MASTER

ESTIMATION OF WIND CHARACTERISTICS
AT POTENTIAL WIND ENERGY CONVERSION
SITES: Volume 1, Technical Report

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I. INTRODUCTION

The Department of Energy (DOE) has as a primary goal the development of "durable and economically viable" wind energy conversion systems that, when attractive to commercial developers, will be incorporated into an overall balanced energy system. As a part of that goal, the development of an economically viable wind energy conversion system for a candidate location requires a knowledge of the wind characteristics applicable to wind energy conversion at that site. The knowledge of the wind characteristics at a given location allows the selection of the most attractive conversion system best suited to optimize the wind energy conversion from the wind characteristics exhibited at that site.

Since long-term wind characteristics at the majority of candidate wind energy sites are not known, methods of estimating site wind characteristics are required. Meteorology Research, Inc. (MRI), under a subcontract to DOE, has developed a methodology that estimates candidate site wind characteristics from surface wind data recorded adjacent to the candidate wind energy site. The Climatology Development Methodology utilizes a numerical airflow model to estimate candidate site winds from surface wind data recorded at a nearby National Weather Service (NWS) or military observing station. A relationship is established in the methodology between the winds observed at the station and the winds modeled for the site. This relationship is applied in the methodology to historical wind data recorded at the data station to generate a 15-year site hub-height wind climatology.

To achieve the DOE goal of placing the most economically viable wind energy conversion system at a site, it becomes necessary to determine the accuracy of the climatology development technique, and to determine the extent of its applicability to sites of differing geographic settings and data station locations. To achieve this goal, the Climatology Development Methodology was applied to eight candidate wind energy sites of differing site geographic settings and data station locations. The performance of the methodology was evaluated by examining the accuracy of the hub-height wind climatologies

generated for each type of site and station geographic setting. The validity of the site wind climatology for a given setting helped establish the accuracy of the Climatology Development Methodology and the extent of its applicability.

This report presents the results obtained in "Estimation of Wind Characteristics at Potential Wind Energy Conversion Sites" under Sub-contract No. B29082-A-E. In the following sections the Climatology Development Methodology developed in this study is presented and the techniques of the methodology discussed. Also presented are the eight candidate site hub-height wind climatologies generated, and a description of each site's geographic setting and data station proximity. The report concludes with an evaluation of the Climatology Development Methodology and a discussion of the study's conclusions and recommendations.

II. EXECUTIVE SUMMARY

A knowledge of the nature or character of wind occurring at a candidate wind energy site is requisite for the selection of a candidate site location and for the evaluation of the site's wind energy conversion potential. It is necessary to know first, the distribution of wind characteristics at a location before an evaluation can be made of the location's potential for a cost-effective wind energy conversion system. A location will be candidate if it can be shown that the wind characteristics at that location exhibit certain attributes that make it an attractive location for wind energy conversion. Also, the type of wind energy conversion system selected will depend upon the character of the wind available at that location for wind energy conversion.

The purpose of this study is to develop a method of estimating remote site wind characteristics that will serve as an effective, inexpensive wind energy siting tool. Since wind measurements are not usually available at candidate locations, any method developed for this purpose will have to generate wind character summaries from meteorological data available in the vicinity of the candidate location. The method will necessarily have to use a technique that estimates winds at a candidate site from data recorded in the site's vicinity. The generation of the wind character summaries then will be accomplished by applying the estimating technique to historical data recorded in the site's vicinity for a specified period of time.

The problem involved in developing a methodology to generate candidate site wind character estimates centers around the applicability of any remote wind estimation technique to estimate site winds for a large variety of site geographic settings and site-to-data-station distances. With the possibility of over a hundred different candidate locations for wind energy conversion, a technique is required that will provide site wind estimates for a large spectrum of site geographic settings and data station locations. The problem arises from the fact that most techniques available for estimating winds at a remote site require certain conditions and requirements to be met concerning site geography and site-to-station distances. Often existing techniques are

designed to certain specifications for certain applications and cannot be applied in a universal manner in their existing configuration for wind energy siting analysis.

The procedure of developing a universal wind energy siting tool selected by DOE and incorporated in this study involves:

1. Applying an existing technique of estimating remote site winds to a variety of site geographic settings and station-to-site distances.
2. Evaluating the performance of the technique and determining the extent of its applicability.
3. Determining refinements that can be made to tailor the existing technique towards a more universal wind energy siting tool.

The technique selected for estimating site winds in this study utilizes a numerical airflow model designed in its present configuration to compute the remote wind field for diffusion and air pollution transport studies. The model is used to establish a relationship between the winds at the candidate site and the winds occurring at a nearby observing station. Station winds are inputted into the model and the corresponding site winds are computed by inputting terrain boundaries into the model domain. The model computes the site wind field by adjusting the model flow field constructed from stations winds to the terrain boundaries. The resulting site winds are mathematically related to the input station winds by computing "modeling functions" for each station wind direction. These modeling functions are then applied to 15 years of hourly station wind observations to generate site wind character summaries. The methodology of constructing a site wind character climatology, then, involves the application of the airflow model to compute site winds, and the construction of the modeling function expressions from the model results. The procedures incorporated in the methodology for computing the site wind field, constructing the modeling function, and generating the candidate site wind climatology are:

1. Conduct a site data survey to determine the availability and format of historical wind data, and the proximity of the data stations to the candidate site;
2. Select the most representative stations within the same geographic region as the candidate site (e.g., coastal stations for coastal sites);

3. Select the model domain (region to be modeled) to include the candidate site, data stations, and all important geographic features in the vicinity;
4. Code the terrain height over the model domain to form the terrain boundary grid;
5. Input selected wind speed values at the data station locations in the model domain (e.g., upslope flow for candidate sites atop mountain ridges, etc.);
6. Input the site's terrain boundary grid;
7. Run the hydrodynamic model to determine the site wind value that corresponds to the selected input wind values at the data stations;
8. Compile the modeled site winds and input station winds and select a new set of input wind values (e.g., flow parallel to the mountain ridge for sites atop a mountain ridge), rerun the model, and compile the modeled versus input wind values;
9. Construct the modeling function relating the modeled site winds to the input wind values;
10. Construct the candidate site wind climatology by converting fifteen years of hourly data station winds into fifteen years of hourly site winds. Hourly site wind values are computed by applying the modeling functions to the hourly station wind values. The hourly site winds are then summarized into tables giving the specific wind characteristic summaries required in the study.

It was found during the study that the airflow model and the method of relating site and station winds contains two inherent assumptions that affect the applicability of the Climatology Development Methodology to sites of certain geographic settings and data station distances.

The model in its present configuration was designed to estimate the remote wind field for diffusion and air pollution transport analyses over a 20-to-30 km scale. The fundamental constraint in applying the model is terrain representation. The model uses the terrain inputted

into the model domain to compute or redirect the airflow in the vicinity of the candidate site. If the terrain is not adequately represented in the site vicinity, the site winds computed will not be representative. Adequate representation of terrain in mountainous region requires the station distance from the site to be no more than 20 km. The model in its present configuration cannot be applied to mountainous regions with a station-to-site distance larger than 20 km. It was found, though, that the model can be applied successfully in nonmountainous regions for a station-to-site distance of 130 km or more. In nonmountainous regions the scale of the terrain grid can be larger than the 20-30 km scale distance originally designed on the model domain.

The modeling function expressions that relate the modeled site winds to the observed station winds also contain requirements on the extent of the methodology's applicability. Again, the requirement is related to station-to-site distance and the site geographic setting. The use of the modeling functions requires that the winds at the data station be climatologically related to the winds occurring at the site. The methodology is not applicable to candidate sites that exhibit consistently two wind speed and direction values for a given data station wind. It was also found that some sites may require the addition of a second wind input in the modeling analysis to initialize the airflow field in the vicinity of the candidate site, in which case, both wind input values, for the "primary" and "secondary" stations, have to be climatologically correlated with each other and with the site wind. A computer program, WNCOR, was developed to determine the extent of climatological flow correlatability. The program has proved to be an invaluable tool in evaluating the applicability of the methodology developed in this study to sites of various geographic settings and station-to-site distances.

The Climatology Development Methodology developed in this study was applied to eight different candidate wind energy sites, each site exhibiting a specific geographic setting and station-to-site distance. The eight sites can be classified as follows:

	Short Station-to Site Distance (<20 km)	Large Station-to-Site Distance (>60 km)
Mountainous Terrain	Holyoke	Boone, San Gorgonio Pass
Nonmountainous Terrain	Huron, Russell	Boardman, Ludington, Montauk Point

The requirements on station-to-site distance and flow correlatability were satisfied for six of the eight sites. The methodology was not applicable to the Boone and San Gorgonio Pass candidate sites because of the large distances between station and site in mountainous regions. It was found in an evaluation of the wind climatology generated for the Boardman candidate site that the Climatology Development Methodology does generate representative wind character summaries when all of the conditions on the methodology are satisfied. The estimated Boardman wind climatology generated from the methodology was compared with the actual wind climatology measured at the Boardman site. Results of the comparison showed that the airflow model in its present configuration can be applied to nonmountainous regions for site-to-station distances as large as 80 km. The Boardman comparison along with the results from the wind correlation analyses, program WNCOR, show that the wind climatologies generated for the six candidate sites are representative of the actual wind conditions occurring at the sites.

A modification to the existing airflow model can make the model more applicable to candidate sites in mountainous regions. The modification would update the computational procedures used in the model and would result in a 50 percent reduction in the cost to run the model. The modification would serve to make the model more applicable to wind energy siting analyses by allowing the model domain size to be adjusted for different candidate site geographic settings and station-to-site distances.

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III. THE WIND CLIMATOLOGY DEVELOPMENT METHODOLOGY

A. An Overview; Considerations in the Modeling of the Candidate Site Wind Field

A wind climatology can be defined in part as a "statistical collective of [wind] conditions during a specified interval of time" (Huschke, 1959). The time interval has been recommended (Panofsky and Brier, 1968) to be at least 15 years in order to ensure a stable statistical representation. The climatology, consisting of the statistical collective, can be in the form of tables or graphs presenting specific statistical summaries of wind characteristics (i. e., wind speed and direction frequency analyses, wind persistency and variability summaries, and other summaries designed to provide information useful in meeting design or engineering criteria). The wind climatology of a given location is most often generated by summarizing wind measurements recorded at that location for fifteen years or longer.

In the absence of wind measurements at a remote site, the generation of a wind climatology requires a method of estimating the winds for a variety of conditions at that site. Two basic methods, presented below, are available to provide this estimate. Both methods estimate wind occurrence for a given condition or synoptic (one-time) situation. Both methods utilize meteorological data available adjacent to the remote location.

The following discussion presents the two basic modeling methods of estimating winds at a remote location. Both methods are discussed relative to their applicability to generating a candidate site wind climatology. The method selected for this study is presented and the reasons for its selection outlined.

1. Determining the Remote Site Wind Field

The two methods available for estimating remote site winds can be characterized as (1) theoretical and (2) empirical. This sense of characterization arises from the method of computation and the input data requirements employed in the estimating procedure. The theoretical method implies that the wind field estimates are derived solely from theoretical relationships between air flow and general atmospheric parameters. Wind observations do not enter into the calculating procedures and often serve only as independent checks for verification. Estimating or "modeling" techniques that employ a largely theoretical approach calculate the remote site wind field by computing separately each individual wind component from separate relationships and combine each component into a final wind field. Ryan computes a sea-breeze component from the coast-inland temperature field (Ryan, 1977). This component is combined with a mountain-valley component, a slope component, a geostrophic component, etc., each derived independently from relationships between pressure, temperature, insolation, etc., and the air flow.

The empirical method requires explicitly the specification of an initial observed flow field. Wind components are observed or specified and are not computed; i.e., mass is not added to the observed field. The calculation procedures employ a modifying technique of redirecting or perturbing the initial field in the vicinity of the site into a final field representative of the flow at the site.

This method is predicated on the assumption that the regional flow field at the remote site can be expressed as the sum of the initial, general flow vector plus a perturbed flow component. The perturbed component can arise solely from terrain inflections or it can arise from a variety of influences ranging from largely empirical to purely theoretical in nature. Many studies utilize a hybridization of both the theoretical and empirical approaches by combining a theoretical perturbation to an empirical technique or vice versa. A spectrum of modeling types exists, therefore, ranging from theoretical to almost entirely empirical in nature. The question arises, what method(s) can be incorporated in the climatology-generating methodology to yield a realistic estimate of site wind climatologies?

The answer to this question becomes apparent when the input requirements of the modeling technique are considered relative to the availability of historical meteorological data in the vicinity of the candidate wind energy sites.

2. The Applicability of Certain Modeling Techniques to the Generation of a Candidate Site Wind Climatology

There are three major factors influencing the selection of a particular modeling technique for incorporation into a climatology-generating methodology:

1. Applicability of the modeling technique to all eight candidate sites
2. Input data requirements of the modeling technique
3. Feasibility of applying the modeling technique to 15 years of data record

Each factor is directly related to the availability of meteorological data in the vicinity of each site and the data requirements of each modeling technique.

a. Applicability of the Modeling Technique to All Candidate Sites

The degree of complexity and the nature of the assumptions used in each modeling technique give rise to certain requirements that must be met to ensure an adequate estimate of remote site winds. Often a particular model type is developed for a specific application to a particular region. Models of this type are usually not easily adaptable to other regions and conditions. Their input requirements for computing wind fields usually entail strategic positioning of data station locations and certain station densities to provide the detail necessary in describing fields of temperature, pressure, insolation, etc., used in the computations. These specialized requirements are most often not satisfied by the availability, proximity, and density of conventional meteorological observing stations near remote locations.

b. Input Data Requirements of the Modeling Technique

Aside from the importance of the location and density of available data stations, the type of data available is also of importance in selecting a modeling technique. If certain parameters required in the calculation procedure are not available in the vicinity of the candidate sites, wind field computation without such parameters may be seriously affected. The criteria for selecting a modeling technique will, therefore, necessarily have to include a technique that utilizes available, conventional measurements.

c. Applying the Modeling Technique to Fifteen Years of Data Record

Any modeling technique employed must be able to use fifteen years of historical record. These modeling methods are available. One method is to compute site winds from available data for each hour for the entire period of record, approximately 131,472 hours. The cost of this approach is prohibitive. The second approach would be to compute a preliminary site wind from a specific combination of input parameters and then apply the frequency of each of these parameters to obtain a final site wind. However, persistent statistics cannot be generated with this technique. The third approach, which is employed in this study, defines a function, f , which relates the input parameters and the site wind; or, $W = f(T, P, I)$.

This modeling function consists of an array indexed by the input parameters T , P , and I . To create the value of W within the array, separate model runs are necessary for different combinations of the input parameters. The complexity of the modeling function is dependent upon the number of input parameters. The number of model runs required to define f increases greatly with the number of parameters required. The selection of a modeling function requires a minimum number of input parameters to estimate site winds. A further detailing of this modeling function is presented in Section III. C. 2 (p. 27).

In summary, a modeling technique compatible with a development program designed to develop a candidate site wind climatology should:

- Be universal in its applicability to various sites
- Be able to use existing configurations of data station locations, densities, and data formats
- Require a minimum number of input parameters for use in calculating a site wind field.

B. The MRI Mass-Consistent Hydrodynamic Boundary Layer Flow Model

The modeling technique selected for this study is flexible enough to meet the previously outlined requirements. The technique is applicable to each of the eight candidate wind energy sites, and the input requirements of the technique are conventional meteorological measurements. Two of these variables are: (1) surface wind observations, w , recorded at data stations located adjacent to the candidate site, and (2), terrain relief representation, T , of the geography encompassing the candidate site and data stations. Therefore, the modeling function, f , that is required to convert meteorological observations at the data station into estimates of candidate site wind, needs only two parameters to be specified: T and w . Since the terrain, T , at any one candidate site is constant for all values of wind, w , at the data station, the modeling function reduces to an expression dependent only on the single variable, w ; i.e., $W = f(w)$ for any one site. This greatly reduces the number of model runs and associated expense required to define the modeling function.

The model is an empirical hybrid, in the sense that observed surface winds are inputted to create an initial two-dimensional horizontal flow field. This "empirical" wind field is then extrapolated in the vertical dimension using a power law relationship to produce an "initial" three-dimensional flow field in three-dimensional space.

The model then introduces a three-dimensional representation of the terrain relief into the initial flow field and performs a succession of calculations across the horizontal to "smooth" the initial field into a final mass-conservative field adjusted to the terrain boundaries. The model, therefore, uses a perturbation technique of calculating site winds.

The assumption explicit in this technique is:

Variations in the velocity field between two locations arise entirely from the deflective influences of terrain surfaces.

Using this modeling technique, if there are no terrain variations between the two locations, the outputted candidate site winds will necessarily be equal to the inputted data station winds.

A computer program-listing is given in Appendix A, along with a description of the methods and procedures required to run the program (program CORE). The following discussion presents the theory, procedures, and calculation technique incorporated within the computer model.

1. Background

The MRI mass-consistent model is a hybrid of a mass-consistent model developed originally at Systems, Sciences, Software (S^3), La Jolla, California. In a technical report written by Sklarew and Wilson (1976), the mass-consistent model was briefly discussed as a sub-model of DEPICT. A similar model, MATHEW (Mass-Adjusted THree-dimensional Wind field model) was developed by Sherman (1978). All three models — the submodel to DEPICT, the MRI model, and MATHEW — have the same theoretical origin: Sasaki (1970a, 1970b). The time-dependent terms in Sasaki's formulation are not included, but the essence of the "variation method" is applied.

The S^3 model was expanded at MRI to encompass a larger geographic region and to provide a larger degree of flexibility in the method of creating an initial flow field. Three subroutines — OPTN 1, OPTN 2, and OPTN 3 — were added to provide initialization of the flow field from sparse surface data, the geostrophic wind field aloft, or any regional boundary conditions specified.

The program in its present configuration consists of fourteen subroutines called by a main program, CORE. Five of the subroutines — DRUM U, DRUM V, DRUM W, DRUM C, and DRUM F — are CDC system routines used in a rotating mass storage configuration for swapping portions of the arrays required for three-dimensional storage of the wind field components and terrain relief. The remaining subroutines and their functions are as follows:

- ZERO - Initializes all arrays
- INPUT - Inputs terrain relief array, and scale factors
(calls input options OPTN1, OPTN2, OPTN3)
- OPTN1 - Inputs sparse surface wind data
- OPTN2 - Inputs geostrophic wind component
- OPTN3 - Inputs specific velocity boundary conditions
- INTERP - Creates a two-dimensional velocity field from the inputted options
- BUILD - Extrapolates the vertical profile of the wind field from the horizontal field created in INTERP
- POTENT - Solves for the final mass conservative field from the initial flow field
- OUTPUT - Outputs the final flow field

The flow diagram of the program configuration used in the study is presented in Figure III-1. OPTN2 and OPTN3 are not used and, therefore, do not appear in the flow diagram. A description of the input parameters is presented in conjunction with a guide for users in Appendix A.

2. Theory

The basis of the modeling theory is the variation method. We design a function which is a function of the wind components (u, v, w) and a Lagrangian multiplier, λ . The function used for the minimization is:

$$E(u, v, w, \lambda) = \int_V [\alpha_1^2 (u - u^\circ)^2 + \alpha_1 (v - v^\circ)^2 + \alpha_2 (w - w^\circ)^2 + \lambda (\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z})] dx dy dz, \quad (III-1)$$

where V is the volume of the domain,
 α_1 and α_2 are weighting functions,
 u° , v° , and w° are the observed wind components.

Performing the variation on (III-1) and assigning the proper constraint and boundary conditions, we obtain the following set of equations:

Wind Adjustment Equations:

$$u = u^\circ + \frac{1}{2\alpha_1^2} \frac{\partial \lambda}{\partial x} \quad (III-2a)$$

$$v = v^\circ + \frac{1}{2\alpha_1^2} \frac{\partial \lambda}{\partial y} \quad (III-2b)$$

$$w = w^\circ + \frac{1}{2\alpha_2^2} \frac{\partial \lambda}{\partial z} \quad (III-2c)$$

Figure III-1. FLOW CHART OF THE MRI HYDRODYNAMIC BOUNDARY LAYER FLOW MODEL, PROGRAM CORE

Figure III-2. THE MODEL DOMAIN AND SCHEMATIC TOPOGRAPHY. The solid cells are shaded to show the discrete representation of topography. The fluid cells are not shown.

Physical Constraint Equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \quad (\text{III-2d})$$

Boundary Conditions:

$$n_x \lambda \delta u = 0 \quad (\text{III-2e})$$

$$n_y \lambda \delta v = 0 \quad (\text{III-2f})$$

$$n_z \lambda \delta w = 0, \quad (\text{III-2g})$$

where n_x , n_y , and n_z are outward unit normals, and δ denotes the first-order variation operator.

We further substitute the wind adjustment equations (III-2a through -2c) into the physical constraint equation (III-2d), and obtain a second-order differential equation of λ :

$$\frac{\partial^2 \lambda}{\partial x^2} + \frac{\partial^2 \lambda}{\partial y^2} + \left(\frac{\alpha_1}{\alpha_2}\right)^2 \frac{\partial^2 \lambda}{\partial z^2} = -2\alpha_1^2 \left(\frac{\partial u^0}{\partial x} + \frac{\partial v^0}{\partial y} + \frac{\partial w^0}{\partial z}\right). \quad (\text{III-3})$$

The values of α_1 and α_2 in the MRI model are assigned to be $1/\sqrt{2}$. According to Sherman (1978), the choice of $(\alpha_1/\alpha_2)^2$ is crucial to what component of wind, horizontal or vertical, is to be adjusted more than the other. If this ratio is larger than 10^{-4} , the adjustment is predominantly in the vertical component; if it is smaller, the horizontal adjustment dominates. In the MRI model, the order of magnitude of the α ratio is incorporated in the scale factor terms, Δx , Δy , and Δz . It can be shown, through an order-of-magnitude analysis, that the selection of the horizontal scale (Δx and Δy) one order of magnitude larger than the vertical scale, Δz , will provide the 10^{-4} magnitude recommended by Sherman. (For terrain scale sizes used in this study, see Table IV-1.)

3. Construction of the Initial Flow Field

a. The Model Domain

The model domain in three-dimensional space is represented by a rectangular volume divided into cells. Each cell has dimensions Δx , Δy , and Δz , and designated by index i, j, k . The domain has a maximum dimension of 40 in x , 30 in y , and 16 in z (Figure III-2). Each cell can be specified to be either fluid or solid. Terrain is inputted into the domain by assigning solid cells in direct relation to the height of the terrain in the region to be modeled. Terrain is, therefore, represented by block increments of solid cells.

