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METHODS FOR SITING SMALL WIND MACHINES*

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by

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ABSTRACT

The question of siting wind energy conversion systems (WECS) represents a balance between the economic, technical and social values of the user and the local citizens. This paper considers the technical issues. Before addressing the technical siting issues, as well as the social and economic ones, a determination of the potential user, the application of the WECS, and the geographical location of the installation must be made. Once these three determinations have been made, the meteorological and topographical characteristics of specific candidate sites must be assessed. Some of the topographical issues discussed in this paper are the effects of siting WECS near bodies of water, near or in trees and forests, around structures and buildings, and in hilly terrain; and some of the meteorological features considered are the effects of local wind circulations, velocity profiles, local turbulence, and hazardous weather elements. In addition to these discussions, we describe the type and availability of pertinent siting information and data. Finally, we outline the information and data being generated by the Site Selection Program Area of the Wind Characteristics Program Element of ERDA's Wind Program.

1. Introduction

The question of siting of wind energy conversion systems (WECS) represents a balance between the economic, technical and social values of the user and the local citizens, whether the WECS is for a small farm or a multi-state region. The social and environmental issues that play a role in siting are the visual impact of the WECS, zoning or code restrictions, liability considerations, the "wind rights" question, noise, aviation hazards, effects on birds, effects on communication systems, and other family and neighborhood values. Some of the economic values that should be considered are the cost of the site analysis, the value placed on the increased power production that results from investing more in system components, and the life-cycle cost of maintaining and operating an installation. Finally, the technical siting issues include the type of WECS being used, the type of storage system being used, the wind and other meteorological characteristics of the candidate site, and the topographical and seismic features of the site. Thus, a good siting policy is one that optimizes the power output based on the constraints imposed by these various issues.

The current paper deals with the technical aspect of siting. If we can improve the siting of WECS from the meteorological and topographical points of view, then the overall siting policy should be improved. The economic results of these improvements will be, at least, threefold:

1. A considerable saving in the siting costs of WECS.
2. More power produced per unit due to locating units in more ideal wind regimes.
3. A more dependable, predictable, and constant source of power due to improved siting criteria.

In the next section of this paper we briefly describe some of the applications and users of WECS. Following this section, the topographical and meteorological aspects of siting are summarized. Section 4 lists some of the data and information that is currently available to aid the investigator in siting WECS.

Finally, in Section 5, we outline the information and data being generated by the Site Selection Program Area of the Wind Characteristics Program Element of ERDA's Wind Program.

2. Applications and Users

There are many applications, both actual and potential, for the small and large wind turbines, [1]*. The energy extracted from the air by these wind turbines may be directly added into an electrical distribution system; may go into energy storage such as hot water or heated materials, fuel cells or H_2 , fertilizer production, propane or methane production, compressed air, flywheels, and pumped hydro-storage; or may be used for a variety of other uses, see Table 1. The application of the WECS and the presence or absence of energy storage place very strong constraints on the siting policy. Since this is the case, it behooves us to strive for the very best technical siting criteria possible.

Large WECS can be interpreted as those turbines whose rated capacities are greater than or equal to 100 KW, while small systems have capacities less than 100 KW. The capacities of small systems may range all the way down to tenths of kilowatts. Table 2 indicates the range of capacities for given WECS applications.

The diameter of the disk cut by the turbine blades and the height of the turbine tower are very important when considering the meteorological and topographical aspects of siting. For example, large diameter turbines may experience severe wind shear due to the variations in wind speed and direction and the variation in turbulent intensity with elevation, see Figure 1. In addition, the location of the hub height with respect to the surrounding structures, vegetation and topographical features will highly influence the efficiency of the turbine. In Table 3, we list the diameters and hub heights of some representative turbines.

*The numbers in square-brackets refer to the references at the end of the paper.

3. Topographical and Meteorological Aspects of Siting

The movement of air over the globe is strongly influenced by the sun's radiation, the rotation of the earth, and the evaporation and condensation of water. These phenomena set up a general circulation pattern over the globe, Figure 2. Embedded in these flow patterns are the continents, the oceans, and many islands. For example, the 50 states of the United States are embedded in the Polar Easterlies, the Westerlies, and the Northeast Trades. These embedded elements strongly perturb the idealized flow patterns shown in Figure 2. The perturbations are due to such phenomena as the ocean currents, the ocean temperatures, the ice and snow covered surfaces, the presence of mountain ranges, the variations in the solar radiation due to the surface properties of the earth, and the temporal and spatial variations of clouds. Because of these perturbations, the availability of wind energy throughout the world is not uniform either in space or time. This statement is supported by the map of "The Annual Availability of Wind Energy in Different Parts of the World" given in Figure 3.

Obviously, the data given in Figure 3 is rather coarse in nature and the map must be cautiously used. The map shows where large areas of the world have good to excellent wind-power potential. However, the "poorer" wind-power areas shown in Figure 3 should not be discounted since the data used to generate the map was so sparse and coarse. Hence, we must focus on smaller areas to get more precise wind-power information, both in time and space.

Figure 4 focuses on the 48 contiguous states. This map gives the annual average wind power in watts/m^2 that is available for extraction. The values in Figure 4 were more highly influenced by mountains, bodies of water and large plains than those given in Figure 3. In addition, Figures 5 to 8 indicate that the wind-power potential over the 48 states can vary significantly from season to season throughout the year.

The seasons of maximum power for the 48 states are usually the winter and spring. For some applications, this time of maximum power coincides with maximum demand for that power. The locations of the high wind-power areas indicated by the map in Figures 4 to 8 are the Texas-Oklahoma Panhandle, the Great Plains, the Rocky Mountains, the Eastern and Western Mountains, the Eastern and Western Coastal Areas, part of the Gulf Coast, and part of the Great Lakes Coastal Area.

The maps given in Figures 4 to 8 are still rather coarse and much important wind data has been filtered out of these diagrams. These maps do not contain the detailed structure that would be produced by individual mountain ranges, large river systems, large bays, and rolling hills. In addition, the time scale given in seasons is far too coarse, especially for the smaller WECS.

The next step in our "focusing" procedure is to look at regions of the country, such as the New England States, the Middle Atlantic States, the Gulf States, the Great Lake States, the Northern and Southern Rockies, the Northwest, the Hawaiian Islands, Alaska, and other regions. At this point-in-time, we have not completed a consistent and detailed evaluation of the wind-power potential of the country on a region-by-region basis. However, this detailed evaluation is currently being performed under the sponsorship of ERDA's Wind Program. In addition to this ongoing systematic, regional evaluation, there are several isolated regional studies on the potential of wind-power that have been completed or are currently being conducted. Some of the regions that have been or are being studied are Michigan, Washington-Oregon, Alaska, California, and Hawaii. However, none of these studies have been sufficiently thorough to properly assess the wind-power potential of the regions in question.

The spatial resolution of a regional study should be sufficient to take into account the large mountain ranges, the large river systems, the large bays separated by long stretches of sea shore, the river valleys and rolling hills of the Plain States, the differences in surface roughness between forested areas and grass-

lands, and the thermal and roughness differences between water and land. The temporal resolution should account for the changes in wind-power potential over the diurnal cycle and should give month-by-month averages of wind-power potential. When the systematic, regional evaluation is completed, the probability of a successful siting of either a small or large WECS will be greatly increased.

Because of the enormity of the problem, it will be a considerable length of time before a national evaluation of wind-power potential is completed on a finer spatial resolution than that given by the regional study. In fact, it is not clear that this finer-resolution evaluation would be cost effective. Wind-power information on these finer scales can be obtained at specific locations in a variety of ways, such as, through the use of mathematical models that are tied to data collected on a regional scale, through the use of physical models of the areas in question, from on-site measurements of wind speed and direction and turbulence intensity, and from the knowledge of how air flows over various terrain and roughness elements. The remainder of this section deals with some of the meteorological and topographical considerations that must be considered when the spatial resolution becomes finer than the regional scales. Obviously, the actual siting of either a small or large WECS system takes place on a much smaller spatial scale than that of the regional evaluations.

3.1 Vertical Profile of Velocity

The formula for the available power in the wind that can be extracted by a turbine can be approximated by:

$$P = p/A \cong \frac{1}{2} C_p \rho [\bar{V}^3 + 3\sigma_v^2 \bar{V}] \quad , \quad (1)$$

where P is the wind power per unit area, p the wind-power, A the area of the vertical disc cut by the blades, C_p the power coefficient, ρ the air density, $\bar{V} = \bar{V}(z)$ the mean horizontal wind speed, z the vertical coordinate, and σ_v the measure of the turbulent intensity in the air. The maximum value of C_p is 0.593 [1]. For the old

farm windmill, C_p is 0.25; for the old Dutch windmill, C_p is 0.19; and for a modern, three-blade wind turbine, C_p is 0.47.

Figure 1 shows an ideal velocity profile over a homogeneous surface. As z increases, the mean horizontal speed tends to increase and the wind vector tends to turn in a clockwise manner (in the Northern Hemisphere). For large machines, this change in speed and direction is very important in assessing the potential output of the machine. Hence, the expression in (1) would have to be integrated over the disk to obtain the potential wind-power output of large WECS. For the smaller WECS, the variation of speed and direction can probably be neglected with respect to the power output. However, the vertical velocity profile is important with respect to the location of the hub height of small WECS.

The second term on the right side of (1) is the added power due to the turbulent fluctuations of the wind around the mean value $\bar{V}$. Equation (1) says that if there are two sites with the same mean wind but different intensities of turbulence, then more power will be produced from the more turbulent site. This may be true; however, the more turbulent site may be "out-lawed" due to structural or operational considerations.

3.2 Effects of Roughness

Figure 9 shows that the vertical profile of the horizontal wind can be greatly affected by the surface roughness. Hence, if a WECS user wants the same power from a turbine sited on a smooth area as from a turbine sited on a rough area, the hub height of the turbine over the rougher surface will have to be at a higher elevation for analogous wind conditions. The difference between the hub heights for the two areas is a function of the relative roughness between the areas in question.

Figure 10 indicates that the transition of the velocity profile from a smooth surface to a rough surface is not immediate, but takes several roughness-element heights downstream of the transition before the new profile is fully developed. This transition zone must also be considered in the siting of WECS.

3.3 Thermal Effects

Local circulations are produced by differential heating or cooling of adjacent surfaces. These motions may enhance or reduce the larger scale motions that are present during this heating or cooling process. Figure 11 shows the effect of the temperature differences between land and water. During a hot, sunny day, the land is warm and the water is cool; hence, a sea breeze circulation is produced. At night, the water retains its heat longer than the land; hence, the water is warmer than the land. Thus, a land breeze circulation is set up. Under the proper conditions, these circulation patterns are strong enough to produce wind power, especially with the smaller WECS. The optimum location of the WECS and the hub height in these situations are dependent upon the temperature differences between the land and water, the topography of the land, the latitude of location, and the larger scale wind patterns. There are many situations in which the larger scale flow features completely mask the effects of the land and sea breezes. However, if this occurs, we should be able to produce even more wind power unless the winds are too severe.

Another thermal effect is the circulation above an urban area, Figure 12. In general, the circulation patterns produced by a city in a calm wind (larger scale motion) will be too weak to produce much wind power. However, the interaction between the larger scale motions and the urban circulation patterns may be such as to reduce or enhance the wind power of the larger scale motions without the urban effects. Hence, this phenomenon should be considered in siting WECS around large cities.

Another important thermal phenomenon is the local circulation produced as convective clouds are formed and as they grow into large precipitating thunderstorms, Figure 13. These circulation patterns may be very strong and will produce wind power over short periods of time. However, convective circulation patterns are not dependable, long term sources of power except in locations where

very pronounced changes in surface characteristics occur and the climate is hot and reasonably dry. Then, a favored location for convection may be present day-after-day during the hot summer season.

3.4 Environmental Hazards

Probably the most important reason for considering strong convective situations in WECS siting is the potential damage that could occur to the turbine. Large, severe thunderstorms produce severe gusting and wind shear, lightning, hail, blowing dust, and even tornadoes. The siting of both small and large WECS should take these hazards into account. In fact, in some of the best wind-power regions of the country we also have the highest frequency of severe thunderstorms. Also, in many of these good wind-power areas, the weather is dry and there is much dirt and dust to be blown around. The occurrence of dust storms in an area may be a detriment to WECS if they are not properly protected against the entrainment of dust into the mechanical and electrical mechanisms.

Many good wind-power sites are at the head or foot of canyons or gorges. In siting WECS in these locations, the possibility of flooding and rock and earth slides should be investigated. Other good wind-power sites are located on mountain tops where heavy snows and icing should be taken into account. Finally, the soil and geological characteristics should be such that the wind turbine is properly supported, and the probability of damages from earthquakes is minimized.

For small WECS, many of the above hazards may be relatively unimportant, unless the turbine is at a remote location. The reason for this is that the small WECS user has probably already considered these hazards before building the more expensive structures in the operation for which the WECS is desired.

3.5 Terrain Effects

Certainly, one of the most important considerations in siting WECS is the terrain at the final location of the turbine and in the neighborhood of the turbine. Figure 14 shows the separation

zones (areas of reverse flow) produced by the flow of air over three different geomorphic geometries. If a wind turbine is sited in a separation zone, it will be very inefficient and will also be in an area of high wind shear. However, if the turbine is properly sited for the prevailing wind situations, then the power produced will be greater at the terrain feature than the power produced on level ground under analogous wind conditions.

The separation zone on top of a plateau extends downstream of the windward edge as far as 2 to 3 times the height of the windward face of the plateau. However, as the roughness elements on the level ground upstream of the plateau increase, the length of the separation zone decreases. The enhancement of wind above the separation zone may be as great as a factor of 2. Thus, the best location for the turbine is in the region of enhanced speed. However, this zone may also be a region of high turbulent intensity. In looking at Figure 14, one should always keep in mind that the separation zones and the enhanced speed areas are not steady state phenomena, but vary as the larger scale motions vary.

Figure 15 gives the various flow regimes that can occur over mountainous terrain. The presence or absence of these regimes depends upon the atmospheric stability, the size and shape of the mountain, and the strength of the large scale flows. If stable conditions persist most of the time, then the best WECS site may be in the enhanced speed area on the lee of the mountain. If neutral conditions persist, then the best site may be on the top of the mountain. In fact, there may even be conditions where the best WECS site is on the windward slopes of the mountain.

Other potential WECS sites are in water on wind gaps, especially in gaps through ridges that are oriented perpendicular to the prevailing winds. Canyons and gorges are also good WECS sites if they are oriented properly with respect to the larger scale motions.

3.6 Combined Roughness, Thermal and Terrain Effects

Figure 16 shows the formation of a valley eddy due to the differential heating within the valley. This figure is an idealized picture of a valley circulation that is basically uncoupled from

the larger scale flow above the canyon. Since there are three important forcing functions (roughness, thermal, terrain) producing complex flow patterns, the resultant pattern over a given area may consist of many regions of integrated and uncoupled flows. Hence, WECS siting in complex terrain is very difficult.

Figure 17 is an idealized mountain-valley system oriented in an East-West direction. At midnight the cold air drains down the side of the canyon and down the main canyon itself. As the sun rises the air rises along the sidewalls of the canyon. By noon the air is completely flowing up the canyon. These mountain-valley breezes are a very good source of wind-power in many sections of the country. The patterns shown in Figure 17 are not influenced by larger scale motions ; if they were, the resultant flows would even be more complex and the siting of WECS would be more difficult.

Other areas where terrain, roughness and thermal properties interact to produce potential wind-power sites are the flow of air over islands, glacier valley winds, the Santa Ana drainage winds from the Great Basin to the Pacific Coast, and many others.

