PROCEEDINGS
OF THE WORKSHOP ON WIND CLIMATE

Asheville, North Carolina
November 12-13, 1979

Edited by
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FOREWORD

Wind data as collected, analyzed and archived are subjected to many uses. Wind data are used in weather forecasting, aviation operations, wind energy assessment, prediction of pollutant dispersion, determination of loads in construction industry, and in agriculture industry. Since impact of wind data is far reaching encompassing many societal problems it is deemed desirable to discuss problems of wind data through a workshop. A group of individuals met in January 1979 to formulate objectives and programs for the workshop. This group included Alan G. Davenport of University of Western Ontario, Jack E. Cermak of Colorado State University, Mike Changery of National Climatic Center, Dave Renne of Battelle Pacific Northwest Laboratories, Phil Landers of Electric Power Research Institute, Robert Kornasiewicz of U.S. Nuclear Regulatory Commission and Kishor Mehta of Texas Tech University.

Overall objective of the workshop was to develop a consensus recommendation for the future wind data collection system through input from meteorologists and engineers. Specific objectives of the workshop were: (1) to illustrate application of wind data, (2) to review available wind data, its quality and limitations, (3) to discuss ways of modelling and characterizing the wind climate from the meteorological data, and (4) to deliberate needs and areas of improvement in acquiring meteorological data for climate description.

Twenty-four professionals from the meteorological and engineering communities who were involved with wind data system were invited to participate in the workshop. The participants made brief presentations and discussed all aspects of wind data system. The presented papers and the discussion by the participants are compiled in the Proceedings. In addition, a consensus recommendation developed by the participants is presented in the front of the Proceedings.

Financial assistance for the workshop was provided by the Electric Power Research Institute and the National Science Foundation. The success of the workshop can be attributed to the individuals who carefully formulated the objectives and the program and to the participants. Discussions and presentations made by the participants permitted development of the consensus recommendation. Efforts of the participants and the organizations toward bringing the workshop and its objectives to fruition are acknowledged.

TABLE OF CONTENTS

Papers of Session I

Papers of Session II

Papers of Session III

WORKSHOP ON WIND CLIMATE

Held in Asheville, NC

November 12-13, 1979

RECOMMENDATIONS

Discussions among meteorologists and engineers during the two-day workshop produced a consensus that a uniform wind data colleciton, processing, and archiving system would be beneficial to the nation. Application of wind data to assess wind energy potential, to serve aviation operations, to determine wind forces on structures, to predict dispersion of air pollutants, and to promote agricultural efficiency can result in a contribution of many billions of dollars to the U.S. economy. However, to realize this potential contribution wind data and associated meteorological data of the following nature should be obtained and archived for all the weather stations throughout the U.S.:

A. SURFACE WIND DATA (10 m above ground)

These data should be obtained three times per hour (20 min module) for every hour of the day and every day of the year.

	Variable	Averaging Time	Primary Uses
1.	Wind speed and direction (derived from components)	20 min	Wind energy, pollutant dispersion, forces on structures, agriculture,* aviation
2.	Peak wind speed/direction	2 sec	Forces on structures
3.	Fastest one-minute speed/direction	1 min	Wind turbine, forces on structures
4.	Fastest-mile wind speed/direction	----	Continuity with previous data
5.	Standard deviation of wind fluctuations	20 min	Pollutant dispersion

* Wind speed and direction data at 3m above ground are also desired for agriculture.

B. LOW LEVEL WIND DATA (at levels of approximately 100 m, 300 m, and 500 m above ground)

These data should be obtained at three-hour intervals every day.

	Variable	Averaging Time	Primary Uses
1.	Wind speed and direction and their fluctuations	20 min	Wind energy, pollutant dispersion, forces on structures, aviation, numerical and physical modelling

C. ASSOCIATED METEOROLOGICAL VARIABLES

	Variable	At Levels Above Ground	Averaging Time	Frequency	Uses
1.	Air temperature	3 m 100,300 & 500m	20 min 1 min	3/hour 8/day	Wind energy, pollutant dispersion, agriculture, forces on structures
2.	Barometric Pressure	3 m	20 min	3/hour	Wind energy, pollutant dispersion, agriculture
3.	Relative Humidity	3 m 100,300, & 500m	20 min 1 min	3/hour 8/day	Wind turbine icing, agriculture, forces on structures

Suggestions of the meteorological variables tabulated above are based on collective thoughts of meteorologists and engineers who are involved with analysis and application of wind data. It is recognized that some of the variables listed in the tables would require innovative techniques of data collection. The improving technology of remote sensing and micro-processors provides an opportunity to develop new methods of data collection. Liason with the participants of the workshop during deliberation of changes in data collection system could be advantageous to everybody concerned.

A quality assurance and control program should be initiated that includes documentation and auditing of instrument specifications, selections, placement, calibration, inspection of installations, and monitoring of data processing and archiving for all National Weather Service as well as other meteorological stations. In addition to this program, an effort is needed to index and evaluate wind data from all available sources for potential use.

A recommendation for determination of atmospheric stability based on routine meteorological measurements should be formulated. This will lead to a systematic basis for predicting atmospheric transport and dispersion.

Effects of complex terrain and surface roughness upon wind structure are in need of further study. Information of this nature is required for use in evaluation of sites for wind energy and dispersion of air pollutants.

Wind structure and statistics associated with tornadoes, hurricanes, downslope flows, extra-tropical cyclones, and thunderstorms are not sufficiently established for prudent application to wind-engineering problems. Acquisition of data for these severe winds is needed particularly for judicious determination of wind forces on structures.

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SESSION I

APPLICATION OF WIND DATA AND DEFINITION OF NEEDS

Chairman: Jack E. Cermak
Rapporteur: Kishor C. Mehta

SESSION I: APPLICATION OF WIND DATA AND DEFINITION OF NEEDS

SUMMARY

Kishor C. Mehta
Jack E. Cermak

Current procedures of wind data collection, analysis and archiving system provides a minimum data base for its application to a variety of societal problems. The on-line wind speed and direction data collected once every hour has been used to a good advantage by the aviation industry. Weather forecasters utilize successfully the surface data and upper level data collected at specific intervals. For application of wind data to assess wind energy, to determine forces on structures, to predict pollutant dispersion and to improve agricultural efficiency, the current procedures of wind data collection, analysis and archiving system do not provide sufficient information. The needs of data for each of these applications were emphasized in the session and are summarized below.

Wind Energy

Wind speed and direction data are absolutely essential for assessment of wind energy potential. It is desirable that continuous data be obtained for determination of potential of cumulative energy. The important variables for application to wind energy are wind speed and its cumulative value, wind direction and its fluctuations, vertical profile of wind speed, and spatial correlation of wind fluctuations.

Wind Forces on Structures

Wind speed and direction data averaged over a length of record between 10 minutes and 60 minutes are most desirable for determination of wind forces on structures. It is essential to have knowledge of two to three-second peak gust and its direction that occur each day. In order to predict probability of a certain windspeed and direction occurring at a location it is necessary to have ten or more years of recorded data for the location. This necessity of a long period of record mandates improving the wind data collection system now to improve determination of wind forces on structures in the future. Large numbers of recording stations (500 to 1000) are desirable to lend credibility to maps of extreme wind occurrences. Mean and extreme wind speeds in special wind regimes such as thunderstorms, hurricanes, tornadoes, and downslope flows need to be recorded to improve design of structures and to mitigate their destructive effects.

Atmospheric Diffusion

Atmospheric diffusion of pollutants can be predicted with more accuracy with wind speed and direction data obtained in higher levels (100m to 500m) of boundary layer. Averaging times of 10 minutes to 60 minutes are desired. Development of atmospheric stability characteristics is needed for solution of the problem of atmospheric diffusion. Knowledge of spatial correlation of wind speed and direction fluctuations are essential to model dispersion of pollutants.

Agricultural Efficiency

Wind information plays an important role in numerous agricultural applications: prediction of heat and mass exchanges in plant communities; determination of water distribution patterns from sprinkler irrigation systems; minimizing drift in aerial application of pesticides; modeling the aerial dispersal of plant pathogens; and design and evaluation of windbreaks and shelterbelts. The wind data desired are wind speed, wind direction, temperature, and relative humidity. The data should be obtained close to the ground (3m) for judging localized effects and in the higher levels (300m-500m) of boundary layer for assessing regional effects.

Location of wind measuring instruments is another important factor that should be considered in wind data collection system. The instruments should be located in flat terrain and away from the buildings such that the collected data are not biased. Collection of gradient (about 500m above ground) wind data eliminates most of the bias due to surrounding terrain. In addition, calibration of instruments, documentation of instrument locations, judicious archiving and analysis of wind data are extremely important for proper application of the data to various problems.

APPLICATIONS OF WIND DATA AND DEFINITION OF NEEDS

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ABSTRACT

An overview of wind-climate definition required to predict occurrence frequencies for wind effects in a selected set of wind-engineering applications is presented. Wind data needed to develop predictions for wind forces on structures and people, air-pollutant concentrations and wind-power utilization are considered. In all applications considered, one-hour average gradient wind data taken at least every four hours provides a basis for definition of wind climate. Daily values of maximum three-second gust speeds for each $22\frac{1}{2}°$ sector at 10 m are needed to define low-level wind climate for design without the use of wind-tunnel tests.

INTRODUCTION

Meteorological variables that describe physical characteristics of wind are used in the decision-making process to help answer a variety of social, economic and technological questions. The following questions are typical of those that occur frequently. Should a populated area be evacuated because of an approaching severe storm or accidental release of radioactive material? What wind loads should be prescribed for structural design by codes? Where should wind-power machines be located? How can wind-effect data obtained by physical-model investigations be related to local climatological characteristics for design and analysis?

Essentially all applications of wind data involve prediction of future events. These predictions may be classified into two general categories. The first category is a prediction of tomorrow's events based upon today's meteorological data; i.e., a short-term forecast. Questions such as the first one listed previously would be in this category. The second category is prediction of the occurrence frequency in a specified time interval for a specified event or combination of events based on statistics of wind data recorded over a long period of time. The last three questions presented in the foregoing paragraph require this type of wind-data application. Applications in the following overview focus entirely on predictions of the second category.

The applications considered in subsequent sections are basic subject areas of the relatively new discipline of wind engineering (1,2). The wind effects of principal interest to this workshop are wind forces on structures, people and plants; transport of air pollutants from power plants, chemical spills and LNG storage facilities; and energy transport to wind-energy conversion systems. In these applications, momentum, mass and energy transport by wind in the atmospheric boundary layer constitute the fundamental physical phenomena that must be addressed.

Physical modeling, primarily in wind tunnels, continues to be the most practical and accurate method for determination of wind effects that result from wind of specified characteristics. Accordingly, an attempt to define wind-data needs must consider wind information required to integrate wind-tunnel derived data with natural wind characteristics for a specific site.

1. WIND EFFECTS ON STRUCTURES AND PEOPLE

Wind pressures, heat transfer and mass transfer on the exterior surfaces of buildings and structures vary both with time and location on the surfaces. The distribution and magnitude of these transfer processes are highly dependent upon geometry (adjacent buildings and local topography) and upon the meteorological variables. The latter variables include the mean wind-speed profile, turbulence scales and intensities, and direction of the mean wind. These variables are significant because they all affect boundary-layer formation, separation, reattachment and, vortex formation on the surface. Other significant meteorological variables that affect heat transfer are air temperature and solar radiation.