The resolution of the solid-cell terrain representation is dependent upon the cell size ($\Delta x, \Delta y, \Delta z$) which is, in turn, dependent upon the size of the model domain. (The importance of the terrain resolution versus domain size as it applies specifically to modeling candidate site winds is discussed in the section entitled "Results of the Climatology Development Methodology", Section IV B 2 d3,)

b. Extrapolation of the Horizontal Wind Field

The initial flow field is constructed from surface winds observed at stations within the region being modeled (the model domain). The surface wind values in u and v components are inputted into the model domain and a distance weighting technique proposed by Barnes (1964) is used to create a two-dimensional horizontal flow field. The wind component at point p with m input stations within a distance $\bar{d}$ radially from p is:

$$v_p = \frac{\sum_{n=1}^m v_n \exp(-r_n^2 / 4P)}{\sum_{n=1}^m \exp(-r_n^2 / 4P)} \quad \text{when } r_n \leq \bar{d}, \quad (\text{III-4})$$

where $\bar{d}$ = the average distance between data stations,
 m = the number of stations within $\bar{d}$ from p,
 r_n = the distance from p to station n,
 v_n = the wind component at station n,
 P = a parameter determining the shape of the weighting factor, selected according to:

$$\bar{d}^2 / 4P = -\ln \epsilon = E.$$

By choosing $E=4$, 98 percent of the influence of of any datum is represented within the circular region whose radius is $\bar{d}$ (if $\bar{d}=18$ grid spaces, $P=20$) (see Barnes, 1964).

Two components, u and v, are calculated by (III-4) to obtain an initial two-dimensional wind field on a pseudo-horizontal plane. The calculated wind components are then assigned to the first fluid cell above the terrain. The calculations in this section are done in the INTERP subroutine.

c. Extrapolation of the Vertical Profile of Wind

The vertical profile of the initial flow field is computed by applying a power law relationship to the surface wind field derived from the inputted surface wind data. Two power law relationships are used to construct the vertical profile. The first relationship computes a boundary layer profile for the surface to 400 feet (122 m). The second relationship computes a "free air" profile for elevations greater than 400 feet (see Sutton, 1953). The relationships are:

$$V = V_o \left(\frac{Z}{Z_o} \right)^{0.25} \quad \text{for } Z_o < Z \leq 400 \text{ ft.} \quad (\text{III-5a})$$

$$V = V_o \left(\frac{400}{Z_o} \right)^{0.25} \left(\frac{Z}{400} \right)^{0.149} \quad \text{for } Z > 400 \text{ ft} \quad (\text{III-5b})$$

where V = velocity at height Z

Z_o = $\Delta Z/2$; height of the midpoint of the first fluid cell

V_o = $V_h \left(\frac{\Delta Z/2}{h} \right)^{0.25}$; velocity applied to the midpoint of the first fluid cell

h = anemometer height

V_h = velocity at anemometer height.

The selection of the power law relationship over the logarithmic law in both the modeling technique and later in the climatology-generating methodology arises from the work done by De Marrais (1959) and from Johnson (1959). De Marrais and Johnson's findings will be presented later in the discussion on the climatology-generating methodology in Section III C 3c1.

In addition to extrapolating the wind profile in the vertical, a constant one-degree veering per 100 ft (De Marrais, 1959) is added to the wind direction in the construction of the initial flow field. The calculations in this section are done in the BUILD subroutine.

4. Solving for the Final Wind Field

To solve III-3, lateral boundary conditions are needed. In the present model configuration, the lateral boundary conditions, given in (III-2e, -2f, -2g), are assigned to be:

$$\frac{\partial \lambda}{\partial n} = 0, \quad (\text{III-6})$$

where n is the direction normal to the boundary.

This condition implies that the wind components normal to the lateral boundaries, i.e., sides and top, are not to be adjusted [see (III-2a through -2c)]. On the terrain boundaries and the interior points, λ is solved from (III-3).

a. Finite difference solution of λ

The differential equation (III-3) and its boundary condition (III-6) are to be solved by finite difference equations. The example of the x-component finite difference approximations of the first and second derivatives are given in the following forms:

$$\frac{\partial ()}{\partial x} \sim \frac{()_{i+1} - ()_i}{\Delta x},$$

$$\frac{\partial^2 ()}{\partial x^2} \sim \frac{()_{i+1} + ()_{i-1} - 2()_i}{\Delta x^2}.$$

where () is a variable which can be λ or (u, v, w) , and Δx is the cell size in the x direction. (The indices in this section and the subsequent sections are abbreviated; only changing index is indicated.)

Due to the interactions of terrain boundaries, a weighting function, a , is required, such that in a fluid cell a is 1 and in a solid cell a is 0. With this consideration the general form for the first and second derivative is:

$$\frac{\partial ()}{\partial x} \sim \frac{a_{i+1} ()_{i+1} - a_i ()_i}{\Delta x},$$

$$\frac{\partial^2 ()}{\partial x^2} \sim \frac{a_{i+1} [()_{i+1} - ()_i] + a_{i-1} [()_{i-1} - ()_i]}{\Delta x^2}.$$

The finite difference form of (III-3) in short form is:

$$A_{ijk} - \lambda_{ijk} D_{ijk} = \epsilon_0, \quad (\text{III-7})$$

where:

$$A_{ijk} = \frac{1}{\Delta x^2} [(a_{i+1} \lambda_{i+1} + a_{i-1} \lambda_{i-1})]$$

$$+ \frac{1}{\Delta y^2} [(a_{j+1} \lambda_{j+1} + a_{j-1} \lambda_{j-1})]$$

$$+ \frac{1}{\Delta z^2} [(a_{k+1} \lambda_{k+1} + a_{k-1} \lambda_{k-1})],$$

$$D_{ijk} = \frac{1}{\Delta x^2} [(a_{i+1} + a_{i-1})] \\ + \frac{1}{\Delta y^2} [(a_{j+1} + a_{j-1})] \\ + \frac{1}{\Delta z^2} [(a_{k+1} + a_{k-1})],$$

and

$$\epsilon_o = -[(a_i u_i^o - a_{i-1} u_{i-1}^o) / \Delta x \\ + (a_j v_j^o - a_{j-1} v_{j-1}^o) / \Delta y \\ + (a_k w_k^o - a_{k-1} w_{k-1}^o) / \Delta z].$$

(1) The relaxation method

The relaxation method is used to solve III-7. The successive n th and $n+1$ st guess of λ_{ijk} are formed:

$$A_{ijk}^n - \lambda_{ijk}^n D_{ijk} = \epsilon_o^n \\ A_{ijk}^n - \lambda_{ijk}^{n+1} D_{ijk} = 0,$$

where the $n+1$ st guess is a perfect guess.

Now we can formulate the iterative equation of λ_{ijk} , i.e.,

$$\lambda_{ijk}^{n+1} = \lambda_{ijk}^n + \epsilon_o^n / D_{ijk}.$$

However, the over-relaxation is used in the model to improve the convergence of the solution. The proper equation is:

$$\lambda_{ijk}^{n+1} = \lambda_{ijk}^n + R \epsilon_o^n / D_{ijk}, \quad (\text{III-8})$$

where R is an over-relaxation coefficient, which is assigned to be 1.75.

(2) The divergence calculations

The different interpolation of ϵ_0 could yield different expressions. In the MRI model, ϵ_0 is expressed as the divergence of (u^0, v^0, w^0) components, and it is written as follows:

$$\begin{aligned}\epsilon_0 &= -\left(\frac{\partial u^0}{\partial x} + \frac{\partial v^0}{\partial y} + \frac{\partial w^0}{\partial z}\right) \\ &= -\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right) + \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\right)\lambda.\end{aligned}$$

At n-step the finite difference form of the above equation is written as follows:

$$\epsilon_0^n = \delta_{ijk}^n + A_{ijk}^n - \lambda_{ijk}^n D_{ijk}, \quad (\text{III-9})$$

where

$$\begin{aligned}\delta_{ijk}^n &= -\left[\frac{1}{\Delta x}(a_i u_i^n - a_{i-1} u_{i-1}^n) \right. \\ &\quad + \frac{1}{\Delta y}(a_j v_j^n - a_{j-1} v_{j-1}^n) \\ &\quad \left. + \frac{1}{\Delta z}(a_k w_k^n - a_{k-1} w_{k-1}^n)\right].\end{aligned}$$

Substituting the expressions for δ_{ijk}^n , A_{ijk}^n into (III-9) and then substituting (III-9) into (III-8) and rearranging the terms, we obtain:

$$\lambda_{ijk}^{n+1} = \frac{R}{D_{ijk}} [A_{ijk}^n + \delta_{ijk}^n] - (R-1)\lambda_{ijk}^n. \quad (\text{III-10})$$

We note that (III-10) contains λ s with $n+1$ values. Therefore, (III-10) is solved successively to obtain the three-dimensional field of λ s.

(3) The boundary values of λ

The terrain boundary solution of λ in (III-10) is treated by the weighting functions, a . It is solved as though the solid cell were fluid, but with the proper "a" values assigned. The lateral boundary condition is handled by assigning λ as a constant equal to zero. This is equivalent to saying that the "a" values in the lateral boundaries are zero, and it is a no-flow-through condition discussed in Sherman's (1978) paper.

b. Adjustment of the Wind Components

The solution of λ obtained through solving (III-10) is used to adjust the wind components. (III-2a through -2c) are used to update the velocity components in the fluid cell. The finite difference equations of (III-2a - 2c) are as follows:

$$u_i^{n+1} = u_i^n + \frac{1}{\Delta x} (a_{i+1} \lambda_{i+1}^n - a_i \lambda_i^n) \quad (\text{III-11a})$$

$$v_j^{n+1} = v_j^n + \frac{1}{\Delta y} (a_{j+1} \lambda_{j+1}^n - a_j \lambda_j^n) \quad (\text{III-11b})$$

$$w_k^{n+1} = w_k^n + \frac{1}{\Delta z} (a_{k+1} \lambda_{k+1}^n - a_k \lambda_k^n) \quad (\text{III-11c})$$

However, at lateral boundaries, the adjustment of the normal components of wind take the following formulations:

$$\begin{aligned} u_i^{n+1} &= u_i^n \\ v_j^{n+1} &= v_j^n \\ w_k^{n+1} &= w_k^n \end{aligned}$$

In other words, the normal component of wind is not adjusted on the boundary.

c. Computational Sequence

A brief description of the calculation sequence is listed in a step-by-step manner as:

- Step 1: Initial horizontal wind calculation
- Step 2: Initial vertical wind calculation
- Step 3: Solve λ_{ijk}^n in all cells
- Step 4: Calculate u_i^{n+1} , v_j^{n+1} , w_k^{n+1}
- Step 5: Repeat steps 3 and 4 until $\delta_{ijk}^n + A_{ijk}^n - \lambda_{ijk}^n D_{ijk}$ reaches a predesigned value; in the present model the tolerance is 10^{-2} .

These calculation steps are included in subroutine POTENT.

5. The Degree of Convergence to a Solution

The boundary values for both the terrain and external model surfaces remain fixed and are not updated once the initial three-dimensional wind field is constructed. The boundary conditions in this model can therefore be characterized as fixed. Berman et al. (1977) have found:

"When terrain is included in an objective wind field analysis, divergence in the grid array is reduced further by variable boundary conditions than when boundary conditions are fixed prior to the iterative procedure."

Berman et al. (1977) show the degree of convergence to a nondivergent solution versus the number of iterations for both a fixed and variable boundary condition. Figure III-3b has been reproduced from their paper. Also shown, in Figure III-3a, is the degree of convergence in the MRI model for the model runs performed on the eight candidate wind energy sites in this study. It should be noted that Berman et al. plot the mean square divergence versus the number of iterations. The plot showing the divergence values for the candidate sites gives the maximum residual divergence versus the number of iterations. The maximum residual divergence shown occurs on the order of 10^{-2} , well above the range of 10^{-4} to 10^{-6} shown by Berman. The larger divergence values encountered in the MRI model arise from the retention of the maximum residual divergence values in the vicinity of terrain with boundaries in both x and y. In these situation, a_{j+1} and a_{j+1} both equal zero, and the only velocity component updated is the vertical component, W. Consequently, the divergence value remains large for these few conditions, and the maximum residual divergence becomes biased towards these larger values. Free air divergence values have been computed and compared with the maximum divergence values. The free air values have been found repeatedly to be of the order of 10^{-3} to 10^{-4} , less than the 10^{-2} retained.

The models' performance was initially checked on the candidate site located in the San Geronio Pass in Southern California. The San Geronio Pass exhibits the largest variation of terrain relief between the primary station and the candidate site. It was found that the solution to a nondivergent wind field diverges after the 56th iteration; i.e., the divergence actually increased from the 56th to 80th iterations. This is due largely to the fixed boundary's values occurring in the vicinity of fluid cells bounded by more than three solid cells. Since the increase in the number of iterations from 56 to 104 did not decrease the divergence appreciably, the number of iterations selected for the remaining candidate site was 56.

Figure III-3a. FLOW DIVERGENCE VERSUS THE ITERATIVE PROCESS (The MRI Model)

Figure III-3b. FLOW DIVERGENCE VERSUS THE ITERATIVE PROCESS (From Berman et al. [1977])

6. Concluding Remarks

The MRI model is different from the models by Sherman (1978) and Sklarew et al. (1976) in terms of solving (III-8). There are some minor differences such as handling the terrain boundary condition. The interpretation of $(u^\circ, v^\circ, w^\circ)$ in all three models differs from the interpretation of Sasaki (1970 a, b). In Sasaki's paper, u° , v° , and w° are treated as observed values, while in the three wind adjustment models, u° , v° , and w° are interpreted as the guess values at n-step iteration. It is unclear at this point what the change in the solutions would be if the $(u^\circ, v^\circ, w^\circ)$ are treated as observed values.

There is still room to improve the MRI model. The iteration of λ_{ijk}^n could be handled as it is done by Sherman (1978). Reformulation of the lateral boundary seems to be another important improvement. The noncentered first-order derivative may be reformulated into a center-difference formulation. A quick direct method of solving elliptic equations (ADI), developed by the National Center for Atmospheric Research, (NCAR) could be implemented. Physical improvement would be to change α_1 and α_2 and the ratio α_1/α_2 . The selection of the ratio should be according to stability classes, and it could improve the convergence of λ as well.

C. The Methodology of Generating a Candidate Site Wind Climatology

1. General

As mentioned previously, the requirement of wind speed persistency statistics in generating a site wind climatology requires the capability of generating hourly candidate site wind estimates over the entire period of climatological wind record (fifteen years). The mass-consistent model has the capability of estimating site winds for a given hour from wind observations recorded during that hour at stations located in the site's vicinity. Since it is economically impossible to compute site winds each hour during the fifteen-year period via separate model runs on hourly station winds, an alternative method was required.

The method used in this study defines a mathematical function, hereafter called a modeling function, that relates the candidate site wind as a dependent variable, dependent upon the value of the input station winds, observed nearby. The modeling function for a given site was defined in the Modeling Methodology by performing a number of model runs, each inputting a separate set of station winds and relating the computed site winds to the input station wind values. The modeling functions were then used in the Climatology Generating Methodology to generate the candidate site wind climatology. The modeling functions were used to convert fifteen years of hourly data station winds into fifteen years of site wind estimates. Summaries were then generated to provide the statistical collective required in this study. In the following sections, the Modeling Methodology and Climatology Generating Methodology are presented in detail.

2. The Modeling Methodology

a. General

The modeling functions for each of the eight candidate wind energy sites were constructed by inputting sets of station input wind values into the model domain selected for each site. The site's domain size was selected to encompass the candidate site and meteorological data stations located adjacent to the site. The input surface wind values at the data stations were used in the model to construct the initial three-dimensional flow field over the model domain. A representation of the terrain relief over the model domain was then inputted in the modeling analysis and the initial flow field was solved in a "model run" to yield the final flow field at the site. The site wind was then compiled with the input wind values.

Other model runs were then performed with different input wind values at each station's location in the domain grid. The modeled site wind values and the input station wind values were included in the compilation. The compilation for each site was then used to construct the modeling function.

The number of input stations used, the resolution of the terrain scale, the size of the model domains selected, and the number of model runs required in each site's modeling analysis all depended upon the availability and proximity of available historical data relative to the candidate wind energy site. The terrain resolution, i.e., the size of the block cell, depended upon the size of the model domain. The model domain size depended upon the distances between the site and the furthest data stations away. The distance to the farthest data stations depended upon the availability of data and the number of stations used in the analysis. The number of stations used and, also, the number of model runs required per site depended upon the requirements of the modeling function. The requirements of the modeling function stem from an assumption implicit in its use: that a functional relationship exists between the winds at the data stations and candidate site (i.e., a station cannot be too distant or, if closer, be separated from the site by geographic features that disassociate the flow between the site and station).

The "representativeness" of an input wind in constructing a "realistic" initial flow field entered into the selection procedure of determining which stations would and would not be used in the modeling analysis for each site. The selection was based on an educated selection, but was primarily governed by the availability of data near the site. Stations too far away were omitted; stations close by were included. It could not be determined initially whether the closest stations were close enough. Generally, with the existing density of meteorological observing stations in the United States, two stations were usually available within 100 miles of each candidate site. These stations were included unless a reason could be found not to include them.

One of the goals of this study was to determine the requirements of the estimating technique, apply the technique to eight different sites, and then evaluate the technique's applicability to different sites with different data availability and geographic settings. The procedure of station selection along with the specific reason for the selection according to candidate site are presented in greater detail in Section IV.B., "Results of the Climatology Development Methodology." Evaluation of the technique follows this section. These two sections are important in the understanding of the methodology's procedure relative to modeling candidate site winds for a variety of data station locations, densities, and site-station geographic settings.

An objective technique of data station selection was developed that aided in the decision process of selecting input data stations for the site modeling analysis. This technique is presented in subsequent paragraphs as a part of an objective modeling procedure developed and used on all candidate sites -- "The Dual Station Modeling Methodology." In the following paragraphs an additional, economic, requirement, stemming from the use of the modeling functions is presented. This concerns the number of model runs required to define the modeling function, f . Following this is a description of a survey conducted on data availability for all candidate sites. The following section presents the Dual Station Modeling Methodology. The section ends with a description of how the modeling function is mathematically determined from the compilation of modeled site and input winds.

b. A Requirement of the Modeling Function, f

In its present configuration the air flow model has the provisions of inputting anywhere from one to as many as eighteen surface wind values for estimating candidate site winds. For n stations in the vicinity of a candidate site the modeling function for n input values will be:

$$V_s = f(V_1, V_2, \dots, V_n), \quad (\text{III-12})$$

where V_s = candidate site wind

It can be shown that the number of model runs required to define the modeling function increases exponentially with the number, n , of input wind values. Even for as few as two input values it can be shown that the number of model runs per site required to define the modeling function would make the technique unfeasible for generating a site wind climatology. To illustrate, consider two data stations, P and C , in the vicinity of a candidate site, S (Figure III-4). The modeling function for $n = 2$ input values is:

$$V_s = f(V_p, V_c) \quad (\text{III-13})$$

Without knowing the relationship of the winds at C to the winds at P ahead of time, the process of defining the function f would require a model run for every possible combination and permutation of input wind values at P and C that might occur during the 15-year period of record, a task that again requires an inordinate number of model runs.

The modeling technique is, therefore, required to define a modeling function that expresses the site wind values solely in terms of a single input wind. The function, once defined, would require only the specification of a single input wind value to provide an estimate of the candidate site winds. The final form of the modeling function in terms of a single, primary station's winds, V_p , is:

$$V_s = f(V_p, V_c)$$

Figure III-4. THE MODELING FUNCTION, f , DESCRIBING THE WINDS AT SITE, s , IN TERMS OF TWO INPUT WIND VALUES OBSERVED AT A PRIMARY STATION, p , AND AT A SECONDARY STATION, c (Each combination of wind direction and speed at p and c requires a model run to determine the corresponding site wind value, V_s)

$$V_s = f(V_p)$$

(III-14)

Such a function would minimize the number of model runs required per site and would enable the construction of the site wind climatology from a single, primary station data record.

c. Candidate Site Data Survey

A data survey was conducted for each of the eight sites to determine availability and proximity of historical wind data record that can be used as primary station input for the wind climatology technique. All National Weather Service (NWS) and military observing stations with at least a 16-observation-per-day frequency were considered as candidate. Highest weight was assigned to those stations with a 24-hour-per-day observing frequency with 15 years of record available on computer tape. Table III-1 lists by site the nearest three stations with historical data record on computer tape or microfilm. Also listed are the period of station record on computer tape and each station's distance from their respective candidate site.

The selection of a primary data station is necessitated in most instances by the availability and accessibility of the historical data to be used in the technique. To assure the recommended 15-year data base and to assure its easy accessibility, it becomes necessary to select the closest station with 15 years of data record on magnetic tape. In some instances, this restriction limits the ability to select the closest station to the site. The Ludington, Michigan, candidate site, for example has the closest data station with 15 years of data on magnetic tape 81 km away from the site (Muskegon) while a closer station, Manistee, is only 46 km away. The data for Manistee are not available on magnetic tape and include 16 observations per day instead of 24. The data for Manistee are available on microfilm and would require a considerable amount of work to keypunch 15 years of data into a format readily accessible for the technique programs. Also, a climatology derived from the Manistee data might be deficient in the description of the nighttime wind characteristics because the 16 observations per day frequency eliminates eight nighttime observing hours.

The closest station with 15 years of record on magnetic tape may not be as representative of the flow field in the vicinity of the candidate site as might a secondary data station with less record or a smaller observation frequency closer by, such as Manistee in the case mentioned above. In such instances, it may be necessary to supplement the single, primary station's winds with a secondary wind input closer to the candidate site. The addition of a closer wind input would enable the construction of an initial flow field more representative of the mean flow in the site vicinity. During the course of the data survey it was found that as many as six of the eight candidate sites might require the inclusion of a second wind input in the modeling technique.