3.7 Effects of Shelterbelts and Buildings

In Figure 18, we show the separation zones both upwind and downwind of a shelterbelt. Siting a WECS in either of these separation zones would be very ineffective. For the case shown in Figure 18, there are two areas of speed enhancement, one upstream of the shelterbelt and one about two tree heights inside the shelter area. If the wind turbine had a tower sufficiently tall, it could take advantage of these areas of speed enhancement. Shelterbelts can also be built so as to funnel air toward a WECS.

Figure 19 shows the separation zones that will form around a building as the air flows over it. The best location for a WECS on top of this building would be in the area of the taller smoke stack. If the turbine was sited too low on the roof of the building, the blades would be in the separation zone and the machine would be inefficient.

3.8 Biological and Geological Indicators

Some of the National Weather Service Stations record the visibility in miles due to dust in the air on a daily basis. Using this data, maps of frequency and diurnal variations of dust storms can be constructed for the USA. This data is a good indication of the presence of high winds, at least high enough to entrain the soil particles into the air. Using this kind of information, it has been shown that the Texas-Oklahoma Panhandle, the Great Plains, Nevada and the Columbia Basin are the dustiest areas in the country [9]. These areas are also known to be good wind-power areas. The reason mountainous and maritime regions are generally free of dust is because of the ground cover, not the lack of wind. Even though the decrease of visibility may be a good indicator of high winds, its importance to turbine siting is probably more from a nuisance or hazard point-of-view than for a wind-prospecting tool.

A more important wind prospecting tool may be the presence of sand dunes. Since dunes propagate differently under low and high wind regimes and since dunes can be observed by various types of remote sensing, they can be used as crude indices of wind speed and direction. An obvious example is the presence of dunes in the lee of narrow passes, such as the Killpecker Sand Dunes near Rawlins, Wyoming. Since active dunes occur in such places as along the shores of Lake Michigan, in Wyoming, Colorado, Nevada, Utah, Texas, California, and in other Southwestern States, the wind-indexing of dunes may produce a usable rough screening tool for wind prospecting.

Probably the most valuable rough screening tool for wind prospecting is the use of wind-deformed vegetation. Vegetation responds to many wind induced phenomena, such as persistent winds during the growing season, very high winds producing breakage, wind and ice storms during the dormant season, wind produced salt spray near coastal areas, and the distribution of seeds and pollens by wind. If all of these wind produced phenomena can be isolated

and the resultant vegetation effects can be indexed as to wind speed and direction, and as to persistent winds vs. severe high winds, then vegetation will be a very valuable wind-prospecting tool. Examples of indices are the amount of deformation or flagging of trees and the eccentricity and compression ratios of tree ring patterns vs. wind speed, direction and duration.

4. Available Information and Data

The National Climate Center, NOAA, at Asheville, NC, collects wind characteristics data from about 600 weather stations throughout the United States from which average wind speeds and directions, the variance or turbulent intensity of the wind, and the monthly and annual average wind power distributions can be obtained. Some of these stations record the winds aloft, as well as at the surface; some stations also record the diurnal variations of wind speed and direction. A catalogue describing the information that is data-banked at Asheville is available and would be useful to many potential WECS users.

In some localities wind data may be obtained from local offices of the National Weather Service, military installations, U.S. Forest Service firetowers and other installations, various state agencies, public utilities, airlines and airports, oil companies, and NASA installations. Low quality data can also be obtained from Coast Guard Stations, lighthouses, and from various ships. In addition, there have been special, intensive field programs conducted throughout the country for short periods of time for the purpose of studying certain aspects of meteorology and the transport of pollutants. The data from these field programs are usually compiled in project reports and many of these are available to the public. These data from the special projects are very site specific but could be very useful to a WECS user in the vicinity of a given project.

5. The Site Selection Program Area

The Site Selection Program Area of the Wind Characteristics Program Element of ERDA's Wind Program is divided into three subareas: Site Screening and Localization Technique Development, Technique Validation and Comparison, and Documentation of Siting Strategies. The subarea on technique development has the objective of identifying and developing techniques that are useful in the site selection process or that can be used to estimate the wind characteristics at a specific site. Techniques currently being examined include numerical and physical modeling, and the use of remote sensors and vegetation to indicate areas of high wind speed. The development of non-modeling techniques will be increased in late FY 1977 with the funding of several tasks to develop innovative, non-modeling techniques for site selection.

The subarea on technique validation and comparison has as its objectives the determination of the accuracy and relative costs of potential site selection techniques. Techniques will be evaluated by application to standard siting scenarios so that both accuracy and relative costs can be compared. The results of this subarea will be used to identify the siting techniques most appropriate to typical siting scenarios.

The objective of the Siting Strategy Documentation Subarea is the preparation of the primary product of the Site Selection Program Area. It covers the preparation and updating of the Siting Handbooks for both Small and Large Systems. In addition, a handbook covering the effects of small scale terrain features on wind is in preparation and should be completed in FY 1979. Since this latter handbook will be of interest to small WECS users, we anticipate that parts of the handbook will be available to the public prior to the availability of the final document.

In Figure 20, we show the current Site Selection contractors. In the following paragraphs we will briefly outline their programs.

5.1 American Wind Energy Association: Bristol, Indiana

The final report on this project is currently in the review process. The report is a survey of historical and current site selection techniques for the placement of small WECS. Included in the work are a survey of early users, siting guidelines given by various manufacturers and an extensive bibliography.

5.2 FWG Associates, Inc.: Tullahoma, Tennessee

The overall objective of this project is to characterize and catalogue microscale terrain features, assess their influence on local wind energy potential, prepare engineering manuals and reports on microscale site selection and enhancement criteria, and design experimental techniques and layouts for verification of the wind energy of a given microscale site. The site portfolio, or handbook, will categorize the vast array of terrain features into a workable number of classes of geometric shapes which are amenable to analysis from a fluid mechanics point-of-view. The microscale features that will be considered in the handbook are listed in Figure 21.

5.3 University of Oklahoma: Norman, Oklahoma

The objectives of this NSF sponsored research are to identify the optimum location of WECS within complex terrain and to predict the wind characteristics for a specific site based on geomorphological and regional meteorological measurements. The report for the one-year pilot study is in the review process.

5.4 Poseidon Research Institute: Los Angeles, California

The objective of this project is to develop a method for predicting locations of high average wind speed over complex terrain under stable and neutral flow conditions. In addition, a criteria will be developed for predicting the occurrence of separation zones downwind of mountainous areas. The mathematical technique being applied in the analysis is the method of Fourier transforms, and it is anticipated that the resultant assessment tool will be rapid and inexpensive to use.

5.5 Research Triangle Institute: Research Triangle Park, NC

The objective of this work is to develop a model that will allow the generation of "faithful" wind statistics at various locations given the wind data collected at nearby weather stations. If this research is successful, then a regional and subregional wind-power evaluation can be easily conducted for all parts of the country based on the data collected at the National Weather Service Stations in the U.S.

5.6 University of Wyoming: Laramie, Wyoming

This research is concerned with assessing the regional applicability of the LANDSAT satellite's imagery as a tool for locating areas of high wind potential through the observations of aeolian geomorphologic features. Data will also be obtained on the use of stabilized dunes as indicators of present-day wind characteristics. The data from this project will be useful in the site screening area of the wind program.

5.7 Oregon State University: Corvallis, Oregon

This work is concerned with the calibration in terms of wind speed, wind deformed vegetation (primarily trees), in order to permit the location of potential wind power sites without the necessity for elaborate wind measurement programs. The investigation is concentrating on five different indices of the wind's effects on conifers. Meteorological and biological measurements will be made at eleven locations in Washington and Oregon. The biological indices that will be calibrated in the study will form the basic material for a portion of a handbook on wind power siting.

5.8 Colorado State University: Fort Collins, Colorado

The objective of this project is to determine the flow phenomena over topography through the use of a wind tunnel. The flow phenomena that is being studied are the variations in mean wind speed, the speed-up factors over the topography, separation zones, turbulent intensities and spectra, insolation and stratification. The topographical features that are being modeled in the

wind tunnel are two-dimensional triangular and sinusoidal hills, ridge sections with canyons and notches, converging valley ridges, pairs of conical hills, and a field validation model. The contributions from this study will provide a great deal of valuable information for the siting handbooks.

5.9 AeroVironment, Incorporated: Pasadena, California

The objective of this program is to demonstrate that a doppler acoustic radar system can be used to assess the local wind field of a candidate WECS site. The proposed advantages of this system over conventional measurement techniques are its portability and the fact that expensive towers are not needed. The remote sensing system developed in the project will enable the observation of localized characteristics of the real three-dimensional wind and the turbulence field in complex terrain at up to 100m above ground level.

5.10 University of Virginia: Charlottesville, Virginia

The near surface winds in the coastal zones will be evaluated for wind energy potential utilizing a sea breeze mesoscale circulation model. The effects of land/sea temperature differences, the large scale velocity field and surface roughness will be explored as they vary along the coastal zones from Mexico to New England. The climatological regions that are being considered in the study are shown in Figure 22. It is assumed that each of these regions have a common climatology and that the number of specific locations that need to be studied in each region can be kept to a minimum. The final results of the study will contribute to the regional and subregional evaluations of wind-power potential along the Eastern and Gulf Coasts.

5.11 Science Applications, Inc.: LaJolla, California

This program is concerned with the development, testing and performance of prototype applications of a wind energy site selection methodology. The method supplements conventional siting studies to achieve greater accuracy and cost-effectiveness by employing a family of sophisticated mathematical models of meso-and micrometeorology over complex terrain. The methodology

will be extensively tested and then will be documented and placed into operational status during FY 1978. The methodology will allow the use of data from meteorology stations to forecast the climatology of nearby sites where wind potential is greater but data are unavailable.

5.12 Lawrence Livermore Laboratory: Livermore, California

The objectives of this project are to classify regional flow patterns and their frequency of occurrence, perform regional flow calculations with a mass-consistent model, construct velocity-duration curves for velocity hot-spots, and validate the computer determined hot-spots by field programs. With the collection of field data, the model will be modified and a final WECS siting methodology will be ready for public use. The driving model in this methodology is less expensive to run than the one used in the SAI siting methodology. The LLL methodology is being tested on the Island of Oahu, Hawaii, see Figure 23.

5.13 Pacific Northwest Laboratory: Richland, Washington

A. Wind Data from Nuclear Plant Sites

A report summarizing the wind data from 104 nuclear power plant sites is in the final stages of review and will be published within the near future. It is felt that this data will be a valuable addition to the existing NWS data sets, and that the data from the towers at these sites will vastly enlarge the multi-layer data presently available. This report embodies the following significant features:

- . Wind data from 104 previously unreported locations.
- . 55 sites that have data at more than one level.
- . 184 joint frequency distributions available for further analysis.
- . Velocity duration curves for each distribution.
- . Site descriptions including locations and topography.
- . Mean wind speeds determined.
- . Average available wind power estimates for each distribution.
- . Assemblage and tabulation of a unique data set.

B. Survey of Wind Measurement Field Programs

A report that identifies and briefly summarizes 139 field programs that have used wind networks (2 to 60 wind measurement sites at a given location) will be published in the very near future. The studies described in the report are mesoscale in areal extent and cover the time period from 1940 to the present. The summary consists of the following items: state or territory where the program took place, purpose of study, location of study, local terrain or environment, time period of study, wind equipment and number of wind measuring sites, approximate area of study, organizations in charge of the study, bibliography, and other additional information. The objectives of this report are to identify and catalog existing meteorological data sets that may be used for model calibration in the Wind Energy Program and to identify data sets that may be used to develop site localization techniques.

C. Model Validation and Comparison

The objective of this ongoing work is to determine the accuracy and relative costs of potential site selection techniques. The techniques will be evaluated by application to standard siting scenarios so that both accuracy and relative costs can be compared. The results will be used to identify the siting techniques most appropriate to typical siting scenarios.

D. Wind Profiles and Flow Fields in Mountainous Terrain

The objective of this project is to assess the current state of knowledge concerning the boundary layer structure and flow fields in mountainous terrains. Once this knowledge has been assimilated and analyzed, the areas of needed research will be identified and an experimental plan for collecting needed data will be proposed.

E. Small and Large WECS Siting Handbooks

Preliminary Small and Large WECS Siting Handbooks will be prepared in FY 1977. These handbooks will be periodically updated as new information is received from the various elements of the Wind Energy Program. The final set of handbooks, as well as all

intermediate ones, will be available to the public.

F. Evaluation of Wind Characteristics and Wind Power at the
Candidate ERDA Sites

In Figure 24, we show the 17 candidate wind turbine generator field-test sites chosen by ERDA in 1976. At these sites there are meteorological towers collecting data at two different levels (150 feet and 30 or 60 feet). From the monthly summaries published by Western Scientific Services, Inc. in Fort Collins, Colorado, we will keep a running total of the potential wind power from these sites, the turbulent intensities at these sites, and other wind characteristics. Since these 17 sites represent a wide spectrum of geographical, topographical and meteorological characteristics, the data obtained from these sites will increase our generic knowledge of siting WECS.

6. References

1. Eldridge, F. R., Wind Machines, NSF-RA-N-75-051, NSF Report, Prepared by Mitre Corp., 76 pp., 1975.
2. Wolff, Ben, "The Federal Wind Energy Program," AWEA Newsletter, Bristol Indiana, 8-11, Spring 1977.
3. These maps were produced by Dennis Elliott of Battelle, Pacific Northwest Laboratories at Richland, Washington.
4. Davenport, A. G., "The Relationship of Wind Structures to Wind Loading," National Physical Laboratory Symposium No. 16, Wind Effects on Buildings and Structures, Her Majesty's Stationary Officer, London, 54-102, 1965.
5. These diagrams were drawn by Dr. Frost of FWG Associates, Inc., in Tullahoma, TN.
6. Alaka, M. A., The Airflow Over Mountains, World Meteorology Organization, Geneva, Switzerland, 1960.
7. Defant, F., "Local Winds," Compendium of Meteorology, Ed. T. F. Malone, Amer. Meteor. Soc., Boston, MA, 655-672, 1951.
8. VanEimern, J., Karschon, R., Razumous, L. A., and Roverson, G. W., Windbreaks and Shelterbelts, Tech. Note 59, World Meteorological Organization, Geneva, Switzerland, 1964.
9. Orgill, M. M., and Sehmel, G. A., "Frequency and Diurnal Variation of Dust Storms in the Contiguous USA," Atmos. Environ., 10, 813-825, 1976.
10. This diagram was prepared by Don Hardy of the Lawrence Livermore Laboratories, Livermore, California.
11. Summary Report: Federal Wind Energy Program, ERDA-77-32, UC-60, Energy Research and Development Administration, Division of Solar Energy, Washington, DC, 20545, 1977.

APPENDIX A

Tables

Table 1. Applications of WECS [1,2].

1. Rural homes
2. Islands
3. Remote village sites
 - a) homes
 - b) cottage industry
 - c) food processing and storage
 - d) emergency and medical facilities
4. Irrigation
5. Telecommunications
 - a) railroad signals
 - b) micro wave relays
 - c) rural, fire, and police communication
 - d) commercial repeater stations
 - e) remote CB and emergency radios
 - f) flood control communications
6. Marine navigation aids
 - a) bouys
 - b) stationary platforms
 - c) lights
7. Aircraft navigation aids
 - a) transmitters
 - b) obstruction lights
8. Offshore exploration and drilling rigs
9. Sewage treatment plant aeration
10. Remote highway traffic and direction signals
11. Advertising structures
12. Remote fire towers
13. Pipeline corrosion control
14. Remote instrument sites
 - a) weather
 - b) seismic
 - c) pollution monitoring
15. Small industrial applications
16. Recreation
 - a) camps and cabins
 - b) trail shelters
 - c) mountain top restaurants and resorts

Table 1 (Cont'd)

- 17. Milling applications
 - a) grains
 - b) power drives - mechanical
 - c) rock crushing - small mine applications
- 18. Pumping water and other liquids
- 19. Structure space heating
- 20. Farms and agriculture
 - a) crop drying
 - b) water heating
 - c) compressed air applications
 - d) fertilizer
 - e) greenhouse heating
- 21. Lake aeration
- 22. Oil well 'flushing'

Table 2. Rated Capacities of WECS.

