensive mountain ranges throughout the state. In March, the winds aloft are from the west through northwest. However, by April and May, the winds aloft move to a more westerly through west-southwesterly direction and become less intense.

Spring is the season of maximum wind power in the lowland areas of the state. More frequent Pacific storm penetration and increased daytime solar radiation provide for good vertical mixing of surface air with the winds aloft, resulting in stronger surface winds, particularly during the day. At night, strong radiational cooling of the surface results in large diurnal temperature ranges and a large diurnal variation in the wind resource. Wind power is estimated to be class 2 in all but the most sheltered areas of the state. This class 2 area includes most of western Utah and southeastern Utah. In western Utah, persistent stable surface conditions occur less frequently than in winter, and strong southwesterly and north-northwesterly

synoptic winds dominate surface flow. Embedded in the class 2 area is the class 3-4 Escalante-Sevier Desert wind corridor, where strong winds are channeled by surrounding mountains. In southeastern Utah, it is estimated that many well-exposed bluffs, cliffs, and mesa locations, which were not classified as ridge crest or mountain summits, will have class 2 and perhaps class 3 wind power.

7.2.3 Summer

In the summer, wind power is estimated to be class 3 on exposed ridge crests and mountain summits above 2,700 m (9,000 ft), and in a portion of the Escalante-Sevier Desert wind corridor near Milford. Winds aloft are weakest during this season, and are predominantly out of the southwest (Westbrook 1980). Except for periods of sub-tropical moisture intrusion, skies are mostly clear over the state and daytime temperatures are hot. At night, clear skies and low humidities result in rapid cooling of the surface and the formation of temperature inversions over lowland areas, bringing near-calm surface winds. Except for the Escalante-Sevier Desert wind corridor, lowland areas of Utah are estimated to have class 1 wind power. However, many exposed locations in southern and southeastern Utah can be expected to have class 2 wind power in some summers. Data from the well-exposed Canyonlands station on Red Sea Flats indicate borderline class 2-3 potential wind power.

7.2.4 Autumn

Although the winds over mountainous areas of the state generally increase from September to November, the surface winds in lowland areas generally decrease. In autumn, because of the intensification of upper-level winds, class 4 and higher wind power is estimated for most exposed ridges and mountain summits above 2,700 m (9,000 ft). At lower elevations, however, decreasing insolation and generally weak surface pressure gradients (both thermally and synoptically caused) result in light winds and an increasing frequency of stable conditions at the surface. Class 1 wind power is estimated for areas throughout the lowland regions of the state with the exception of the central Escalante-Sevier Desert wind corridor, which is estimated to have class 2 wind power.

7.3 FEATURES OF SELECTED STATIONS

Table 7.2 gives the location and annual average wind speed and power density for thirteen stations in Utah. Graphs of other features of the wind resource are shown in Figures 7.10 to 7.16. Seven of these

stations are located in the Great Salt Lake Basin, two are in the Escalante-Sevier Desert wind corridor, three are in the canyons area of southwestern Utah, and one is located at the southwestern edge of the San Rafael desert in southeastern Utah.

Bryce Canyon Airport is located in Johns Valley a few kilometers north of Bryce Canyon National Park in south-central Utah. Although prevailing winds in this area are southwesterly, the predominantly westerly wind direction at the airport indicates sheltering effects by the higher Paunsaugunt Plateau a few kilometers southwest, and the Sevier Plateau to the northwest. Highest wind speeds appear to be associated with south-southeasterly flow, which is channeled up the Paria River valley and over the Pink Cliffs to the airport. Sites located on the better-exposed ridges and plateaus surrounding the airport are expected to have higher wind power than that which is indicated by data from the airport.

Cedar City Airport, situated at the base of the Hurricane Cliffs in the Cedar Valley, is relatively sheltered by the Harmony Mountains 19 km (12 mi) southwest, and by the higher terrain 5 km (3 mi) east of the airport. There appears to be some enhancement of southwesterly and northerly winds by the Hurricane Cliffs. However, data from this borderline class 1 - class 2 station show frequent light winds (20% calm) as a result of nighttime stable air drainage into the Cedar Valley.