Table III-1
CANDIDATE DATA STATIONS

Site	Data Station	Distance From Site (km)	Period of Record on Computer Tape (Yrs)	Observing Frequency* (Hrs/Day)	Only Available On Microfilm
Boone, N. C.	Hickory, N. C.	60	6.0	24	
	Bristol, Tenn.	71	>20.0	24**	
	Asheville, N. C.	117	>20.0	24	
Ludington, Mich.	Muskegon, Mich.	81	>20.0	24**	
	Cadillac, Mich.	93	6.0	24	
	Manistee, Mich.	46	--	16	X
Holyoke, Mass.	Chicopee Falls, Mass.	12	>20.0	24	
	Westfield, Mass.	11	3.5	24	
	Windsor Locks, Conn.	35	>20.0	24	
Montauk Pt, N. Y.	Westhampton, N. Y.	61	18.5	24	
	New London, Conn.	32	4.5	24**	
	Block Island, R. I.	35	1.5	24	
Boardman, Ore.	Pendleton, Ore.	78	>20.0	24	
	Dallesport, Wash.	104	17.0	24	
	Pasco, Wash.	88	1.0	24	
San Geronio Pass, Calif.	Norton AFB, Calif.	63	>20.0	24	
	March AFB, Calif.	63	>20.0	24	
	Palm Springs, Calif.	15	--	17	X
Huron, S. D.	Huron, S. D.	7.5	>20.0	24	
	Watertown, S. D.	96	6.5	24	
	Mitchell, S. D.	72.5	--	16	X
Russell, Kan.	Russell, Kan.	5	>20.0	24#	
	Salina/Schilling, Kan.	113	12.6	24	
	Salina/Municipal, Kan.	105	5.0	24	

* May vary with station history

** Less than 24 hours/day for part of record

Part of record missing

d. The Dual Station Modeling Methodology

A modeling technique was developed that allows the specification of two input station winds to compute the site winds, and also allows the construction of a modeling function that expresses the site winds in terms of only one of the input wind values. As mentioned previously, referring to Figure III-4, if the relationship between the winds at C and P is not known ahead of time, model runs would be required on all possible combinations of input wind values so as to construct the modeling function, f , of Eq. (III-13):

$$V_s = f(V_p, V_c).$$

If a functional relationship can be found between the winds at P and the winds at C such that:

$$V_c = F(V_p) \quad (III-15)$$

Then, substituting Eq. (III-15) into Eq. (III-13) gives the desired form of the modeling function, Eq. (III-14):

$$V_s = f(V_p)$$

If a functional relationship can be found between the winds at the primary station and the winds of the secondary station, the secondary station's winds, V_c , can be determined by specifying only the observed winds at P and using the relationship Eq. (III-15). If Eq. (III-15) can be determined, the winds at the secondary station can be expressed as a dependent variable, dependent only upon the single independent variable, V_p . The resulting modeling function, Eq. (III-14), then expresses the site winds solely in terms of the only independent variable, V_p .

Providing a relationship exists between the primary and secondary station winds, the dual station modeling methodology allows the specification of two wind values for initializing the site wind field. It also allows the resulting site winds computed from the initial field to be expressed, solely in terms of a single input wind value. The modeling function thus constructed, when applied to a single, primary station's wind, will produce a site wind value derived originally from two input winds.

In the event a relationship cannot be found between the primary and secondary station's winds, the modeling function, f , Eq. (III-13), cannot be reduced to the final form required in the climatology, Eq. (III-14). The number of model runs required to define the function, V_c and V_p not being correlated, would make the dual station analysis unfeasible. The recourse in this event is to utilize a single station modeling technique using a single input station's winds to construct the initial flow field. The resulting site wind would be related directly to the single input value, and the modeling function would be in the form of Eq. (III-14).

(1) Wind Correlation Program, WNCOR.

The dual station modeling technique utilizes a correlation program, developed for the study, to determine if wind speed and wind direction relationships exist between the primary and secondary station's winds. Four years of hourly surface wind observations from each station are read simultaneously to generate wind speed and direction correlation statistics by primary station wind direction quadrant. A listing of program WNCOR appears in Appendix A.

Four types of summaries are generated in program WNCOR; they are:

1. Wind speed regression analysis
2. Delta wind direction frequency analysis
3. Secondary station wind direction frequency analysis, all hours
4. Secondary station wind direction frequency analysis, daytime hours only

All four summaries comprise a set, and a total of five sets are generated, one each for four primary station wind direction quadrants; NE, SE, SW, and NW, and one set for all primary station wind directions. In addition, two secondary station wind direction frequency analyses are generated for calms at the primary station: (1) for all hours, and (2) during daytime hours only.

Examples of the four summaries generated by Program WNCOR appear in Figures III-5 through III-8. These figures represent one of the five sets generated for the candidate wind energy site which is located near Holyoke, Massachusetts. The primary station selected for the Holyoke site is Chicopee Falls AFB. The secondary station is Barnes Municipal Airport located at Westfield, Massachusetts. The set shown summarizes all wind conditions occurring during a NE (NNW-NE) wind at Chicopee Falls.

Figure III-5 reproduces the wind speed scatter diagram for all northeasterly winds at Chicopee Falls. Displayed on the diagram are the computed wind speed regression relationship, the correlation coefficient, the standard error of estimate, and the slope error (one sigma). Each character displayed within the scatter diagram represents the number of observations, divided by ten, occurring at a certain wind speed combination.

Figure III-5. WIND SPEED REGRESSION ANALYSIS: HOLYOKE, MASSACHUSETTS, FOR
PRIMARY STATION WIND DIRECTION NNW-NE

DELTA WIND DIRECTION FREQUENCY ANALYSIS
 FOR CHICOPEE FALLS, MASS (CHI) WIND DIRECTION: NNW-NE PERIOD: FROM 1/ 1/49 TO 1/ 1/52

Figure III-6. DELTA WIND DIRECTION FREQUENCY ANALYSIS FOR
 PRIMARY STATION WIND DIRECTION NNW-NE

WESTFIELD, MASS. (WES) WIND DIRECTION FREQUENCY ANALYSIS: ALL HOURS
 FOR CHICOPEE FALLS, MASS (CHI) WIND DIRECTIONS: ANN- NE PERIOD: FROM 1/ 1/49 TO 1/ 1/52

Figure III-7. SECONDARY STATION WIND DIRECTION FREQUENCY ANALYSIS, ALL HOURS

WESTFIELD, MASS. (WES) WIND DIRECTION FREQUENCY ANALYSIS: 0700-1800 LST
 FOR CHICOPEE FALLS, MASS (CHI) WIND DIRECTION: ANN- NL PERIOD: FROM 1/ 1/44 TO 1/ 1/52

Figure III-8. SECONDARY STATION WIND DIRECTION
 FREQUENCY ANALYSIS, DAYTIME HOURS

The number "1" plotted represents 1 to 10 observations, "2" represents 11-20 observations, etc., up to "*", representing 360 or more observations at the specified speed pair. The "+" symbols display the one-to-one wind speed correspondence line.

A total of five wind speed regression relationships are generated, one each for four primary station wind direction quadrants and one for all primary stations' winds. These set of wind speed relationships correspond to Eq. III-15 for computing secondary station wind speed values from a given primary station wind direction and speed.

Figure III-6 reproduces the "Delta Wind Direction Frequency Analysis" for NE wind directions occurring at Chicopee Falls. The diagram displays the frequency of directional difference occurring between Chicopee Falls and Westfield, Massachusetts. The directional difference is obtained by subtracting the primary station's wind direction from the secondary station's wind direction. A high occurrence frequency of zero, therefore, represents a high frequency of the same wind direction occurring at both locations simultaneously. The occurrence frequency of directional difference is represented by a histogram, each bar represented by two "X"s. The frequency for no directional difference with northeasterly flow at Chicopee is, from the graph, 30 percent. The combined occurrence frequency of directional difference ranging $\pm 23^\circ$ is 72 percent in this example.

The "Delta Wind Direction Frequency Analysis" was designed to determine the directional difference occurring for each wind speed regression relationship computed from the wind speed values. Four pairs of equations are, therefore, used to describe Eq. (III-15). Each pair describes the wind speed and direction correspondence occurring between the primary and secondary stations for four wind direction quadrants. Equation (III-15) can be written more specifically as:

for wind speed:

$$V_{cj} = E_j V_{pj} + F_j \quad (\text{III-16})$$

for wind direction:

$$d_{cj} = d_{pj} + G_j \quad (\text{III-17})$$

where:

j = wind direction index; e.g., 1 for NE, 2 for SE.
 V_p and V_c = primary and secondary station wind speed
 d_p and d_c = primary and secondary station wind direction
 E_j and F_j = wind speed regression coefficients determined
from Program WNCOR
 G_j = directional difference determined by WNCOR.

Eqs. (III-16 and -17) are utilized in the modeling technique to compute the secondary station wind input value that corresponds to a specified primary station wind input.

The secondary station wind direction frequency analyses, Figures III-7 and III-8, were included in the statistical analysis to determine the variability of a secondary station's wind direction for a given primary station wind quadrant. Two summaries were constructed (one for all hours and one for daytime hours only) to detail the occurrence of bimodal distributions in the secondary station wind direction, both diurnal and terrain-related. Northeasterly wind directions at Chicopee Falls may be accompanied by northeasterly winds at Westfield during the daytime, but might be accompanied by northwesterly, drainage-dominated flow at night. These summaries were included to provide a finer resolution to the description of the directional relationship, Eq. (III-17).

The decision as to whether a wind relationship actually exists between the primary and secondary data station was based largely on the degree of correlation exhibited by the wind speed regression analyses. The dual station modeling technique was employed in the modeling methodology when wind speed relationships exhibited a correlation coefficient of 0.55 or better.

The degree of scatter present in the regression analyses occurs in part from the method of observation used by the NWS and military. Both record a one-minute average wind speed and direction value observed on or near the hour. Since one-minute averages vary through the course of an hour, the comparison of two one-minute averages observed at two different locations will exhibit a larger degree of variability than, say, if hourly average winds were compared instead. A regression analysis, then, for a comparison of one-minute averages would show a better correlation if hourly averages were used in place of the one-minute values. The correlation coefficients in the analyses were, therefore, considered as lower-bound estimates of the climatological flow correlatability occurring historically between the two locations.

(2) Primary and Secondary Data Stations Selected for the Dual Station Modeling Technique

The inclusion of a second wind input in the modeling technique does not detract from the final estimate of site winds. If, for instance, a single station wind input is considered sufficient to initialize the flow field, the addition of a second wind input would not detract from the final site wind estimate. It was mentioned previously that as many as six of the candidate sites might require a second wind input in the modeling technique. This conclusion was more intuitive than objective because there is no real method of objectively determining apriori whether a second input wind is vital in the modeling technique.

It was considered better to conservatively assume that a site might require two wind input values and then employ the dual station modeling technique. Since the application of the program WNCOR to four years of secondary and primary station data is relatively inexpensive, approximately 40 dollars, it was decided to use the dual station modeling technique on all candidate sites. Table III-2 lists by site the primary and secondary data stations selected in the dual station modeling methodology. (It was found during the course of the study that the single station modeling technique is more applicable when the primary station is located considerably closer to the site than the secondary station. The single station modeling technique was used for two such sites: Russell, Kansas, and Huron, South Dakota.)

Hourly wind observations for two secondary data stations, Manistee (Ludington site) and Palm Springs (San Gorgonio Pass site) were not available on computer tape. Two years of hourly wind observation for both secondary stations were key-punched from microfilm copy for use in the regression analyses.

Six regression analyses were performed to determine primary and secondary station wind relationships for six of the eight candidate sites. Results of the analyses appear in Appendix B.

(3) The Modeling Function, f

Once the number of input stations has been determined, the next step in constructing a candidate site wind climatology is to determine the relationship between the primary station and candidate site winds, i.e., compute the modeling function, f . The modeling function is constructed by performing model runs on selected primary station, and corresponding secondary station's windspeed and direction values. The resulting site wind values can then be related through the modeling function to the inputted primary station's winds.

Table III-2

PRIMARY AND SECONDARY DATA STATUS USED IN THE
MODELING TECHNIQUE

Candidate Site	Type of Station Analysis	PRIMARY STATION				SECONDARY STATION			
		Station Name	Period of Record	No. of Years	Distance From Site	Station Name	Period of Record	No. of Years	Distance From Site
Boone, NC	dual	Bristol, TN	1/49-12/63	15	71 km	Hickory, NC	1/49-12/53	5	60 km
Montauk Pt, NY	dual	Westhampton, NY	5/51-4/64	13	61	New London, CT	5/51-12/54	3.6	32
Ludington, Michigan	dual	Muskegon, MI	1/48-12/62	15	81	*Manistee, MI	1/61-12/62	2	45
San Geronio Pass, CA	dual	March AFB, CA	1/49-12/63	15	63	*Palm Springs, CA	1/61-12/62	2	15
Russell, Kansas	single	Russell, Kansas	1/50-12/64	15	5	-----	----	-	--
Boardman, Oregon	dual	Pendleton, Oregon	1/50-12/64	15	78	Dalesport, WA	1/50-12/54	5	104
Holyoke, MA	dual	Chicopee Falls, MA	1/49-1/64	14	12	Westfield, MA	1/49-5/52	3.4	11
Huron, SD	single	Huron, SD	1/50-12/64	15	7.5	-----	----	-	--

* Data on microfilm

For a given primary station wind direction it can be shown that there will exist a unique site wind direction and speed value for every primary station wind speed. The modeling function for a given primary station wind direction can therefore be expressed in the form:

for wind speed:

$$V_s = A V_p + B \quad (\text{III-18})$$

for wind direction:

$$d_s = d_p + C V_p + D \quad (\text{III-19})$$

The first expression assumes that, for a given primary station wind direction, the candidate site wind speed will be linearly related to the primary station's wind speed. The second expression assumes that the wind direction at the candidate site equals the wind direction at the primary station plus a correction that is linearly dependent upon the primary station's wind speed. Since V_p and V_c are specified, both expressions represent two independent equations with two unknowns. Two model runs are therefore required per primary station wind direction to define the coefficients A, B, C, and D.

Through the course of the study it was found that the wind direction correction factor in Eq. (III-19) varied between 0.2 and 8.0 degrees, depending upon the amount of terrain slope in the vicinity of the candidate site. Wind direction values recorded by the National Weather Service and the military, over a fifteen-year span, are based on the 16-point compass. The natural error occurring within the primary station wind direction, d_p , is plus or minus 11.25 degrees. It was unnecessary, therefore, to include the correction factor expression in Eq. (III-19), since the limits of the correction factor fall within the error limits of the values for the primary station's wind directions. So the final expression of the modeling function, f, is:

$$V_{si} = A_i V_{pi} + B_i \quad (\text{III-20})$$

$$d_{si} = d_{pi} \quad (\text{III-21})$$

where i = wind direction index (on a 1- to 16- point compass).

(4) Construction of the Modeling Function, f

The modeling functions constructed in this study were designed to express candidate site 150-ft (hub-height) winds in terms of 150-ft primary station winds. The functions are constructed by inputting 150-ft primary station winds into the air flow model to compute the 150-ft candidate site winds. The modeling function coefficients A_i and B_i are computed for a given primary station wind direction from two model runs inputting two different primary station's wind speeds at the 150-ft level. Equation III-20, therefore, expressly relates candidate site and primary station winds 150 ft above ground level (agl).

Two model runs are required per primary station wind direction to determine the values of the coefficients A_i and B_i . The maximum number of model runs for any given site would be two times sixteen or thirty-two model runs, defining coefficients A_i and B_i for sixteen points of the compass. Originally it was anticipated that eight model runs would sufficiently describe the coefficients. It was assumed that the variations of A_i and B_i with direction were gradual enough that eight model runs would suffice to describe the trend of A_i and B_i with direction.

In order to test the assumption, the candidate site located near Holyoke, Massachusetts, was selected and nine model runs were performed to determine the maximum number of runs actually required per site. The Holyoke candidate wind energy site was selected because it exhibits the largest terrain gradients in the site's immediate neighborhood. The number of model runs required to define the coefficients for Holyoke would establish an upper-bound estimate of the number of runs required for the remaining sites. Table III-3 lists all of the model runs performed on the Holyoke candidate site. Listed are nine primary station wind direction and speed input values and their corresponding modeled candidate site winds. Also listed are the A and B coefficients computed from the nine model runs.

Six model runs, two runs each for three selected primary station wind directions, were performed to determine the A and B values for the primary station's wind directions of north, south and west. It was anticipated that the maximum values of A and B would occur for flow directions with the largest upslope component while minimum values of A and B would occur for flow directions with the smallest upslope component. The Holyoke site exhibits the maximum near-site terrain gradient to the west and the minimum to the south, with a secondary minimum slope gradient to the north. The six model runs were, therefore, selected to provide a profile of maximum and minimum A and B coefficients versus direction. Three additional model runs for intermediate wind directions

Table III-3

MODEL RUNS FOR HOLYOKE, MASSACHUSETTS CANDIDATE SITE

Direction	150-ft Input Winds at Primary Station		150-ft Modeled Site Winds		Calculated Coefficient		Interpolated Coefficient	
	deg	m/s	deg	m/s	A	B	A	B
N	360.8	10.0	359.3	12.7				
	360.8	20.0	358.8	25.2	1.27	0	1.27	0
NNE							1.46	0
NE							1.62	0
ENE							1.72	0
E	090.3	10.0	098.2	17.5	1.75		1.76	0
ESE							1.72	0
SE	136.5	19.8	131.9	32.2			1.62	0
SSE							1.46	0
S	180.8	10.0	178.7	12.6				
	180.8	19.9	178.3	25.0	1.26	0	1.27	0
SSW							1.46	.131
SW							1.62	.262
WSW							1.72	.393
W	270.3	10.0	277.7	18.1				
	270.3	19.9	278.0	35.5	1.76	.524	1.76	.524
WNW							1.72	.393
NW	315.5	9.9	310.4	16.5	1.67		1.62	.262
NNW							1.46	.131

E, SE, and NW were performed to determine intermediate coefficient values occurring between the anticipated maximum and minimum values.

Three values of the B coefficient were obtained from the nine model runs; two values were zero, and the other was 0.524 mps. Intermediate values of B were interpolated linearly between the three calculated values for each 16-point wind direction. These values are listed in Table III-3. Five A coefficients were computed from the nine model runs. Figure III-9 graphically displays the five computed values, depicted on the graph by X's. These five points were fitted to a curve and intermediate values of A were computed from the expression for the curve:

$$A = 1.27 + 0.49 |\sin \theta| \quad ,$$

Where: θ = primary station wind direction degrees.

The plot of the curve is displayed in Figure III-9. The A values interpolated for each 16-point wind direction are given in Table III-3.

This modeling procedure of determining the A and B coefficients of the modeling function, f, was performed in a similar manner for each candidate wind energy site. The number of model runs required to define the function varied from a minimum of four runs to a maximum of nine runs per site depending upon the complexity of the terrain at the site.

3. The Climatology Development Methodology

The modeling functions developed in the Modeling Methodology are applied in the Climatology Development Methodology to generate a candidate site hub-height wind climatology. A climatology generating program, Program WIND, applies the modeling functions to hourly values of primary station winds to generate hourly estimates of candidate site hub-height wind values. These estimates are used in the program to generate the specific wind character summaries required in this study. In the following paragraphs, the procedures and techniques used in the Climatology Development Methodology are presented and discussed. Also presented are examples of the wind character summaries generated from the climatology generating program, Program WIND.

a. The Methodology

As mentioned previously, the modeling functions, Eq. (III-20, 21) specifically relate candidate site and primary station winds at the 150-foot

Figure III-9. COMPUTED AND INTERPOLATED VALUES OF THE A COEFFICIENT VERSUS PRIMARY STATION WIND DIRECTION

Candidate Site = Holyoke, Massachusetts
 Primary Station = Chicopee Falls, Massachusetts

level. Most primary station winds are measured at elevations less than 150 ft, ranging from 15 ft to as high as 115 ft in this study. The primary station's winds at 150 ft for any given hour are computed in the methodology by applying a power law wind relationship to the hourly winds measured at anemometer height. The exponent of the power law relationship is determined for each hourly wind value from the hourly stability computed via the STAR method (discussed in c., following on this page).

Once the 150-ft primary station wind has been determined, the hourly candidate site wind at hub-height is computed by applying the modeling function associated with the observed primary station wind direction, i , Eq. (III-20), to the extrapolated primary station's 150-ft wind value. The hourly site wind estimate is then summarized into five hub-height wind character summaries.

b. The Data Base

The wind character summaries are generated from 15 years of hourly primary station surface observations. The 15-year data base consists of hourly WBAN NWS or military surface observations coded on magnetic tape in the National Climatic Center (NCC), card deck 1440, TDF 14 tape format. The period of record selected for all primary data stations comprised a 15-year period within the period January, 1948 to December, 1964. NWS station tape data records later than 1964 contain three hourly surface observations, as opposed to hourly, and were therefore not used in the study.

c. The Climatology-Generating Program, WIND

The candidate site wind character summaries are generated in the climatology-generating program, WIND, by reading hourly surface observations from the primary station's data base. Hourly values of primary station wind speed, wind direction, cloud ceiling height, and cloud cover are read and hourly candidate site hub-height wind values are computed using the method outlined above.

The program consists of a main program, WIND, and two subroutines, SUN and STAR. Subroutine SUN constructs monthly tables of insolation class values. These values are used in subroutine STAR to compute the hourly stability class for determining the power law exponent. A listing of program WIND and subroutines SUN and STAR appear in Appendix A. A flow diagram illustrating the computational procedures incorporated in program WIND is given in Figure III-10.

PROGRAM WIND

Figure III-10. FLOW DIAGRAM, CLIMATOLOGY-GENERATING PROGRAM WIND.

(1) Computing the 150-foot primary station wind

The 150-ft primary station's winds are computed using a power law relationship:

$$V_{150} = V_h \left(\frac{150}{h} \right)^p, \quad (\text{III-22})$$

where h = station anemometer height in feet.

Since anemometer heights vary prior to 1965, program WIND updates the value of h in Eq. (III-22) each time the primary station's anemometer height changes. Values of h and dates of anemometer height change were obtained from "Station History" tabulations available through the NCC.

Values of the power law exponent, p , in Eq. (III-22) are determined in the program from the stability class computed by subroutine STAR. The hourly stability class, A-G, is computed from the solar insolation class determined by subroutine SUN and observed values of hourly cloud cover and cloud ceiling height using the Pasquill method outlined by Turner (Turner, 1963). The p value for the hour is selected from a table listing p values versus stability class:

Stability Class	A	B	C	D	E	F	G
p	0.10	0.15	0.20	0.25	0.30	0.35	0.40

The values of p by stability class were selected from a consensus of p values from the table provided by Sutton, p. 238 (1953), De Marrais (1959), and LeHau and Haugen (1960).

The power law expression, versus the logarithmic relationship, affords the opportunity of constructing a stability dependent wind profile. De Marrais in a study using wind observations recorded at the Brookhaven National Laboratory compared the differences in the wind profiles computed from both the power law and logarithmic law relationships (De Marrais, 1959).

De Marrais found:

"The logarithmic law generally shows larger errors than the power law and is better during superadiabatic regimes only... These findings show that the power law is generally more accurate than the logarithmic law. Because there appeared to be a systematic error in the logarithmic law."

De Marrais summarized his findings:

1. A reasonable representation of a wind profile can be obtained with the power law,
2. The logarithmic law requires an added parameter, viz. lapse rate, to give results comparable to those of the power law.

Johnson, in a similar study using winds observed at O'Neil, Nebraska found similar results (Johnson, 1959); Johnson found:

" . . . over prairie grass and over a snow surface the wind increased more rapidly than predicted by the logarithmic law while, except under strong inversion conditions, the data are well represented by a simple power law. "

The power law allows the ability to easily adapt a stability parameter to compute the wind profile. The logarithmic law without the stability correction mentioned by De Marrais does not afford this opportunity.