Capacity	Application
0 - 100 Kw	On-Site Generation of Electricity, Mechanical Energy Conversion, Etc.
20 - 250 Kw	Generation of Electricity for Small Public Cooperatives and Municipal Utilities.
500 - 3000 Kw to larger multi-unit systems greater than 10 MW	WECS for Electricity Generation for Utilities.
500 - 3000 Kw to larger multi-unit systems	WECS for Remote Areas for the Generation and Transmission of Electricity, Fuel, Etc.

Table 3. Diameters and Hub Heights of Representative WECS.

TYPE	RATED CAPACITY (KW)	APPROXIMATE DIAMETER (feet)	APPROXIMATE HUB HEIGHT (feet)
Jacobs Wind Turbine	1.8 <u>to</u> 3.0	14	30 <u>to</u> 50
Win Power Turbine	1.25 <u>to</u> 1.8	12	30 <u>to</u> 50
Dunlite Turbine	2	12	40 <u>to</u> 60
ERDA/NASA MOD OA	200	125	100
MOD 1	1500	200	154
MOD 2	1500	300	200

APPENDIX B

Figures

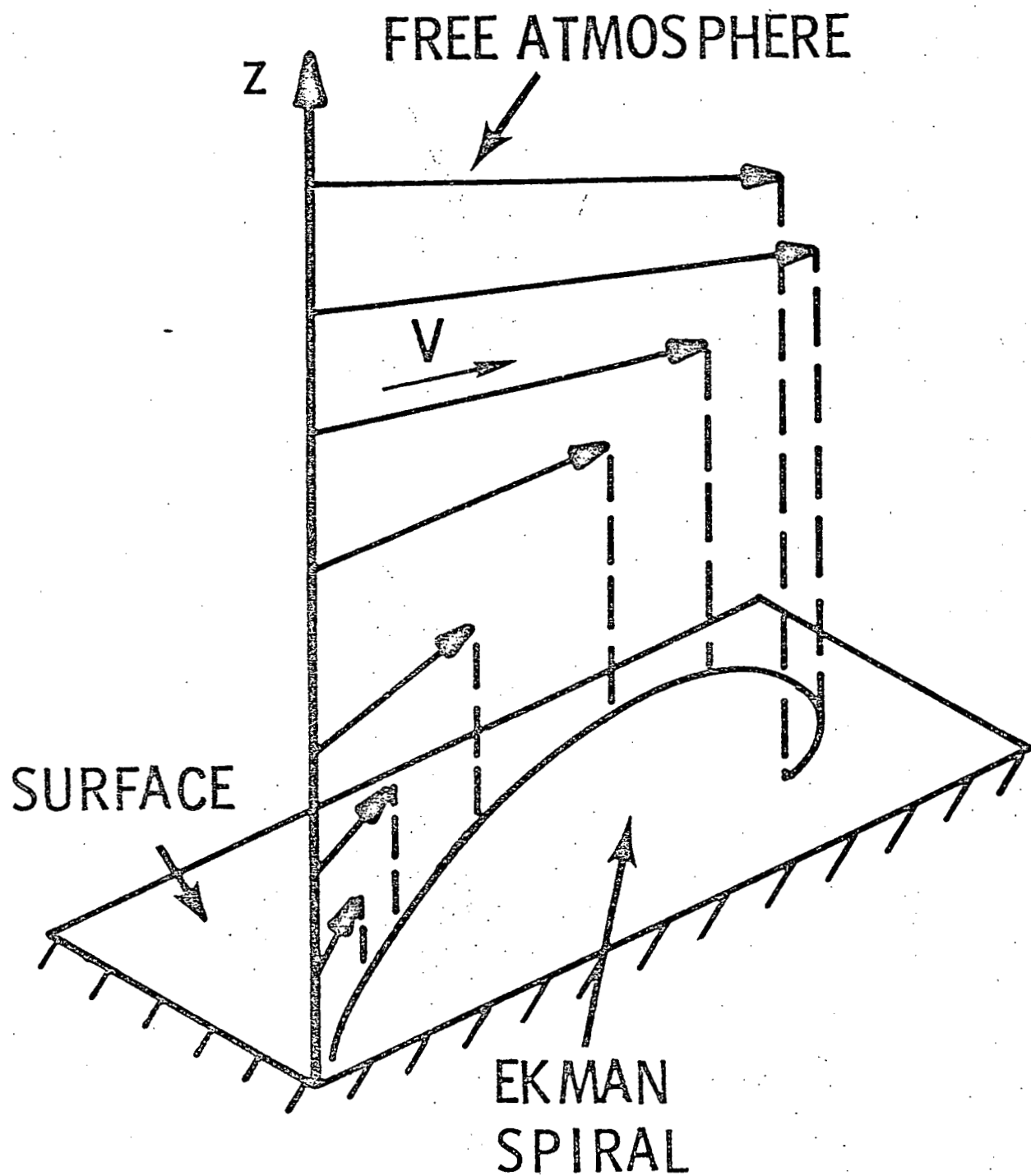


Figure 1. The Ekman Spiral: The Change in Wind Speed and Direction with Elevation.

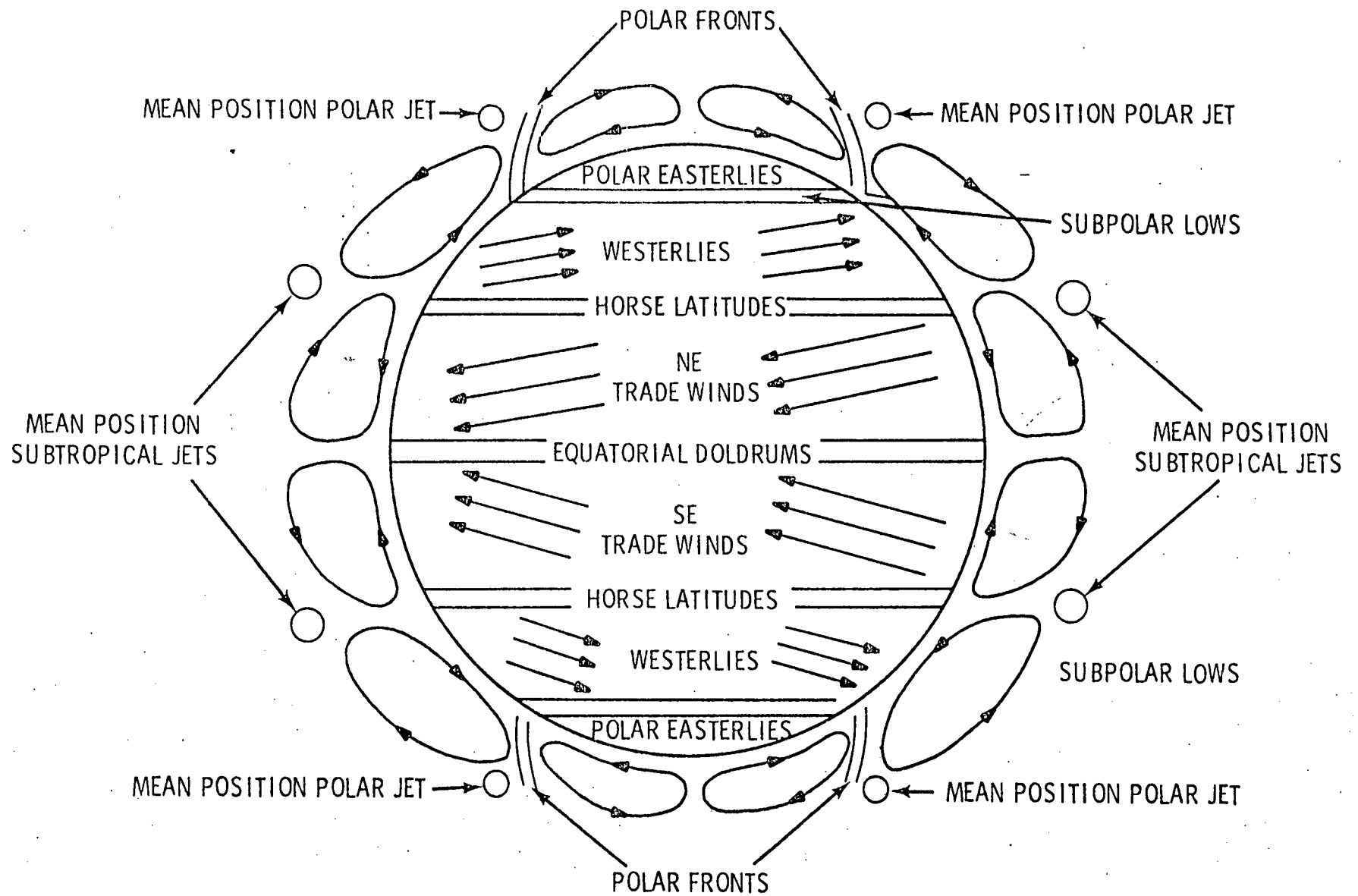


Figure 2. The General Circulation of the Globe.

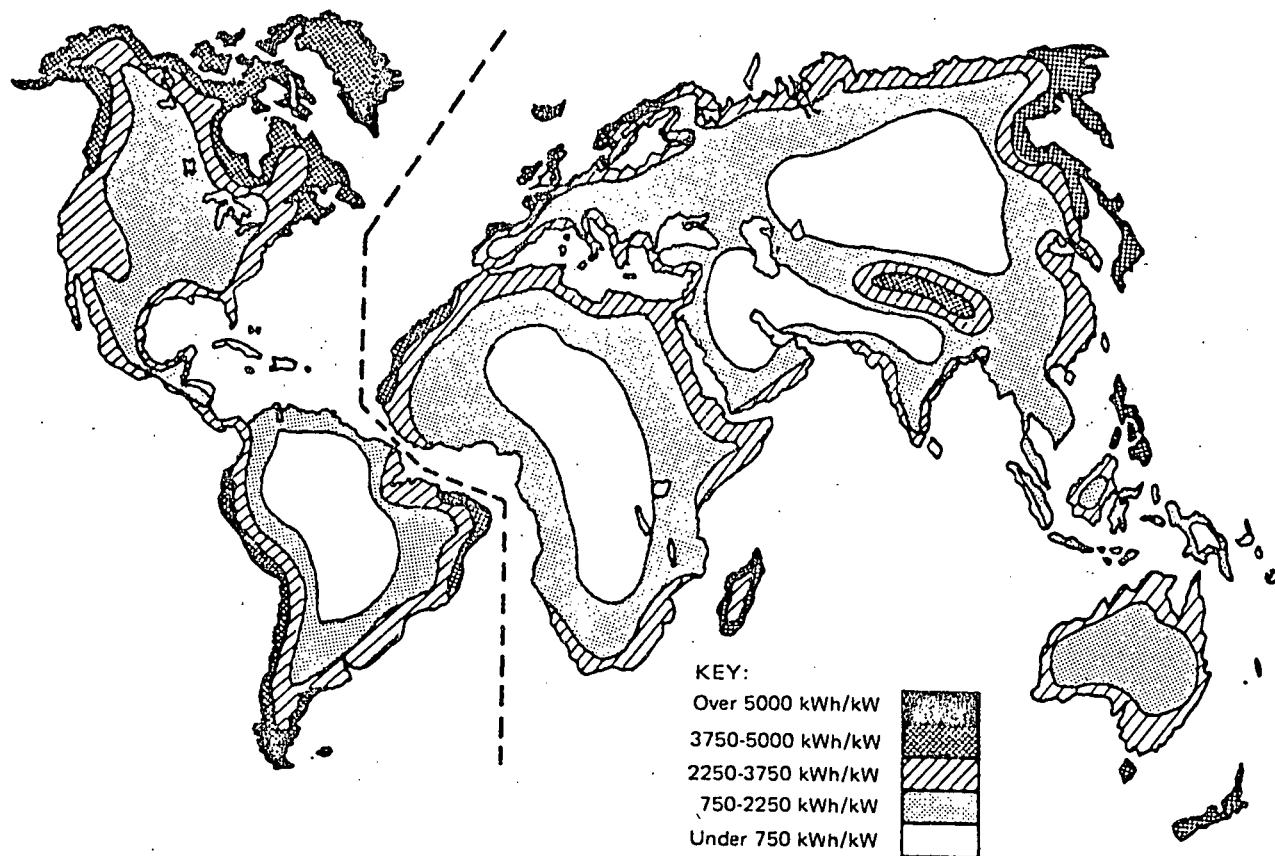


Figure 3. Annual Availability of Wind Energy in Different Parts of the World (in Terms of Estimated Number of kWh/Year per Rated Kilowatt Outputs for Wind Machines Designed for Rated Wind Speeds of 25 Miles per Hour) [1].