Delta Airport appears to be representative of locations in the northern part of the Escalante-Sevier Desert wind corridor. The station is well exposed to prevailing south-southwesterly winds which are apparently enhanced by the Canyon Mountains and Pavant Mountains to the east and southeast, respectively. This station also receives frequent nighttime and morning stable air drainage from the Sevier River valley to the northeast.

Dugway Proving Ground/Michaels AFB (Air Force Base) is located in the southeastern portion of the Great Salt Lake Desert. The AFB site, located in the Government Creek Basin in an area known as the Dog Area, is moderately-well exposed to prevailing southerly winds. However, because of its low elevation relative to the mountains to the north and east, it has a high frequency of calms (>30%) and weak downslope drainage flow from the east and southeast. The direction associated with the strongest winds is north-northeast, a result of terrain enhancement by the Cedar Mountains to the north.

Fairfield CAA (Civil Aeronautics Administration) is located at the northern end of the Cedar Valley near the southeastern point of the Oquirrh Mountains. The strong influence of Oquirrh Mountains drainage flow is apparent at Fairfield by the high frequency of northerly winds. This relatively sheltered station appears to be on the southern fringe of the Great Salt Lake Basin circulation regime, and is somewhat removed from the Escalante-Sevier Desert wind corridor.

Hanksville Airport is located on the southwestern edge of the San Rafael Desert in southeastern Utah. This station appears to be locally well-exposed to prevailing winds and is probably representative of desert valleys in the lee of the mountains of south-central Utah. The variability of wind directions and high occurrence (approximately 20%) of calm conditions suggest the absence of a dominant mountain-valley circulation; however, there are some indications of northwest drainage winds.

Lucin CAA is at a well-exposed location on the northwestern edge of the Great Salt Lake Desert. Data from this site appear to be representative of stations on the floor of the Great Salt Lake Desert, where there is good exposure to synoptic winds during the day, but where nighttime stable surface conditions frequently dissociate surface winds from winds aloft. At Lucin, downslope drainage flow from the Grouse Creek and Goose Creek Mountains results in a high frequency of winds from the west-northwest and northwest.

Milford Airport is located in the Escalante-Sevier Desert wind corridor. The station is well exposed to prevailing south-southwesterly winds that are channeled by the Wah Wah and San Francisco Mountains to the west of the corridor and by the Mineral and Black Mountains to the east. This station shows the highest annual average wind power of all stations listed in Table 7.2. However, during the period from 2/52 to 12/64, observations were made during the daytime only.

Ogden CAA is located in the Great Salt Lake Basin, approximately 26 km (16 mi) east of the lake shore near the Wasatch Mountain foothills. The site is approximately 8 km (5 mi) from Ogden canyon, in an urban setting on the west edge of town, far enough from the canyon to be representative of wind characteristics on the floor of the Great Salt Lake Basin.

Ogden/Hill AFB is situated approximately 8 km (5 mi) south of the city of Ogden, near the mouth of the Weber River canyon.

Frequent strong downslope drainage flow from the canyon results in generally stronger winds during the early morning hours than those in the afternoon.

Salt Lake City International Airport is located near the southeastern shore of the Great Salt Lake, near the base of the Wasatch Range. Wind characteristics at the airport are typical of mountain-valley circulations. Although the site is well-exposed to synoptic winds, the high frequency of opposing downslope (south-southeasterly) flow and stable surface conditions result in this site, and all stations in the eastern Salt Lake Basin, having lower average wind power than would be expected from synoptic winds alone. However, because of the strong nighttime stable air drainage from the Wasatch Mountains, narrow canyons on the west side of the Wasatch Range are expected to have moderately strong down-valley winds after sunset. In these canyons, the combination of enhanced upslope and downslope flow should result in higher wind power than that in the exposed basin.

St. George CAA is located in extreme southwestern Utah and is surrounded by higher terrain. As a result, the site is sheltered from prevailing winds. The station is located in the Virgin River basin near the lowest elevation in the state; consequently, wind data from this site are not representative of well-exposed locations on the surrounding higher terrain.