(2) Computing the candidate site hub-height wind

The hub-height candidate site winds are computed by applying the modeling function corresponding to the observed primary station wind direction in Program WIND. Sixteen values of A_i and B_i (Eq. III-20) determined from the modeling methodology are indexed in the program by primary station wind direction. The corresponding values of A_i , B_i for each hourly primary station wind direction are used to construct the linear modeling function (Eq. III-20). One hundred fifty foot primary station's wind speeds are substituted into the equation and the resulting hub-height site winds computed.

A two-second peak gust is computed for hub-height winds greater than or equal to 19 meters per second. The two-second gust is computed by multiplying the hub-height wind by a gust factor of 1.3. The 1.3 value represents the 90th percentile for a two-second gust from a one-minute mean wind speed at a height of 75 to 100 ft (Sissenwine, et al., 1973). The gust factor is applied only to wind speeds greater than or equal to 19 m/s to compute a gust value greater than or equal to the cut-out speed of 25 m/s.

(3) The wind character summaries

Examples of the wind character summaries generated for the candidate site at Holyoke, Massachusetts appear in Figures III-11 to III-15. A total of five summary types are generated by Program WIND. They are:

- Monthly and annual wind speed summaries
- Annual wind speed and direction summaries
- Seasonal and diurnal wind speed summaries
- Wind speed persistency summary
- A peak-gust frequency summary.

(a) Monthly and annual
wind speed summaries

Three tables generated by Program WIND relate candidate site wind speed monthly and annual occurrences. Figure III-11 lists average site wind speeds for two-meter-per-second wind speed intervals by month, by annual occurrence. (Annual summaries in this study present wind statistics cumulated over the entire period of record, over all months. They present an average for all years, not a yearly average). Also listed are the average wind speeds, by month, averaged over all hours of the month, for all months.

Two additional tables, not shown, are generated using the same format as Figure III-11. These tables contain wind speed percent and number frequency summaries by month, by wind speed groups.

(b) Annual wind speed and
direction summaries

Three additional tables generated by Program WIND summarize annual (total) wind speed occurrence by wind direction sector. Figure III-12 lists average site wind speeds for two-meter-per-second wind speed intervals by wind direction. The other two tables, not shown, present wind speed percent and number frequency by wind direction, by wind speed groups.

(c) Seasonal and diurnal
wind speed summaries

Five tables are generated by Program WIND to summarize seasonal and diurnal wind variability. Four tables present seasonal wind speed diurnal variability for the seasonal month combinations of December-February, March-May, June-August and September-November. The fifth table summarizes the annual diurnal wind variability. Figure III-13 presents the diurnal wind variability for December-February for the Holyoke candidate site. The top list of figures presents the average wind speed by two meter per second speed category for daytime, 0700-1800 LST; for nighttime, 1900-0600 LST; and for all hours (December-February). The remaining list of figures give the percent and number frequency of wind speed groups for the same time period intervals.

MONTH	CALM	01-02 (M/S)	03-04 (M/S)	05-06 (M/S)	07-08 (M/S)	09-10 (M/S)	11-12 (M/S)	13-14 (M/S)	15-16 (M/S)	17-18 (M/S)	19-20 (M/S)	21-22 (M/S)	23-24 (M/S)	25+ (M/S)	PER MO.
JAN	.00	2.12	3.63	5.53	7.46	9.46	11.45	13.49	15.56	17.62	19.56	21.59	23.54	28.49	8.43
FEB	.00	2.08	3.66	5.55	7.46	9.44	11.49	13.48	15.58	17.59	19.58	21.67	23.40	28.70	8.67
MAR	.00	2.22	3.65	5.56	7.51	9.46	11.52	13.51	15.58	17.59	19.59	21.60	23.49	27.75	9.36
APR	.00	2.18	3.70	5.57	7.52	9.42	11.50	13.56	15.56	17.55	19.63	21.59	23.49	28.57	9.52
MAY	.00	2.15	3.70	5.49	7.47	9.46	11.48	13.53	15.58	17.53	19.57	21.61	23.45	27.50	8.01
JUN	.00	2.19	3.66	5.54	7.49	9.44	11.47	13.53	15.48	17.42	19.65	21.54	23.52	27.32	7.24
JUL	.00	2.15	3.66	5.52	7.48	9.41	11.49	13.49	15.49	17.38	19.45	21.51	23.51	26.79	6.36
AUG	.00	2.18	3.65	5.50	7.47	9.40	11.44	13.53	15.45	17.40	19.54	21.62	23.69	26.89	6.11
SEP	.00	2.11	3.69	5.53	7.44	9.43	11.50	13.50	15.45	17.35	19.60	21.64	23.41	27.22	6.36
OCT	.00	2.12	3.69	5.54	7.48	9.44	11.46	13.50	15.59	17.48	19.58	21.57	23.42	27.66	6.88
NOV	.00	2.15	3.67	5.53	7.47	9.43	11.49	13.48	15.66	17.39	19.54	21.58	23.47	28.33	7.85
DEC	.00	1.99	3.63	5.54	7.51	9.44	11.50	13.48	15.52	17.50	19.59	21.60	23.50	28.27	7.91
ANN	.00	2.14	3.67	5.53	7.48	9.44	11.48	13.51	15.55	17.51	19.58	21.60	23.48	28.19	7.72

TOTAL OBSERVATIONS READ= 131343.

HOLYOKE, MASS. FROM CHICOPEE FALLS, MASS.
 AVERAGE WIND SPEED BY MONTH, BY WIND SPEED GROUP
 PERIOD OF RECORD: 1/ 1/49 TO 12/31/63

Figure III-11. MONTHLY AND ANNUAL WIND SPEED FREQUENCY SUMMARY

DIRECTION	CAEM	01-02 (M/S)	03-04 (M/S)	05-06 (M/S)	07-08 (M/S)	09-10 (M/S)	11-12 (M/S)	13-14 (M/S)	15-16 (M/S)	17-18 (M/S)	19-20 (M/S)	21-22 (M/S)	23-24 (M/S)	25+ (M/S)	PER DIR
N	.00	2.06	3.58	5.49	7.51	9.43	11.46	13.46	15.48	17.49	19.51	21.57	22.97	25.65	7.99
NNE	.00	2.23	3.73	5.59	7.40	9.39	11.48	13.74	15.79	17.32	19.61	21.60	23.08	27.68	8.97
NE	.00	2.20	3.69	5.53	7.57	9.34	11.35	13.36	15.54	17.32	19.43	21.73	23.69	29.71	9.00
ENE	.00	2.10	3.58	5.32	7.35	9.48	11.55	13.45	15.60	17.87	19.44	21.63	23.62	30.14	9.84
E	.00	2.13	3.61	5.35	7.46	9.65	11.60	13.61	15.52	17.16	19.14	21.22	23.95	29.93	9.05
ESE	.00	2.10	3.57	5.40	7.31	9.46	11.52	13.34	15.41	17.10	19.70	21.59	23.30	26.87	8.83
SE	.00	2.22	3.66	5.51	7.43	9.32	11.31	13.24	15.39	17.71	19.78	21.60	23.40	27.20	7.75
SSE	.00	2.18	3.70	5.60	7.39	9.27	11.53	13.73	15.52	17.27	19.55	21.69	23.57	25.92	7.75
S	.00	2.09	3.63	5.52	7.53	9.43	11.49	13.47	15.42	17.47	19.46	21.64	23.79	27.03	7.96
SSW	.00	2.16	3.79	5.62	7.47	9.43	11.54	13.72	15.68	17.23	19.60	21.50	23.20	26.71	10.18
SW	.00	2.30	3.68	5.58	7.50	9.34	11.24	13.34	15.52	17.78	19.40	21.61	23.63	27.31	9.63
WSW	.00	2.14	3.64	5.49	7.45	9.52	11.49	13.36	15.47	17.40	19.73	21.69	23.50	27.82	10.42
W	.00	2.14	3.67	5.52	7.50	9.47	11.56	13.43	15.33	17.08	19.48	21.12	23.45	28.30	11.57
WNW	.00	2.06	3.68	5.51	7.52	9.52	11.52	13.36	15.53	17.62	19.65	21.61	23.51	28.65	14.05
NNW	.00	2.13	3.68	5.54	7.54	9.46	11.43	13.40	15.49	17.72	19.51	21.78	23.61	27.96	12.13
NW	.00	2.14	3.72	5.57	7.44	9.41	11.54	13.65	15.71	17.59	19.65	21.55	23.21	26.69	10.13
ALL	.00	2.14	3.67	5.53	7.48	9.44	11.46	13.51	15.55	17.51	19.58	21.60	23.46	28.19	7.72

TOTAL OBSERVATIONS READ= 131343.

HOLYOKE, MASS. FROM CHICOPET FALLS, MASS.
 AVERAGE ANNUAL WIND SPEED BY DIRECTION, BY WIND SPEED GROUP
 PERIOD OF RECORD: 1/ 1/49 TO 12/31/63

Figure III-12. ANNUAL WIND DIRECTION FREQUENCY SUMMARY

Figure III-13. DIURNAL WIND VARIABILITY FREQUENCY SUMMARY

TIME		01-02	03-04	05-06	07-08	09-10	11-12	13-14	15-16	17-18	19-20	21-22	23-24	25+ BY DA/NT	ALL HRS	
CALM		115	117	178	185	185	146	122	108	88	56	30	25	41	19-06LST	16205
(M/S)		115	117	178	185	185	146	122	108	88	56	30	25	41	19-06LST	16205
ALL HRS		221	227	370	379	365	241	225	190	144	100	47	44	69	19-06LST	32427
(M/S)		221	227	370	379	365	241	225	190	144	100	47	44	69	19-06LST	32427
TIME		01-02	03-04	05-06	07-08	09-10	11-12	13-14	15-16	17-18	19-20	21-22	23-24	25+ BY DA/NT	ALL HRS	
CALM		115	117	178	185	185	146	122	108	88	56	30	25	41	07-18LST	16205
(M/S)		115	117	178	185	185	146	122	108	88	56	30	25	41	07-18LST	16205
ALL HRS		221	227	370	379	365	241	225	190	144	100	47	44	69	07-18LST	32427
(M/S)		221	227	370	379	365	241	225	190	144	100	47	44	69	07-18LST	32427

TOTAL OBSERVATIONS HEAD = 131345

WOLYUK, MASS. FROM CHICPEE FALLS, MASS.
 A) AVERAGE WIND SPEED BY SEASON, BY DAY/NIGHT, BY WIND SPEED GROUP
 B) PERCENT FREQUENCY OF HOURLY WIND SPEED GROUPS BY SEASON, BY DAY/NIGHT
 C) NUMBER FREQUENCY OF HOURLY WIND SPEED GROUPS BY SEASON, BY DAY/NIGHT
 SEASON: OCT-SEP
 PERIOD OF RECORD: 1/1/49 TO 12/31/65

[illegible]

TOTAL OBSERVATIONS HEAD= 131343.

MULYURT, MASS. FROM CHICOPEE FALLS, MASS.
FREQUENCY DISTRIBUTION OF THE NUMBER OF CONSECUTIVE HOURS
WITH WIND WITHIN SELECTED SPEED RANGES
PERIOD OF RECORD: 1/ 1/49 TO 12/31/65

Figure III-14. WIND SPEED PERSISTENCY SUMMARY

GUST SPEED (M/S)	25-29	30-34	35-39	40-44	45-49	50-54	55-59	60-64	65-69	70-74	75-79	80-84	85-89	90-94	95-99	100+
NUMBER OF CASES	4544	1720	534	254	40	39	3	5	0	1	0	0	0	0	0	0

TOTAL OBSERVATIONS READ= 131343.

HOLYOKE, MASS. FROM CHICOPEE FALLS, MASS.
 THE FREQUENCY DISTRIBUTION OF CALCULATED WIND GUSTS EXCEEDING 24 M/S
 PERIOD OF RECORD: 1/ 1/49 TO 12/31/63

Figure III-15. TWO-SECOND GUST
 FREQUENCY SUMMARY

(d) Wind speed persistency summary

One table is generated in Program WIND that summarizes the persistency of wind speeds less than or equal to four meters per second, greater than four meters per second, between ten and twenty-four meters per second, and greater than twenty-four meters per second. Figure III-14 presents the persistency summary for the candidate site at Holyoke, Massachusetts. The table lists the number of occurrences of wind durations for a specified wind condition. To illustrate: from the table, the winds at the Holyoke site remained greater than 4 m/s for over 73 consecutive hours seventy times in the fifteen year period.

(e) A peak-gust frequency summary

One table is generated in Program WIND to provide a frequency of wind gusts exceeding cut-out speed. Figure III-15 illustrates the two-second peak-gust frequency for wind speed gusts occurring above 25 m/s for the candidate site at Holyoke, Massachusetts. The number frequency gives the number of two-second gusts occurring within a speed group over the fifteen-year period.

(A total of thirteen tables are generated by Program WIND to provide the specific wind character summaries required in this study. All candidate site wind character climatologies generated by Program WIND for each site are presented in Appendix C.)

IV. RESULTS OF THE CLIMATOLOGY DEVELOPMENT METHODOLOGY

The methodology developed in this study to generate a candidate site wind climatology was applied to each of the eight candidate wind energy sites. This section presents the results of the Climatology Development Methodology (1) universal to all sites, and (2) specific to each candidate site. In the following paragraphs, a comparison between the maximum modeling function coefficient values and the near-site terrain gradient is presented for all candidate sites. Following this comparison, the methodology's results applicable to each individual site are presented by candidate site. The modeling procedures used in the methodology for each site are discussed, and the wind climatologies generated from the methodology are presented. The format of the presentation includes, for each site:

1. A site description, giving the geographic location, terrain features, and wind exposure of the candidate site.
2. A description of the data station selected, giving the locations and geographic settings of the primary and secondary stations and the reasons for their selection.
3. A presentation of the primary and secondary station wind relationship, showing the degree of wind correlation existing between the primary and secondary stations.
4. A description of the candidate site model domain showing the region modeled at each site and the grid terrain representation.
5. A presentation of the candidate site wind climatology presenting highlights of the wind climatology generated, the normalized velocity frequency curves, and a comparison of the primary station and candidate site wind climatologies.

A. The Modeling Functions, Findings Universal to All Candidate Sites

1. The A and B Coefficients

During analysis, the B coefficient of the modeling function expression, Eq. (III-20), equaled zero for all model runs with the exception of the candidate site at Holyoke, Massachusetts. For the Holyoke site, the B coefficient equaled zero for nine of the sixteen primary station wind directions and reached a maximum value of 0.524 meters per second. As a result, modeling functions applied in the climatology generating program WIND were reduced even further from the expressions given in Eq. (III-20). The final expression of the modeling functions used in the development program are:

$$V_{si} = A_i V_{pi} \quad (IV-1)$$

$$d_{si} = d_{pi} \quad (IV-2)$$

Thus, the modeling functions describe a linear relationship of site to primary station winds with a y-intercept of zero. Model runs inputting a calm primary station wind will necessarily result in a calm wind computed for the candidate site.

It is evident from Eq. (IV-1) that the frequency of calm winds in the site wind climatology will be equal to the frequency of calms occurring at the primary station. Also, the site wind climatology will equal the primary station wind climatology when the A coefficients equal, or nearly equal one. For A values greater than one, site wind speeds will be higher than the primary station winds and the site wind climatology generated will exhibit higher wind speed characteristics than those occurring at the primary station. The value of the A coefficients thus provides an indication of the similarity of the generated site wind climatology to the observed primary station wind climatology.

2. The A Coefficient Versus the Candidate Site Wind Climatology

The modeling function A coefficients computed for all eight candidate wind energy sites are presented in Figure (IV-1). The A coefficients computed from model runs for each candidate site are plotted versus primary station wind direction. A coefficient values for selected primary station wind directions are plotted on the graph as X. The A coefficients for intermediate primary station wind directions are represented on the graphs by curves fitted to the computed values.

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Figure IV-1. THE MODELING FUNCTION COEFFICIENT "A" VERSUS PRIMARY STATION WIND DIRECTION FOR ALL CANDIDATE SITES

Dividing both sides of the modeling function expression Eq. (IV-1) by the primary station wind speed, V_{pi} , gives an expression for the modeling function coefficient A:

$$A_i = \frac{V_{si}}{V_{pi}} \quad (IV-3)$$

The A coefficient for a given primary station wind direction is equal to the ratio of candidate site and primary station's wind speeds. For A coefficients equal to one the site wind speed equals the station wind speed and the site wind climatology will be identical to the primary station's wind climatology.

Five of the eight candidate sites modeled in this study show modeled wind speeds equaling 95 percent to 115 percent of the primary station wind speeds (see Figure IV-1). Two additional sites, Ludington and Boardman, have modeled winds equaling 85 percent to 93 percent of the winds occurring at their respective primary stations. Thus, for a primary station wind speed of 10 meters per second, seven candidate sites will have wind speed values ranging from 8.5 to 11.5 meters per second and four of the seven will have wind speeds ranging from only 10 to 11 meters per second.

The candidate site wind climatologies generated from the modeling functions for four candidate sites will therefore be almost identical to the wind climatologies exhibited at their respective primary stations. Additionally, three of the site wind climatologies will be very similar to the wind climatologies exhibited at their respective primary stations.

3. The A Coefficient Versus the Near-Site Terrain Gradient

The principal assumption used in generating a candidate site wind climatology in this study is:

- Variations in the velocity field between two locations arise entirely from the deflective influences of terrain surfaces.

Modeled candidate site winds showing little or no variations from the observed primary stations winds thus indicate that the terrain inputted into the model in the modeling procedure did not significantly affect the redirection of the air flow in the site vicinity.

As previously indicated, the maximum model coefficient values will occur for the primary station wind directions associated with the maximum site upslope flow. The candidate site selected to examine the relationship between the modeling function coefficient value and the near-site terrain gradient is located near Holyoke, Massachusetts. This site was selected because it exhibits the largest near-site terrain gradient. Consequently, Holyoke has the largest A coefficient values and exhibits the largest variation with primary station wind direction (Figure IV-1).

Table IV-1 presents a listing of the normalized maximum near-site terrain gradient occurring over a distance of 1 Δx and 3 Δx from the site location for each candidate site. The gradient values were obtained from the terrain representation inputted into the model. Therefore, they represent the maximum terrain gradient "seen" by the model. Also listed in the table are the scale sizes of the model domain cells used to represent the terrain configuration in block increments for each site. For comparison, the maximum A coefficients modeled for each site are included.

Figure IV-2 is a plot of the A coefficient versus the maximum near-site terrain gradient over 1 Δx from the site. It should be noted that the values of the terrain gradient appearing in Table IV-1 and Figure IV-2 are determined from the terrain representation inputted into the model. These values will generally vary from the actual terrain gradient in proportion to the model domain scale selected (Δx , Δy , Δz) and the terrain slope in the site vicinity. The scatter appearing in Figure IV-2 most likely arises from the variability between the terrain representation from one site to the next. In general, the terrain gradient representation will tend to underestimate the near-site terrain gradient for large domain scale values in mountainous regions. The question of terrain scale representation is addressed more fully in the following sections. The results of the Climatology Development Methodology, by candidate site, will also be presented.

B. Results of the Climatology Development Methodology, by Site

1. The Boardman Candidate Wind Energy Site

a. Site Description

The Boardman candidate site is located in the Pacific Northwest, in the northeast portion of the state of Oregon, within the Columbia River basin (Figure IV-3). The site is 18 km south of the Columbia River at the base of the foothills to the Blue Mountains. Its elevation is 212 m (695 ft), about 91 m

Table IV-1

TERRAIN SCALE REPRESENTATION VS. A COEFFICIENT

<u>Site</u>	<u>Δx</u> (m)	<u>Δz</u> (m)	<u>$\Delta z / \Delta x$</u>	Maximum Terrain Slope in Vicinity of Site		Maximum A Coefficient
				within 1 Δx m/1000m	within 3 Δx m/1000m	
Holyoke	480.0	30.48	.0635	381.0	169.3	1.76
Huron	215.4	4.57	.0212	63.6	28.3	1.10
Boone	1972.8	106.7	.0541	54.1	18.3	1.15
Boardman	2500.0	76.2	.0305	0	10.2	0.91
Montauk Pt.	2245.6	12.2	.0054	5.4	1.8	1.01
Russell	189.6	6.10	.0320	32.2	10.7	1.08
San Gorgonio	2000.0	152.4	.0762	76.2	50.8	1.09
Ludington	3254.0	12.2	.0038	18.7	6.2	0.87

Figure IV-2. THE MAXIMUM "A" COEFFICIENT VERSUS THE MAXIMUM NEAR-SITE TERRAIN GRADIENT.

Figure IV-3. THE BOARDMAN CANDIDATE WIND ENERGY SITE LOCATION

(300 ft) above the Columbia River Valley floor. The terrain at the site is smooth, sloping away from the site to the northeast through north, towards the river, and to the northwest at an average rate of 4 to 5 m/km (Figure IV-4). The terrain to the southeast through southwest slopes upwards away from the site at an average rate of 11.6 m/km towards the foothill region.

Figure IV-4 details the terrain contour corresponding to the Boardman site hub-height elevation, 258 m (the 850-ft dashed contour). Also detailed is the terrain contour corresponding to twice the hub-height elevation at the Boardman site, 305 m (the 1000-ft contour). The site is completely exposed at site hub-height level to the west-northwest, looking outwards into the river valley, through north, towards the river, and to the east-northeast, towards the eastern end of the river valley. The exposure becomes limited south of east, through south, and to the southwest by the higher terrain of the foothill region. The predominating flow direction should be up and down the valley, roughly parallel to the 303-m (1000-ft) contour.

b. Data Stations

The primary data station selected in the dual station modeling analysis is the NWS airport office, located at the Pendleton, Oregon airport, 78 kilometers due east of the Boardman site (Figure IV-3). The station is located in the southeastern portion of the Columbia River Basin at an elevation of 457 m (1500 ft) approximately 244 meters (800 ft) above the Boardman site. The Pendleton station is the closest observing station to the site and, in addition, has available over fifteen years of hourly surface observations on magnetic tape.

The weather service office at Pendleton airport is located in rolling country which slopes generally upwards toward the Blue Mountains about 24 km to the east and southeast. The station exposure is similar to the exposure at the site, being in the same river basin, with better exposure to the south.

The secondary station selected in the dual station modeling analysis is the NWS airport office at The Dalles, Washington, located 104 km west of the Boardman site (Figure IV-3). The Dalles station is located in the Columbia river valley as it narrows into the Columbia River Gorge through the Cascade Mountain Range (Figure IV-5). The Dalles station was selected in the analysis to provide an input wind west of the Boardman site. Figure IV-5 details the 305-m (1000-ft) contour in the vicinity of the station. The station elevation is 105 m (343 ft), 200 meters below the terrain highlighted by the darkened contour in Figure IV-5.