Information related to wind pressures obtained by wind-tunnel tests is currently being provided to structural engineers and architects for design purposes on more and more projects as buildings become more wind sensitive. This information includes local maximum pressure fluctuations, mean forces and moments, fluctuating forces and moments on the overall structure, fluctuating deflections, and accelerations. All these data are measured on small-scale physical models subjected to simulated boundary-layer winds generated in meteorological wind tunnels (3). This procedure provides correct input of mean wind-speed distributions, turbulence scales and intensities, and mean wind direction but depends upon National Weather Service records for wind speed, direction and temperature data at a particular site. A rigid model is usually used to obtain mean forces and moments either through integration over the surfaces of mean pressures measured at many piezometer taps or directly by mounting the model on a six-component balance. The local maximum (peak) pressures required for curtain-wall design are also obtained from pressure measurements on a rigid model. Measurements of mean wind speed and turbulence intensity are usually made at street-level locations to evaluate wind effects on pedestrians. All of the fluctuating quantities --base moments and shear, torque, deflections and accelerations--caused by instantaneous distribution of pressures over the exterior surfaces are usually obtained from measurements on a simplified aeroelastic model. An example of a typical comprehensive wind-tunnel investigation for the model shown in Fig. 1 is presented in Ref. (4).

When wind-tunnel tests are not used to determine wind loading on a structure building codes and/or the ANSI A58.1 standard (5) are used to establish minimum wind loads for design. The ANSI A58.1 maps of extreme fastest-mile wind speeds for 25-, 50-, and 100-year mean recurrence intervals are commonly used to determine appropriate reference pressures and wind speeds for use with wind-tunnel derived data.

Stress analysis for primary-frame members of the United States Steel Office Building by Robertson and Chen (6) showed that the combination of high thermal loading with modest wind speeds produced maximum stress in some members. In order to account for these effects during design, wind data must be analyzed to obtain joint probabilities for combinations of wind speed, air temperature and wind direction.

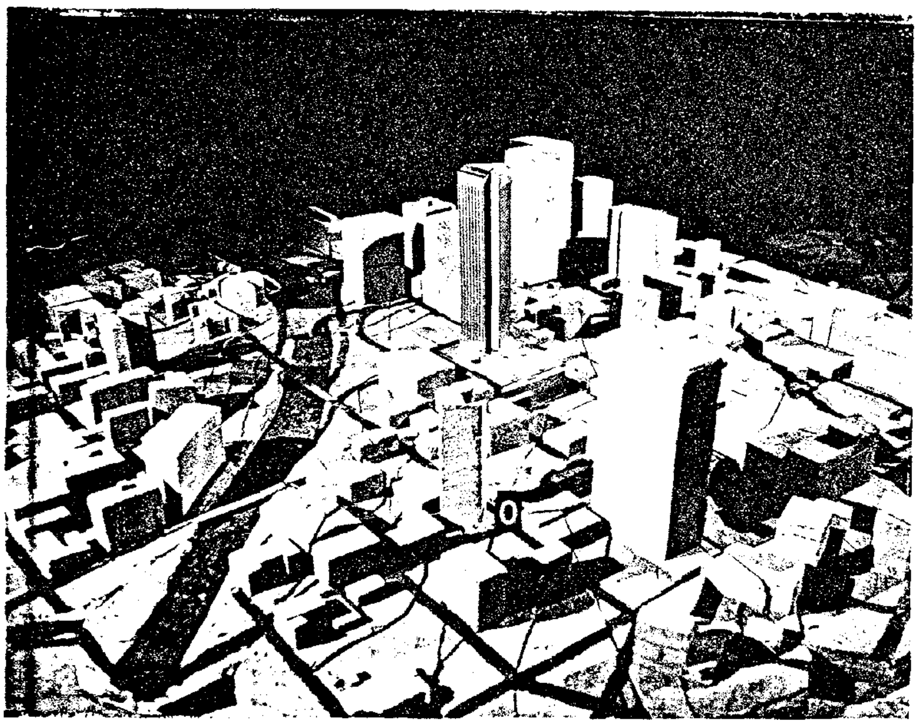

Figure 1. Model (1:300 scale) of Proposed Seattle Hotel (triangular building at center background) in Boundary-Layer Wind Tunnel Looking South and Surrounding Buildings (4).

Wind-pressure data for buildings are being utilized in numerous applications other than in design of building frames and cladding. Such applications include design for natural ventilation; estimation of heat loss by infiltration; determination of effects on heating, air-conditioning, and ventilating systems; prediction of internal movement of smoke and gas caused by fires; and design of building entrance systems for safe operation during strong winds.

a. Local Peak Pressure Fluctuations

Rational design of curtain walls for modern buildings requires information on the distribution of peak pressure fluctuations over exterior building surfaces. Specifications and designs of cladding, glass and mullions are commonly based on information such as shown in Fig. 2 for one side of the Seattle Hotel (4). Numbers assigned to each contour are absolute values of the peak pressure coefficient

$$|C_p|_{max} = \frac{|p - p_\infty|_{max}}{0.5\ \rho\ U_g^2}$$

in which $p - p_\infty$ is the maximum or minimum 10-15 second average difference between pressure at a pressure tap on the building and the undisturbed atmospheric pressure p_∞ at the building location, ρ is the mass density of air and U_g is the hourly mean wind speed at gradient-wind elevation. The peak-pressure difference for each tap location used to develop the contours is the maximum value measured for all wind directions considered (often 36 at 10° increments). Assuming that the design value for U_g has equal probability of occurrence from any wind direction, data of the type shown in Fig. 2 can be used directly for design. However, at sites where strong winds occur with greater frequency in specific sectors, a more refined set of design pressures may be obtained by determining the probability density distribution for U_g with respect to wind direction (7) and then determining a set of peak pressures that will have the same probability of occurrence at all measurement points.

Curtain wall design for tall buildings must consider another pressure difference that must be added to the peak wind pressures obtained from wind-tunnel tests. This pressure difference is caused

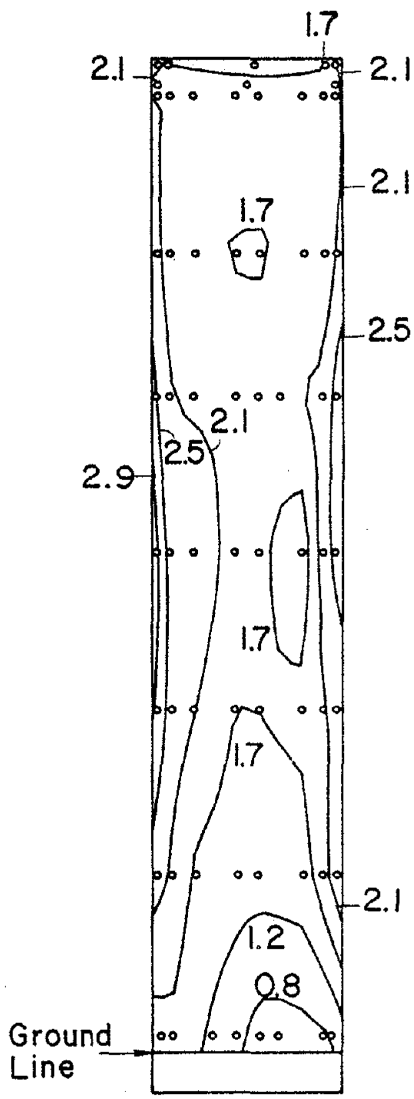

Figure 2. Contours of Maximum Peak Pressures Coefficients $|C_p|_{max}$ for South Elevation of Seattle Hotel (4).

by stack effects resulting from air temperature difference inside and outside of the building (6). Accordingly, the joint probability density for mean air temperature and wind speed is required to establish design pressures with equal occurrence probabilities.

b. Dynamic Responses

Wind pressures acting on tall buildings, towers and suspension bridges produce fluctuating resultant forces and moments that can cause significant dynamic effects. The dynamic responses of greatest interest are base moment and shear, deflections and accelerations. Wind-tunnel tests using aeroelastic models confirm the expectation that these responses depend strongly upon mean wind direction, mean wind speed and wind turbulence characteristics. Peak base moments for the Seattle Hotel (4) given in Fig. 3 illustrate dependence upon mean wind direction and mean wind speed expressed as the reduced velocity U_g/nb where n is a natural frequency and b a side length of the building. Peak accelerations and deflections vary with these meteorological data in a similar manner.

Data of the type shown in Fig. 3 may be applied to design by establishment of the return period for peak moment of given magnitude (7). This again requires determination of the joint probability of wind speed U_g and wind direction from National Weather Service (NWS) data taken near the site. Additional meteorological information--joint probability of temperature and water content (icing conditions) and wind speed--is needed for comprehensive design of towers, bridges and transmission lines (8). Icing of such structures often results in geometrical changes that promote dynamic excitation as well as an increase in dead load.

c. Local Wind Characteristics

Buildings and other obstacles to air movement can result in a wind environment near ground level that is uncomfortable or sometimes dangerous for pedestrians (9). Wind-tunnel studies show that the characteristics are strongly dependent upon mean wind speed and direction at gradient height as well as local geometrical features (4). An illustration of this dependence is shown by Fig. 4 in which relative mean wind speed U/U_g and turbulence intensity $(u^2)^{\frac{1}{2}}/U_g$ (u is

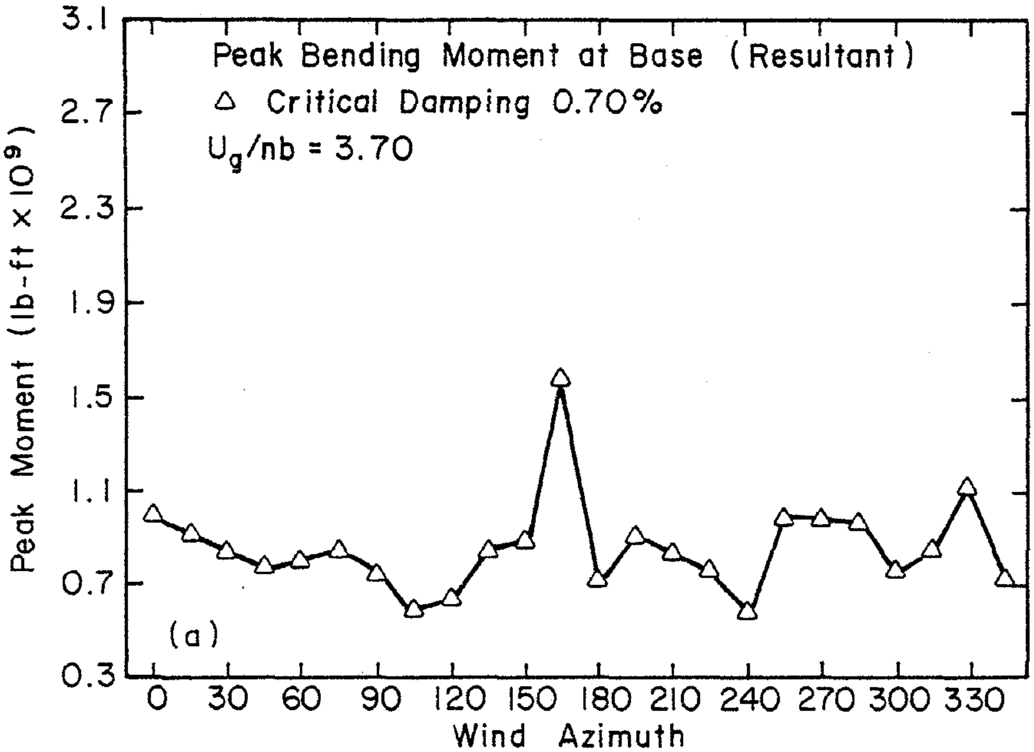

Figure 3a.