Wendover Airport is located on the western edge of the Great Salt Lake Desert, near the Utah-Nevada border. The station is on the desert floor, approximately 13 km (8 mi) west of the Bonneville Salt Flats. The Toana Range and Goshute Mountains to the northwest and southwest, respectively, and the Silver Island mountains to the northeast, are a source region for cold air that flows into the Salt Lake basin, sheltering the station from winds aloft. Data from this station appear to be representative of locations in the western Great Salt Lake Desert.

7.3.1 Interannual Wind Power and Speed

Five stations have selected periods of record of ten years or more during which the anemometer was not moved (Figure 7.10). In general, the interannual wind power variability is quite low throughout Utah, with only Milford and Cedar City showing variability across multiple wind power classes. Salt Lake City International Airport, Wendover, Dugway Proving Ground, and Bryce Canyon all had annual average wind power that stayed within or close to

the class 1 category during the entire period of record. This illustrates the persistent effect of nighttime stable conditions on surface winds in low elevation areas of the state.

Interstation comparison of annual trends in the wind power resource is very difficult for most of the stations analyzed because of the effects of downslope drainage patterns and local terrain orientation on local winds. For local comparison, Cedar City and Milford, both located in Esclante-Sevier Desert wind corridor, had wind power maxima in 1955 and minima in 1957. Salt Lake City International Airport and Ogden/Hill AFB had minima in 1957 and in 1966. No other stations had minima that corresponded to the minima for Bryce Canyon in 1962, Cedar City in 1965, or Milford in 1964. In general, it appears that two or three years of wind data at most desert valley locations are adequate to assign a wind power class, and that additional interstation comparison of annual average wind power can be applied on a large scale with only limited success.

7.3.2 Monthly Average Wind Power and Speed

Cedar City, Bryce Canyon, Wendover, and Hanksville, show maximum average wind speed in the spring (Figure 7.11). Little difference exists between spring and summer average wind speeds at Delta, Milford, St. George, Ogden, Ogden/Hill AFB, and Salt Lake City International Airport, although spring wind power is about 20 to 30 percent higher than summer wind power at these stations. In general, stations located in the eastern Great Salt Lake Basin have relatively small monthly variations in wind speed and power, a consequence of the recurrent daytime-nighttime mountain-valley circulations throughout the year. This is best illustrated by the four-and-one-half year period at Ogden. At all stations analyzed, minimum wind power occurs during the late summer, fall, and early winter.

At Fairfield and Lucin, because of the short period of record, monthly averages shown may deviate significantly from long term monthly averages. The two stations have nearly identical monthly average wind speed distributions, based on data from the same year, 1949.

7.3.3 Diurnal Wind Speed By Season

All of the stations shown in Figure 7.12 except Ogden CAA, Ogden/Hill AFB, and Lucin, show maximum daily wind speeds during the afternoon for all seasons. Ogden CAA, Ogden/Hill AFB, and Lucin all have average wind speed maxima occurring shortly after

sunrise during winter. Maximum winds generally occur after the nighttime surface temperature inversion is burned off and either surface winds are linked to synoptic winds, or an upslope valley circulation develops. In the afternoon, increased surface heating causes good vertical mixing of the lower atmosphere, and maximum surface wind speeds generally occur during the time of the highest surface temperature. The duration of maximum winds varies from season to season. Cedar City, Hanksville, Bryce Canyon and St. George all show maximum wind speed periods that begin earlier and last longer in spring and summer than they do in autumn and winter.

Salt Lake City International Airport, Ogden CAA, Ogden/Hill AFB, and, to a lesser degree, Lucin, have low diurnal variations in wind speed. This is typical of stations near the perimeter of the Great Salt Lake Basin, where the speed of the nighttime downslope drainage winds from the mountains equals or exceeds upslope or synoptic daytime wind speeds. In this type of flow pattern, minimum wind speeds generally occur around sunset, during the transition from upslope or synoptic flow to downslope drainage flow. If no dominant nighttime drainage flow exists, as is the case for most of the other stations analyzed, the minimum wind speed will occur shortly after sunrise, when the depth of the stable air is greatest.

7.3.4 Directional Frequency and Average Speed

Prevailing strong winds are mostly from the south-southwest through southwest at stations throughout the Escalante-Sevier Desert wind corridor and other portions of southern Utah. In northern Utah, particularly in the area of the Great Salt Lake Basin, prevailing strong winds are mostly north-northwesterly on the west side of the lake basin and are either southerly or northerly on the east side.