Figure IV-4. TERRAIN RELIEF IN THE VICINITY OF THE BOARDMAN CANDIDATE SITE

⊗ = Site Location

Highlighted Solid Contour = Twice Hub-Height Terrain Contour (305 m, 1000 ft)

Highlighted Dashed Contour = Hub-Height Terrain Contour (290 m, 950 ft)

Figure IV-5. TERRAIN RELIEF IN THE VICINITY OF THE SECONDARY DATA STATION, THE DALLES, WASHINGTON

○ = Station Location

Highlighted Contour = Terrain Elevation 200 m (660 ft) Above The Station Elevation, (1000-ft Contour)

The exposure at The Dalles is limited to the north and south due to low station elevation and the constriction in the Columbia River Valley by the Cascade Mountains. The flow at The Dalles should therefore be primarily through the river valley and be predominantly west to east or east to west.

c. Wind Correlation Analysis, Pendleton, Oregon and The Dalles, Washington

Program WNCOR was run on four years of simultaneous surface observations at Pendleton and The Dalles for the record period of 1 January 1957 to 31 December 1960. The results of the analysis are presented in Appendix B. The correlation coefficients for the wind speed regression analyses for four Pendleton wind direction quadrants are:

<u>Pendleton Wind Direction Quadrant</u>	<u>Correlation Coefficient</u>
Northeast	0.23
Southeast	0.11
Southwest	0.13
Northwest	0.42

The wind speeds at The Dalles are very valley-dependent, showing no relationship in value to the winds at Pendleton, for all Pendleton wind directions. In addition, examination of The Dalles wind direction frequency analyses shows distinct bimodal wind direction distributions for most of the Pendleton wind direction values.

The dominant east-west valley influence on the flow character at The Dalles disassociates the air flow within the canyon region from that occurring on the valley floor in the Columbia Basin. Consequently, the air flow within the canyon cannot be predicted from the Pendleton winds and initialization of the air flow within the canyon proper cannot be computed from the regression relationships. A single station modeling analysis, therefore, was employed in the climatology development methodology for generating the Boardman wind climatology. The winds at Pendleton were used to initialize the flow field in the Columbia River Basin within the model domain selected.

d. The Boardman Model Domain

The horizontal extent of the model domain selected in the Boardman modeling analysis is illustrated in Figure IV-6 by dashed lines. The domain size was selected to encompass the candidate site on the west and

Figure IV-6. THE HORIZONTAL MODEL DOMAIN SELECTED FOR THE BOARDMAN CANDIDATE SITE MODELING ANALYSIS

the primary station to the east. The domain extends to the south to include the north face of the Blue Mountains, and to the north to the lowest portion of the river basin. The maximum horizontal distance in the domain from east to west is 100 km, and 75 km from north to south. The maximum vertical dimension is 1219 m (4000 ft), encompassing the minimum domain elevation of 76 m at the valley floor to a maximum elevation of 1295 m in the Blue Mountains. The fluid and solid cell scale dimensions are the maximum horizontal and vertical distances divided by 40, 30, and 16; the maximum model domain scale. The dimensions of the terrain and fluid cells are:

	$\frac{\Delta x}{2500}$	$\frac{\Delta y}{2500}$	$\frac{\Delta z}{76.2}$
Scale Size (m)	2500	2500	76.2
Scale Size (ft)	8202	8202	250

The terrain within the Boardman model domain is represented by block increments of solid cells dimensioned 2500 m by 2500 m by 76 meters. The terrain representation for the Boardman site model domain is given in Figure IV-7. In the figure, the relative terrain elevation is represented by the number of vertical block increments, ΔZ . The difference in elevation between any two locations is obtained by subtracting the block increment number of the two locations and multiplying by Δz . The maximum domain scale in the vertical is 16. Terrain values represented by 16s in the terrain grid correspond to terrain features extending above the top of the model domain.

The maximum near-site terrain gradient at the Boardman site: (1) observed from maps and (2) represented by the model grid is shown below.

Measured from Maps			From the Terrain Grid	
Over 500 m	Over 1000 m	Over 8000 m	Over 1 Δx	Over 3 Δx
7 m/km	15 m/km	11.2 m/km	0 m/km	10.2 m/km

The terrain in the vicinity of the Boardman site is represented by a single solid cell 2.5 km square centered on the site location. The cell top surface, being flat, represents a constant site elevation extending $1/2 \Delta x$, 1250 m, from the site to the north, south, east, and west. The near-site terrain gradient thus equals zero over the surface of the single terrain cell out a distance $1/2 \Delta x$ from the site. For distances from the site greater than $1/2 \Delta x$, the adjacent terrain cells come into play, and the difference in elevation between the adjacent terrain cells establish the site terrain gradient for distances greater than 1250 m.

Figure IV-7. MODEL DOMAIN TERRAIN REPRESENTATION IN THE BOARDMAN MODELING ANALYSIS

The terrain in the vicinity of the Boardman candidate site has a slope gradual enough that the large horizontal terrain scale selected in the analysis does not detract from the site terrain representation within $1/2 \Delta x$ from the site. The terrain slope over a larger distance, 7 to 8 km, is sufficiently represented by the terrain grid; 10.2 m/km representing an observed gradient of 11.2 m/km.

e. The Boardman Candidate Site Wind Climatology

Six model runs were performed in the Boardman modeling analysis for four barrier incident wind directions of northeast, southeast, southwest, and northwest. The model coefficients computed from the model runs appear in Figure IV-1. These coefficients were incorporated in the climatology generating program, WIND, to generate the Boardman candidate site wind climatology from the Pendleton data base. Fifteen years of hourly surface observations were used for the record period 1 January 1948 to 31 December 1964. The wind character summaries generated from program WIND appear in Appendix C.

The normalized velocity frequency curve for the entire period of record, for all conditions at Boardman, is presented in Figure IV-8. The curve was constructed from the three Boardman wind speed frequency tables appearing in Appendix C. The abscissa and ordinate values of the curve were computed from the tables by the following expression:

$$y_i \text{ (ordinate value)} = \bar{V} * [P(V_i)]$$

$$x_i \text{ (abscissa value)} = V_i / \bar{V}$$

where

i = the two-meter-per-second wind speed interval
(14 intervals from 0-25 m/s)

V_i = the average wind speed occurring for each interval
(1st table)

$P(V_i)$ = the occurrence frequency of the velocity interval
(2nd table)

$\bar{V}$ = the 15-year average wind speed = 5.41 mps
(1st table)

Figure IV-8. THE BOARDMAN CANDIDATE SITE NORMALIZED VELOCITY FREQUENCY CURVE ($\bar{V} = 5.41$ mps)

The Boardman candidate site wind climatology generated in this study is quite similar to the wind climatology observed at the Pendleton airport station. The modeling functions computed from the modeling methodology for the Boardman site show close correspondence between the site and station's wind direction and speed values. As mentioned previously, the largest computed site station wind direction difference for all eight candidate sites is less than the natural error occurring on the observed 16-point primary station wind direction. The modeling function relating the site and primary station wind direction sets the candidate site wind direction value equal to the primary station's wind direction (Eq. IV-2). The wind direction frequency summaries for the Boardman site generated from the modeling function thus will be equal to the wind direction frequencies occurring at the Pendleton airport station.

The correspondence between the Boardman site hub-height wind speeds and the Pendleton 150-ft wind speeds can be determined by examining the A coefficients computed from the modeling analysis. The A coefficients computed for the Boardman candidate site are all less than one, and range in value from a maximum of 0.91 to a minimum of 0.88. The Boardman hub-height wind speed values thus computed from the modeling function, Eq. IV-2, will be equal to 88 to 91 percent of the 150-ft Pendleton winds. The Boardman wind speed summaries generated from the application of the modeling function in the climatology generating program will produce Boardman site wind speed summaries that represent a 9 to 12 percent wind speed reduction from the values observed at the Pendleton airport.

The primary reason for the decrease in wind speed values between the Pendleton station and the Boardman site arises from the elevation difference existing between the two locations, 244 meters. If it is assumed that the Pendleton 150-ft wind speed is identical to the Boardman free-air wind speed at the same elevation, 503 m (1650 ft) msl, the site hub-height wind speed, 244 m (800 ft) below, would be, using Eq. III-6, 69 percent of the 150-ft Pendleton winds. The A coefficient, using only the station-to-site height difference and a power law relationship, would be less than the A coefficient computed via the modeling technique. The modeling analysis thus reflects the height difference between the two locations, but to a lesser degree than an extrapolation downwards of the Pendleton winds via a power law relationship.

2. The Boone Candidate Wind Energy Site

a. Site Description

The Boone candidate wind energy site is located at the crest of the Blue Ridge Mountains near the northern boundary of Tennessee and North Carolina, in North Carolina (Figure IV-9). The site is located on top of a knob, 1.5 km northeast of the city of Boone. The knob comprises the eastern extent of a ridge oriented west-northwest / east-southeast, located to the north and northwest of Boone. The ridge and site overlook a mountain pass through the Blue Ridge Mountain crest. The knob is one of the highest terrain features in the vicinity of Boone. It overlooks lower elevations in all directions except west. The wind exposure at the site is excellent, unobstructed in all directions.

The terrain near the Boone candidate site is mountainous with a maximum elevation relief of approximately 460 m (1500 ft) from the top of the mountain ridge to the floor of the mountain pass, just west of Boone. The site is located atop of Howard Knob at an elevation of 1347 m (4420 ft). The terrain slopes away from the site in all directions, except west, at an average rate of 360 m/km (Figure IV-10).

b. Data Stations

The primary data station selected in the dual station modeling analysis is the NWS airport office located at the Tri-City airport, 28 km southwest of Bristol, Tennessee (see insert to Figure IV-9). The Tri-City station is the closest station to Boone with a 15-year data record available on magnetic tape. The station is located 71 km from the Boone candidate site, across the Blue Ridge Mountain crest to the west, beyond several intermediate mountain ranges. The station's elevation is 463 m (1520 ft), approximately 884 meters (2900 ft) lower than the Boone site elevation. The station is located in a broad valley oriented northeast to southwest, and paralleled by mountains to the west and the Blue Ridge Mountain Range to the east.

The secondary station selected in the dual station analysis is the NWS airport office at Hickory, North Carolina. The Hickory station is located in the Piedmont region of North Carolina, 60 kilometers south-southeast of the Boone candidate site. The station is the closest observing station to the site and has no major terrain features obstructing its exposure to the site. The station elevation at Hickory is 362 m (1190 ft), approximately 985 m (3232 ft) below the Boone candidate site. The terrain surrounding the station is gently rolling with an average

Figure IV-9. THE BOONE CANDIDATE WIND ENERGY SITE LOCATION, ⊗

Figure IV-10. TERRAIN RELIEF IN THE VICINITY OF THE BOONE CANDIDATE SITE

⊗ = Site Location

relief of 75 m (250 ft) up to the base of the Blue Ridge Mountains 30 km northwest of the station. The terrain slope increases from this point to an average rate of 22 m/km up to the mountain pass region below the candidate site.

The station at Hickory was selected in the dual station modeling analysis to provide an input wind in the modeling analysis on the east side of the Blue Ridge Mountain crest. The winds at Hickory inputted into the modeling analysis will supplement the initial flow field constructed from the winds at the Tri-City airport. The initial flow field constructed from the Tri-City winds will be representative of the flow field west of the Blue Ridge crest, but will probably not be representative of the field on the east side of the crest in the Boone site vicinity. A second wind input, at Hickory, is therefore required to supplement the construction of the initial flow field in the vicinity of the Boone candidate site. The Hickory station is the closest observing station to the site, and has available five years of hourly surface observations on magnetic tape.

c. Wind Correlation Analysis, Bristol,
Tennessee and Hickory, North Carolina

Program WNCOR was run on three years of simultaneous surface observations at Bristol and Hickory for the record period 1 January 1949 to 31 December 1951. The results of the analysis are presented in Appendix B. The correlation coefficients for the wind speed regression analyses for four Bristol wind direction quadrants are:

<u>Tri-City Wind Direction Quadrant</u>	<u>Correlation Coefficient</u>
Northeast	0.41
Southeast	0.34
Southwest	0.28
Northwest	0.50

Examination of the wind speed regression and the delta wind direction frequency analyses show that the winds at the Hickory and Tri-City airports are not sufficiently related to provide an input wind relationship for the dual station modeling analysis. The Blue Ridge Mountains lying between the two stations are responsible for the low degree of correlatability between the Hickory and Tri-City wind directions and wind speed values. A single station modeling analysis was therefore selected to estimate the Boone site winds in the climatology-generating methodology.

The primary station used in the Boone single station modeling analysis is the airport office located at Hickory, North Carolina. The original station, Bristol, was not used in the analysis primarily because of its location relative to the Boone candidate site and the crest of the Blue Ridge Mountains. The station at the Tri-City airport near Bristol is located on the opposite side of the mountain crest beyond several intermediate mountain ranges lying between the station and the site. It was decided that winds observed at the Tri-City airport could not initialize the air flow in the vicinity of the candidate site, on the opposite side of the crest. The air flow had to be initialized from a station located on the same side of the crest. The station at the Hickory airport was therefore selected as the primary station in the single station modeling analysis.

d. The Boone Model Domain

(1) The domain dimensions and scale sizes

The horizontal extent of the model domain selected in the Boone modeling analysis is illustrated in Figure IV-11 by dashed lines. The domain size was selected to encompass the terrain features in the vicinity of the site to the north, and the Piedmont region in the vicinity of the primary station to the south. The maximum domain dimensions are 78.9 km north and south, 59.2 km east and west, and 1707 m in the vertical. The scale dimension thus of the fluid and solid cells in the model domain are:

	<u>Δx</u>	<u>Δy</u>	<u>Δz</u>
Scale size (m)	1973	1973	106.7
Scale size (ft)	6473	6473	350

(2) Terrain representation

The terrain within the model domain is represented by block increments of solid cells dimensioned 1973 m by 1973 m by 106.7 m. The terrain representation for the Boone site model domain is given in Figure IV-12. The maximum near-site terrain gradient of the Boone site (1) observed from maps and (2) represented by the terrain grid is:

<u>Measured from Maps</u>		<u>From the Terrain Grid</u>	
Over	Over	Over 1 Δx	Over 3 Δx
500 m	1000 m	(1973 m)	(5919 m)
360 m/km	240 m/km	54.1 m/km	18.3 m/km

Figure IV-11. THE HORIZONTAL MODEL DOMAIN SELECTED FOR THE BOONE CANDIDATE SITE MODELING ANALYSIS
 — — = MODEL DOMAIN BOUNDARIES

Figure IV-12. MODEL DOMAIN TERRAIN REPRESENTATION IN THE
BOONE MODELING ANALYSIS

The terrain in the vicinity of the Boone site is represented by a single solid cell 2 km square centered on the site location. The terrain in the vicinity of the site within one kilometer in all directions from the site is thus represented by a flat surface. The elevation of the surface, the vertical grid number, is determined by averaging the terrain elevation over the grid square, 3.9 square kilometers. The average height assigned to the square representing the Boone site is 1090 m (3575 ft). This value represents the average terrain height of the area encompassing Howard Knob and the adjacent valley regions. The knob and the valleys and their terrain gradients are therefore averaged over and are consequently not represented by the terrain grid.

(3) The terrain blocking effect

The representation of terrain features important in the modeling analysis is dependent upon the scale size of the terrain cells. The scale size, in turn, is dependent upon the size of the model domain and, therefore, the distance between the site and primary station. For large station-to-site distances the horizontal terrain scale, Δx and Δy , will be large, and sharp terrain features will be smoothed by terrain averaging in the terrain grid. This "blocking effect" is illustrated in Figure IV-13. The figure shows the terrain grid representation for the same terrain features for two different site-to-station distances, 7.5 km and 63 km. The horizontal distance scale, Δx , for both distances is 250 m and 2000 m, respectively. The terrain represented by the terrain cells for the shortest site-to-station distance details the terrain relief in the vicinity of site S. The hill and valley and terrain gradients in the vicinity of the site are adequately represented by the block representation. The same hill and valley are averaged over by the larger block size associated with the larger station-to-site distance. The gradients represented by the larger blocks over one Δx are equal to the height difference of the average terrain relief represented by the block surfaces. The maximum near-site terrain gradient thus represented by the Boone terrain and over one Δx (54 m/km) does not adequately represent the actual maximum terrain gradient down the east face of Howard Knob (360 m/km).

The blocking effect is a relative phenomenon largely dependent upon the terrain relief. For the same large station-to-site distance, consider two terrain configurations - first, for mountainous regions in the site vicinity, such as Boone, the blocking effect smooths the terrain gradient near the site. For the same station distance, a second type of terrain configuration, smooth or gently sloping at the site such as Boardman, the large terrain cells will not misrepresent the near-site terrain gradient.

Figure IV-13. TERRAIN REPRESENTATION VERSUS SITE-TO-STATION DISTANCE (The Blocking Effect)

The Boardman site does have mountainous terrain in the model domain, but the terrain in the vicinity of the Boardman site is not mountainous and is therefore not smoothed.

e. The Boone Candidate Site Wind Climatology

Eight model runs were performed in the Boone modeling analyses for six barrier incident wind directions: north, northwest, southwest, southeast, east, and northeast. The modeling function coefficients computed from the model runs appear in Figure IV-1. These coefficients were incorporated in the climatology-generating program; WIND, to generate the Boone candidate site wind climatology from the Hickory data base. Five years of hourly surface observations were read for the record period 1 January 1949 to 31 December 1953. The wind character summaries generated from program WIND appear in Appendix C. The normalized velocity frequency curve for all conditions at Boone is presented in Figure IV-14.

The Boone candidate site wind climatology generated in this study is quite similar to the wind climatology observed at the Hickory airport station. The wind direction frequency summaries at the site will be identical to those occurring at the airport station, for reasons mentioned in the discussion of the Boardman site wind climatology. The A coefficients computed for the Boone candidate sites vary from a maximum of 1.15 to a minimum of 0.96. The Boone hub-height wind speed values thus will be equal to 96 percent to 115 percent of the 150-ft wind speed values at Hickory. The Boone wind speed summaries represent an average five percent increase over the Hickory climatological wind speed values.

The similarity in the two climatologies, as evidenced by the modeling function coefficients, indicates the terrain inputted in the model domain did not affect appreciably the air flow between the candidate site and primary station. A terrain dependency is evident in the variation of A versus primary station wind direction. The A coefficients reach a maximum value of 1.15 for wind directions, east-northeast and west-southwest, representing the largest upslope flow component in the site vicinity. The A values reach a minimum value of 0.96 for flow directions along the Blue Ridge Mountain crest. The magnitude of the maximum A value, though, will be underestimated primarily due to the lack of near-site terrain gradient representation in the terrain grid. The lack of representation, as mentioned previously, arises from the large site-to-station distance occurring between the site and the primary station, Hickory.

Figure IV-14. THE BOONE CANDIDATE SITE NORMALIZED VELOCITY FREQUENCY CURVE ($\bar{V} = 3.64$ mps)

The location of the primary station relative to the candidate site is important, but it is possible for the primary station to be located too close in mountainous regions. Possible localized influences may decouple the airflow in the station vicinity from the overall general airflow that needs to be modeled. If the primary station in the Boone modeling analysis were located at the base of Howard Knob, at the bottom of the valley, the winds would probably be quite different from those observed at the Hickory airport. The air flow would more than likely be strongly valley-dependent and would therefore exhibit a strong bimodal direction distribution. With the small-scale distance arising from the small station-to-site distance, the terrain in the site vicinity would be sufficiently represented by the block cell. The site winds modeled to the terrain boundaries would be computed from the initial flow field constructed from the valley winds. The winds computed for the site will be representative as long as the winds observed in the valley are not decoupled from the air flow aloft. Such a decoupling often occurs, especially in mountain terrain, e.g., the mountain-valley wind.

The best location for an input wind in mountainous terrain is either atop of a mountain ridge or in a broad valley region where the airflow measured is not susceptible to any localized mesoscale effects that decouple the observed air flow from the overall general air flow pattern. The Hickory airport station is located in a region that is unobstructed to the general airflow. The initial flow field constructed from the Hickory winds will be representative of the general climatological flow over the entire region modeled.

There is uncertainty whether the climatology generated for the Boone site is representative of the overall wind power spectrum exhibited at the Boone site. There is some indication in the wind correlation analyses that the climatological airflow observed at Hickory is similar in magnitude to the airflow occurring on the other side of the candidate site, at the Tri-City airport. The wind vectors at the two stations are not correlatable in time, but the flow magnitude is comparable if the scatter produced by migratory (time-dependent) synoptic-scale and mesoscale circulation systems is reduced.

The time-dependent statistics in the Boone wind climatology (wind persistency summaries, diurnal wind summaries, and the gust summary) will probably be biased towards the Hickory wind climatology, because of the lack of local, near-site terrain representation. It is possible, though, that the wind speed summaries might be more representative of the average wind conditions occurring at the Boone site.

3. The Holyoke Candidate Wind Energy Site

a. Site Description

The Holyoke candidate wind energy site is located in New England, in Massachusetts, five km north-northwest of the city of Holyoke (Figure IV-15). The site is located atop of the Mount Tom Mountain Range overlooking the Connecticut River valley to the east and the Mahan River valley to the west. The Holyoke candidate site is located 1.4 km north of Mount Tom on Deadtop at an elevation of 335 m (1100 ft).

The terrain in the vicinity of the Holyoke site slopes sharply away from the site to the east and west at an average rate of 365 m/km, down 260 m to the river valley floors. The terrain to the north and south slopes away from the site at varying rates, along the crest of the Mount Tom Range (Figure IV-16). Deadtop is the second highest point on the Mount Tom range. Exposure at the site is excellent in all directions.

b. Data Stations

The primary station selected in the dual station modeling analysis is the Air Force office at the Chicopee Falls/Westover AFB airport. The Chicopee Falls AFB station is the closest observing station to the site with fifteen years of data record on magnetic tape. The station is located 12 km east-southeast of the Holyoke site in the Connecticut River valley. The station is located at an elevation of 74 m (244 ft), approximately 261 m (856 ft) below the Holyoke site. The terrain in the vicinity of the Chicopee Falls AFB station is flat with little or no terrain relief. The station is well exposed in all directions with no terrain features obstructing the station's exposure to the site.

The secondary station selected in the analysis is the NWS airport office at Barnes Municipal airport, located just north of Westfield, Massachusetts. The secondary station is located on the west side of the Mount Tom Range in the Mahan River Valley, approximately 11 km south-southwest of the Holyoke site. The station is located at an elevation of 82 m (270 ft), approximately 253 m (830 ft) below the Holyoke site. The terrain in the vicinity of Westfield is flat with only minor variations. The station is exposed to all wind directions, and no terrain features obstruct the station's exposure to the site.

The primary and secondary stations selected in the modeling analysis provide excellent initialization of the air flow field on both sides of the candidate site. Both stations are located in strategic positions near the center of the river valley floors, within 15 km of the site.