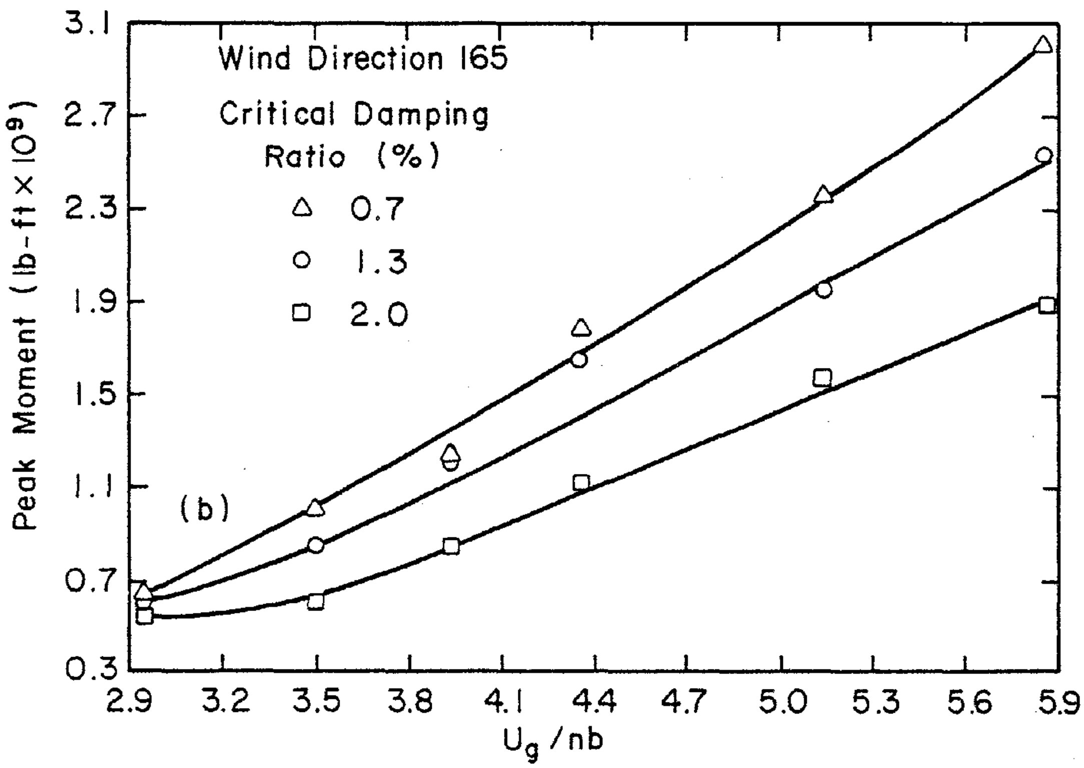

Figure 3b.

Figure 3. Peak Base Moment for Seattle Hotel (4).

fluctuation from mean value U) five feet above ground near the southeast corner of the Seattle Hotel are presented.

Data of the type given by Fig. 4 must be integrated with the joint probability for gradient wind speed and direction near the site to provide information for arriving at decisions regarding remedial action. An example of probabilities for mean wind speed U and peak wind speed $U + 3(\overline{u^2})^{\frac{1}{2}}$ in the form of "percent of time exceeded" is presented in Fig. 5. In cold climates a more complete assessment of wind effects on pedestrians includes consideration of "wind chill." This consideration requires integration of local wind data (Fig. 4) with joint probability for gradient wind speed and mean temperature such as given by Fig. 6

d. Summary of Wind Data Needs

A major application of wind data is in definition of wind climate for integration with local wind effects at a particular site obtained through wind-tunnel tests. Statistics of the gradient wind speed are most useful for this purpose. In particular, probability distribution of the one-hour mean gradient wind speed U_g with respect to direction are needed. For comprehensive wind-effect investigations these data should be coupled with joint probabilities for mean temperature and relative humidity.

In the absence of wind-tunnel tests low-level wind data are required to treat wind effects on structures. For this most common application, statistics of the fastest-mile wind speed at 10 m (available in Ref. 5) are commonly used. Unfortunately, duration time of the fastest mile wind speed depends upon the wind speed itself. A more useful measure of extreme wind speed at low level would be the gust speed for a prescribed gust duration. A duration time of about 3 seconds is appropriate.

Wind-speed statistics are urgently needed for severe storms--tornadoes, hurricanes, thunderstorms and downslope flows. Since each storm type may form a distinct population, statistics for each type should be developed individually using data separated from the usual boundary-layer wind data.

BASIC WIND DATA NEEDS

1. One-hour averages of gradient wind speed, direction and temperature every four hours.

2. Daily extreme gust speed (approx. 3 second duration) at 10 m for each 22½° sector.

3. Daily extreme stability indices.

4. Mean water content, temperature and wind speed for icing conditions.

5. Mean and extreme wind speeds for tornadoes, hurricanes, thunderstorms, and downslope flows.

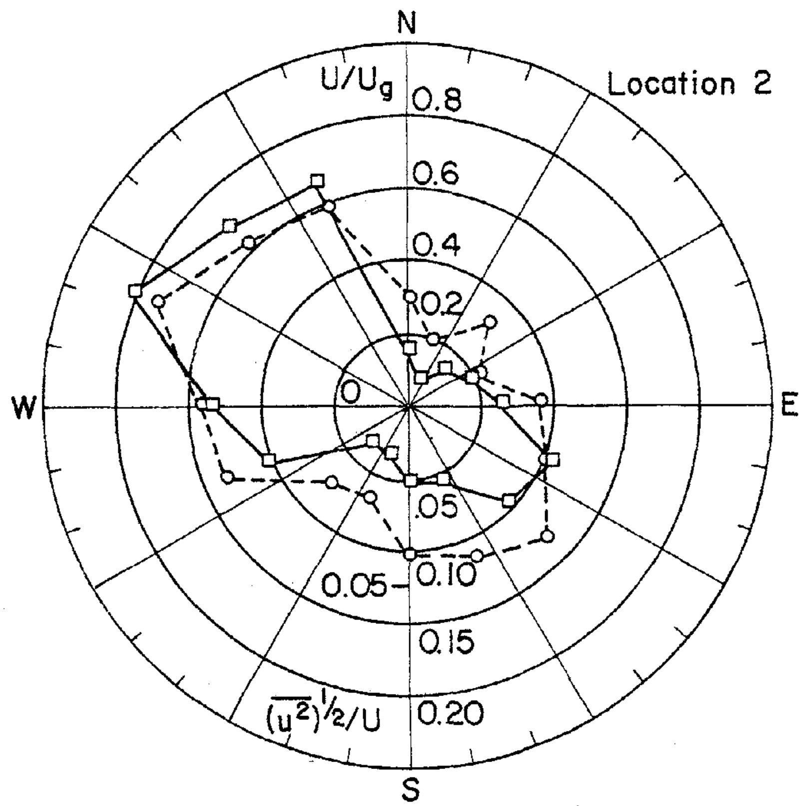

Figure 4. Mean Wind Speed and Turbulence Intensities Near Southeast Corner of Seattle Hotel 5 ft Above the Ground (4).

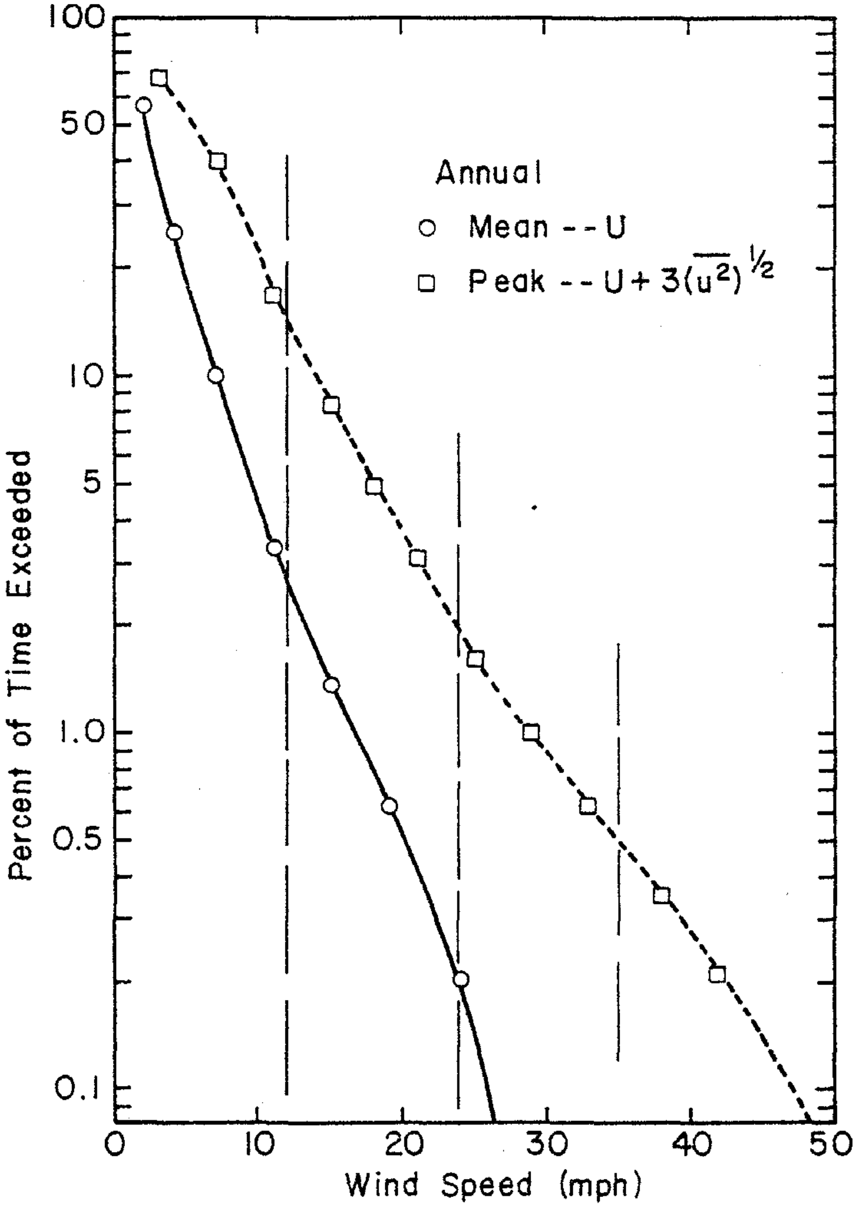

Figure 5. Wind Speed Probabilities for Wind Data of Figure 4 Combined with Climatological Data (4).

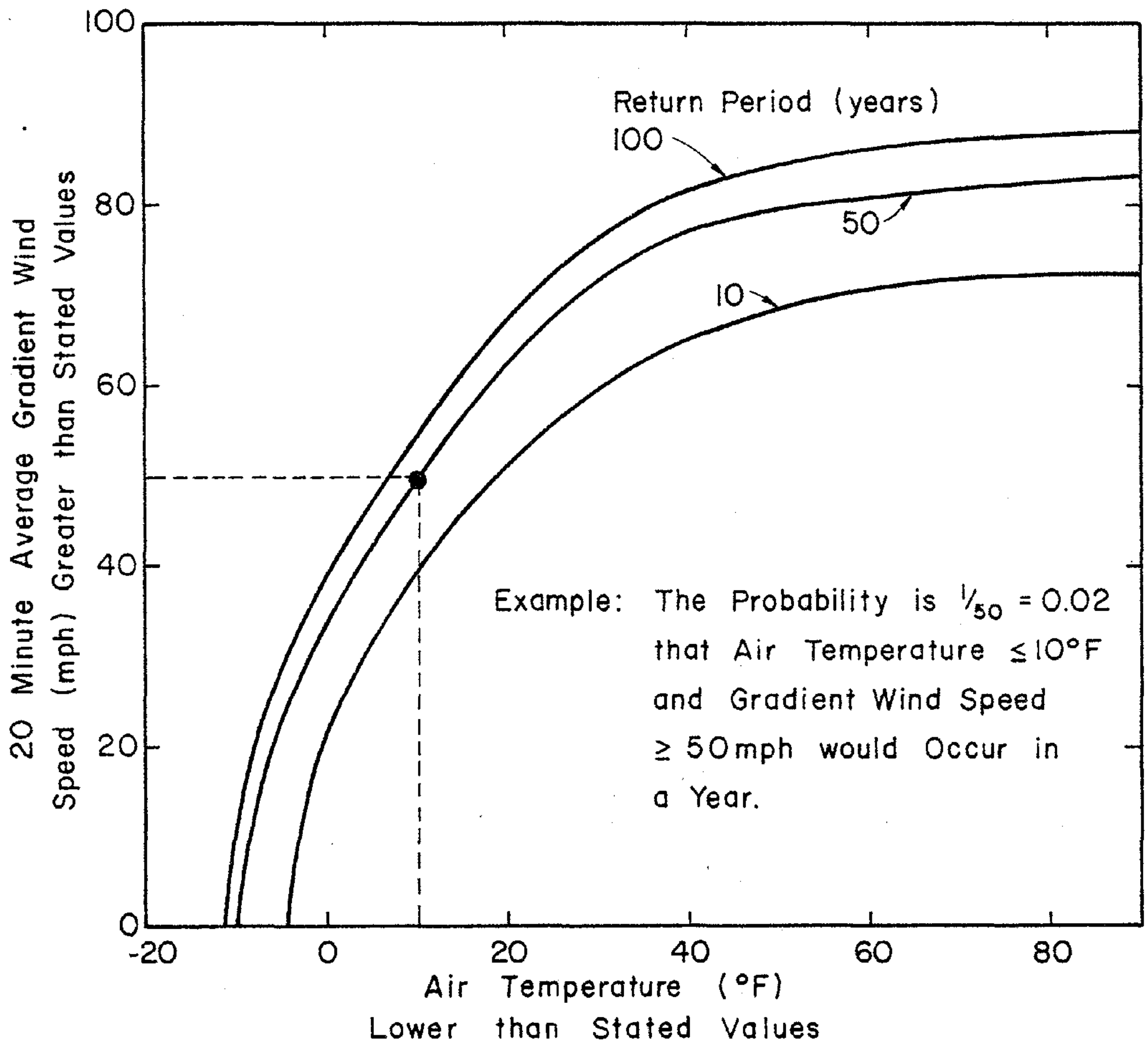

Figure 6. Joint Probability of Gradient Wind Speed and Air Temperature at Pittsburgh (6).