Terrain channeling and enhancement of synoptic winds or mountain-valley circulations, and terrain sheltering, are the main factors that determine the frequency distributions of wind speed and direction. The north-south bimodal distribution of wind direction and relatively high mean wind speed at Milford are results of ter-

rain channeling of synoptic winds. This phenomenon is also exemplified, to a lesser degree, at Bryce Canyon for winds from the southeast and west. Data from nearly all lowland stations in Utah, with the possible exceptions of well-exposed desert and basin locations, show the presence of downslope drainage winds from higher surrounding terrain. In general, these drainage winds are light, and in many wind direction distributions are represented by the most frequent direction. For example, the west-northwest, east-southeast, and northwest peaks in the percent directional frequency curves for Lucin, Ogden/Hill AFB, and Hanksville, respectively, are the result of drainage winds.

7.3.5 Annual Average Wind Speed Frequency

Comparison of the annual wind speed distribution with the Rayleigh distribution for each station is presented in Figure 7.14. Observer bias and high wind speed sensor threshold (start-up velocity) distort the wind speed distribution at most of the stations. Observer biases are apparent from the peaks at 2, 5 and 8 m/s (5, 10, and 15 kts) at ten of the fifteen stations for the periods of record shown. Observer bias is apparent in data from Fairfield, Hanksville, Lucin, Milford (7/49 to 1/52), St. George, Bryce Canyon, Delta, Dugway Proving Ground, and Cedar City. Wind speed sensor start-up speed at most stations analyzed is above 0.67 m/s and in some cases appears to be above 1 m/s. This results in an unreasonably large number of calms and an uneven distribution of wind speeds below 2 m/s. However, because the contribution of low wind speeds to annual average wind power is small, threshold problems such as these are not significant in the annual average wind power estimate. Data from Milford (2/52 to 12/64) show the distribution of wind speed that most closely resembles the Rayleigh distribution.

7.3.6 Annual Average Wind Speed and Power

The percentage of time that a given wind speed or power is exceeded is shown in Figures 7.15 and 7.16. 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 7.1. Geographic Map of Utah

FIGURE 7.2. Topographic Map of Utah

FIGURE 7.3. Land-Surface Form Map for Utah

LAND-SURFACE FORM LEGEND

PLAINS

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

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

OPEN HILLS AND MOUNTAINS

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

HILLS AND MOUNTAINS

D3	HILLS
D4	HIGH HILLS
D5	LOW MOUNTAINS
D6	HIGH MOUNTAINS

TABLELANDS

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

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

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)

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 7.4. NCC Station Locations in Utah

FIGURE 7.5. Locations of Stations Used in Utah Wind Assessment

FIGURE 7.6. Utah Annual Average Wind Power

Classes of Wind Power Density at 10m and 50m (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 7.1. Areal Distribution (km²) of Wind Power Classes in Utah

Power Class	Land Area	% Land Area	Cumulative Land Area	% Cumulative Land Area
1	194,791	91.2	213,650	100.0
2	13,581	6.4	18,859	8.8
3	3,581	1.7	5,278	2.5
4	1,126	0.5	1,697	0.8
5	508	0.2	570	0.3
6	<100	<0.1	<100	<0.1
7	0	0.0	0	0.0

0 50 100 MILES

0 50 100 KILOMETERS

PNL 3195 WERA-8

FIGURE 7.7. Certainty Rating of the Utah Wind Resource

CERTAINTY RATING LEGEND

Rating	Definition
1	<p>The lowest degree of certainty. A combination of the following conditions exists:</p> <ul 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> <ul 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> <ul 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 7.8. Areal Distribution of Wind Resource in Utah (Power Classes 2 and 3); Percent of Land Area With or Exceeding Power Class Shown. An asterisk denotes 100%.

FIGURE 7.8 (Continued). Areal Distribution of Wind Resource in Utah (Power Classes 4 and 5); Percent of Land Area With or Exceeding Power Class Shown.