Figure 4. Annual-Average Wind Power at 50m Above Higher Elevations [3].
(watts/m²)

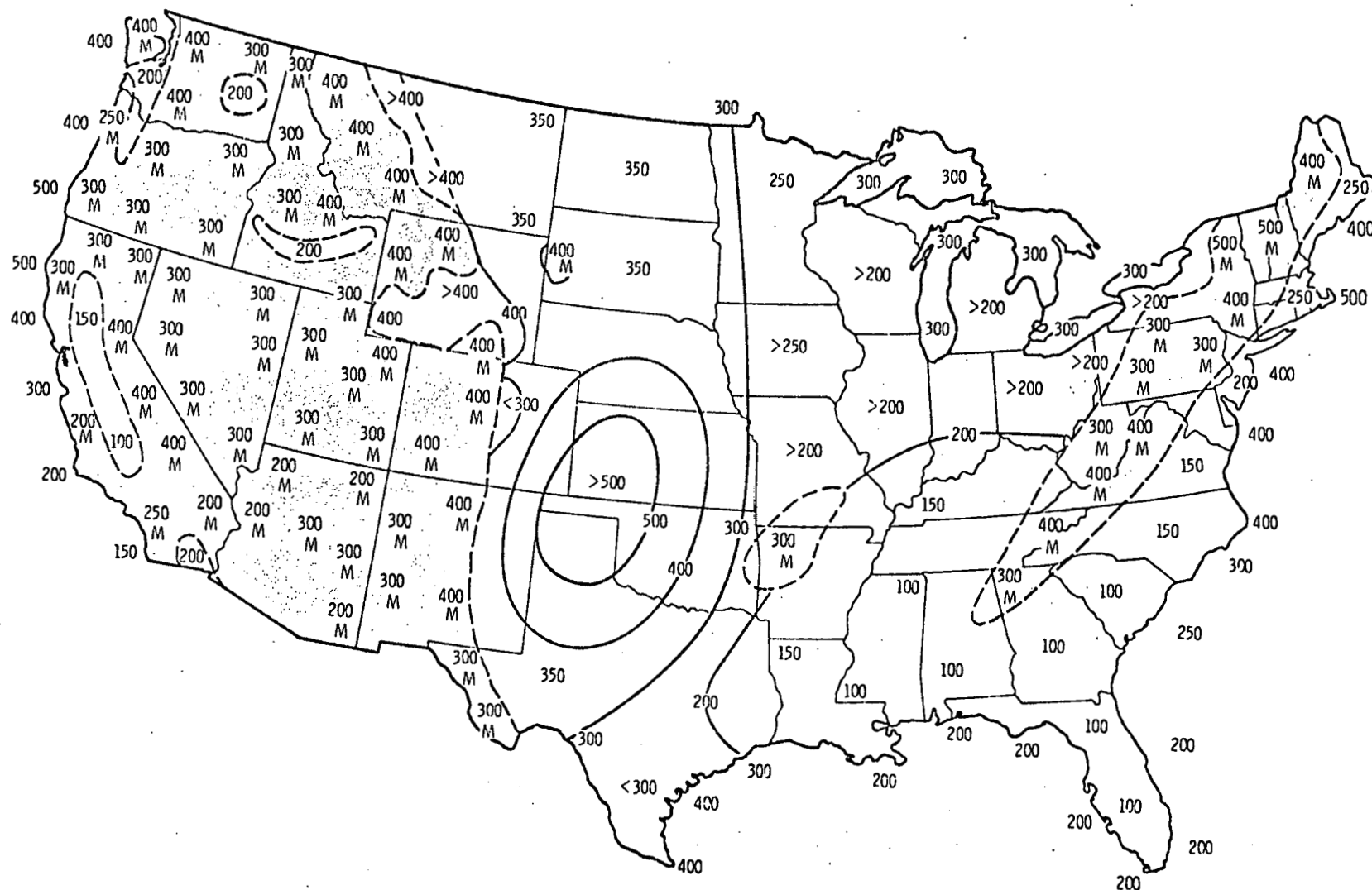


Figure 5. Spring-Average Wind Power at 50m Above Higher Elevations [3].
(watts/m²)

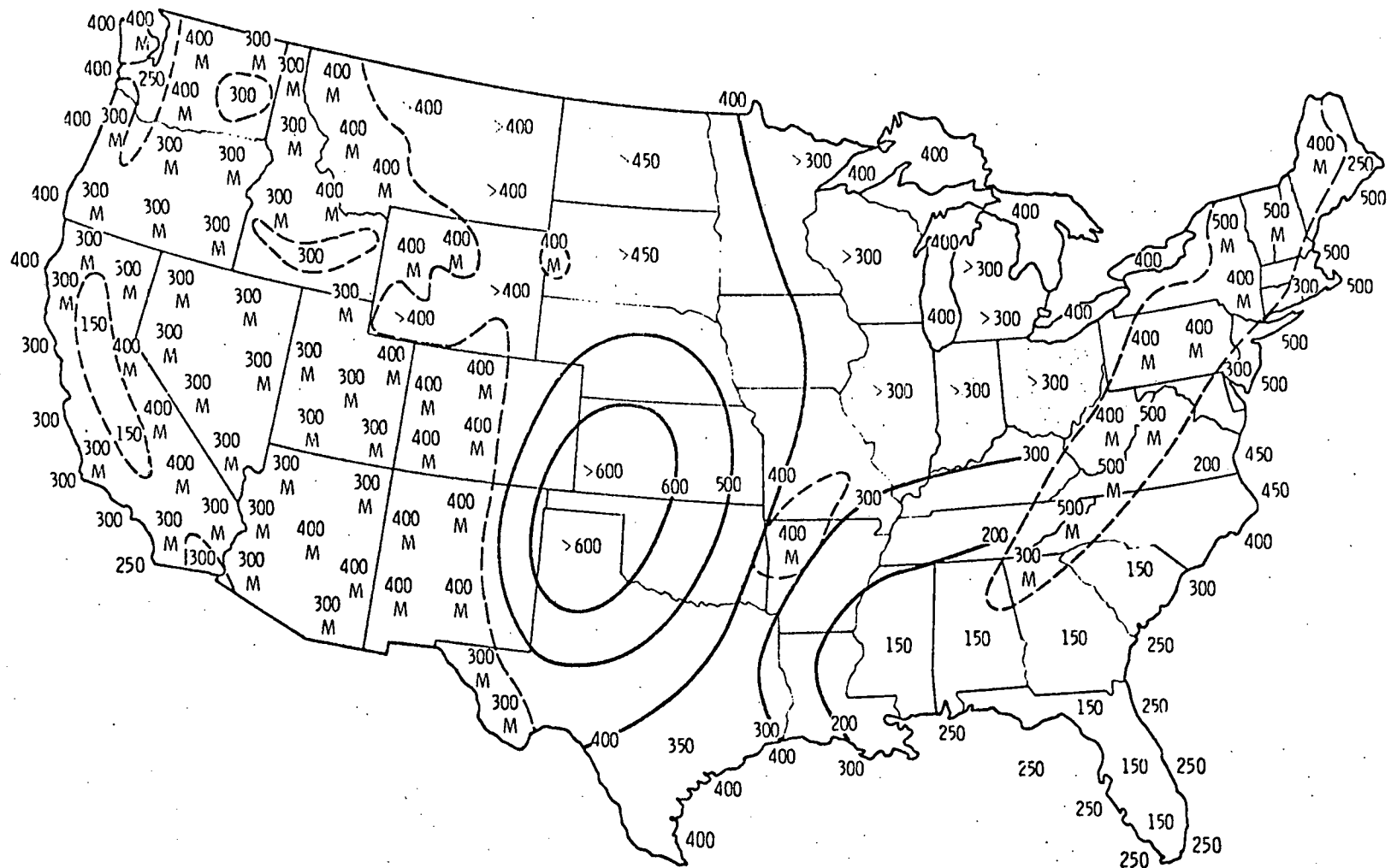


Figure 6. Summer-Average Wind Power at 50m Above Higher Elevations [3].
(watts/m²)

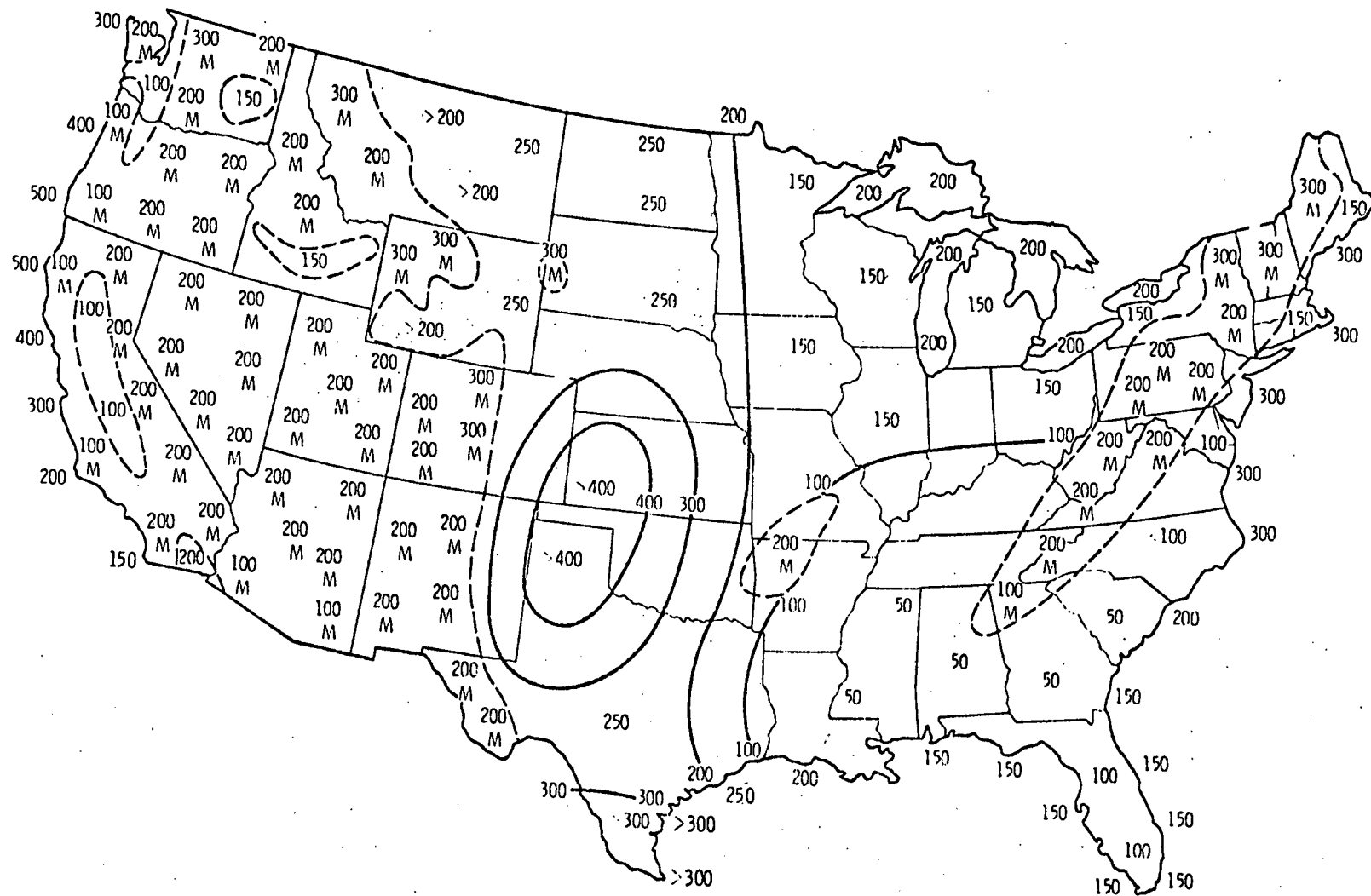


Figure 7. Fall-Average Wind Power at 50m Above Higher Elevations [3].
(watts/m²)

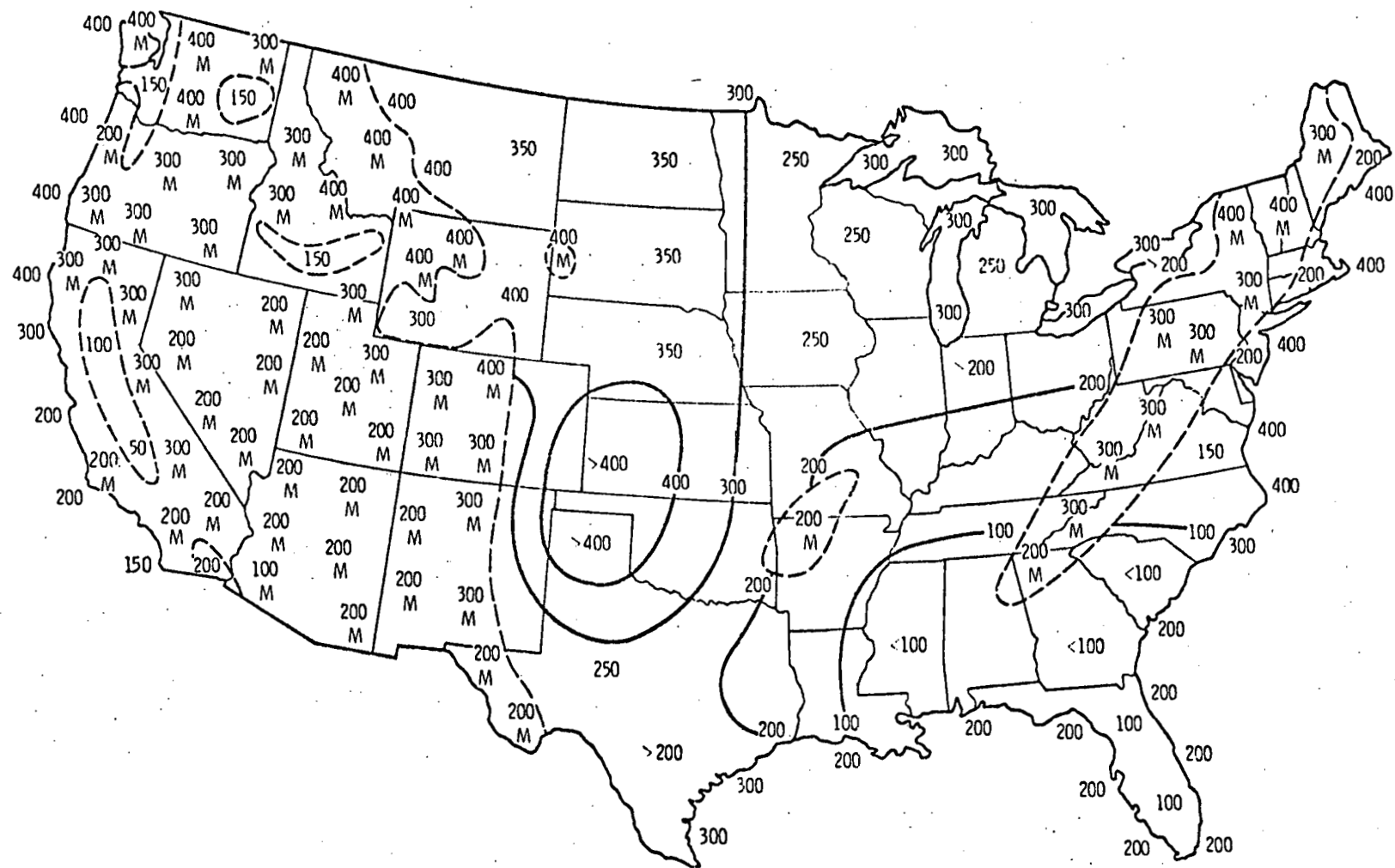
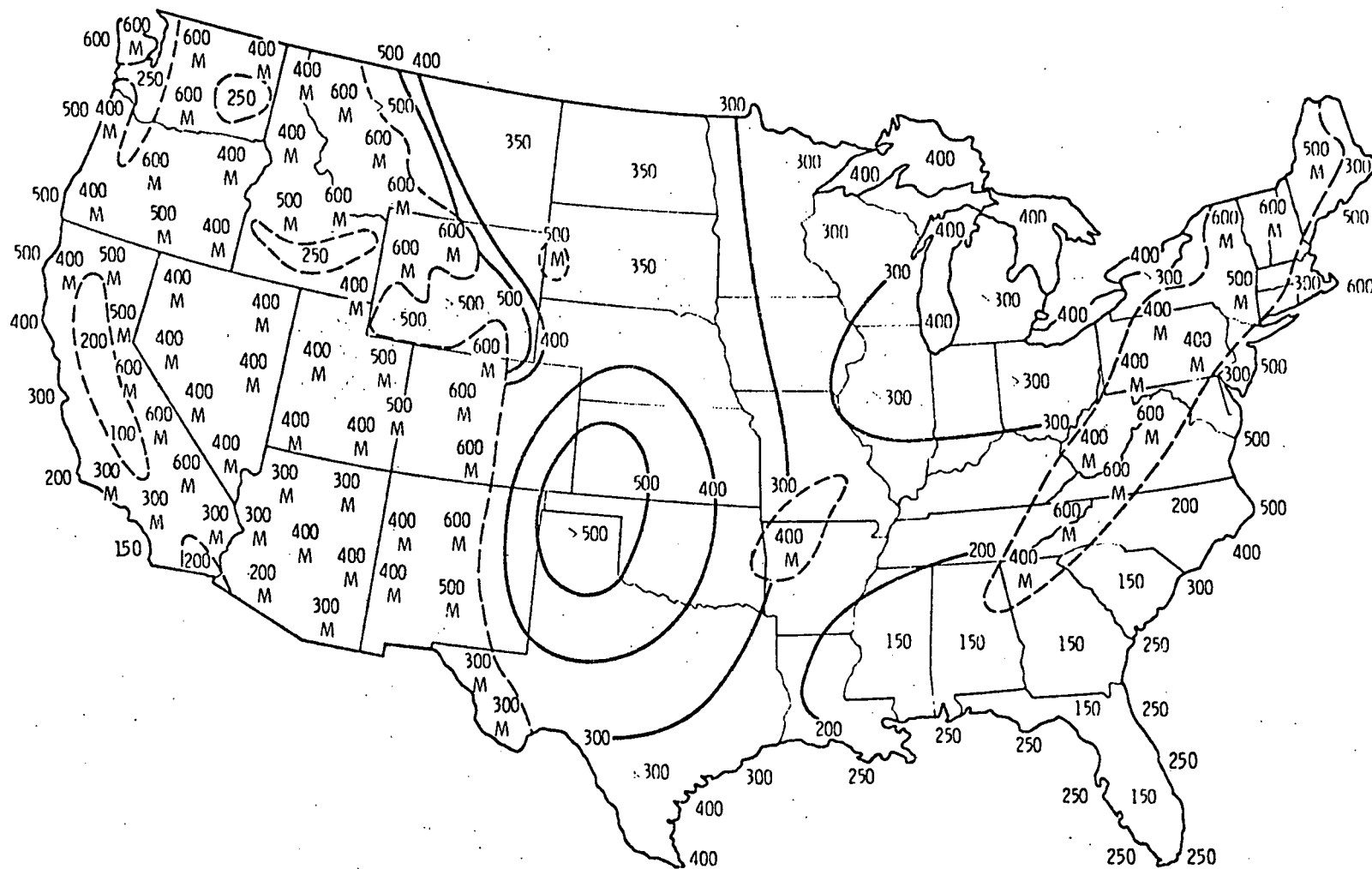