Figure IV-15. THE HOLYOKE CANDIDATE WIND ENERGY SITE LOCATION

Figure IV-16. TERRAIN RELIEF IN THE VICINITY OF THE HOLYOKE CANDIDATE SITE

⊗ = Site Location

c. Wind Correlation Analysis, Chicopee Falls and Westfield

Program WNCOR was run on three years of simultaneous surface observations at Chicopee Falls and Westfield for the record period 1 January 1949 to 31 December 1951. The results of the analysis are presented in Appendix B. The correlation coefficients for the wind speed regression analyses for four Chicopee Falls wind direction quadrants are:

<u>Chicopee Falls Wind Direction Quadrant</u>	<u>Correlation Coefficient</u>
Northeast	0.70
Southeast	0.70
Southwest	0.65
Northwest	0.69

Examination of the wind speed regression and delta wind direction frequency analyses show that the winds at Westfield are climatologically correlated to the winds occurring at Chicopee Falls. The wind speed and wind direction correlation analyses show a close correspondence between the wind directions and wind speeds at the two stations. All delta wind direction frequency analyses show a nearly normal frequency distribution centered around the zero directional difference. The majority, 70 percent, of all surface wind directions observed at Westfield for the three year period were within 23 degrees of the wind direction observed at Chicopee Falls. The wind speed regression analysis for all wind speeds observed at Westfield show a 0.72 correlation with the wind speeds observed at the Chicopee Falls AFB station. The dual station modeling technique was therefore used in the Holyoke site modeling analysis. Wind direction and speed values were selected for the primary station at Chicopee Falls and corresponding Westfield wind speed and direction values were computed from the regression relationships. These values were then inputted into the Holyoke model domain to compute the Holyoke candidate site hub-height winds.

d. The Holyoke Model Domain

(1) The domain dimensions and scale sizes

The horizontal extent of the model domain selected in the Holyoke modeling analysis encompasses the Chicopee Falls AFB to the east, the Barnes municipal airport to the west, and the candidate site to the north, Figure IV-15. The maximum domain dimensions are 14.4 km north and south, 19.2 km east and west, and 488 m in the vertical. The scale dimensions of the fluid and solid cell in the model domain are:

	<u>Δx</u>	<u>Δy</u>	<u>Δz</u>
Scale Size (m)	480	480	30.48
Scale Size (ft)	1575	1575	100

(2) Terrain representation

The terrain within the model domain is represented by block increments of solid cells dimensioned 480 m by 480 m by 30.5 m. The terrain representation for the Holyoke model domain is given in Figure IV-17. The maximum near-site terrain relief at the Holyoke site (1) observed from maps and (2) represented by the terrain grid are:

<u>Measured from Maps</u>		<u>From the Terrain Grid</u>	
Over	Over	Over 1 Δx	Over 2 Δx
500 m	1000 m	(4800 m)	(960 m)
262 m	280 m	183 m	244 m

The block representation of the peak of Deadtop does slightly average the site terrain elevation over a one-quarter square kilometer area. The site elevation represented by the site grid square (Figure IV-17) is equal to 305 m (1000 ft), one hundred feet less than the actual elevation at the site. The terrain relief thus computed over 1 Δx from the site is less than the actual relief computed from the unaveraged site elevation. The terrain grid does adequately represent the near-site terrain gradient within 2 Δx , 960 m, of the site.

e. The Holyoke Candidate Site Wind Climatology

Nine model runs were performed in the Holyoke modeling analyses for six barrier incident wind directions: north, northwest, west, south, southeast, and east. The modeling function coefficients computed from the model runs appear in Figure IV-1. These coefficients were incorporated in the climatology generating program, WIND, to generate the Holyoke candidate site wind climatology from the Chicopee Falls AFB data base. Fifteen years of hourly surface observations were read for the record period 1 January 1949 to 31 December 1963. The wind character summaries generated from program WIND appear in Appendix C. The normalized velocity frequency curve for all conditions at the Holyoke candidate site is presented in Figure IV-18.

The Holyoke candidate site wind climatology atop of the Mount Tom Range is significantly different in wind speed character than the wind climatology observed in the river valleys below. The modeling functions computed from the Holyoke modeling analysis show that the site wind directions are equal to the wind directions observed at Chicopee Falls, but the site wind speeds are as much as 27 to 76 percent higher than the wind speeds observed at the Chicopee Falls AFB.

The similarity found in the modeling analysis between the wind directions at the site and Chicopee Falls is consistent with the wind direction distributions found between the primary and secondary stations, located on both sides of the mountain range. The flow direction being climatologically the same on both sides of the Mount Tom Range will more than likely be the same climatologically at the site, less than 15 km away.

Figure IV-17. MODEL DOMAIN TERRAIN REPRESENTATION IN THE HOLYOKE MODELING ANALYSIS

Figure IV-18. THE HOLYOKE CANDIDATE SITE NORMALIZED VELOCITY FREQUENCY CURVE ($\bar{V} = 7.72$ mps)

The modeling analysis for the Holyoke site indicates a large terrain dependency on the values of the modeling function coefficients versus primary station (and candidate site) wind direction. The A coefficients, (Figure IV-1) exhibit two maxima associated with the site wind directions of east and west. These directions correspond to the east and west faces of the Mount Tom Range where the largest terrain gradients in the vicinity of the site are found. The values of the A coefficient decrease north and south as the component of flow orthogonal to the mountain face decreases. The minimum A values are reached for site wind directions of north and south, corresponding to flow directions parallel to the Mount Tom Range.

The Holyoke candidate site wind climatology generated in this study will exhibit the same wind direction occurrence frequency as that observed at the Chicopee Falls AFB. The wind direction and speed character summaries generated for the Holyoke site will exhibit the same wind direction character as that observed at Chicopee Falls, but will exhibit a higher wind speed character dependent upon wind direction. Strong post-frontal west to northwest winds at the site will be as much as 76 percent higher in magnitude than post-frontal winds observed at Chicopee Falls, while northerly and southerly winds at the site will generally average around 27 percent higher.

4. The Huron Candidate Wind Energy Site

a. Site Description

The Huron candidate site is located in the southeastern portion of South Dakota, approximately 8 km northeast of the city of Huron, Figure IV-19. The site is located atop a small bluff overlooking the James River at an elevation of 396 m (1300 ft). The site is approximately 19 m (62 ft) above the James River floodplain to the northeast through southeast. The terrain to the southwest, through south, to the northeast lies at roughly the same elevation as the site. The terrain at the site is flat with only minor variations due to the river geography. The exposure at the site is excellent in all directions.

b. The Data Stations

The primary data station selected in the modeling analysis is the NWS office at Howe's municipal airport, located 7.5 km southwest of the Huron candidate site. It is the closest observing station to the site, and in addition, has over 15 years of hourly surface observations available on magnetic tape. The next closest station to the site is 72.5 km from the site near the city of Mitchell, South Dakota. Hourly surface

Figure IV-19. THE HURON CANDIDATE WIND ENERGY SITE LOCATION

observations recorded at Mitchell are not available on magnetic tape. Consequently, the station of Mitchell cannot be used in the analysis. The third closest station to the Huron candidate site is located 96 km away, near the city of Watertown, South Dakota. Hourly surface observations recorded at Watertown are available on magnetic tape, but the data record available is only 6.5 years. So, consequently, the station at Watertown cannot be used as the primary data site in the Huron modeling analysis.

Since the primary station selected in the Huron modeling analysis is considerably closer than the other candidate data stations, it was decided to use only the single station at Huron to initialize the model flow field. It can be shown from Eq. III-4 that secondary station input values will have little effect on initializing the air flow in the site vicinity when the distance, d , from the secondary station and candidate site is much larger than the distance separating the site and the primary data station. The single station modeling analysis was therefore used in the Huron candidate site climatology development methodology.

c. The Huron Model Domain

(1) The domain dimensions and scale sizes

The horizontal extent of the model domain selected in the Huron modeling analysis encompasses the Howe municipal airport to the west and the Huron site to the northeast, Figure IV-19. The maximum domain dimensions are 8.6 km east and west, 6.5 km north and south, and 73 m in the vertical. The scale dimension of the fluid and solid cells on the model domain are:

	Δx	Δy	Δz
Scale Size (m)	215.4	215.4	4.57
Scale Size (ft)	707	707	15

(2) Terrain representation

The terrain within the model domain is represented by block increments of solid cells dimensioned 215 m by 215 m by 4.6 m. The terrain representation for the Huron model domain is given in Figure IV-20. The maximum near-site terrain relief at the Huron site (1) observed from maps and (2) represented by the terrain grid are:

Figure IV-20. MODEL DOMAIN TERRAIN REPRESENTATION IN THE HURON MODELING ANALYSIS

<u>Measured from Maps</u>		<u>From the Terrain Grid</u>	
Over	Over	Over 1 Δx	Over 2 Δx
500 m	1000 m	(215 m)	(430 m)
23 m	23 m	13.7 m	18.3 m

The small station-to-site distance, along with the relatively flat terrain over the model domain, results in a detailed representation of the terrain features by the terrain grid. The near-site terrain gradients at the Huron candidate site are adequately represented by the terrain grid squares in the terrain grid representation.

d. The Huron Candidate Site Wind Climatology

Five model runs were performed in the Huron modeling analyses for four barrier incident wind directions: northeast, southeast, west, and northwest. The modeling function coefficients computed from the model runs appear in Figure IV-1. These coefficients were incorporated in the climatology generating program, WIND, to generate the Huron candidate site wind climatology from the Huron airport data base. Fifteen years of hourly surface observations were read for the record period 1 January 1950 to 31 December 1964. The wind character summaries generated from program WIND appear in Appendix C. The normalized velocity frequency curve for all conditions at the Huron candidate site is presented in Figure IV-21.

The Huron candidate site wind climatology generated in this study is nearly identical to the wind climatology observed 7.5 km away at the airport office at Howe's municipal airport. The Huron site winds computed in the modeling analysis ranged from four to ten percent higher than the winds observed at the airport station. The site wind direction values computed are equal to the wind directions observed at the airport station. The wind character summaries thus generated for the candidate site at Huron will be equal with respect to the direction occurrence frequency, and be slightly higher with respect to the wind speed character than those values observed at the Howe municipal airport.

The terrain inputted into the model domain, as mentioned previously, is quite representative of the terrain in the model domain. The results of the Huron modeling analysis therefore indicates that the terrain between the airport station and the candidate site does not appreciably change the flow characteristics between both locations at hub-height.

Figure IV-21. THE HURON CANDIDATE SITE NORMALIZED VELOCITY FREQUENCY CURVE ($\bar{V} = 8.15$ mps)

5. The Ludington Candidate Wind Energy Site

a. Site Description

The Ludington candidate wind energy site is located in Michigan, 7.5 km south of the city of Ludington, Figure IV-22. The site is located approximately 150 meters inland from Lake Michigan atop a bluff overlooking the lake to the north-northwest, through west, and to the south. The site elevation is 250 m (820 ft) msl, approximately 73 m (250 ft) above lake level.

The terrain atop the bluff is comprised of rolling hills sloping downwards then upwards inland from the site. The highest terrain in the vicinity of the site is located 800 to 1300 meters east of the site at an elevation of 268 m (880 ft), approximately 18 m (60 ft) higher than the site. The wind exposure at the site is excellent in all directions, and is open to the lake fetch to the northwest through south.

b. Data Stations

The primary station selected in the dual station modeling analysis is the NWS airport office located at Muskegon, Michigan, 81 kilometers south of the Ludington candidate site. The Muskegon airport station is the closest observing station to the site with 15 years of data record on magnetic tape. The Muskegon airport is located 5.5 km inland from Lake Michigan at an elevation of 191 m (628 ft), 59 m (192 ft) lower than the Ludington site. The terrain in the vicinity of the Muskegon airport station is flat, and the wind exposure is excellent in all directions.

The secondary station selected in the analysis is located at the Manistee-Blacker airport northeast of the city of Manistee, Michigan, approximately 46 km north-northeast of the Ludington site. The Manistee station is the closest observing station to the site, and is located 5 km inland from the shore of Lake Michigan. The station elevation is 189 m (619 ft) msl, approximately 61 m (200 ft) lower than the Ludington site. The terrain in the vicinity of the airport station is flat, and the wind exposure is excellent in all directions.

c. Wind Correlation Analysis, Muskegon and Manistee, Michigan

Program WNCOR was run on two years of simultaneous surface observations recorded at Muskegon and Manistee for the record period 1 January 1961 to 31 December 1962. (Data for Manistee were not available on magnetic tape so two years of hourly surface observations

Figure IV-22. THE LUDINGTON CANDIDATE WIND ENERGY SITE LOCATION

were keypunched for the analysis.) The results of the analysis are presented in Appendix B. The correlation coefficients from the wind speed regression analyses for four Muskegon wind direction quadrants are:

<u>Muskegon Wind Direction Quadrant</u>	<u>Correlation Coefficient</u>
Northeast	0.61
Southeast	0.68
Southwest	0.59
Northwest	0.57

Examination of the wind speed regression and delta wind direction frequency analyses show that the winds at Manistee are climatologically correlated to the winds occurring at Muskegon. The wind speed and wind direction correlation analyses show a close correspondence between the wind directions and wind speeds at the two stations. All delta wind direction frequency analyses show a nearly normal frequency distribution centered around the zero directional difference. The majority, 70 percent of all surface wind directions observed at Manistee for the two-year period, were within ± 23 degrees of the wind direction observed at Muskegon. The wind speed regression analysis for all wind speeds observed at Manistee show a 0.64 correlation with the wind speeds observed at the Muskegon airport. The dual station modeling technique was therefore used in the Ludington modeling analysis. Wind direction and speed values were computed from the regression relationships. These values were then inputted into the Ludington model domain to compute the Ludington candidate site hub-height winds.

d. The Ludington Model Domain

(1) The domain dimensions and scale sizes

The horizontal extent of the model domain selected in the Ludington modeling analysis encompasses the Muskegon airport to the south, the Manistee airport to the north, the lake fetch to the west, and the inland terrain to the east (Figure IV-22). The maximum domain dimensions are 130 km north and south, 97.6 km east and west, and 195 m in the vertical. The scale dimensions of the fluid and solid cells in the domain are:

	<u>Δx</u>	<u>Δy</u>	<u>Δz</u>
Scale Size (m)	3254	3254	12.2
Scale Size (ft)	10,676	10,676	40

(2) Terrain representation

The terrain within the model domain is represented by block increments of solid cells dimensioned 3254 m by 3254 m by 12.2 m. The terrain representation for the Ludington model domain is given in Figure IV-23. The maximum near-site terrain relief at the Ludington site (1) observed from maps and (2) represented by the terrain grid is:

<u>Measured from Maps</u>		<u>From the Terrain Grid</u>	
Over 500 m 73 m	Over 1000 m 73 m	Over 1 Δx (3254 m) 61 m	Over 2 Δx (6508 m) 61 m

The terrain in the vicinity of the candidate site on top of the lake front bluff is well represented by the terrain blocks despite their large horizontal scale. The block terrain representation does adequately represent terrain that is in itself naturally blocked. The lake front bluff in the site vicinity rises abruptly within 150 m from the (flat) lake surface up a height of 73 m to the relatively flat bluff top. The elevation of the bluff represented by the grid block is averaged over a 10.6 square kilometer area, and is therefore less than the unaveraged site elevation. Consequently, the elevation of the site grid square above the lake surface, 61 m, is less than the actual elevation, 73 m, determined from the unaveraged terrain relief, but only by 12 meters.

e. The Ludington Candidate Site Wind Climatology

Nine model runs were performed in the Ludington modeling analysis for eight barrier incident wind directions: north, northwest, west, southwest, south, southeast, east, and northeast. The modeling function coefficients computed from the model runs appear in Figure IV-1. These coefficients were incorporated in the climatology-generating program, WIND, to generate the Ludington candidate site wind climatology from the Muskegon data base. Fifteen years of hourly surface observations were read for the record period 1 January 1948 to 31 December 1962. The wind character summaries generated from program WIND appear in Appendix C. The normalized velocity frequency curve for all conditions at Ludington is presented in Figure IV-24.

The Ludington candidate site wind climatology generated in this study is quite similar to the wind climatology observed at the Muskegon airport station. The modeling function coefficients computed from the modeling analysis are all less than one, and range in value from a maximum of 0.87 to a minimum of 0.88. The Ludington hub-height wind speed values computed in the climatology are thus 12 to 13 percent less than the winds at the 150-ft level above the Muskegon airport.

Figure IV-23. MODEL DOMAIN TERRAIN REPRESENTATION IN THE LUDINGTON MODELING ANALYSIS

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Figure IV-24. THE LUDINGTON CANDIDATE SITE NORMALIZED VELOCITY FREQUENCY CURVE ($\bar{V} = 5.65$ mps)

The similarity of the Ludington and Muskegon wind climatology is consistent with results obtained in the wind correlation analysis performed on Manistee and Muskegon. The winds at Manistee were found to be climatologically correlated with the winds at Muskegon. Since Ludington is located between Manistee and Muskegon, it follows that the winds at Ludington are also correlated with the winds at Muskegon. As mentioned previously, the exposures at all three locations are excellent with no obstructions in any direction. Also, all three locations are within 5 km of the lake front, in the same climatological regimes.

6. The Montauk Point Candidate Wind Energy Site

a. Site Description

The Montauk Point candidate wind energy site is located near the eastern tip of Long Island in New York, Figure IV-25. The site overlooks a bay on the north side of the Island facing Block Island Sound to the north. The site is located 9 km west of Montauk Point Light at an elevation of 1.5 m (5 ft).

The terrain in the vicinity of the site is flat with only minor relief variations. The maximum terrain elevation in the vicinity of the site is located 3 km southwest of the site at an average elevation of 15 m (50 ft), approximately 14 m (45 ft) above the site. The wind exposure at the site at hub-height is excellent in all directions.

b. Data Stations

The primary station selected in the dual station modeling analysis is the Air Force office at the Suffolk County AFB at Westhampton Beach, Long Island, 61 km southwest of the Montauk Point candidate site. The Suffolk County AFB station is the closest observing station to the site with 15 years of data record on magnetic tape. The station is located on the seaboard side of Long Island, inland 4.5 km from the coast. The station elevation is 20 m (67 ft), approximately 19 m (62 ft) higher than the site. The terrain at the station slopes upwards to the north to an average maximum elevation of 46 m (150 ft), approximately 25 m (83 ft) above the airport. The wind exposure at the station is excellent, unobstructed in all directions.

The secondary station selected in the analysis is located at the New London-Groton airport, south of the city of Groton, Connecticut. The New London-Groton station is the closest observing station to the site, located 32 km from the site to the north across the Block Island Sound. The station is located 1.5 km inland at an elevation of 3 m (10 ft),

Figure IV-25. THE MONTAUK POINT CANDIDATE WIND ENERGY SITE LOCATION

approximately 1.5 m (5 ft) above the site elevations. The terrain in the vicinity of the airport station is flat and the wind exposure is good in all directions.

c. Wind Correlation Analysis, Suffolk County
AFB and New London

Program WNCOR was run on three and one-half years of simultaneous surface observations recorded at the Suffolk AFB and Groton airports for the record period 1 May 1951 to 31 December 1954. (The data record for New London contains an observation frequency less than 24 per day for part of the record.) The results of the analysis are presented in Appendix B. The correlation coefficients from the wind speed regression analyses for four Suffolk wind direction quadrants are:

<u>Suffolk Wind Direction Quadrant</u>	<u>Correlation Coefficient</u>
Northeast	0.58
Southeast	0.60
Southwest	0.50
Northwest	0.51

Examination of the wind speed regression and delta wind direction frequency analyses show that the winds at the Groton airport are climatologically correlated to the winds occurring at the Suffolk County AFB airport. The wind speed and wind direction correlation analyses show a close correspondence between the wind directions and wind speeds at the two stations. All delta wind direction frequency analyses show a nearly normal frequency distribution centered around the zero directional difference. (The method of recording wind observations at the Groton airport changed during the record period used in the analysis. A majority of the surface wind directions were recorded using the 8-point compass and wind speeds reported in 5 mph steps. Consequently, the delta wind direction occurrence frequency is weighted towards -23 degrees.)

The majority, 64 percent, of all surface wind directions observed at the Groton site for the 3.5-year period were within ± 23 degrees of the wind direction reported at the Suffolk County AFB, despite the directional bias recorded at Groton. The wind speed regression analysis for all wind speeds observed at Groton show a 0.55 correlation with the wind speeds observed at the Suffolk airport, despite the 5 mph grouped bias reported at Groton. The dual station modeling analysis was therefore used in the Montauk Point modeling analysis.

d. The Montauk Point Model Domain

(1) The domain dimensions and scale sizes

The horizontal extent of the model domain selected in the Montauk Point modeling analysis encompasses the Suffolk County AFB airport to the southwest and the Groton airport to the northwest, Figure IV-25. The maximum domain dimensions are 89.8 km east and west, 67.4 km north and south, and 195.2 m in the vertical. The scale dimensions of the fluid and solid cells in the model domain are:

	<u>Δx</u>	<u>Δy</u>	<u>Δz</u>
Scale Size (m)	2245.6	2245.6	12.2
Scale Size (ft)	7367	7367	40

(2) Terrain representation

The terrain within the model domain is represented by block increments of solid cells dimensioned 2246 m by 2246 m by 12.2 m. The terrain representation for the Montauk Point model domain is given in Figure IV-26. The maximum near-site terrain relief at the Montauk Point site (1) observed from maps and (2) represented by the terrain grid is:

<u>Measured from Maps</u>		<u>From the Terrain Grid</u>	
Over	Over	Over 1 Δx	Over 2 Δx
500 m	1000 m	(2246 m)	(4492 m)
1.5 m	1.5 m	12.2	12.2

The terrain in the vicinity of the Montauk Point Site is represented by a single solid cell 2.2 km square centered on the site location. The cell top surface, being flat, represents a constant site elevation extending $1/2 \Delta x$, 1123 m, from the site. The near-site terrain gradient thus equals zero over the surface of the terrain cell out 1123 meters to the next adjacent cell. The actual terrain relief of only 1.5 m over 1000 m is adequately represented by the gridded relief.

e. The Montauk Candidate Site Wind Climatology

Five model runs were performed in the Montauk Point modeling analysis for five primary station wind directions, north, west, southwest, southeast, and east. The modeling function coefficients computed from the model runs appear in Figure IV-1. These coefficients were incorporated in the climatology-generating program, WIND, to generate the Montauk Point candidate site wind climatology from the Suffolk County AFB

Figure IV-26. MODEL DOMAIN TERRAIN REPRESENTATION IN THE MONTAUK POINT MODELING ANALYSIS

station data base. Thirteen years of hourly surface observations were read for the record period 1 May 1951 to 29 April 1964. The wind character summaries generated from program WIND appear in Appendix C. The normalized velocity frequency curve for all conditions at the Montauk Point candidate site is presented in Figure IV-27.

The Montauk Point candidate site wind climatology generated in this study is identical to the wind climatology observed at the Suffolk County AFB airport. All site winds modeled in the analysis were within 2 percent of the winds inputted at the Suffolk County AFB. The modeling function A coefficients ranged in value from a maximum of 1.01 to a minimum of 0.995.