FIGURE 7.9. Seasonal Average Wind Power in Utah (Winter, Summer)

FIGURE 7.9. (Continued). Seasonal Average Wind Power in Utah (Spring, Autumn)

TABLE 7.2. Utah Stations with Graphs of the Wind Characteristics

Station	Station Name ^(a)	Lat N (deg, min)	Long W (deg, min)	Elevation (m)	Period of Record (month, year)	Anem. Height (m)	Annual Average Speed (m/s)			Annual Average Power (watts/m ²)		
							Anem Ht	At 10 m	At 50 m	Anem Ht	At 10 m	At 50 m
Bryce Canyon, Utah	Bryce Canyon Airport	37, 42	112, 09	2316	11/48-12/64	7.6	3.2	3.3	4.1	47	53	105
Cedar City, Utah	Cedar City Airport	37, 42	113, 06	1712	12/64-12/78	6.1	3.7	4.0	5.1	81	100	200
Delta, Utah	Delta Airport	39, 23	112, 31	1452	4/49-12/54	7.3	3.6	3.8	4.8	87	99	198
Dugway Proving Ground, Utah	Michaels AFB	40, 11	112, 56	1329	3/53-3/57	9.1	2.6	2.6	2.6	54	56	112
Fairfield, Utah	Fairfield CAA	40, 21	112, 03	1514	11/48-7/50	17.7	3.7	3.4	4.3	104	81	162
Hanksville, Utah	Hanksville Airport	38, 25	110, 42	1360	11/48-12/54	7.6	2.6	2.7	3.4	50	56	112
Lucin, Utah	Lucin CAA	41, 22	113, 50	1346	11/48-3/50	7.6	4.0	4.1	5.2	80	90	179
Milford, ^(b) Utah	Milford Airport	38, 26	113, 01	1534	7/49-1/52 2/52-12/64 ^(b)	9.1 9.1 ^(b)	4.0 ^(b) 5.6 ^(b)	4.0 ^(b) 5.6 ^(b)	5.1 ^(b) 7.1 ^(b)	107 ^(b) 190 ^(b)	111 ^(b) 197 ^(b)	222 ^(b) 394 ^(b)
Ogden, Utah	Ogden CAA	41, 12	112, 01	1354	1/48-5/52	10.1	4.0	4.0	5.1	79	79	157
Ogden, Utah	Hill AFB	41, 07	111, 58	1459	5/58-12/7C	4.0	3.4	3.9	4.9	60	89	178
Salt Lake City, Utah	Salt Lake City International Apt.	40, 46	111, 58	1287	7/54-7/60 7/60-12/78	10.1 6.1	3.8 4.0	3.8 4.2	4.8 5.3	64 73	64 90	127 180
St. George, Utah	St. George CAA	37, 03	113, 31	884	11/48-12/54	7.6	3.0	3.1	3.9	50	56	112
Wendover, Utah	Wendover Airport	40, 44	114, 02	1292	6/60-11/76	6.7	3.1	3.3	4.1	61	72	144

^(a) AFB - Air Force Base; CAA - Civil Aeronautics Administration Facility.

^(b) Station had less than 12 observations per day from 2/52-12/64.

FIGURE 7.10. Interannual Wind Power and Speed for Utah

FIGURE 7.11. Monthly Average Wind Power and Speed for Utah

FIGURE 7.12. Diurnal Wind Speed by Season for Utah

— PERCENT FREQUENCY LEFT ORDINATE - PERCENT
 - - - WIND SPEED RIGHT ORDINATE - M/S
 PNL-3195 WERA-8
 ABSCISSA - WIND DIRECTION

FIGURE 7.13. Directional Frequency and Average Wind Speed for Utah

— ACTUAL DISTRIBUTION ORDINATE — PERCENT
 - - - - - RAYLEIGH DISTRIBUTION ABSCISSA — M/S
 PNL-3195 WERA-8

FIGURE 7.14. Annual Average Wind Speed Frequency for Utah

ORDINATE - PERCENT

ABSCISSA - M/S

PNL-3195 WERA-8

FIGURE 7.15. Annual Average Wind Speed Duration for Utah

ORDINATE - PERCENT
ABSCISSA - WATTS/M²

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FIGURE 7.16. Annual Average Wind Power Duration for Utah

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