Figure 8. Winter-Average Wind Power at 50m Above Higher Elevations [3].
(watts/m²)



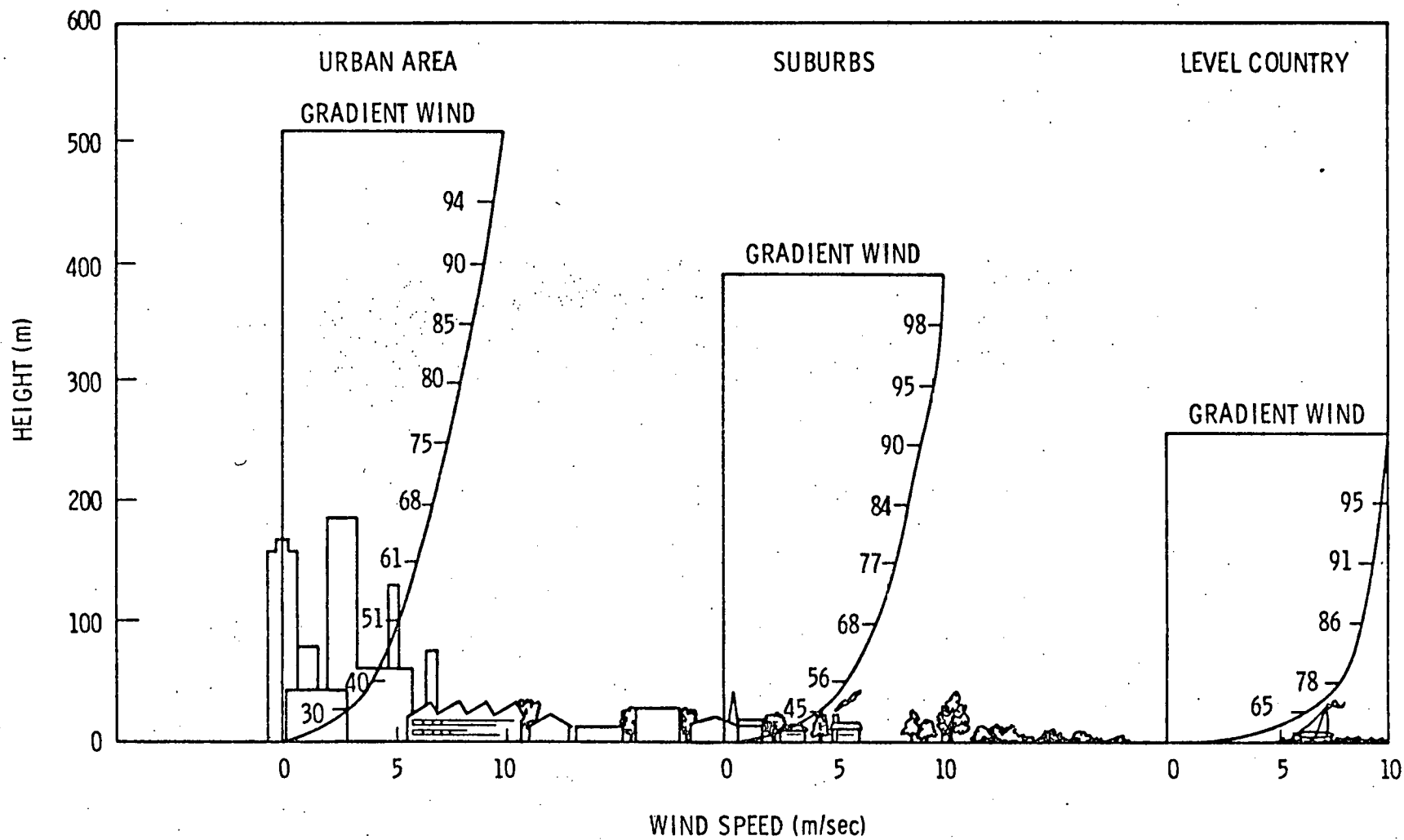


Figure 9. The Effects of Roughness on the Vertical Profile of Velocity [4].

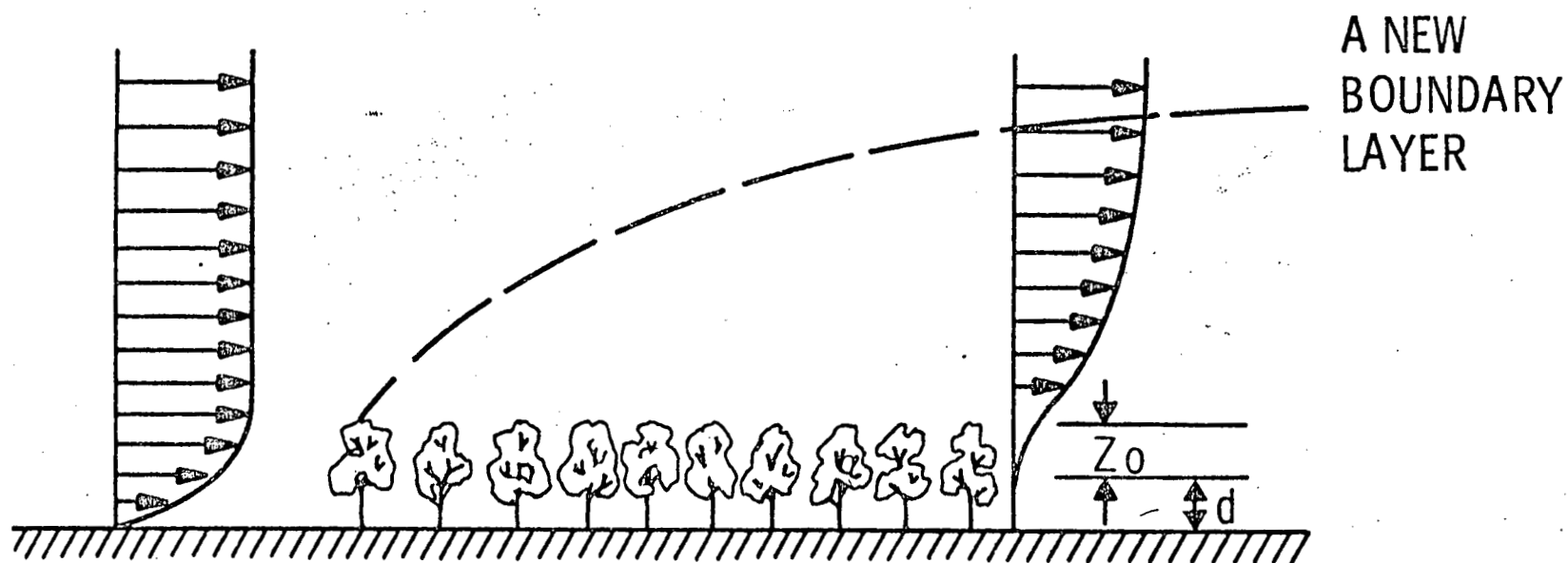


Figure 10. Transitional Air Flow from Grasslands to Forests.

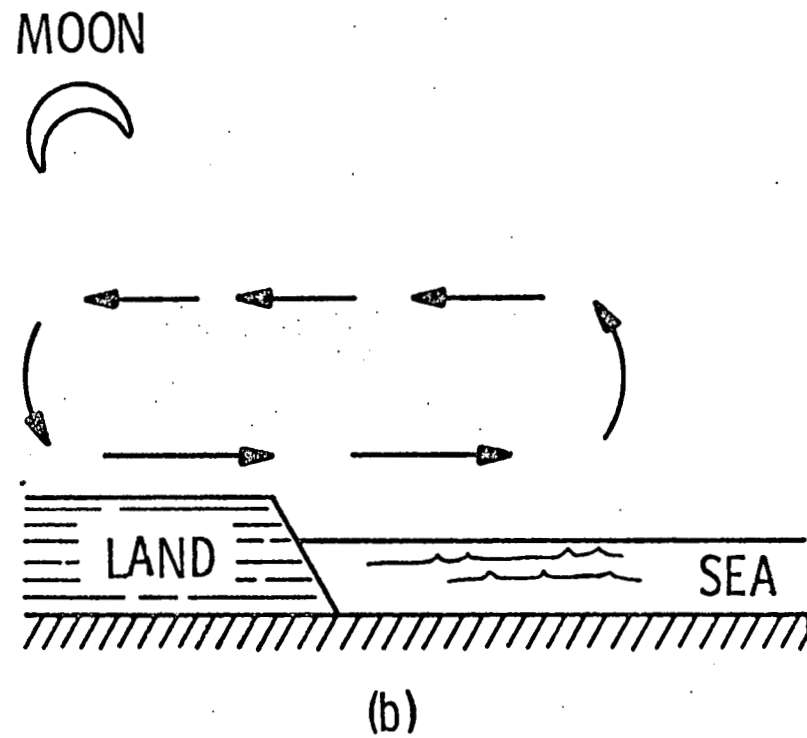
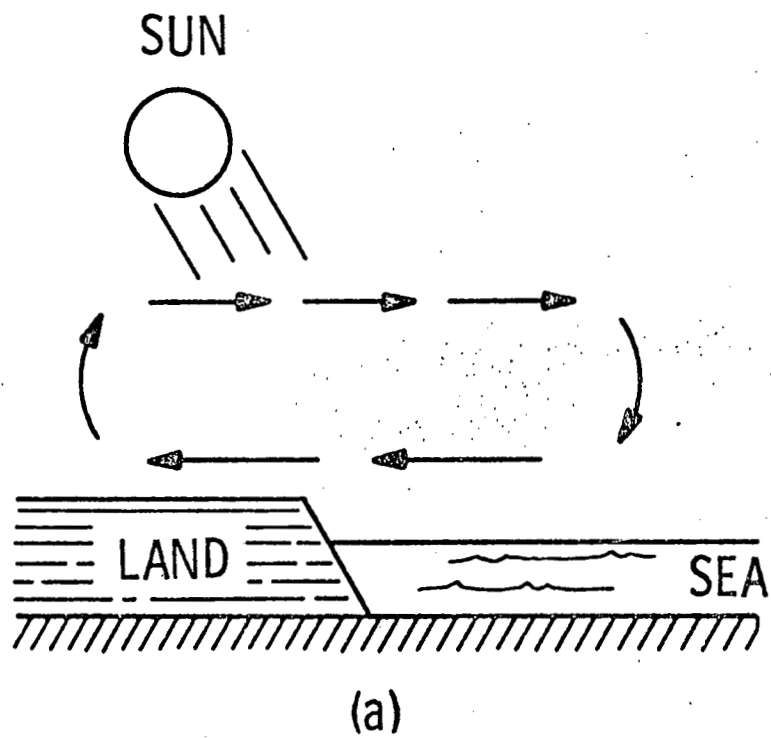


Figure 11. Land and Sea Breezes.

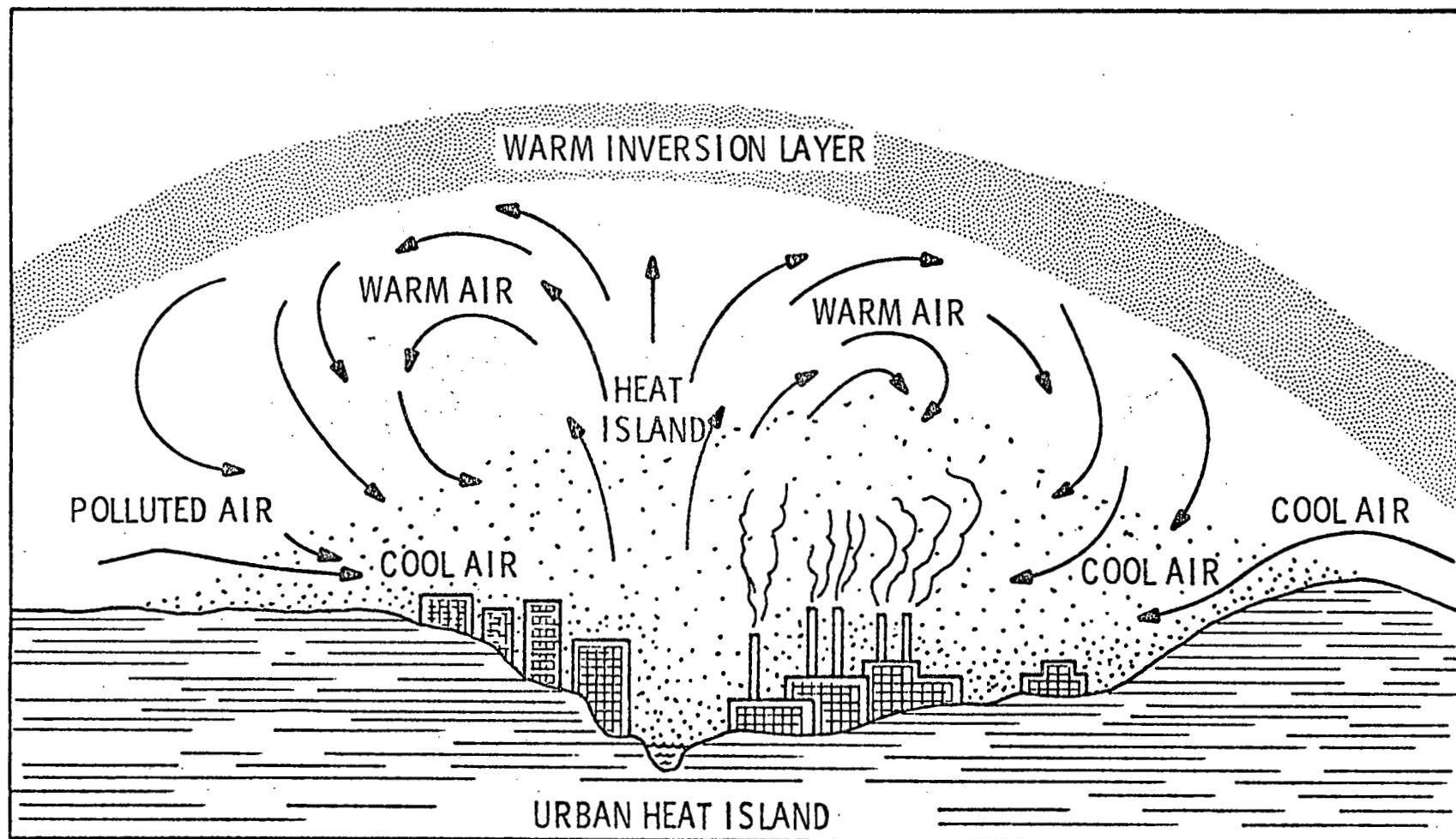


Figure 12. The Circulation Above an Urban Heat Island, with Calm Wind.