The similarity of the Montauk Point and Suffolk wind climatologies is, again, consistent with results obtained in the wind correlation analysis performed on Suffolk and Groton. The Montauk Point site lies between the two locations in the same geographic region, and the exposure at all three locations is similar. The correlation analysis show that the flow across the eastern half of Long Island, across the Block Island Sound, and along the coast of Connecticut is uniform and climatologically related.

7. The Russell Candidate Wind Energy Site

a. Site Description

The Russell candidate wind energy site is located in the northwestern portion of Kansas, approximately 4.5 km south of the city of Russell, Figure IV-28. The site is located atop a small hill at an elevation of 564 m (1850 ft). The terrain in the vicinity of the site is generally flat with a maximum relief of 28 m (90 ft) over a 2 km distance east of the site. The wind exposure at the site is excellent in all directions.

b. The Data Stations

The primary data station selected in the modeling analysis is the NWS airport office at Russell municipal airport, located 4 km southeast of the city of Russell (Figure IV-28). The Russell Municipal Airport

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Figure IV-27. THE MONTAUK POINT CANDIDATE SITE NORMALIZED VELOCITY FREQUENCY CURVE ($\bar{V} = 6.12$ mps)

Figure IV-28. THE RUSSELL CANDIDATE WIND ENERGY SITE LOCATION

is located 5 km northeast of the Russell candidate site at an elevation of 568 m (1862 ft). It is the closest observing station to the site, and in addition has over 15 years of hourly surface observation available on magnetic tape. The next two closest stations to the site are 105 and 113 km away at the Schilling and Municipal airports near Salina, Kansas. Both stations do not have a 15-year period of record available on magnetic tape. The single station modeling analysis was, therefore, selected in the modeling analysis at Russell.

c. The Russell Model Domain

(1) The domain dimensions and scale sizes

The horizontal extent of the model domain selected in the Russell modeling analysis encompasses the Russell Municipal airport to the northeast and the Russell candidate site to the southwest (Figure IV-28). The maximum domain dimensions are 7.6 km east and west, 5.7 km north and south, and 97.6 m in the vertical direction. The scale dimensions of the fluid and solid cells in the model domain are:

	<u>Δx</u>	<u>Δy</u>	<u>Δz</u>
Scale size (m)	189.6	189.6	6.1
Scale size (ft)	622	622	20

(2) Terrain representation

The terrain within the model domain is represented by block increments of solid cells dimensioned 190 m by 190 m by 6.1 m. The terrain representation for the Russell model domain is given in Figure IV-29. The maximum near-site terrain relief at the Russell site (1) observed from maps and (2) represented by the terrain grid is:

<u>Measured from Maps</u>		<u>From the Terrain Grid</u>	
Over	Over	Over $1\Delta x$	Over $2\Delta x$
100 m	500 m	(190 m)	(379 m)
1.5 m	7.6 m	6.1 m	6.1 m

Figure IV-29. MODEL DOMAIN TERRAIN REPRESENTATION IN THE RUSSELL MODELING ANALYSIS

The small station-to-site distance, along with the relatively flat terrain over the model domain, results in a detailed representation of the terrain features by the terrain grid. The near-site terrain gradients at the Russell site are adequately represented by the terrain grid squares in the terrain grid representation.

d. The Russell Candidate Site Wind Climatology

Four model runs were performed in the Russell modeling analyses for four barrier incident wind directions: northeast, southeast, west, and north. The modeling function coefficients computed from the model runs appear in Figure IV-1. These coefficients were incorporated in the climatology-generating program, WIND, to generate the Russell candidate site wind climatology from the Russell airport data base. Fifteen years of hourly surface observations were read for the record period 1 January 1950 to 31 December 1964. The wind character summaries generated from program WIND appear in Appendix C. The normalized velocity frequency curve for all conditions of the Russell candidate site is: presented in Figure IV-30.

The Russell candidate site wind climatology generated in this study is nearly identical to the wind climatology observed 5 km away at the Russell municipal airport. The Russell site winds computed in the modeling analysis ranged from two to eight percent higher than the winds observed at the airport station. The modeling function A coefficients computed from the modeling analysis range from a maximum of 1.08 to a minimum of 1.02.

The terrain inputted into the model domain, as mentioned previously, is quite representative of the terrain in the model domain. The results of the Russell modeling analysis, therefore, indicate that the terrain between the airport station and the candidate site does not appreciably change the flow character between both locations at hub-height.

8. The San Gorgonio Pass Candidate Wind Energy Site

The San Gorgonio Pass candidate wind energy site is located in southern California on the desert side of the San Gorgonio Pass, approximately 14 km north-northwest of the city of Palm Springs, Figure IV-31. The site is located in the Coachella Valley at an elevation of 360 m (1180 ft), approximately 402 m (1320 ft) below the highest elevation of the pass region. The Coachella Valley forms the northern slope of the eastern pass entrance region, Figure IV-32. The terrain in the valley and at the site is smooth, sloping from the lowest portion of the Coachella Valley to the south near Whitewater River, upwards to the north at a constant

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Figure IV-30. THE RUSSELL CANDIDATE SITE NORMALIZED VELOCITY FREQUENCY CURVE ($\bar{V} = 9.13$ mps)

Figure IV-31. THE SAN GORGONIO PASS CANDIDATE WIND ENERGY SITE LOCATION, ⊗

Figure IV-32. TERRAIN RELIEF IN THE VICINITY OF THE
SAN GORGONIO PASS CANDIDATE SITE

⊗ = Site Location

average rate of 29 m/km. The terrain slopes northwestward past the site up to the base of the desert foothills of the San Bernardino Mountains, 3.5 km west-northwest of the site. The wind exposure at the site is open to the San Gorgonio Pass to the west through southwest, and open to the Coachella Valley to the north through south.

b. Data Stations

The primary data station selected in the modeling analysis is the Air Force office at the March AFB airport near the city of Riverside. March AFB station is located on the western side of the San Gorgonio Pass, 63 km west of the San Gorgonio Pass candidate site. The station is located at an elevation of 468 m (1535 ft), approximately 108 m (355 ft) above the candidate site, and 294 m (965 ft) below the highest elevation of the San Gorgonio Pass. The March AFB station is the closest station to the site with 15 years of data record on magnetic tape.

The terrain in the vicinity of the Air Force station is smooth, sloping generally from the west to the east upwards at an average rate of 10 m/km towards the San Gorgonio Pass, located 30 km to the east-northeast, Figure IV-31. The wind exposure at the station is open to marine influence to the northwest through south. The terrain to the north and southeast constricts the station's exposure towards the east into the opening of the San Gorgonio Pass.

The secondary station selected in the dual station modeling analysis is located at the Palm Springs airport on the east side of the Pass, approximately 15 km south-southeast of the San Gorgonio Pass candidate site. The Palm Springs station is the closest observing station to the site, and lies approximately 223 m (732 ft) below the site at an elevation of 137 m (448 ft). The terrain in the vicinity of the Palm Springs airport is smooth, sloping away from the airport to the southeast through east and upwards to the west through northwest. The wind exposure at the airport is restricted to the south through west-northwest by the eastern slopes of the San Bernardino Mountain Range. The station's exposure is open to the San Gorgonio Pass to the west-northwest through northwest and is open to the Coachella Valley to the north through southeast.

The Palm Springs airport station was selected in the dual station modeling analysis to provide an input wind value on the east side of the San Gorgonio Pass. The winds inputted at the Palm Springs airport supplement the initial flow field constructed from the winds inputted on the west side of the San Gorgonio Pass at March AFB.

c. Wind Correlation Analysis, March AFB and Palm Springs

Program WNCOR was run on two years of simultaneous surface observations recorded at March AFB and Palm Springs for the record period 1 January 1961 to 31 December 1962. (Data for Palm Springs were not available on magnetic tape so two years of hourly surface observations were keypunched for the analysis.) The results of the analysis are presented in Appendix B. The correlation coefficients from the wind speed regression analyses for four March AFB wind direction quadrants are:

<u>March AFB Wind Direction Quadrant</u>	<u>Correlation Coefficient</u>
Northeast	0.30
Southeast	0.14
Southwest	0.25
Northwest	0.26

It should be noted before presenting the results of the analysis that the anemometer at the Palm Springs airport had a high threshold speed during the record period used in the analysis. The lowest wind speed reported at Palm Springs is 4 m/s, evident on all of the wind speed scatter diagrams generated in the analysis. Wind speeds less than 4 m/s were reported during the record period as calms. Consequently, the analyses show a high percentage, 48%, of calms at the Palm Springs airport. It should also be noted that the observation frequency at the Palm Springs airport during the record period averaged 16 per day as opposed to 24 per day.

Examination of the wind speed and the delta wind direction frequency analyses show that the winds at the March AFB and Palm Springs airports are not sufficiently related to provide an input wind relationship for the dual station modeling analysis. The mountain ranges surrounding the San Gorgonio Pass region are responsible for the low degree of correlatability between the March AFB and Palm Springs wind directions and wind speeds. The San Bernardino Mountains separate the coastal inland valleys from the inland desert regions of southern California. Data stations lying on both sides of the San Gorgonio Pass in the San Bernardino Mountains thus lie in two different climatological regimes. The air flow within the two different regions are decoupled and therefore not correlatable.

d. The San Gorgonio Pass Model Domain

(1) Domain dimensions and scale sizes

The horizontal extent of the model domain selected in the San Gorgonio Pass modeling analyses encompasses the March AFB airport to the west, the Coachella Valley to the east, and the mountain terrain surrounding the San Gorgonio Pass and candidate site, Figure IV-31. The maximum domain dimensions are 80 km east and west, 60 km north and south, and 2438 m in the vertical. The scale dimensions of the fluid and solid cells in the model domain are:

	<u>Δx</u>	<u>Δy</u>	<u>Δz</u>
Scale Size (m)	2000	2000	152.4
Scale Size (ft)	6562	6562	500

(2) Terrain representation

The terrain within the model domain is represented by block increments of solid cells dimensioned 2000 m by 2000 m by 152.4 m. The terrain representation for the San Gorgonio Pass model domain is given in Figure IV-33. The maximum near-site terrain relief at the San Gorgonio Pass (1) observed from maps and (2) represented by the terrain grid are:

<u>Measured from Maps</u>			<u>From the Terrain Grid</u>	
Over	Over	Over	Over 1 Δx	Over 2 Δx
1000 m	2000 m	3000 m	(2000 m)	(4000 m)
42 m	91 m	171 m	152.4 m	152.4 m

The large variations in terrain relief occurring within the San Gorgonio Pass model domain makes it necessary to represent the vertical terrain resolution in 152.4 m (500 ft) blocks. The maximum vertical dimension of the model domain is 2438 m (8000 ft). The maximum terrain relief occurring within the model domain is over 10,000 ft, from Palm Springs to the peaks of Mount San Gorgonio and San Jacinto. The tops of both peaks, therefore, extend out of the top of the model domain, Figure IV-33. In order to represent the terrain in finer vertical resolution the maximum vertical domain dimension would have to be reduced, and consequently, more mountaintop terrain would extend beyond the top of the model domain. Air diverted by terrain boundaries through the top of the model domain is lost and consequently, will not return down the backside of the terrain barrier. It is necessary, therefore, in the modeling analysis

Figure IV-33. MODEL DOMAIN TERRAIN REPRESENTATION IN THE SAN GORGONIO PASS MODELING ANALYSIS

to keep at a minimum the amount of terrain surfaces extending through the top of the model domain.

e. The San Gorgonio Pass Candidate Site
Wind Climatology

Five model runs were performed in the San Gorgonio Pass modeling analysis for five pass incident wind directions: northeast, east, south, southwest, and west. The modeling function coefficients computed from the model runs appear in Figure IV-1. These coefficients were incorporated in the climatology-generating program, WIND, to generate the San Gorgonio Pass candidate site wind climatology from the March AFB data base. Fifteen years of hourly surface observations were read for the record period 1 January 1949 to 31 December 1963. The wind character summaries generated from program WIND appear in Appendix C. The normalized velocity frequency curve for all conditions at the San Gorgonio Pass candidate site is presented in Figure IV-34.

The San Gorgonio Pass site wind climatology generated in this study is nearly identical to the wind climatology observed at the March AFB airport. The modeling function A coefficients computed in the modeling analysis range in value from a maximum of 1.09 to a minimum of 1.01. The San Gorgonio Pass hub-height wind speed values computed in the climatology are thus 1 to 9 percent higher than the winds at the 150 ft level above the March AFB airport.

The similarity of the San Gorgonio Pass and March AFB wind climatologies is inconsistent with results obtained in the wind correlation analysis performed on Palm Springs and March AFB stations. As mentioned previously, results from the wind correlation analysis indicate that the winds on the desert side of the San Gorgonio Pass are climatologically decoupled from the airflow on the west side of the Pass in the coastal inland valley. The wind climatologies on both sides of the San Gorgonio Pass will thus be different from each other and will exhibit wind characteristics attributable to each climatological region. The similarity in the two wind climatologies arises in this study from the inability in the modeling analysis to initialize the airflow field on the east side of the San Gorgonio Pass.

Figure IV-34. THE SAN GORGONIO PASS NORMALIZED VELOCITY FREQUENCY CURVE ($\bar{V} = 2.91$ mps)

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V. EVALUATION OF THE CLIMATOLOGY DEVELOPMENT METHODOLOGY

A. General

Once a method of estimating the wind characteristics at a candidate wind energy site has been developed, it becomes necessary to evaluate the method's effectiveness as a viable wind energy siting tool. An effective siting tool will provide, at a low cost, accurate estimates of site wind characteristics for a large variety of site geographic settings and site-to-station distances.

The procedure selected in this study to develop an effective wind energy siting tool incorporates an existing technique, designed for other purposes, into a methodology that generates site wind character estimates from available wind data observed in the site's vicinity. The methodology employs the use of a numerical airflow model, originally designed for diffusion and air pollution transport analyses, to compute site winds from available wind data recorded in the site's vicinity. Both the model and methodology of applying the model, contain certain inherent assumptions that are necessary for their implementation. The assumptions define certain requirements that have to be met before the model and modeling results can be applied to generate accurate wind character estimates. An evaluation of the methodology's performance thus will examine the requirements of the computational procedures involved, so as to determine the extent of the methodology's applicability. Once the extent of its application is known, candidate sites meeting the requirements can be determined and the accuracy of their wind climatologies can be evaluated. Also, once the extent of the methodology's applicability in its current configuration is known, improvements can be determined that will tailor the methodology toward the universal wind energy siting tool desired.

In the following sections the Climatology Development Methodology developed in this study is examined for its applicability as a viable wind energy siting tool. The evaluation is presented in a format that provides potential users of the methodology a convenient guide for determining

the applicability of the methodology to sites of differing geographic settings and data station location. The presentation will also serve to guide users in their selection of data stations and terrain grid representations.

In the next section, assumptions inherent in the methodology are examined and the extent of the methodology's applicability discussed. By examining the requirements on terrain representation and site-to-station distance, the applicability of the methodology to each of the eight candidate sites can be determined. Requirements listed in the following section will also serve to delineate for future site evaluations which sites the methodology in its current configuration can be applied to.

An evaluation of the accuracy of the wind character summaries generated by the methodology follows the section on the discussion of the methodology's requirements. The wind climatologies generated in this study are evaluated by comparing directly the wind climatology measured at the Boardman candidate site with the wind climatology generated from the Pendleton data base. The Boardman site is strategic in the evaluation of the methodology's applicability to nonmountainous regions over large station-to-site distances. The Boardman site is the only site that affords the opportunity to directly compare the estimated wind climatology with the actual climatology observed at the candidate site. Performance of the methodology on the Boardman site will give a strong indication of the accuracy of the wind character summaries for five of the eight candidate wind energy sites.

An evaluation of the methodology's cost-effectiveness will conclude this section. The cost per site is given along with a breakdown of the price per run of each of the methodology's programs. Since run-time prices are quite variable, the costing presented includes the type of computer used and an estimate of the computer "wall-clock" times. Also given are material costs and labor time estimates necessary for applying the methodology.

B. Requirements for the Application of the Climatology Development Methodology

The applicability of the Climatology Development Methodology in estimating candidate site wind character is dependent upon the availability and proximity of historical wind data in the vicinity of the candidate wind energy site. The methodology contains two fundamental assumptions inherent in the application of the airflow model and the model function expressions. These assumptions give rise to two basic requirements

concerning terrain and data representation that have to be satisfied before the methodology can be applied successfully to estimate site wind characteristics.

The first requirement concerns the applicability of the modeling function relationships for various site-to-station distances and geographic settings. The fundamental assumption inherent in the application of the modeling function expressions is:

- A functional relationship exists between the winds occurring at the candidate site and the primary data station.

The use of the modeling function's relationships presupposes that one, and only one, site wind value exists for each value of wind occurring at the primary data station. This assumption implicitly requires that the winds at the site be climatologically correlated with the winds occurring at the data station. The modeling functions will not be applicable to site-to-data station configurations where two different site winds consistently occur for one given primary station wind value.

The second requirement in the application of the Climatology Development Methodology concerns the applicability of the diffusion airflow model, in its present configuration, to candidate sites exhibiting large site-to-station distances. The fundamental assumption employed in the application of the airflow model is:

- Variations in the velocity field between two locations arise entirely from the deflective influences of terrain surfaces.

Since terrain boundaries are the only features influencing the redirection of the airflow in the modeling analyses, it is important to accurately represent the terrain relief in the model terrain grid. It has been shown that accurate terrain representation is dependent upon the scale size of the terrain grid cell. It has also been shown that the terrain cell size is dependent upon the distance in the modeling analysis between the candidate site and the primary data station. Consequently, the availability of data in the vicinity of a candidate site determines the degree of terrain representation that is possible with the current model domain dimensions.

In order to determine the extent of the climatology development methodology's applicability it becomes necessary to determine limits to the distance that can occur between site and station where the methodology will still be applicable. In the following paragraphs, limits are assigned to the site data station distances by evaluating the methodology's performance on each of the eight candidate wind energy sites analyzed in this study. The results of the evaluation are presented in a format that provides potential users of the methodology a guide for determining which locations the methodology is applicable to, and to aid users in the selection of representative data stations and terrain grid relief.

1. Selection of the Data Stations: Data Representation

The correlatability of flow occurring between the primary station and candidate site is strongly terrain-dependent. Flow correlatability in mountainous terrain will be largely affected by the complexity of the terrain relief occurring between the station and candidate site. Consequently, the maximum distance at which correlation will still occur will be smaller than the distance associated with nonmountainous regions. Thus, analysis of the methodology's applicability will have to stratify distance limitations by terrain relief.

An invaluable tool for evaluating climatological flow correlatability is the wind correlation program, WNCOR, developed originally for examining primary and secondary station wind relationships. Program WNCOR is a decisive tool for determining whether or not the modeling function requirements can be satisfied for a given site. By evaluating the wind relationship between two NWS or military observing stations surrounding the candidate site, the degree of climatological flow correlatability, and consequently, the applicability of the modeling function expressions can be determined. In the following paragraphs the results of program WNCOR are used to establish limits to the extent of the maximum "correlation distance" versus terrain configuration. In general, any geographic feature that consistently decouples the airflow between the primary station and candidate site will have an effect on the representativeness of the primary station's winds for use in the modeling methodology.

a. Data Representation: Little or No Terrain Variation Between the Primary Station and the Candidate Site

For large station-to-site distances in regions with little or no terrain variations, there will be some distance, d , where the airflow between a station and site becomes decoupled. At that distance, the scatter in the wind speed relationship becomes dominated by the effects of migratory synoptic-scale pressure systems. Applications of program WNCOR in this study show flow correlations occurring in the Ludington and Montauk Point sites for distances up to 130 km. WNCOR analyses for Boardman show a flow decoupling at a distance of 180 km, but the lack of flow correlation probably arises from terrain variations occurring at The Dalles station, and is not associated with the synoptic-scale flow variability. Upper bound estimates of the maximum distance, d , cannot be determined from the eight candidate site analyses conducted in this study. If station-to-site distances larger than 130 km are encountered, it is recommended that program WNCOR be used to determine the flow correlatability from two adjacent NWS or military stations.

b. Data Representation: Large-Scale Terrain Variation Between the Primary Station and the Candidate Site

As the terrain relief between the primary station and candidate site increases, the extent of the flow correlatability becomes inversely proportional to the magnitude of the terrain relief occurring between the primary station and candidate site. WNCOR analyses for the Boone candidate wind energy site show a flow decoupling across the Blue Ridge Mountains, between the Tri-City and Hickory airports, at a distance of 130 km. The analyses for the San Geronio Pass candidate site, which exhibits larger terrain variations, show a flow decoupling across the San Bernardino Mountains, between the March AFB and Palm Springs airports, at a distance of 72 km. As d decreases, however, there will come a distance where the terrain "between" becomes the terrain "surrounding" the candidate site and data station. Instead of relating airflow across several mountain ranges, the problem becomes relating the airflow across a mountain ridge or through a mountain valley. WNCOR analyses for the Holyoke candidate wind energy site show a flow correlation in two river valleys, separated by the Mount Tom Range, at a distance of 16 km. If the distances between the data stations for the

Boone and San Geronio Pass candidate sites were shorter, it could be surmised that there would be some distance where flow would be correlated. The exact distance cannot be parameterized versus terrain relief in this study. However, it can be estimated that the extent of flow correlatability in mountainous regions will be related to the scale of the local valley or ridge, like Holyoke, approximately 20 km.

c. Data Representation: Within a Persistent Mesoscale Circulation System

It can be seen from the above discussion that the extent of flow correlatability within a mountainous region is dependent upon the proximity of the candidate site and data station relative to the terrain relief. As mentioned previously (Section IV. B. 2. e.), a data station will be representative within a mountainous region if its winds are not decoupled from the general, climatological airflow by mesoscale influences. The winds at a candidate site will be correlated with the winds at a primary station if the flow at both locations is not consistently decoupled from the general, climatological airflow by mesoscale influences. It is important to note if a candidate site is located within a localized, persistent mesoscale circulation system, the primary station, in order for its winds to be correlated, must also lie within the same sphere of influence. An example of such a situation is the persistent mesoscale circulation associated with land-water interface. If a candidate site lies within a sea-breeze zone, a data station in order for its winds to be correlated, must also lie within the same zone. The data stations selected in the modeling analyses for the Ludington and Montauk Point candidate sites were selected, not only for their close proximity to the sites, but also because all stations selected lie less than six km from the lake or ocean shore. Consequently, wind correlation analyses show a flow correlation between the data stations for both sites. The relationships involved are further complicated by the island zone for the Montauk Point site, but the wind direction frequency analyses for the Muskegon and Manistee stations show excellent correspondence in wind direction occurrence frequency for both the lake and land effect breezes.