2. MASS AND HEAT TRANSPORT BY WIND

Wind data are vital to the treatment of many air-pollution and agricultural problems. Determination of concentrations of SO_2, radioactive gases, and H_2S from fossil fuel, nuclear, and geothermal power plants; CO, hydrocarbons, and NO_x from parking garages and dense traffic; methane from liquid natural gas (LNG) spills; and toxic fumes from chemical spills are common cases involving the dispersion of gases (2). Evaporation from soil and water surfaces; evapo-transpiration from plants; and transfer of heat, water vapor and CO through plant canopies are closely related to agricultural productivity (10). The transport of solids is encountered in dispersion of silver iodide over complex terrain for cloud seeding, snow drifting and soil and sand movement.

When the boundary geometry is complex (composed of buildings, trees, uneven terrain) fluid modeling is commonly used to establish short-range dispersion characteristics. Numerical models and mathematical dispersion models are particularly appropriate for making short-range predictions over flat, open terrain and for long-range dispersion investigations.

Gradient wind statistics of the type indicated in Section 1.d are also needed for use with either fluid, numerical, or mathematical modeling in order to establish exceedance statistics for concentrations such as shown in Fig. 6 for wind speed. However, because diffusion by turbulence in sensitive to thermal stratification of the atmosphere (11) additional wind data is required. Needed information consists of mean wind speed and temperature measured at a minimum of three elevations. Ideally, this information would be available for a time sufficiently long to establish joint probabilities for an atmospheric stability index (Richardson number) and wind direction.

3. WIND POWER UTILIZATION

Two major aspects of wind affect the location, design and operation of wind-power machines. Available wind-power and its distribution with respect to time is the first and most vital consideration. The second most important consideration is the extreme wind speeds and their recurrence interval. The former wind characteristics determine, in large part, the feasibility of developing a wind-power conversion installation at a particular site while the later determines wind loading to achieve low probability for damage by wind.

Hourly observations of wind speed by the NWS (a 1-5 minute average observed each hour adjusted to a standard height of 10 m) are commonly used to estimate available wind-power. These wind speeds, assumed to be representative of the hour average, are cubed to obtain available wind energy per unit area normal to the wind direction. Figure 7, reproduced from a report of studies on wind-power variability by Reed (12), illustrates the typical large variability of monthly-average available wind-power. The basic data used for these estimates are deficient in two respects. One deficiency, probably the least serious, is representation of an hourly average by a much shorter time average. A more serious deficiency is with respect to spatial displacement between location of the wind-data observations and a potential wind-power site. Both of these deficiencies can be overcome most directly by observation and use of hourly-mean gradient wind speeds U_g. The magnitude of U_g is less site sensitive than the hourly obervations at NWS anemometer locations (usually airports). When corrected for direction change with height resulting from Coriolis acceleration, U_g can be utilized with numerical models and/or physical models to predict wind-power availability at potential sites for wind-power installations that are displaced horizontally and vertically (on hills) from locations of wind-data observations (13).

Prevention of catastrophic failure of a tower and/or wind turbine and trouble-free operation of a wind-power installation can be achieved only if extreme winds are accounted for during the design process. Wind-data for this purpose is of the same type required to determine wind effects on structures as summarized in Section 1.d.

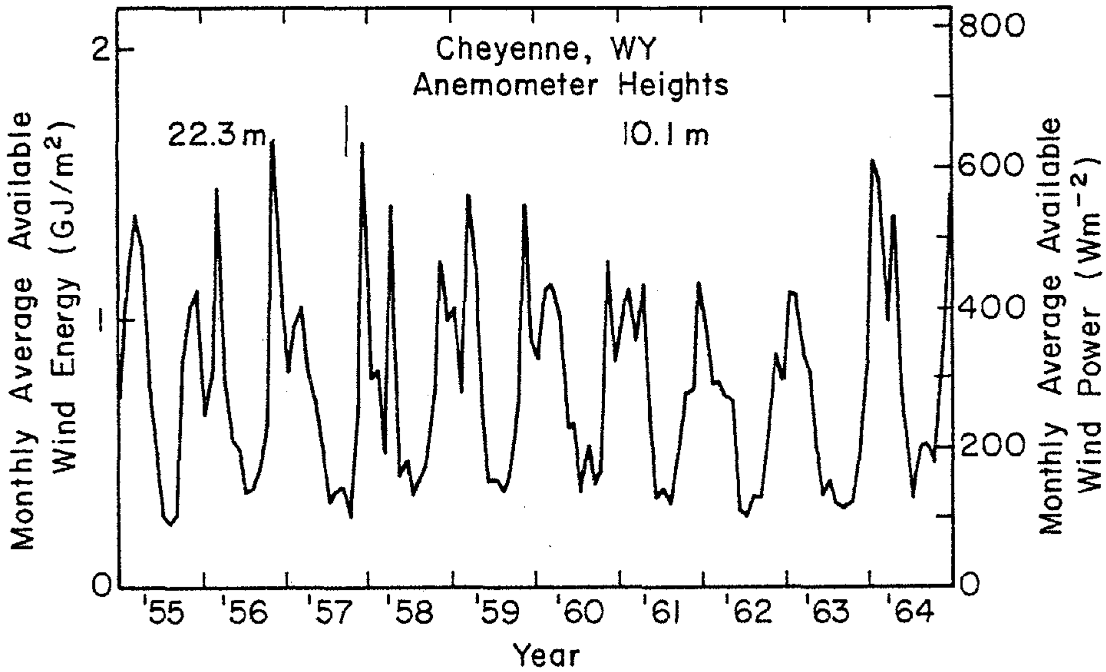

Figure 7. Time Series of Monthly Average Available Wind Power Cheyenne, WY., at 10 m Height (12).

4. CONCLUSIONS

The problem of predicting occurrence frequencies over a given time interval for wind effects associated with wind forces on structures, transport of mass and heat and wind-power utilization requires meteorological data that will enable determination of joint probabilities for combination of wind speed, temperature, thermal stability and water content of air as functions of wind direction. Basic data needed to make reliable predictions are the following:

a. one-hour averages of gradient wind speed, direction and temperature taken at least every four hours at primary NWS stations,

b. daily values of extreme gust speed (approximately 3 second duration) at 10 m height for each 22.5° sector,

c. vertical gradients of mean temperature and wind speed for determination of extreme thermal stratification statistics,

d. mean water content, mean temperature and mean wind speed for determination of icing statistics, and

e. wind-speed statistics for tornadoes, hurricanes, thunderstorms and downslope flows.

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WIND DATA APPLICATION IN DEVELOPING THE ANSI A58.1-1980 STANDARD*

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ABSTRACT

THE ANSI standard on minimum design loads in buildings and other structures has recently undergone a routine review and revision. A critical part of this review involved an analysis of climatological wind data collected at National Weather Service Stations throughout the country. A general description is given in this report of the various steps taken in this analysis including data selection criteria and collection, data reduction and statistical analysis, wind field analysis and special regions consideration. It is concluded that while the wind data are probably not of the quality desired, sufficient information is available to produce a guide useful for assessing structural design loads.

INTRODUCTION

The current ANSI (American National Standards Institute) standard A58.1-1972, "Building Code Requirements for Minimum Design Loads in Buildings and Other Structures," has just undergone a periodic revision. It is intended to govern load assumptions for dead, live, wind, snow, earthquake, litho- and hydrostatic loads in the design of buildings and other structures which are subject to building code requirements.

The A58 Windloads Subcommittee has, among other things, produced an updated national map of annual probable extreme wind speeds to be used in assessing wind loads on structures. This report, after a brief review of previous wind map versions, will indicate data selection criteria establishment and collection, data homogenization and reduction, statistical analysis, extreme wind field map analysis and treatment of special regions. Finally, some of the data problem areas will be discussed with some

*This work was supported by the United States Department of Energy.

suggestions offered for their improvement. The actual application of wind data to building loads will not be discussed here as that is covered by other papers at this workshop.

1. BASIC WIND SPEEDS

In general it is the short duration high speed wind bursts (several seconds to minutes) that are of greatest concern to structural integrity. Thus, the recorded weather element known as the "fastest mile" traditionally has been used as a reliable record of maximum wind. (Thom, 1955). There are other reasons besides tradition for selecting the fastest mile and some of them will be mentioned later.

The basic speed data and their analysis used for the revision have been reported (Simiu, Changery, & Filliben, 1979), and the procedures used will be summarized briefly here. Restrictions placed on extreme wind speed records selected were:

- at least 10 years of reliable record length,
- generally open terrain (i.e., airports) exposure,
- extreme speeds reported as fastest mile (exceptions noted below),
- known anemometer exposure and height history.

These selection criteria resulted in a total of 129 airport weather station records being used. At five locations some of the yearly extreme fastest miles were approximated from a knowledge of the fastest observed one-minute mile for some of the record years. At 34 other stations the extreme annual speeds had been estimated by station personnel for at least one year, five stations for at least two years, and two stations for three years.

Although the U. S. primary weather station network of surface observations numbers about 700 (Changery, 1975), the necessity to achieve as meteorologically homogeneous a data set as possible resulted in the elimination of roughly 80% of these records. The remaining usable airport stations with fastest mile indicating equipment (which often use separate sensors from those used for measuring the official hourly one-minute observation) totaled 129 with a median record length of 32 years ranging from 10 to 54 years.

2. ANALYSIS AND APPLICATION

For each station, the yearly fastest mile speed value was normalized to a standard reference height above ground of 10 m. The normalizing expression uses the well-known 1/7 power law of the height ratio and a term which allows for the short averaging time of the fastest mile as compared to the longer averaging period (1 hour) for which the 1/7 power law is generally valid (Simiu et al, 1979).

The statistical analysis of each station series, also discussed in the above reference and presented in a following paper at this workshop, was accomplished in three stages:

- test each series against extreme value distributions,
- calculate the optimum values for the distribution parameters,
- estimate extreme winds at various probability levels, or equivalently for various return periods (2, 25, 50, 100 years, etc.).

From the results of this analysis it was found that ratios of values for given return periods, e.g., 25/50 and 100/50 were relatively constant with only minimum scatter. It was therefore decided to analyze the map for only the 2% probability level (50 year return period) and indicate the resulting ratios for the 5% and 1% levels. These ratios, 0.95 and 1.07, respectively, have been dubbed the "importance factor."