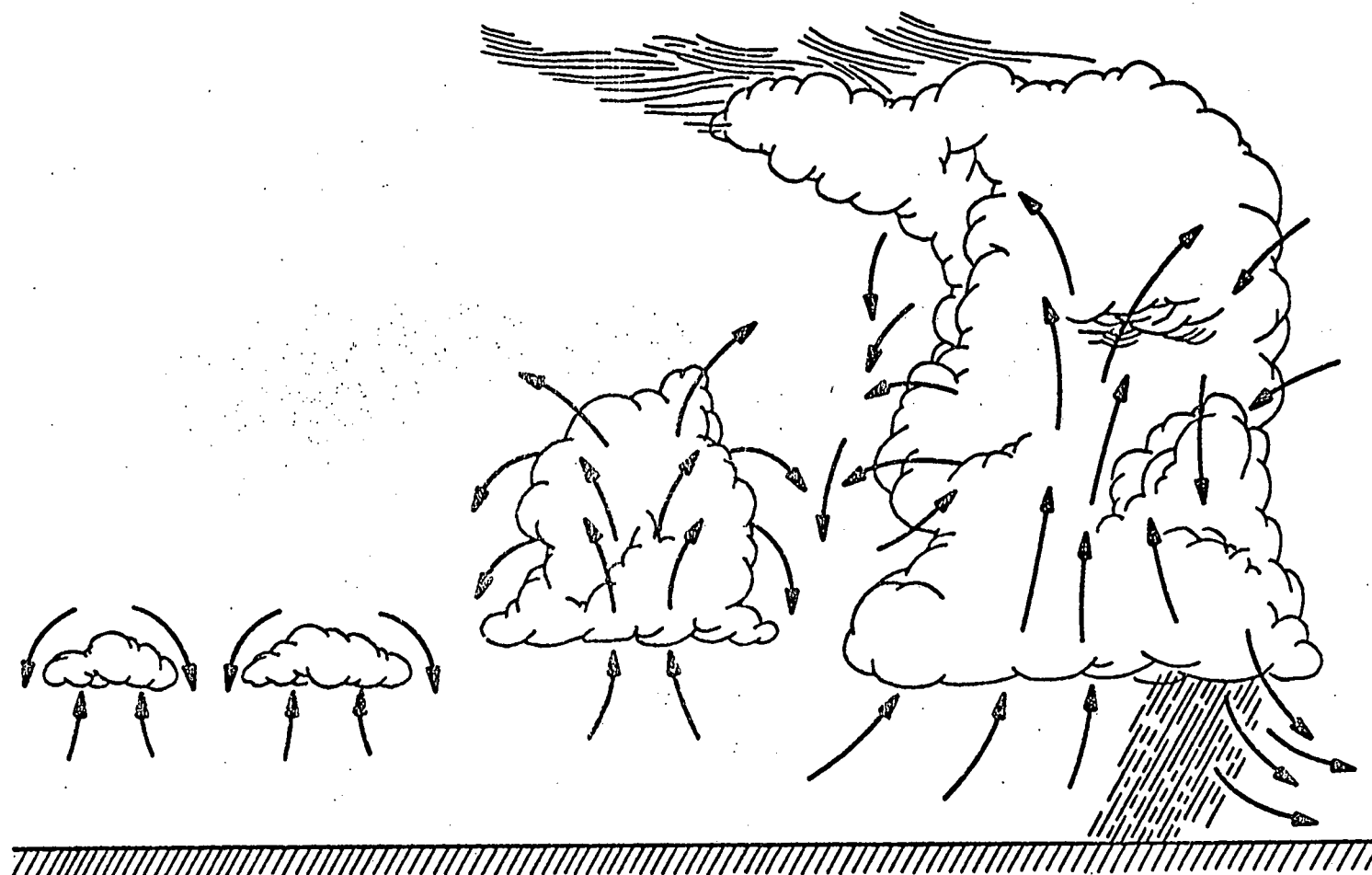
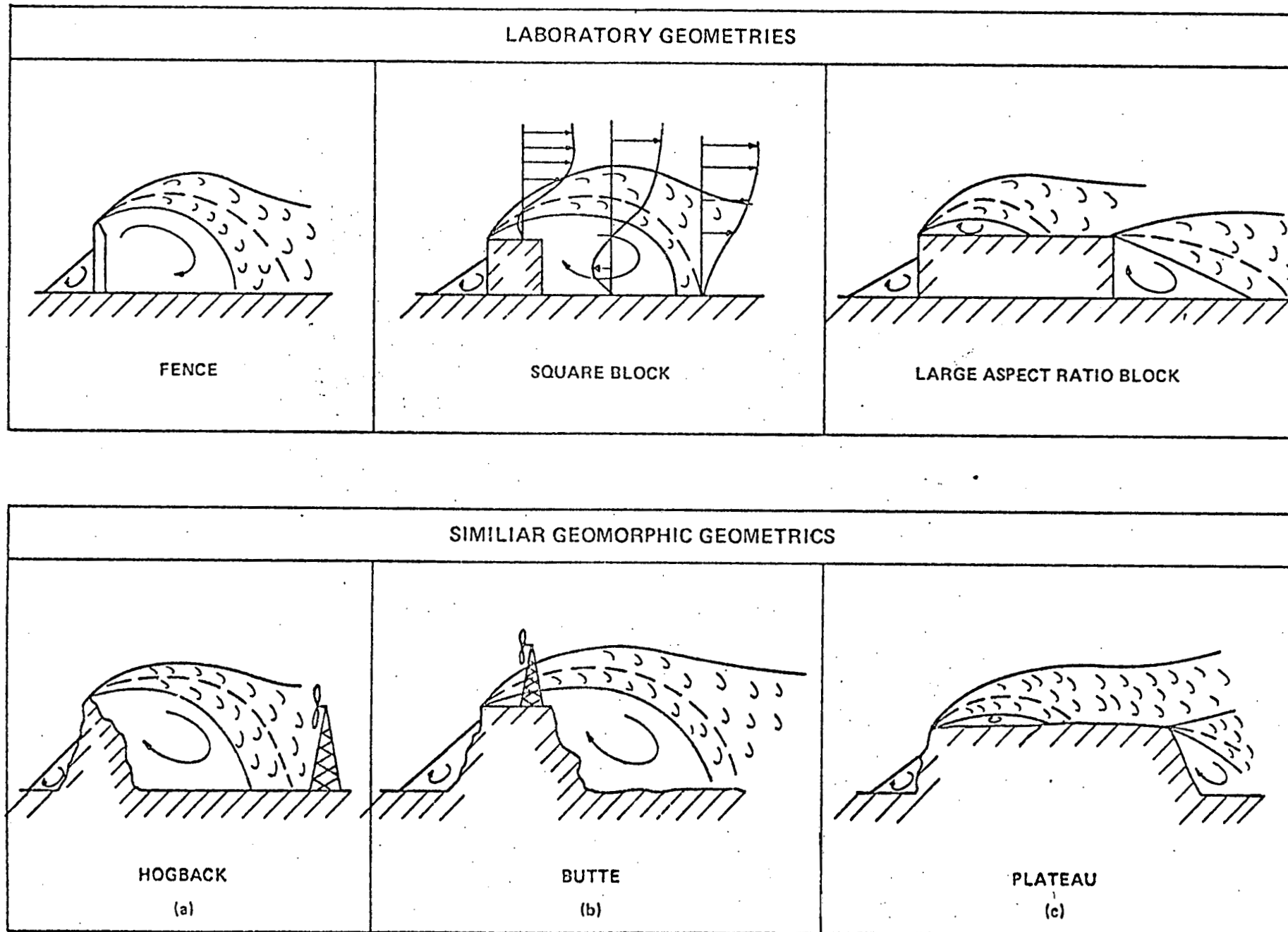
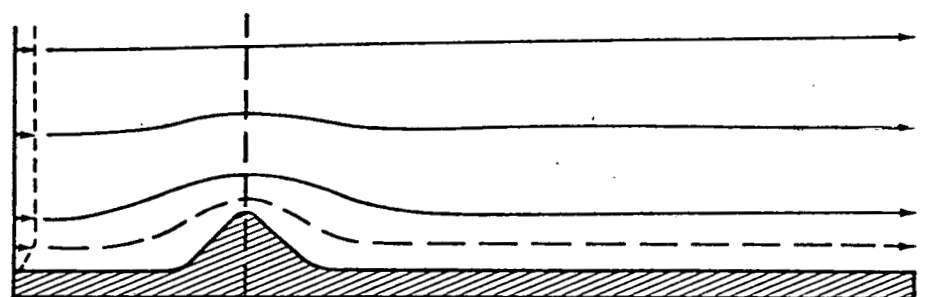


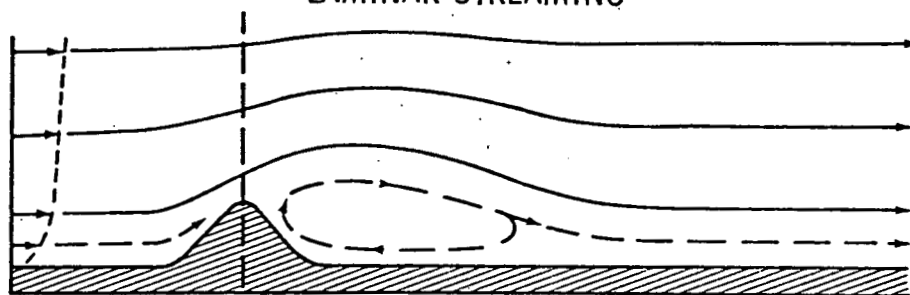
Figure 13. Local Circulation Due to Convective Motions.

Figure 14. Typical Separation Regions for Two Dimensional Flows [5].

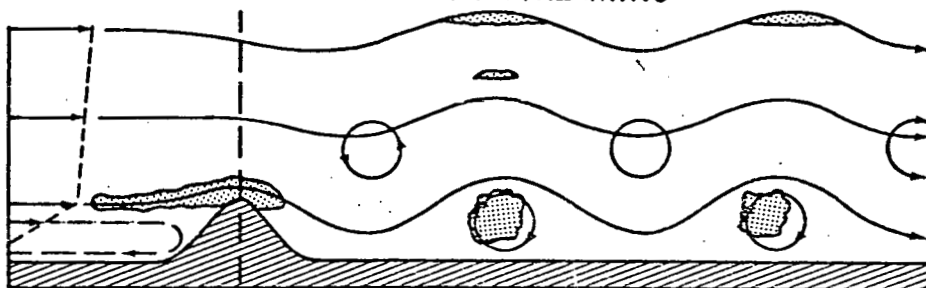




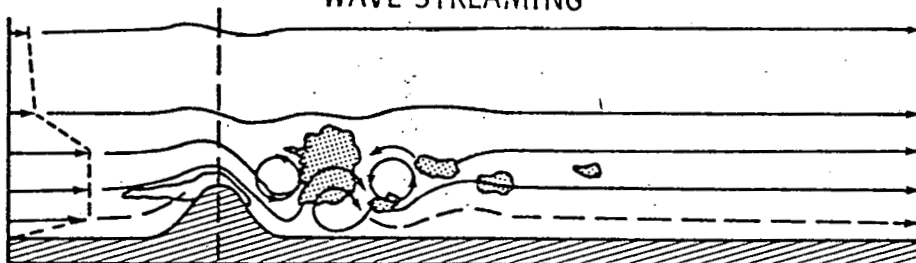
LAMINAR STREAMING



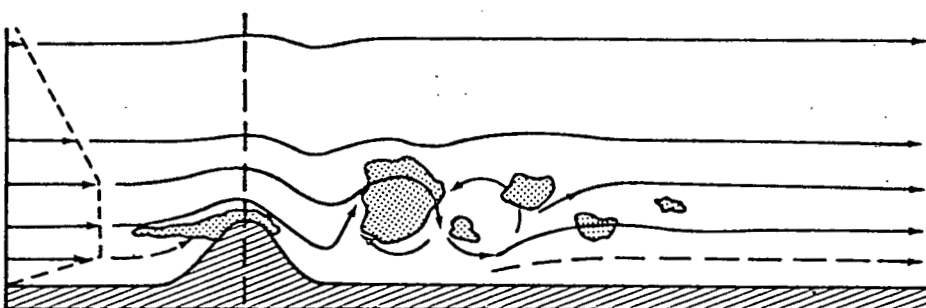
STANDING EDDY STREAMING



WAVE STREAMING



ROTOR STREAMING



ROTOR STREAMING

Figure 15. Various Flow Regimes Over Mountainous Terrain [6].