The problem of flow correlatability within persistent mesoscale mountain-valley or seabreeze zones is unique to the particular geographic configuration associated with a particular station-to-site combination. Orders of magnitude can be assigned to the distances limiting flow correlatability in this study. However, it is recommended that the program

WNCOR be applied to specific situations of site-station geography in order to determine specific limits of model function applicability for each particular site-to-station distance and geography encountered.

2. Selection of the Terrain Grid; Terrain Representation

The applicability of the numerical airflow model to various site geographic settings and data station distances is dependent, also, on the distances and terrain relief occurring between the data stations and candidate site. The airflow model in its present configuration is designed to estimate the airflow over a size scale designed originally for diffusion and air pollution transport analyses. The model domain size was designed for model applications within a localized valley or plains region with a size scale associated with diffusion and trajectory analyses over a distance of 20-30 km. The maximum model domain size (40, 30, 16), therefore, was originally designed to represent terrain relief by square blocks dimensioned 500-750 m in the horizontal scale. The model has been applied successfully in mountainous regions across mountain ridges and adjacent valleys with a maximum domain size of 30 km in the largest domain dimension. The model in its current configuration was not designed to estimate airflow in mountainous regions across several mountain ranges on the order of 60 to 100 km.

The applicability of the numerical airflow model in mountainous regions will be limited by the size of the distance occurring between the data stations and candidate site. Large distances require a larger terrain scale representation in the terrain grid. It was found in the Boone modeling analysis that large terrain cells smooth over local terrain features that are fundamental in modeling localized site wind-flow. The "blocking-effect", described in Section IV.B.2.d.(3), occurs in the terrain grid representation for mountainous regions when the distance between the site and data station is large. Near-site terrain gradients represented by adjacent grid cells are underestimated and the resultant modeled winds at the site show little, or no, change from the original input wind field.

a. Mountainous Regions

It is necessary in the application of the airflow model to determine the maximum site-to-station distance that can be used to model airflow in the candidate wind energy site modeling analyses. The maximum domain dimension in mountainous regions can be established from original design criteria to be on the order of 30 km. Modeling analyses conducted on the Holyoke candidate site though would indicate a better scale representation on the order of 20 km. It was found in the Holyoke

modeling analysis that the terrain representation of Deadtop, the location of the candidate site, was slightly averaged within the 480 m square representing the site elevation. A larger scale size would serve to average the site elevation over further and would consequently reduce the grid representation of the near-site terrain gradient.

b. Valley or Plains Regions

The fact that the airflow model was originally designed for a 20-30 km area does not mean that the model, in its present configuration, cannot be applied over a greater distance successfully. The application of the model to mountainous terrain is limited by the ability to accurately represent terrain relief by block increments. For smaller terrain relief, a larger cell size will adequately represent the terrain over the model domain. There is, though, some extent where the gridded terrain representation will not represent the actual terrain relief in the site's vicinity.

The modeling analyses for the Boardman, Ludington, and Montauk Point candidate wind energy sites show that the terrain inputted in the modeling analyses did not significantly affect the windflow in the vicinity of each candidate site. This means that either (1) the terrain in the vicinity of each site does not affect the airflow between the primary station and candidate site, or (2) the terrain grids inputted into the model are not representative, and consequently smooth over important terrain features responsible for redirecting the site airflow. The terrain block horizontal scale sizes for the Boardman, Ludington, and Montauk Point candidate sites are 2.5 km, 3.25 km, and 2.25 km, respectively. All three candidate sites are located in regions that exhibit relatively flat terrain features over the entire model domain.

In order to determine the extent of the airflow model's applicability to candidate sites with large station-to-site distances, it becomes necessary to examine the accuracy of the wind climatology generated for one of the three sites mentioned above. In the next section, the wind climatology generated for the Boardman candidate wind energy site is compared with the observed wind climatology recorded at the site. The distance from the Boardman site to the primary station at Pendleton is 78 km, three kilometers less than the distance at the Ludington site, and seventeen kilometers greater than the distance at the Montauk Point site. The accuracy of the wind climatology generated for the Boardman site will determine the representativeness of the terrain grid inputted in the Boardman modeling analyses. The results of the Boardman comparison will also give a good indication of the applicability of the airflow model to candidate sites exhibiting large station-to-site distances within nonmountainous regions.

3. The Boardman Candidate Site Wind Climatology Comparison

The Boardman candidate wind energy site is the only site of the eight modeled in this study that affords the opportunity to directly compare the wind climatology generated from the Climatology Development Methodology with the actual wind climatology occurring on-site. All candidate sites have a wind measurement program, but the Boardman site is the only candidate site that has over one year of hourly wind data available to generate a site wind climatology at this time. Portland General Electric (PGE) has maintained a 230-ft meteorological tower at the Boardman candidate site since April, 1973. Four and one-half years of hourly wind observations are available for generating a site wind climatology that can be used to evaluate: (1) the performance of the climatology development methodology and; (2) the applicability of the numerical airflow model to sites exhibiting large station-to-site distances in nonmountainous regions. The accuracy of the wind climatology generated for the Boardman site will give an indication of the accuracy of wind climatologies generated for the remaining sites where wind data are not available for a direct comparison.

Program WIND was modified to read hourly 130-ft wind direction and speed values from the PGE data base. (One-hundred-fifty-foot wind observations were not recorded at the Boardman site until the 1977 season.) The modified version of the program summarizes directly, without any height corrections, the winds read at 130 ft. Consequently, the hub-height wind climatology generated from the PGE data base presents a summary of the Boardman 130-ft wind character.

Program WIND was run on the entire PGE data base period of record, from 1 April 1973 to 30 September 1977, to generate the observed Boardman candidate site wind climatology. Wind character summaries generated from the PGE data base appear in Appendix C. (The wind observations recorded at the Boardman site are hourly averages, compared to one-minute averages observed at the Pendleton airport. Consequently, it should be kept in mind in the comparison that the wind climatology exhibits wind character summaries obtained from two different averaging techniques.)

a. The Comparison

The Boardman candidate site wind climatology is generated in the Climatology Development Methodology by applying modeling function relationships to the 150-ft Pendleton winds computed from surface winds observed at the Pendleton airport. The accuracy of the climatology

generated depends upon the ability of the modeling functions to accurately estimate the hub-height winds at the Boardman site from the winds observed at the Pendleton airport. Two modeling functions are used in the methodology; one for computing the Boardman wind direction, the other for computing Boardman wind speed. The accuracy of the Boardman wind climatology can thus be evaluated by comparing the wind direction and wind speed summaries generated from the estimated and observed Boardman wind climatologies.

(1) Wind direction comparison

Figure V-1 presents the wind direction occurrence frequency for the Boardman candidate wind energy site: (1) observed from the PGE data base, and (2) estimated from the Climatology Development Methodology. It was mentioned previously (Section IV.B.1.e.) that the wind direction difference modeled in the Boardman modeling analysis was less than the natural error occurring in the observed 16-point primary station wind direction. The modeling function for computing the Boardman wind direction in program WIND, therefore, equates the Boardman and Pendleton wind directions. Consequently, the wind direction occurrence frequency computed from the methodology in Figure V-1 is actually the wind direction occurrence frequency for the Pendleton airport.

The observed Boardman wind direction occurrence frequency shows a distinct preference for the west-southwest direction, which is roughly parallel to the 303-m contour along the foothills of the Blue Mountains (Figure IV-4). The Pendleton wind direction occurrence frequency exhibits a similar preference, but with less frequency and directed more westerly, along the southern periphery of the Columbia River Basin. The Pendleton airport station has a second peak in direction frequency from the southeast, down the Blue Mountains northwestward towards the station. The second peak in the southeasterly quadrant probably arises from nighttime drainage flow off the Blue Mountains.

The wind direction distributions for both Boardman and Pendleton show definite localized directional differences that arise from the different terrain relief occurring at each location. It should be noted, however, that some degree of difference in the distribution is probably due to the different time periods and record lengths used in the two analyses. The Boardman wind climatology generated from the PGE data base represents a 4.5-year wind character summary. It is possible that the wind direction occurrence frequency would exhibit a "smoother" distribution with direction if the period of record were 15 years as opposed to the 4.5-year period used. Also, differences might arise from the different averaging techniques used at each station to record the hourly wind direction values.

Figure V-1. COMPARISON OF THE ESTIMATED AND OBSERVED BOARDMAN CANDIDATE SITE HOURLY WIND DIRECTION OCCURRENCE FREQUENCY

(2) Wind speed comparison

Results of the model analysis conducted on the Boardman candidate wind energy site indicate that the terrain representation inputted into the modeling analysis has little effect on the difference in airflow speed occurring between the Boardman candidate site and the Pendleton airport station. The modeling function A coefficients computed from the modeling analysis indicate that the wind speed occurring at the Boardman site at hub-height will be on the average 90 percent less than the wind speed 150 ft above the Pendleton airport. This difference, as mentioned previously, arises mostly from the height difference between the locations, and not from localized terrain features at both locations. It is clear, comparing the wind direction frequencies between the Boardman site and the Pendleton station, that localized terrain features at each location do affect the airflow direction in the vicinity of the candidate site and airport station. It is important to determine if the local terrain relief also affects the wind speed difference occurring between each location. If it does, the terrain represented by the Boardman terrain grid is not representative, and the scale size of the terrain grid does not adequately represent the terrain relief that is important in modeling airflow. If this is the case, the airflow model in its present configuration will not be applicable to candidate sites with station-to-site distances on the order of 78 km in relatively uniform terrain geography.

It is possible, though, that the terrain features responsible for the difference in wind direction occurrence frequency are far enough removed from the site and station so as to have very little effect on the airflow speed between the two locations. Drainage flow off the Blue Mountains in the nighttime hours will exhibit localized directional characteristics that will be related to the orientation of the mountain range, not in the vicinity of the site, but away from the site in the foothill region. If the mountainous terrain is far enough removed from the site and station, it will have very little effect on the speed of the drainage flow once the flow crosses the foothill region and enters into the Columbia River Basin where the site and station are located. Pressure gradient flow will not be affected inside of the basin far enough removed from the mountain influence. The airflow speed and direction of the pressure driven flow up and down the river valley, then, should not be different between the two locations as long as the terrain within the basin is relatively flat.

If the frequency distributions presented in Figure V-1 are characteristic of a preferred drainage direction distribution, the distribution of the average wind speed by direction should indicate which directions are associated with the weaker drainage flow, and which directions are

associated with the stronger pressure gradient flow. Figure V-2 gives the average wind speed by direction for the Boardman candidate site (1) observed from the PGE data base, and (2) estimated from the Climatology Development Methodology. The average wind speeds plotted in the figure present the average wind speed for all conditions, day and night, averaged for a given direction over the entire period of record.

The distribution of average wind speeds by direction, estimated by the Climatology Development Methodology from the Pendleton data base, shows excellent agreement with the distribution observed at the Boardman site. The close correspondence in the average wind speed values and the close correspondence in their distribution with direction shows that the winds observed at the Pendleton airport station are climatologically related to the winds occurring at the Boardman site. The estimated distribution curve shows that the terrain in the vicinity of the site and station has little effect on the distribution of average wind speed with direction. Also, the close correspondence of the wind speed averages indicates that the distribution of wind speed by direction computed from the modeling functions agrees closely with the actual wind speed distribution with direction occurring at the site. The distribution also shows that the stronger up-valley gradient flow occurs with the same magnitude and in the same directions at both the Boardman site and the Pendleton airport station. This means that the airflow within the Columbia River Basin is not redirected or changed in magnitude by terrain features as it traverses the basin from the Boardman site to the Pendleton airport. The distribution also shows that the drainage flow occurs with the same strength regardless of preferred direction at both locations and is, therefore, not affected by the terrain located at a distance in the foothill region.

Figures V-3 and V-4 present, respectively, the occurrence frequency and normalized velocity frequency of hourly Boardman wind speeds (1) observed from the PGE data base and (2) estimated from the Climatology Development Methodology. The frequency distribution estimated from the Pendleton data base exhibits a higher occurrence frequency of lighter wind speeds ranging from 3-4 m/s than that observed at the Boardman site. Also, there is a corresponding decrease in wind speed occurrence frequency estimated from the methodology for higher wind speeds in the order of 7-18 m/s. The reason for the difference in wind speed occurrence frequency can be found by examining Figure V-1 and V-2. The Pendleton airport station exhibits a higher wind direction occurrence frequency (Figure V-1) for wind direction of east-southeast than does the Boardman candidate site. The corresponding average wind speeds associated with the southeast quadrant at Pendleton is approximately 3-4 m/s. The Boardman site has a higher occurrence frequency of winds

Figure V-2. COMPARISON OF THE ESTIMATED AND OBSERVED BOARDMAN CANDIDATE SITE AVERAGE WIND SPEED BY DIRECTION

Figure V-3. COMPARISON OF THE ESTIMATED AND OBSERVED BOARDMAN CANDIDATE SITE HOURLY WIND SPEED OCCURRENCE FREQUENCY

Figure V-4. COMPARISON OF THE ESTIMATED AND OBSERVED BOARDMAN CANDIDATE SITE NORMALIZED VELOCITY FREQUENCY CURVES

from the south-southwest to west-northwest than does the Pendleton airport. The average (southwest to west) wind speed at the Boardman site ranges from 5 to 9 m/s.

The higher frequency of southwest-to-westerly winds at Boardman thus accounts for the larger frequency of higher wind speeds at the site. Estimates of site wind speeds computed from the Pendleton winds for south-east flow, nighttime drainage flow, will underestimate the Boardman wind speed when the Boardman wind direction, corresponding to southeasterly flow at Pendleton, is from the southwest. This situation probably occurs in the early morning or late evening. The penetration of the southwesterly gradient flow in the Columbia River Valley probably reaches Pendleton later in the morning. Consequently, Pendleton experiences a higher frequency of drainage-dominated hours. Likewise, the drainage flow probably affects Pendleton at earlier hours in the evenings.

b. Results of the Comparison

The comparison presented in this section shows that the numerical airflow model is applicable to candidate wind energy sites exhibiting large site-to-station distance with relatively flat terrain. It was found that terrain features in the relative proximity, though not necessarily near the site, might have an effect on the distribution of wind direction character. This, in turn, might affect the wind speed frequency distribution estimated in the methodology, if the terrain relief produces localized meso-scale circulations. Airflow speed is not affected by terrain relief outside of the immediate vicinity of the site-to-station area.

C. Evaluation of the Candidate Site Wind Climatologies

The applicability of the Climatology Development Methodology to each of the eight candidate wind energy sites is summarized in Table V-1. Two sites--Boone and San Geronio Pass--do not meet at least one of the requirements of the methodology, so the climatologies generated for these sites are not applicable. All the remaining six sites satisfy all the requirements of the modeling functions and the airflow model terrain representation.

In the absence of wind data recorded on the site, it is difficult to determine directly the accuracy of the wind climatologies generated. The Boardman candidate site is the only site of the six that does have

Table V-1
THE APPLICABILITY OF THE CLIMATOLOGY
DEVELOPMENT METHODOLOGY

Candidate Site	Applicability of the Modeling Functions	Applicability of the Airflow Model	Accuracy of the Wind Climatology
Boone	N/A	N/A	N/A
San Gorgonio Pass	N/A	A	N/A
Boardman	A	A	A
Ludington	A	A	A
Montauk Point	A	A	A
Holyoke	A	A	A
Huron	A	A	A
Russell	A	A	A

wind observations available for a direct comparison. The comparison presented prior to this section confirms the applicability of the methodology to candidate sites exhibiting large station-to-site distances in relatively uniform terrain. The results of the comparison indicate that the climatologies generated for sites exhibiting similar terrain and station configurations will also be representative. The wind climatologies generated for the Montauk Point and Ludington candidate sites can therefore be considered representative. It should be noted that the degree of representation is relative. The Boardman wind climatology generated in this study is not perfect, but the comparison shows that the wind character estimates are quite representative. Likewise, the Ludington and Montauk Point wind climatologies will not be perfect. The degree of representativeness, though, can be considered good,

primarily because all of the requirements of the methodology have been satisfied. With this same argument, the wind climatologies generated for the remaining sites, Huron, Russell, and Holyoke, can also be considered representative. Detailed evaluation of the accuracy of each individual site climatology will have to wait until a data base similar to the Boardman data base is available for each candidate site.

D. Evaluation of the Cost-Effectiveness of the
Climatology Development Methodology

The methodology developed in this study is almost entirely computerized. Three computer programs, WNCOR, CORE, and WIND, form almost all of the analyses required for generating a site wind climatology. Time is required initially to survey sites for data availability and to code the model domain terrain grid, but once this is accomplished a minimum amount of labor is required to code input values for the production programs. The site wind climatology is generated from program WIND once the modeling function coefficients have been specified. Additional labor may be required upon completion to analyze the climatology generated and to compare the results with existing data for specific detailed evaluations. Also, additional labor may be required to report the results of the climatology in conjunction with a detailed site description and data accountability. The approximate cost of generating a single wind climatology is given in Table V-2. Costs are only included for the time, materials, and computer fees for generating the wind character summaries and do not include costs for evaluating or reporting the wind climatology. All costs included in the table do not include fee adjustments and therefore represent only the first approaches to the net total cost. In addition, it is assumed that all data used in the analysis are available from the National Climatic Center on computer tape. Costs for keypunching secondary station surface observations, as was done for the Ludington and San Geronio Pass candidate site, would be in addition to the costing presented.

The largest costs in the methodology arise from the running of program CORE. It should be noted that program CORE was written several years before the date of this report. Since then, computational techniques have been developed that, if incorporated in the program, would reduce the run-time and result in a cost reduction of approximately fifty percent.

Table V-2

COST OF GENERATING A CANDIDATE
SITE WIND CLIMATOLOGY

Description	Hours	Cost per Hour	Total Cost
<u>Computer Runs</u>			
WNCOR, 1 run (HP 2100 MX)	0.57	\$ 75.00	\$ 43.00
CORE, 8 runs (CDC Cyber 72)	1.7	400.00	680.00
WIND, 1 run (HP 2100 MX)	3.0	75.00	225.00
<u>Materials</u>			
Primary Station Data			120.00
Secondary Station Data			60.00
Miscellaneous (maps, etc.)			25.00
<u>Labor</u>			
Computer Coding	40.0	7.50	300.00
Total Net Cost			\$1,453.00

VI. CONCLUSIONS

The Climatology Development Methodology developed in this study can be used as an effective wind energy siting tool as long as certain requirements on data representation are satisfied. These requirements are realistic and concern the representativeness of available data in the site's vicinity. There are two basic requirements concerning data representation, and both stem from the application of the numerical airflow model, designed for other purposes, to the unique problem of estimating site wind character for a variety of site geographic settings and data station distances. The design of the airflow model and the methodology of applying the model to obtain wind character estimates contain certain inherent assumptions that limit the methodology's applicability to certain types of site geographic settings and data station distances. The assumptions are most often satisfied for candidate sites located in nonmountainous regions by the availability of conventional meteorological observing stations located at some distance, d , from the site. The existing density of observing stations in the United States usually means that there will be some one station within 100 km from the candidate site. It was found that the methodology developed in this study is applicable to candidate sites located in nonmountainous regions for distances up to at least 130 km. Occasionally, the terrain between the station and site will exert enough influence on the flow between the two locations that a second station will be necessary to generate the site wind climatology. The methodology has provisions for including a second station if that station also meets the requirements of the methodology.

The application of the airflow model in mountainous regions is limited by the model's present configuration. The model can be applied successfully in mountainous regions with station-to-site distances of 20-30 km, depending upon the terrain configuration in the vicinity of the site. It was found in the modeling analysis that the representation of the near-site terrain gradient is fundamental in modeling site winds. The model domain dimensions in the model's present configuration can only represent near-site terrain gradients adequately when the station-distance from the site is less than 30 km. For larger distances in mountainous regions, the model domain grid averages over the important terrain features in the site's vicinity.

The Climatology Development Methodology developed in this study does generate accurate estimates of site wind characteristics as long as the requirements on data representation are satisfied. Two of the eight sites evaluated in this study did not meet the requirements of the methodology and, consequently, the wind climatologies generated for both sites are not accurate. Both sites are located in mountainous regions with station distances greater than 50 km. The remaining six candidate sites do satisfy all of the methodology's requirements. Application of the airflow model to all but one of the six sites predicted that the terrain between the site and data station does not affect the airflow between the two locations. This prediction was verified on the one site exhibiting the largest terrain variations of the five. A comparison of the estimated wind climatology with the observed wind climatology for the Boardman candidate site showed that the estimated wind climatology is accurate as long as the requirements of the methodology are satisfied.

It stands to reason that there will be some distance, d , between a candidate site and data station where any technique of estimating site winds will not provide accurate site wind estimates. It also stands to reason that that distance, d , will be much shorter in mountainous regions when the influences of mountains and valleys work to negate a station's representativeness of the general climatological airflow. Since data station distance is not a factor in selecting a candidate wind energy site, there will be circumstances where estimating candidate site wind characteristics will be very difficult. Fortunately, the density of available meteorological data allows the possibility of modifying existing techniques into specialized wind energy siting tools designed specifically for the purposes required by the DOE. The expansion of the model domain scale in the current airflow model will make the model more applicable to mountainous regions with larger station-to-site distances.

VII. RECOMMENDATIONS

The model domain scale was not expanded on this study primarily because an increase in the domain size would have dramatically increased the operating cost of the model in its present configuration. As mentioned previously, the airflow model used in this study was developed several years prior to the date of this report when the state-of-the-art on solving the Poisson's equation used an iterative technique. The model with its current domain size, 40 by 30 by 16, requires the use of special disk read and write subroutines for use on the CDC Cyber 72. The velocity components, u, v, and w, and the stream function are all stored within arrays, each dimensioned 40 by 30 by 16. Each array is read in from disk, updated, and read out to disk in each iterative step. The read and write subroutines are called in the iterative process in do-loops nested at the fourth and fifth level. Three of the nested do-loops, at the last three levels, are dimensioned 40, 30, and 16, the model domain size. Increasing the domain size just a few sizes would dramatically increase the i-o and computer run time costs of operating the model in its present configuration.

Recently (Busbee et al. [1970]), an innovation in solving the Poisson's equation has been developed that requires no iterative processes. The "direct method" technique solves for the final nondivergent wind field in a single step using a matrix inversion technique. The direct method is used in a numerical airflow model developed for diffusion analyses by Yocke et al. (1977). It is recommended that the direct method technique be adapted specifically for the modeling of candidate site winds. The direct method technique would decrease the cost of operating the airflow model with its present domain size by 50 percent. Incorporation of the direct method technique would also allow the model domain size to be inputted as a variable quantity rather than fixed. This would allow the model domain terrain grid size to be fixed at 500 m and, consequently, the terrain for all candidate sites would be adequately represented for all types of site geographic settings. The direct method technique and variable domain size would increase the methodology's applicability in mountainous regions.

Subroutines incorporating the direct method technique already exist in-house at MRI. Modification of the numerical airflow model would, therefore, require only a modest effort to update the diffusion model into a model more directly applicable to a universal wind energy siting tool.

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