The estimated 2% values for each of the 129 stations were plotted on a base map of the coterminus United States and a wind field analysis was hand constructed for values of 70 miles per hour and above (Fig. 1). Values less than 70 mph were ignored because of the minimum design wind loading of 10 psf (pounds-force per square foot) specified in the standard. The wind field analysis considered the analysis of the 1972 version, comments from climatologists and others on local peculiarities existing in regions of special topography, and a separate hurricane region study done by Botts, et al, (in preparation).

As is necessary for many meteorological analyses, some professional judgment was applied to the details of contour pattern creation and smoothing. Committee deliberation and approval were also used to formulate the final version.

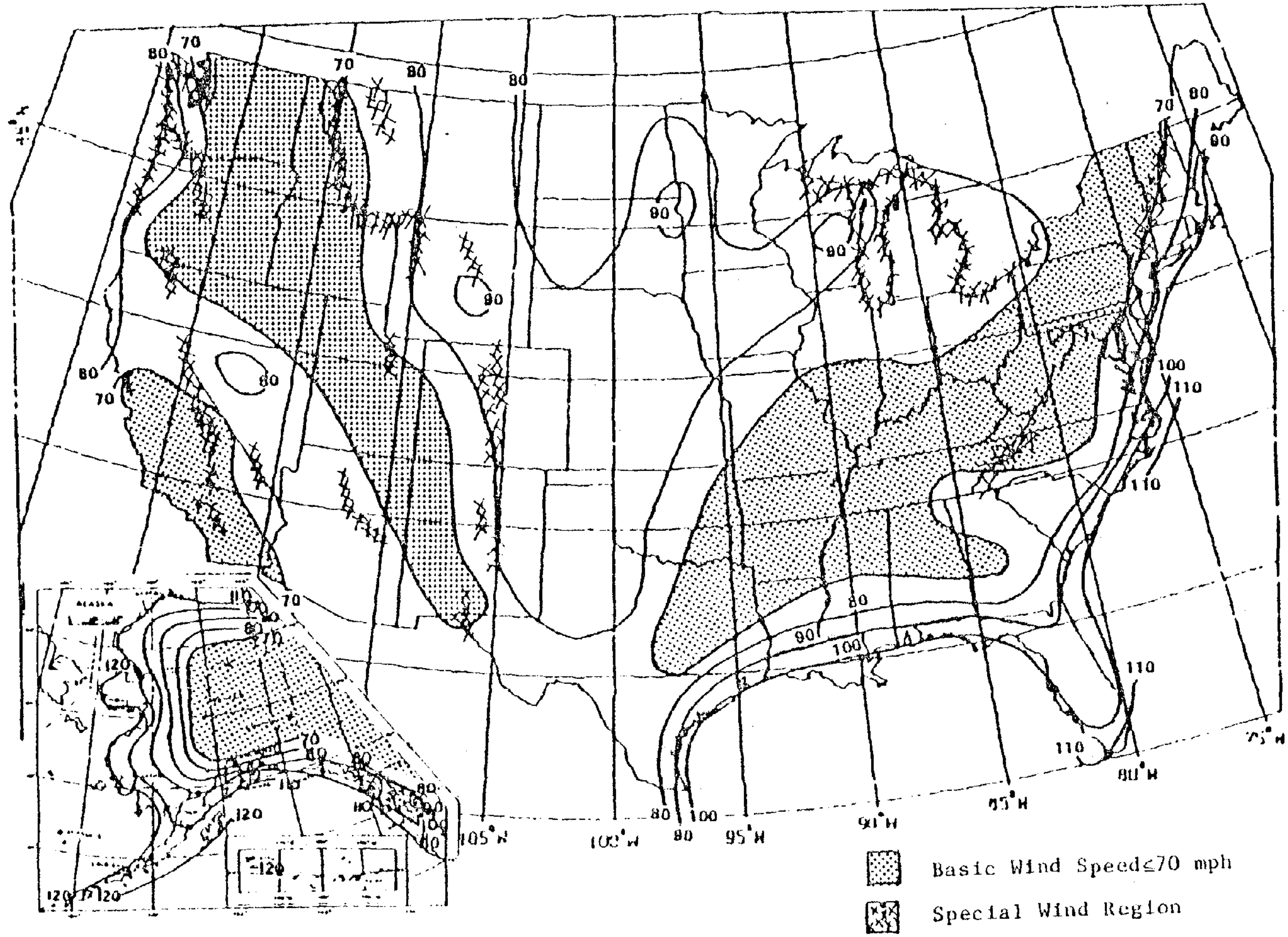

Figure 1 Basic Wind Speed in Miles per Hour at 10 Meters (32.8 ft) Above Ground

3. DEFINITION OF NEEDS

Uniform instructions for standard weather observing and reporting techniques are provided in Federal Meteorological Handbook No. 1, "Surface Observations" (formerly known as Circular N). The record of regular hourly and intermittent prescribed special observations are maintained on a daily form, MF1-10 (formerly WBAN-10). Wind speeds are generally read from a continuous trace recorder ("gust recorder") and averaged over a one-minute interval (Fig. 2). Currently, these wind sensors are located on a 20-foot pole near the airport runway; however, many changes have occurred in instrument location and height over the years.

Usually, the sensors which indicate passage of one statute mile of wind (Fig. 3) are connected to an "operations recorder" or "multiregister." This sensor may or may not be close by the continuous speed recorder described above. At the end of each day the station observer records the time, direction and the value of the fastest mile for that day on the form 10B. If such equipment is not available or is inoperative, the so-called "fastest observed one-minute wind speed" and its direction and time are reported. This value comes from the largest entry made on form 10A throughout the day and may or may not be the actual fastest one-minute wind speed that occurred that day. The peak wind (speed, direction, time) for the day as read from the gust recorder is also entered on form 10B. This value is the maximum instantaneous deflection observed from the day's speed trace recording.

At each month's end all stations submit their MF1-10's and their trace recorder charts to the National Climatic Center (NCC). Subsequent extraction of maximum wind data was done from these forms to compile the annual value for each station for as many years as the record reliably existed.

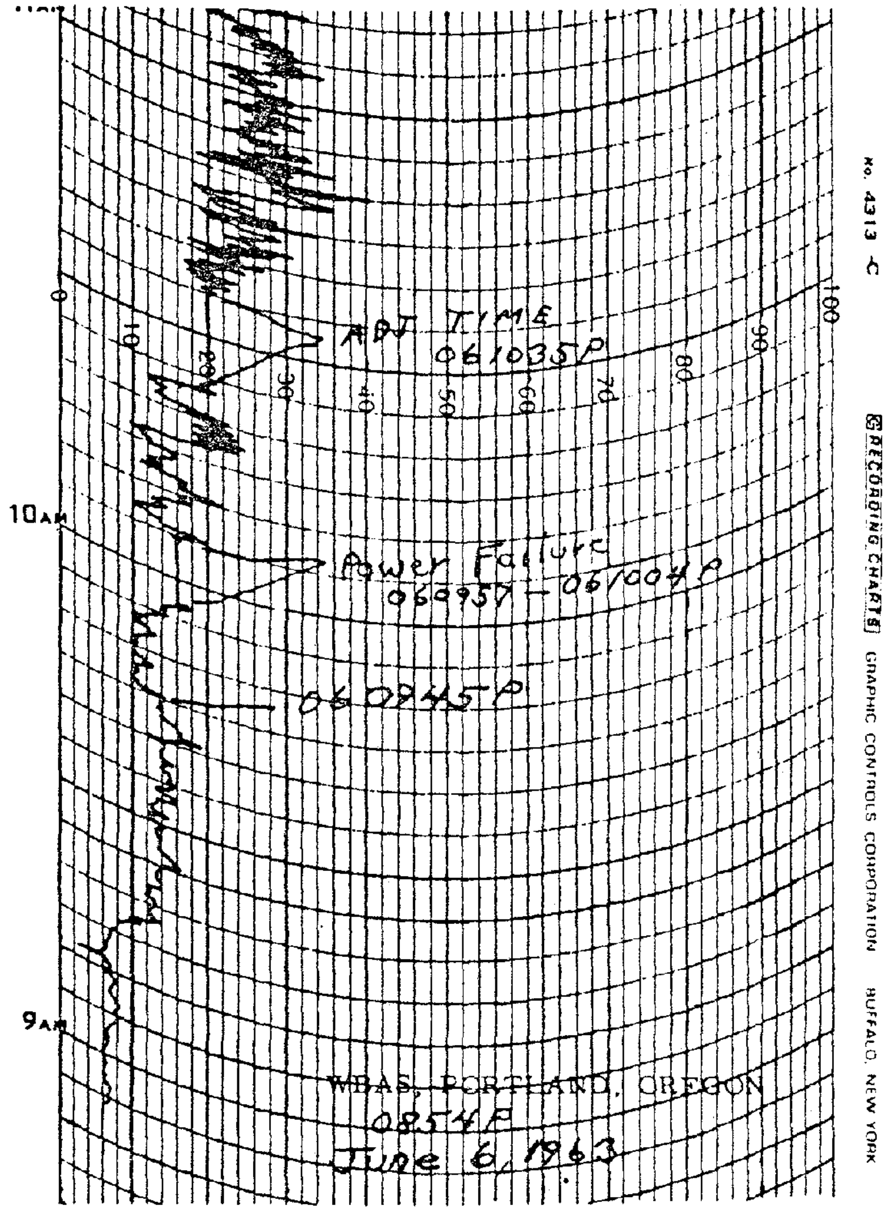

Figure 2. Wind Speed Recorder Chart.

(From FMH #1A)

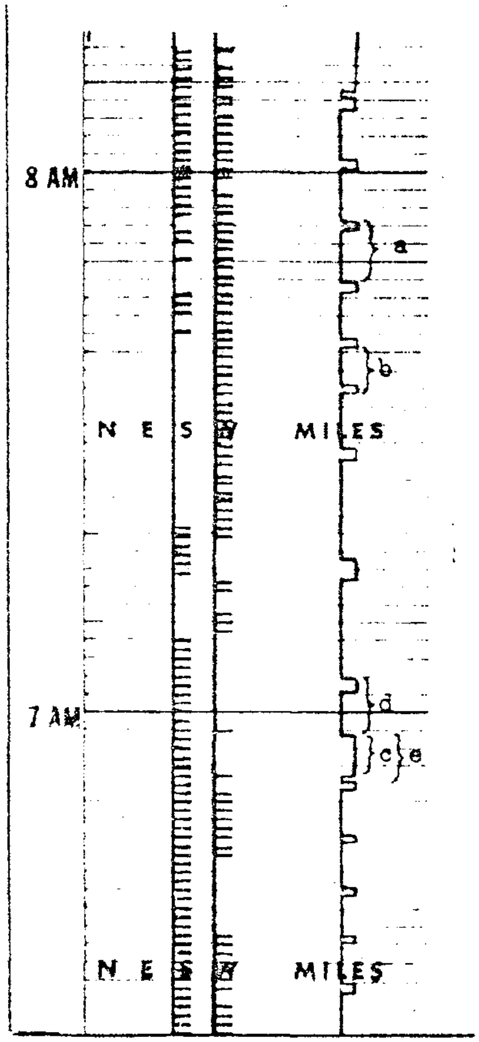

Figure 3. Wind Data from Operations Recorder.
(From FMH #1B)

Of the three daily summarized maximum winds reported (fastest mile, fastest observed one-minute wind speed, peak gust), the fastest mile is considered the most appropriate and consistent element in terms of applicability to structural response. Since it is truly an integrated measurement, there is probably less adverse impact from gust-caused sensor overshoot and recorder pen oscillation than is so typically seen in high speed gust records.

The above paragraphs describe the existing extreme wind data that are available. The following list defines some basic needs for the overall system of wind measurement, recording and archiving which would lend maximum credibility to derived maps of extreme wind occurrence:

- reliable wind sensing and recording equipment,
- automated data processing and recording,
- long term (>10 years) records,
- uniform and well documented sensor locations, exposure and height,
- system-wide quality assurance and control documentation,
- 500 to 1000 stations (especially more dense coverage for regions of special topography and concern).