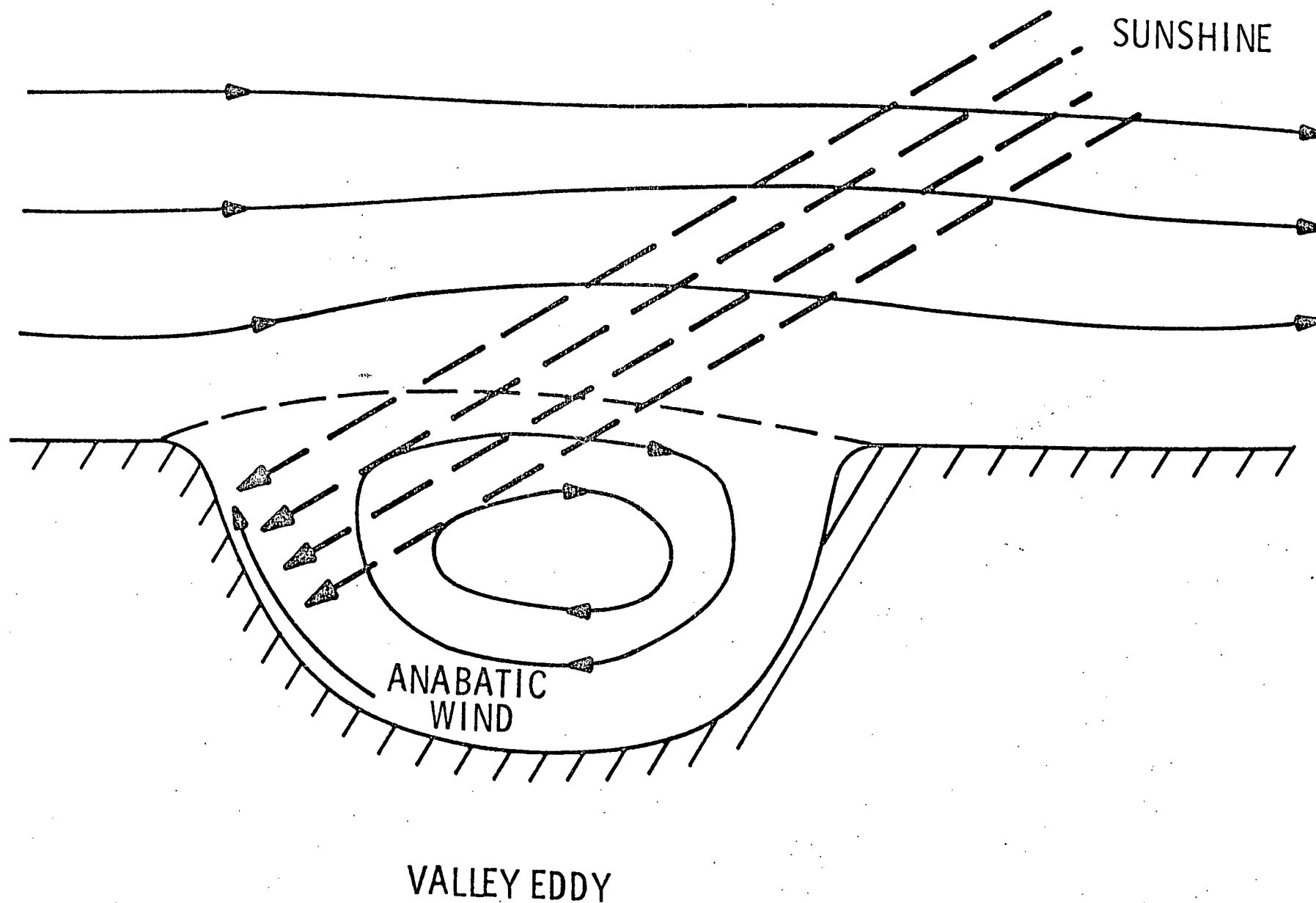
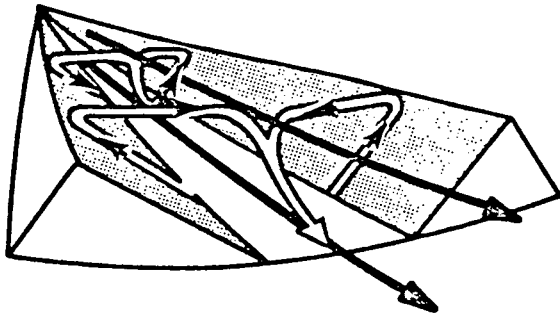
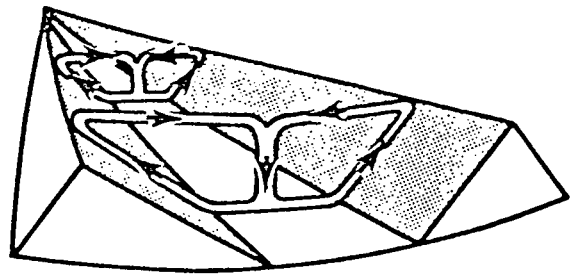


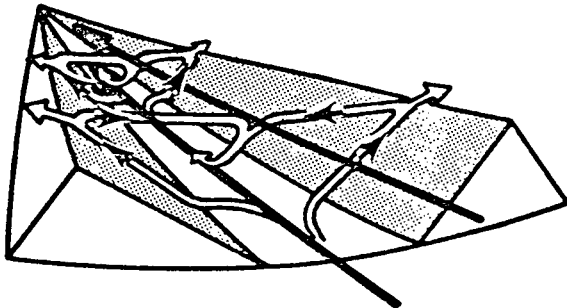
Figure 16. Valley Eddy Produced by Differential Heating (Separated Flow).



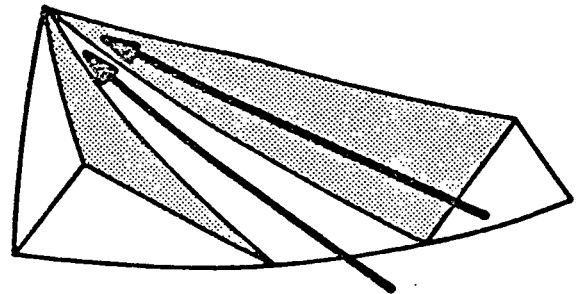
(A) SUNRISE



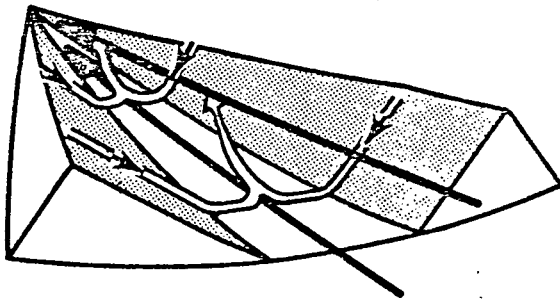
(B)



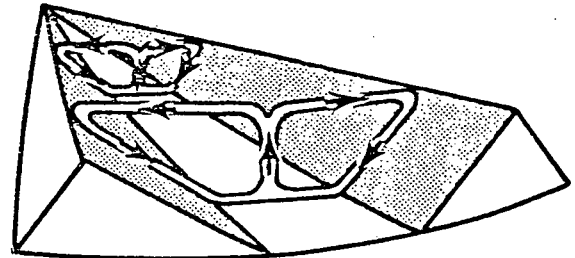
(C) NOON



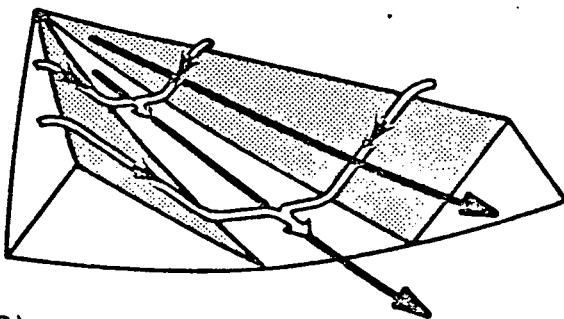
(D)



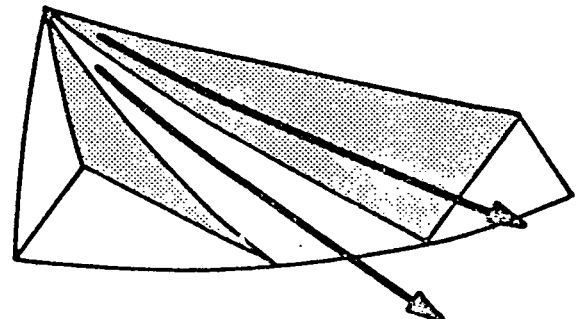
(E) EVENING



(F)



(G) MIDNIGHT



(H)

Figure 17. Mountain-Valley Breezes [7].

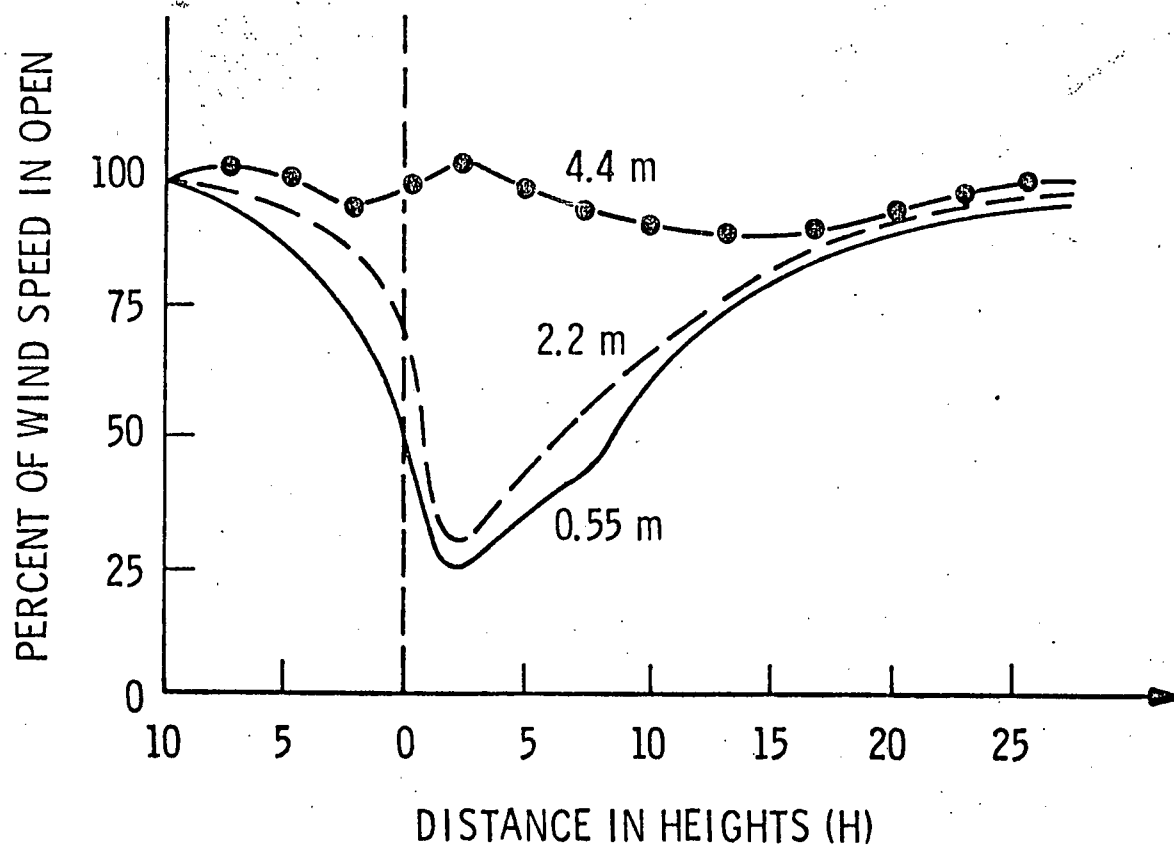
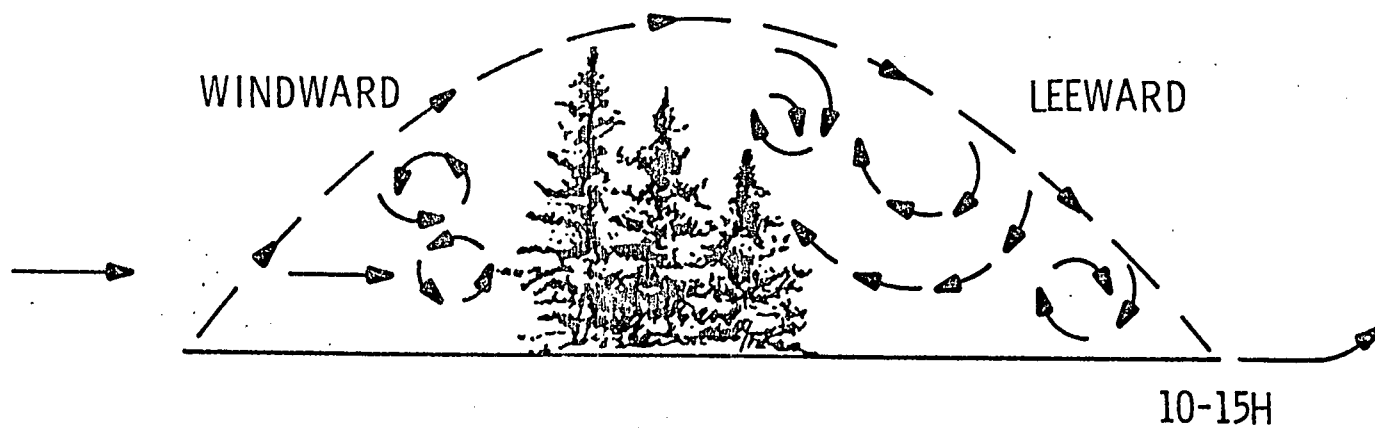
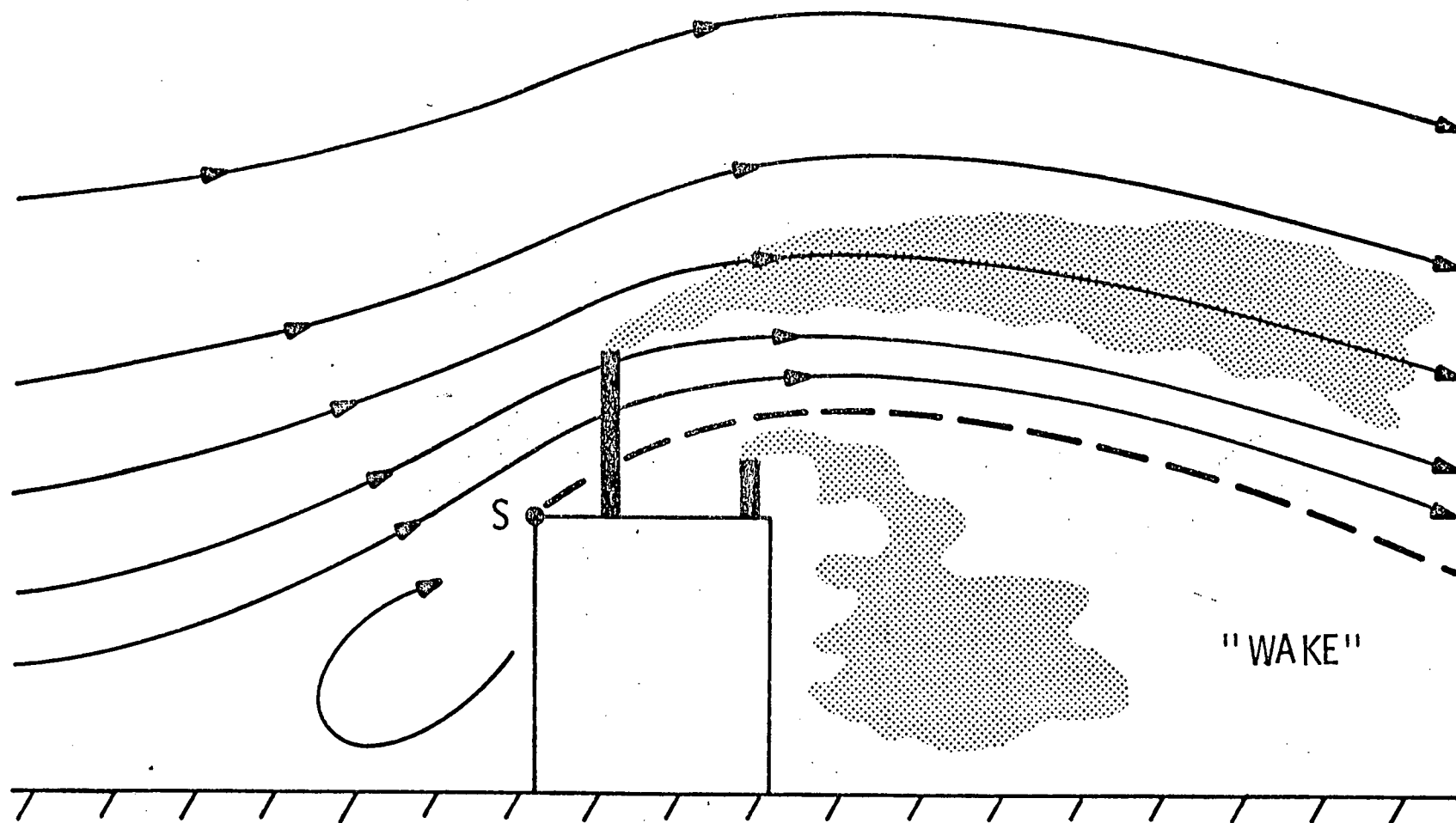


Figure 18. Air Flow Over a Wooded Patch or over a Shelter Belt [8].



SEPARATION AND WAKE

Figure 19. Separation and Wakes Around Blunt Structures.