If wind data were recorded digitally and at a sufficiently rapid rate, >1 Hz, then speeds averaged over a multiple of averaging times of interest to structural designers could be derived. This could, of course, lead to comprehensive wind variance spectra calculations useful for many applications.

4. CONCLUSION

While there may be many valid reasons for the existing data archive not being of the desired optimum quality, it is, nevertheless, a useful exercise to take stock and reevaluate the many aspects of wind (and other) data collection and try to upgrade them. The data applied in developing the A58 standard were selected and processed to yield a valid and useful guide for establishing wind loads around the country. While the data are not optimum, they are considered adequate to this purpose.

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APPLICATION OF WIND DATA TO BUILDING LOADS AND DEFINITION OF NEEDS

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ABSTRACT

A discussion of the use of wind data for calculation of building wind loads is presented. Because of the availability of wind tunnels to determine structure/wind interaction, the uncertainty in wind magnitude statistics currently represents the largest uncertainty in determination of wind loads. Several areas for research are suggested for application to the analysis of fastest mile winds for extreme event prediction and to the analysis of hourly wind data. These suggestions would extend the fastest mile extreme value analysis to include wind direction and would determine means of transferring data from one location to another. Research is needed to provide corrections to data to account for the presence of nearby buildings. Analysis of hourly data is needed to correct deficiencies in existing published data and to break the data into more useable 12 hour day/night segments.

INTRODUCTION

The economics of modern building design increasingly dictates that the various loads to which a structure may be subjected during its expected lifetime be determined as closely as possible. Many of the loads that control the design of a building or structure, including the wind load, have a probabilistic nature. The need for increased accuracy in wind load prediction is for an improved knowledge of the probability distributions of those loads. Fluctuation in wind load on a structure has two basic components--fluctuations due to changing wind speed and direction and fluctuations which result from wind/structure interactions such as zones of separated flow, vortex shedding phenomena or galloping.

Most building designers obtain wind loads for design from building code requirements. Some building codes now in use do not attempt to treat the stochastic nature of wind loads at all but rely on simple statically applied loads. Some codes, including the ANSI A58.1 standard (1) which is in use in some localities, describe separately the wind speed portion of the load providing maps of wind speed based on extreme value analysis and specify pressure or force coefficients for the structure which are combined with the wind data to obtain the load.

Improved accuracy in determination of local pressure coefficients, integrated force coefficients or dynamic response can be achieved through use of wind-tunnel testing (2), see Figure 1. Wind-tunnel testing is used primarily on large structures where economic benefits accrue to an improved design loading or on unusually shaped structures where building code provisions cannot provide realistic loading coefficients. The wind-tunnel results are combined with local wind data in the process of scaling from model to full scale. Another use of wind data for building design purposes is the determination of wind magnitudes in pedestrian areas for prediction of pedestrian comfort levels. This application is associated primarily with wind-tunnel measurements in which fluctuating velocities are measured in pedestrian areas in a model and scaled to prototype values using statistics of wind speed and direction obtained from standard meteorological sites. Some guidance on location and strength of pedestrian winds can be obtained without wind-tunnel measurements from publications such as reference 3 with a knowledge of local wind statistics.

With the ability to determine aerodynamic coefficients through wind-tunnel tests, currently the largest uncertainty in specification of wind loads on buildings and structures is associated with uncertainties and limitations in available wind statistics. The purpose of this paper is to highlight where primary uncertainties lie and to indicate areas of data reduction and research which would have a direct bearing on the ability of engineers to accurately predict wind loadings.

1. EXTREME WINDS

Maps of extreme wind magnitudes for the United States have been produced by Thom (4) using a Type II extreme value distribution. These maps for 25, 50 and 100-year recurrence winds are incorporated in the ANSI A58.1 (1). New maps of extreme value winds using, for most stations, a Type I extreme value analysis of fastest mile winds are in preparation for inclusion in the revised ANSI standard currently under development. These maps will provide wind magnitude without consideration of wind direction. Thus the designer is required to consider the same wind velocity approaching from all directions. There are many instances where economies in design may result from consideration of variation in wind magnitude with direction.

a. Influence of Wind Direction

Figure 2 shows fastest mile data from one station, the Seattle-Tacoma airport, which has been analyzed by a Type I distribution. In addition to the usual analysis which selected the one largest fastest mile wind each year regardless of wind direction (called 'all wind directions' in the figure), an extreme value analysis was also performed on 8 sets of data, one for each recorded wind direction, in which the largest fastest mile each year for each wind direction was used. Based on Figure 2, it is evident that strong winds come predominantly from the south through west directions. The 100-year east-wind magnitude is less than the southwest 5-year wind magnitude. It is also evident that the 100-year 'all wind directions' analysis shows a similar magnitude to the southwest wind which has the largest magnitude. This feature is characteristic of stations which this author has reduced in this way. An analysis of data in the form of Figure 2 for all stations with 25 years of fastest mile records would be useful for building design purposes.

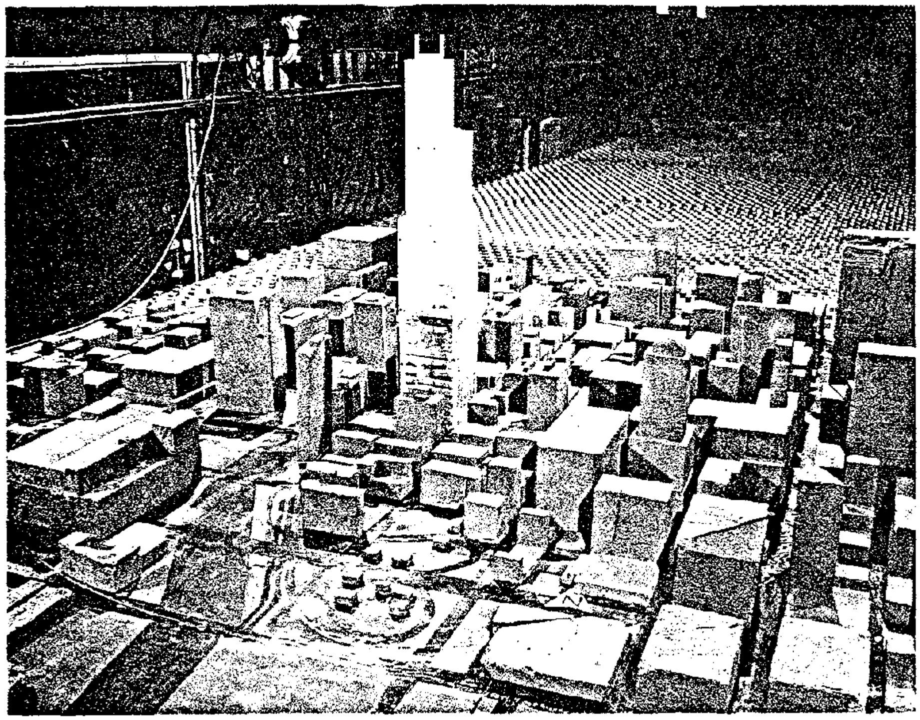

Figure 1. Building Model Undergoing Wind Tunnel Test.

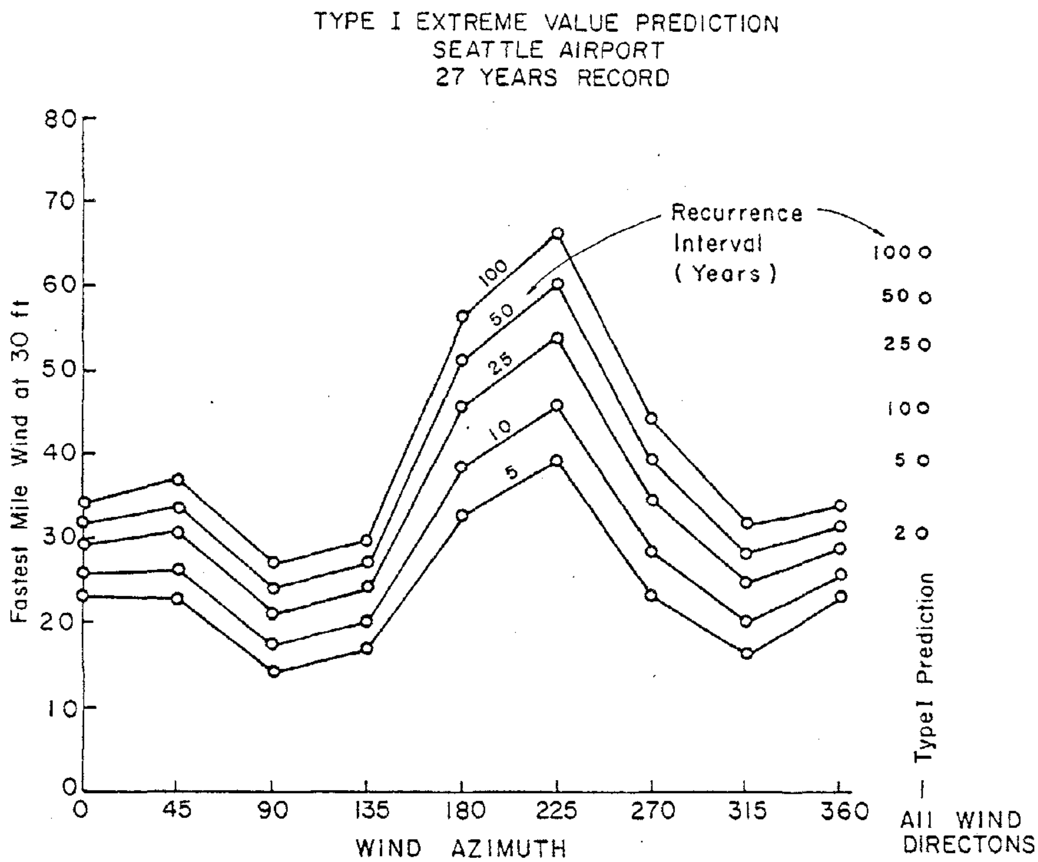

Figure 2. Analysis of Extreme Winds

Before analysis of fastest mile winds by wind direction is considered for many stations, errors resulting from hidden data should be estimated. Hidden-data errors can arise when the largest fastest mile wind for the year from a particular direction is not recorded because a larger fastest mile occurred on that day at a different wind direction. Research to estimate the frequency of occurrence and magnitude of hidden-data errors would permit error estimates to be applied to results of extreme value analysis.

Research currently underway by the author on statistical characteristics of pressure fluctuations on buildings appears to be yielding an analytical technique which could be of value in processing wind data to independently verify extreme wind values obtained from fastest mile data analyzed by wind direction. Verification of this technique should be available within about one year.

b. Influence of Location

An additional research need is the determination of the geographical area over which wind data obtained at a given station is valid. In other words, the transfer of wind statistics from a station with a long record to other locations in that region represents a definite need for analysis of building wind loads. This research may require a three-pronged approach: analysis of wind data stored at the National Climatic Center, analysis of wind data at 'nonstandard' stations or from newly installed anemometers at sites selected specifically for this type of study, and physical modeling in wind tunnels of wind flow over small-scale topographic models.

c. Influence of Nearby Buildings

Wind-velocity data obtained at airports is often considered representative of an open-country environment. Development of regions surrounding airports into residential or industrial areas may require an assessment at various periods in time to determine whether or not corrections to the data are required to provide equivalent open-country wind statistics.

A potentially more serious error in recorded data is the presence of individual airport buildings located upwind of an anemometer site. The momentum velocity defect in the wake of a building can extend to 15 or 20 building heights in moderately rough (mean velocity power law profile = 0.25) surroundings as shown in Figure 3 taken from reference 5. In this figure, x is distance downwind and H is the building height. In a smoother environment (0.14 power law) with a slight stability in the approach boundary layer (bulk Richardson number = 0.023), the building wake can extend to distances in excess of 60 building heights as shown in Figure 4 taken from reference 6. The momentum defect becomes a velocity excess near the ground after $x/H = 20$ due to effects of the horseshoe vortex which wraps around the building aligning the vorticity axis with the flow. For a structure with its sides oriented at 45 degrees to the approach flow, the roof-vortex axis can align itself with the flow in the building wake resulting in an excess velocity detectable in excess of 80 building heights downwind as shown in Figure 5 (7).

Because building wake effects can be seen at heights of 1.5 to 2.5 H, the wake effects of a 50 foot building could be measured at elevations of about 100 feet and for distances of more than 3000 to 4000 feet downwind. Many airport anemometers are placed within these distances of airport structures.

2. WIND DATA FOR PEDESTRIAN WINDS

Wind data providing percentages of occurrence based on wind direction and speed with resolution of 0.1 percent or less are adequate for prediction of pedestrian winds. The weather service has published a Summary of Hourly Observations for many stations which incorporates 1-minute averages obtained each hour for a 5 to 10 year period during the 1950's. Frequency distributions are produced for each month and on an annual basis. Figure 6 shows mean and peak velocities at three pedestrian locations integrated over wind direction with annual hourly summary data to produce percent time exceeded plots. Criteria for acceptable pedestrian velocities

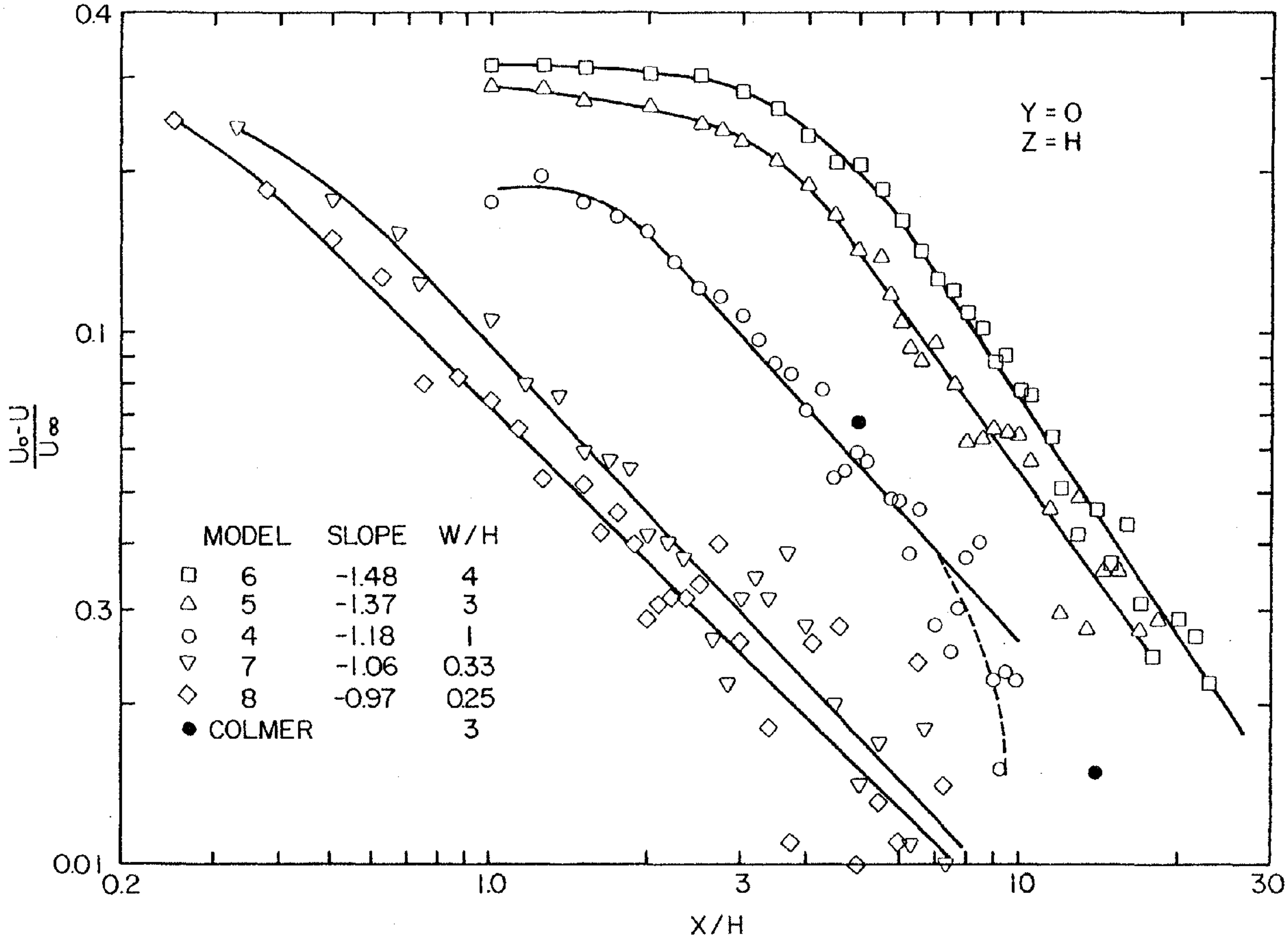

Figure 3. Mean Velocity Defect in the Wakes of Rectangular Buildings.

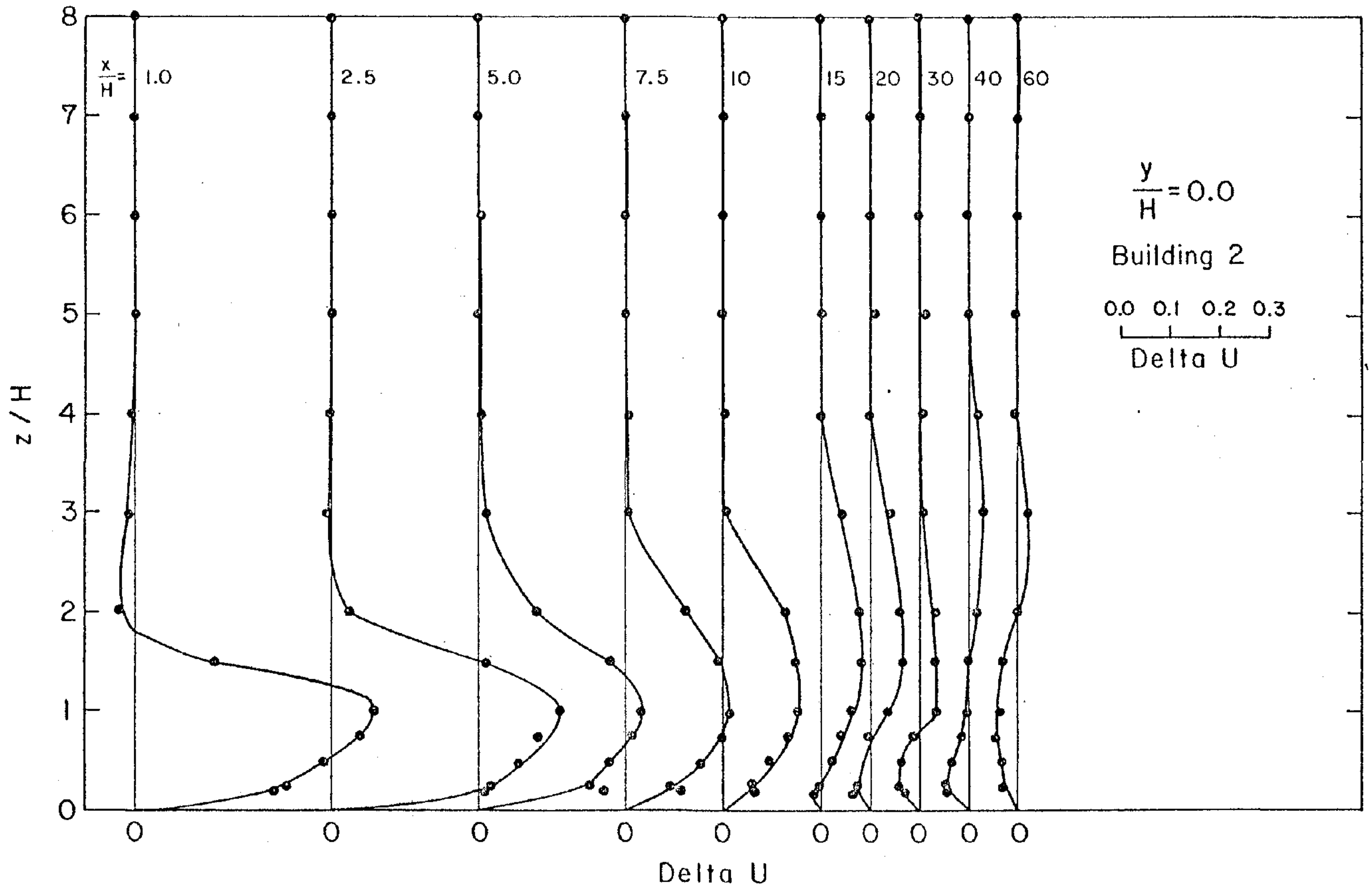

Figure 4. Centerline Vertical Profiles of Mean Velocity Defect behind a Rectangular Building in a Slightly Stable Boundary Layer.

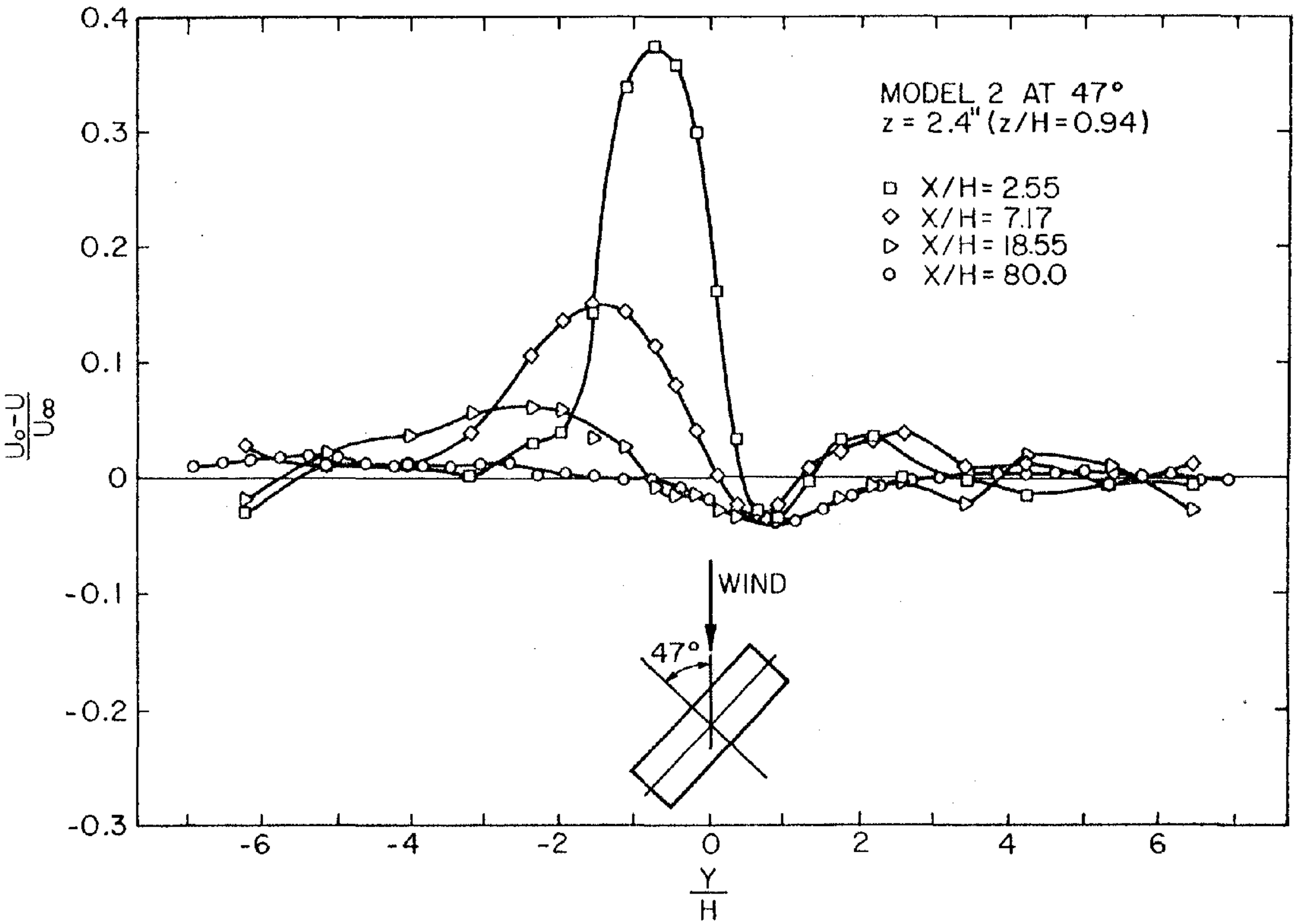

Figure 5. Lateral Profiles of Mean Velocity Defect Showing Vortex Wake Extending 80 Building Heights Downwind.