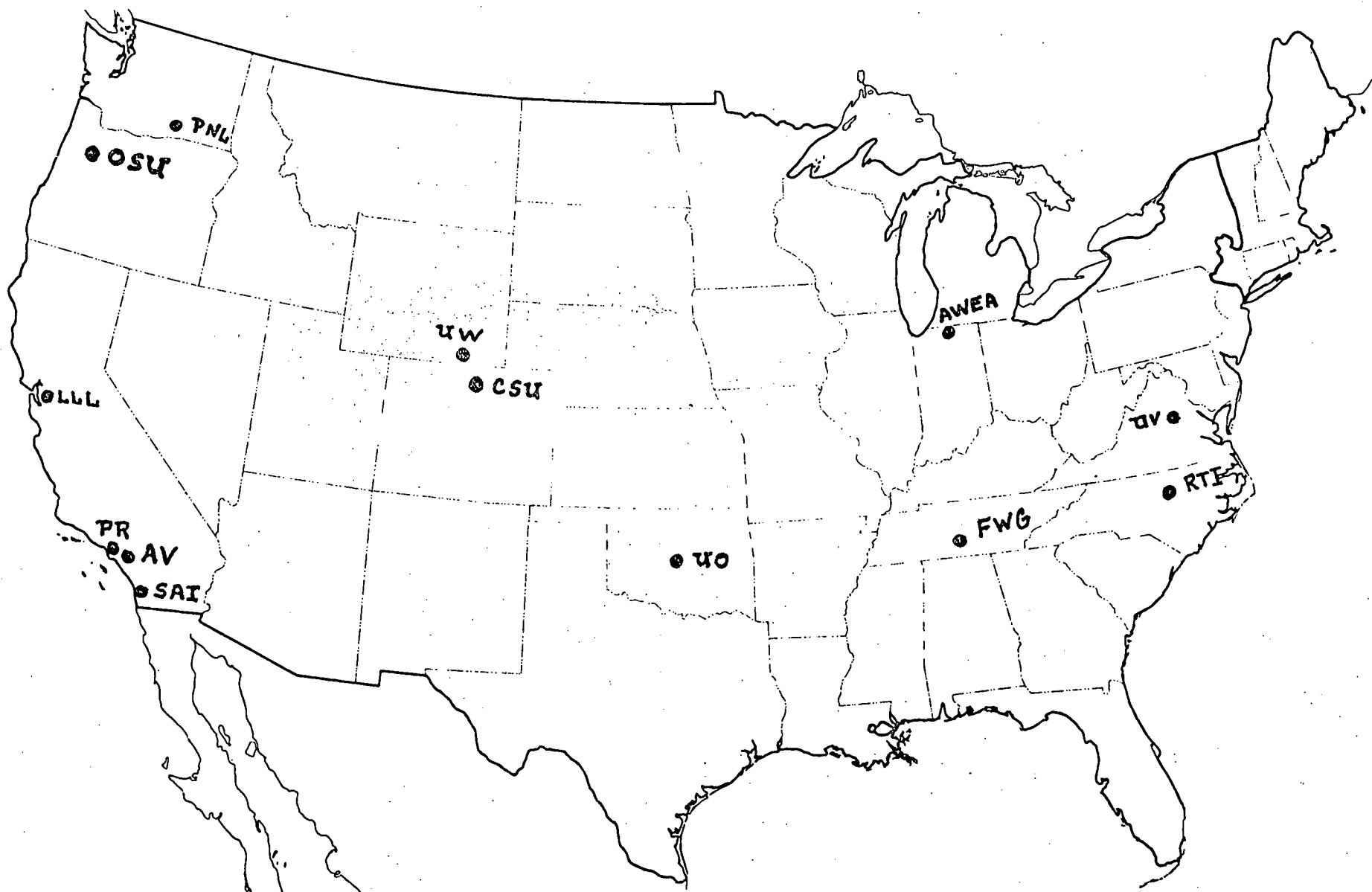


Figure 20. Site Selection Contractors.

Figure 21. Micro-Scale Terrain Breakdown [5].

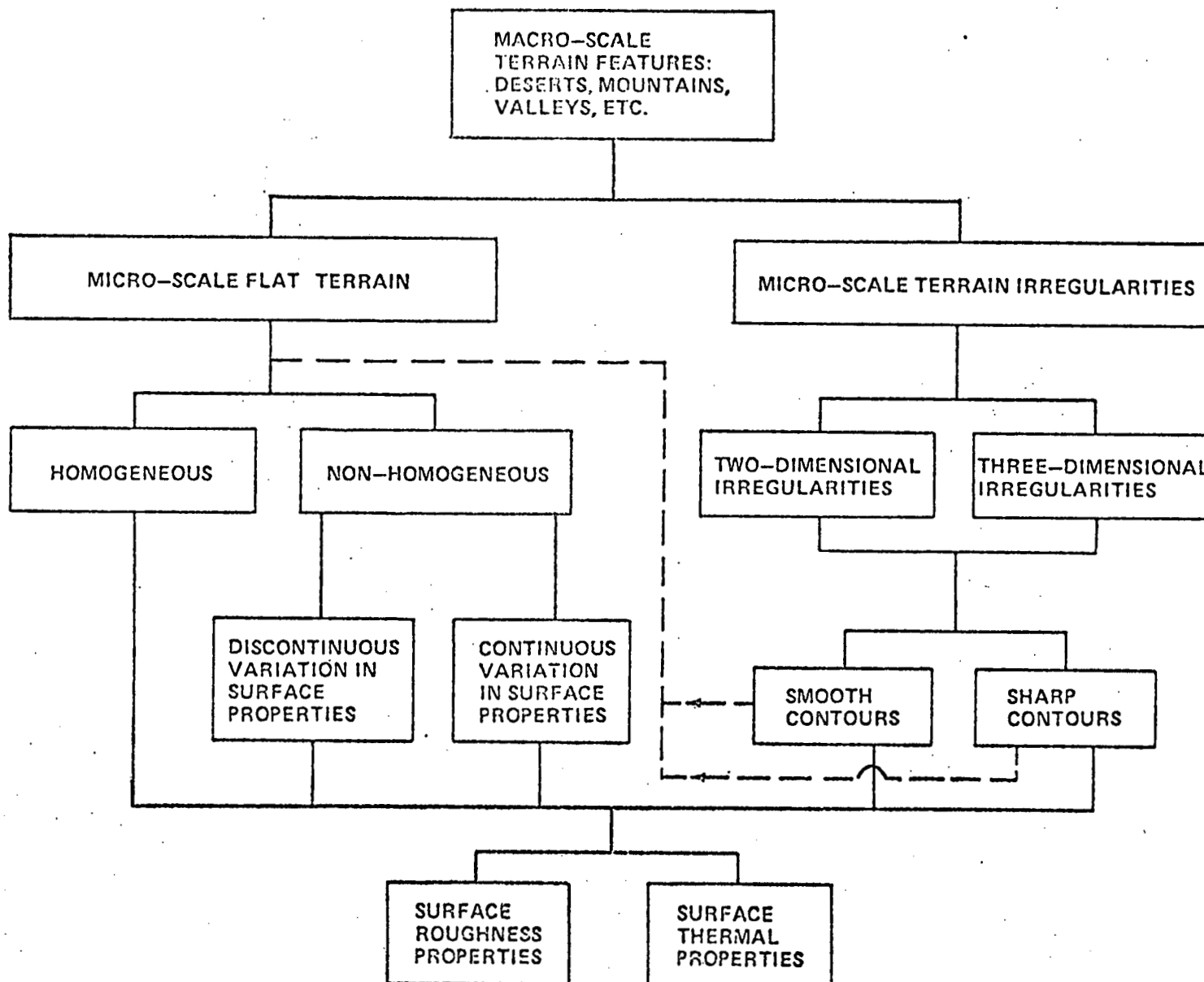
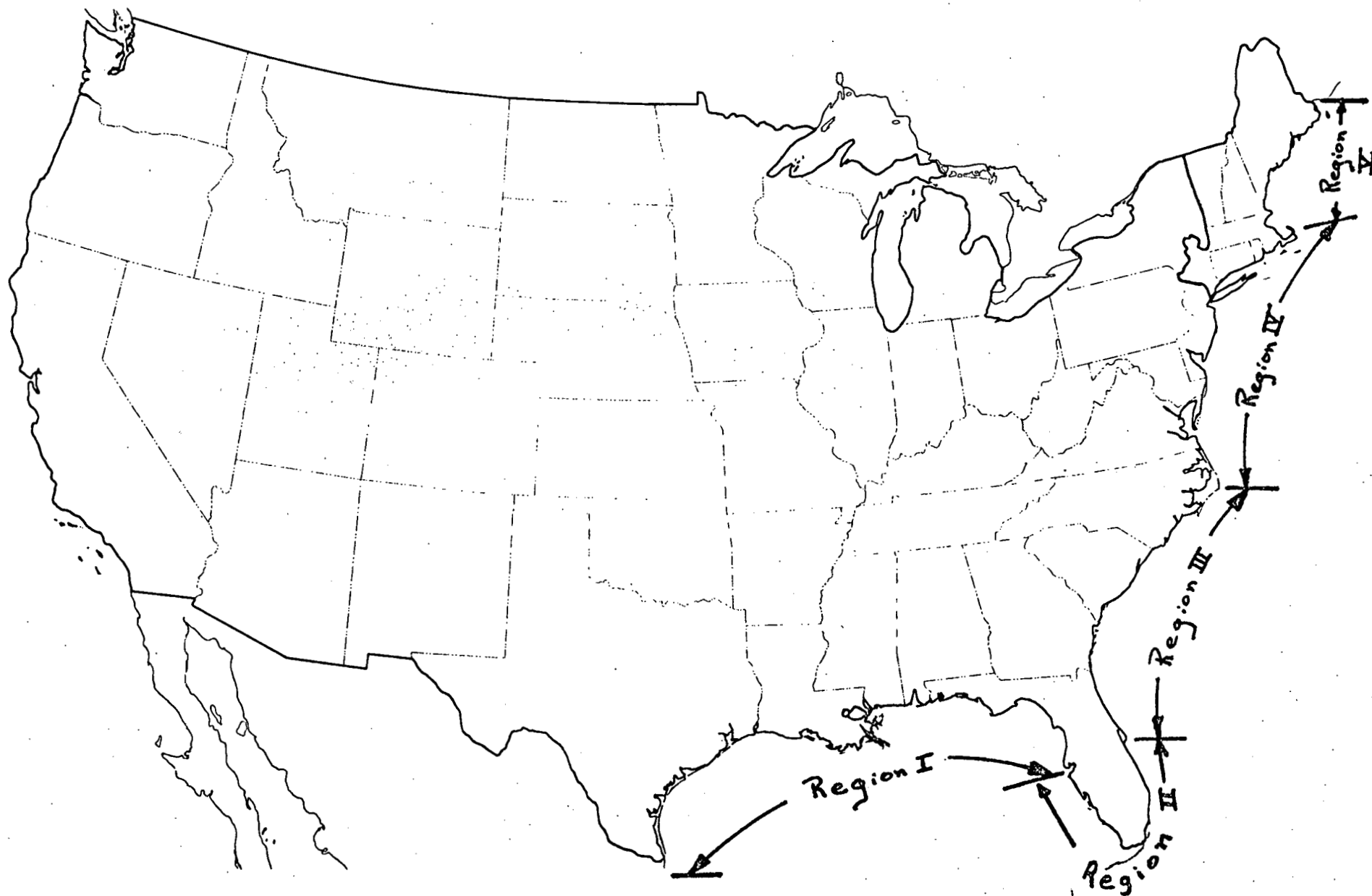


Figure 22. University of Virginia's Wind-Power Climatological Regions Along the Gulf and East Coasts.



OAHU, HAWAII

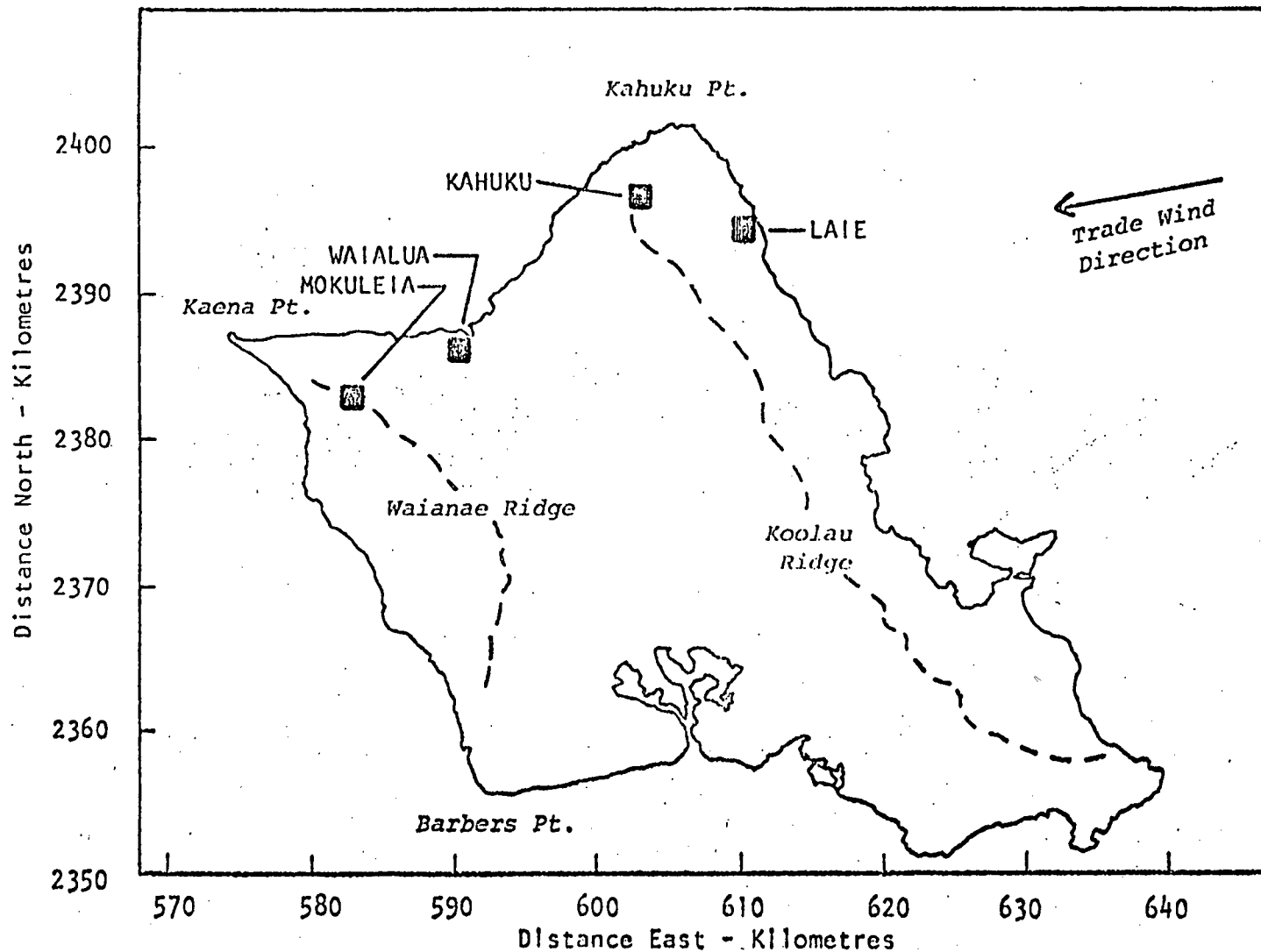


Figure 23. Locations of the four wind velocity measurement stations installed in the northern part of the island of Oahu, Hawaii. The Waianae and Koolau ridge lines are indicated by the dashed lines [10].

Figure 24. 17 Candidate WTG Field-Test Sites [11].