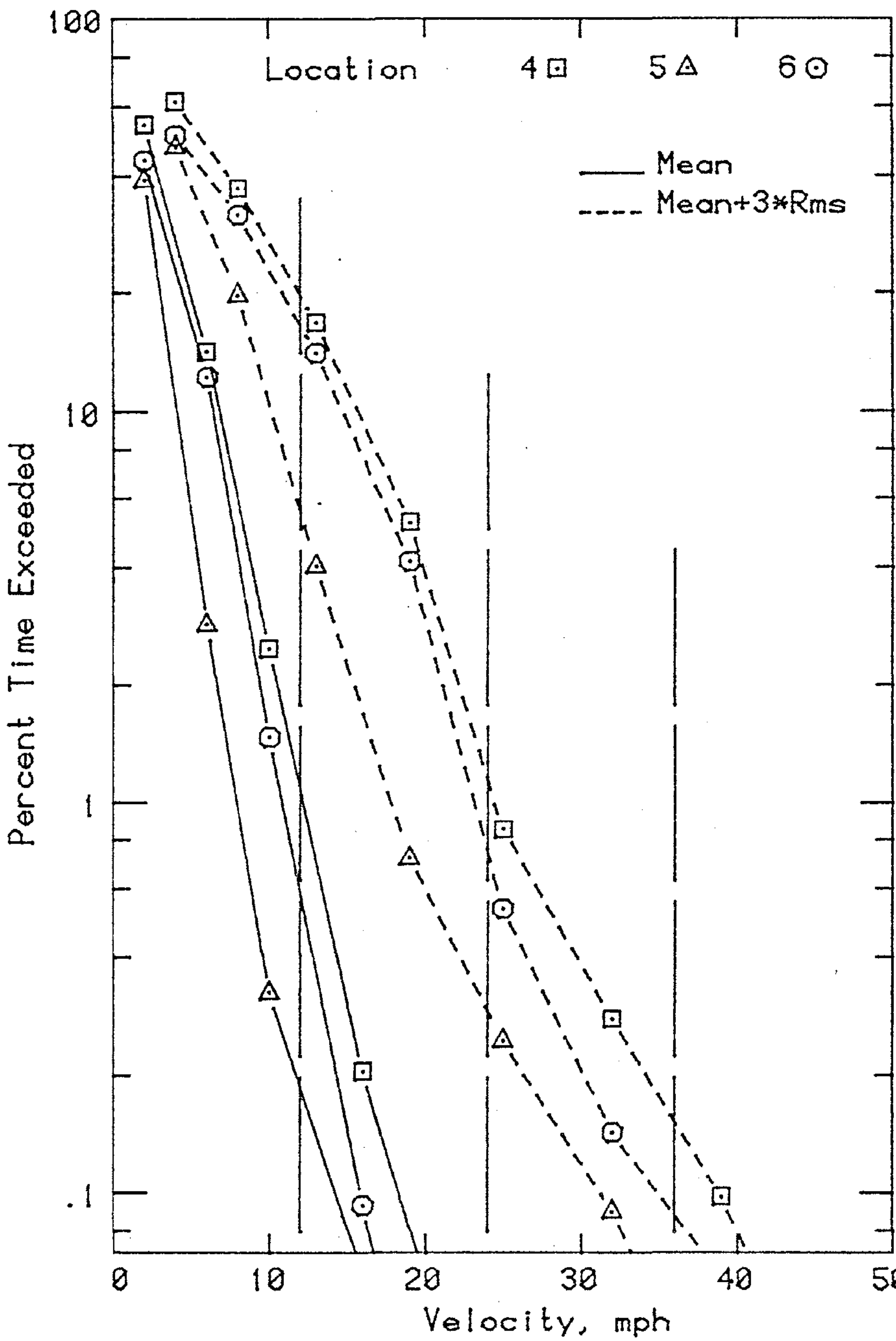

Figure 6. Percent Time Exceeded for Mean and Peak Velocities at Three Typical Pedestrian Locations.

which have been proposed by various investigators (8) are based on frequency distributions of meteorological data averaged over one hour. It is not clear precisely how pedestrian comfort criteria can be established using available 1-minute average data which is comparable to criteria based on 1-hour average data. One-hour average frequency distributions for U.S. stations would be of great value.

Additional problems are evident in the Summary of Hourly Observation data as currently compiled. Many stations report frequency distributions only to the nearest 1 percent. At some stations, averages were performed across time frames in which anemometer height changed, apparently without consideration of that effect on the results.

A recompilation of frequency distributions of hourly wind data is needed to eliminate existing problems. In addition, compilations by 12 hour day/night segments would permit a more realistic assessment of wind magnitudes which affect pedestrians who are present more during the daytime than at night.

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WIND DIRECTION FLUCTUATIONS

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ABSTRACT

Wind impinging on wind turbine blades at an angle θ from their plane imparts less energy, by $1 - \cos^3\theta$, than wind perpendicular to that plane. Wind turbines turn into the wind very slowly, so do not receive maximum energy. Winds which fluctuate through 30° to 50° during 15-minute periods provide only 83 to 93% as much energy as a wind constant in direction. At points only 12 meters apart, wind directions measured every second have correlations of 0.65 to 0.85, so that the total energy incident on large blades is further reduced. Many more detailed measurements are needed of the variations of wind directions, as well as speeds, with time and distance.

1. PROBLEM

Fluctuations in wind direction can degrade the performance of a large wind turbine as much as, if not more than, the concurrent fluctuations in wind speed. This aspect of wind climatology has not been investigated as much as has wind speed variation, perhaps because few tabulations are available of direction changes of periods of a few seconds to a few minutes. This note is intended to call attention to the problem, and offer preliminary estimates of its magnitude.

The largest wind turbines currently operating, or under construction, have blade diameters of 30 to 90 m, rotate about once per second but revolve ("yaw") very slowly, only 10° to 20° per minute. (Rotation is around the hub, revolution around the tower, as in astronomy; Earth rotates daily, revolves annually.) This slowness in revolution, compared to the rapidity of wind direction changes, causes the air molecules to impinge at less than normal incidence, transferring to the blades less than the total thrust of the wind.

An actual horizontal wind at speed w (m/s, knots, mph, ft/min, etc.) blowing at an angle θ from the perpendicular to a blade or other flat, vertical object, has a component v (in the same units) normal to the object:

$$v = w \cos\theta .$$

The energy available to the rotating blades, however, depends on the cube of this normal component:

$$E_v = \frac{1}{2}\rho v^3 = \frac{1}{2}\rho w^3 \cos^3\theta = E_w \cos^3\theta ,$$

where ρ is air density and E_v and E_w are, respectively, the energies of the normal component and of the total wind. In most estimates of available wind energy, E_w as computed from observed winds is assumed to apply to a proposed wind turbine, without regard to wind directions.

The relative reduction in available energy because the wind is not perpendicular to the plane of the wind turbine blades is

$$q(\theta) = (E_w - E_v)/E_w = 1 - \cos^3\theta .$$

This reduction q is 10% at 15.1°, 20% at 21.8°, 30% at 27.4°, and 40% at 32.5°. The variation of q with incidence angle θ is shown in Fig. 1, along with the reduction in wind speed itself. Also shown are the relative reduc-

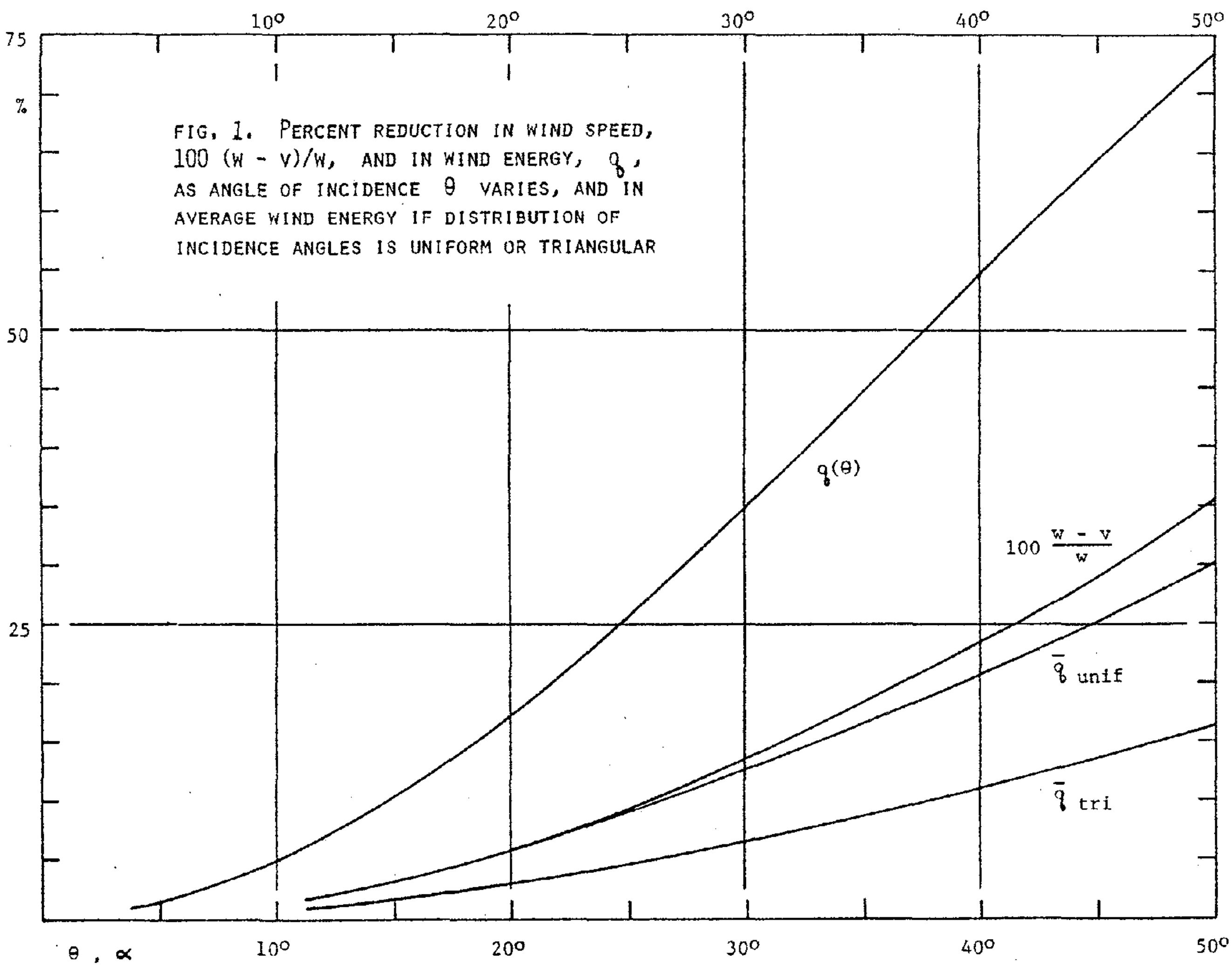

FIG. 1. PERCENT REDUCTION IN WIND SPEED, 100 (W - V)/W, AND IN WIND ENERGY, q, AS ANGLE OF INCIDENCE θ VARIES, AND IN AVERAGE WIND ENERGY IF DISTRIBUTION OF INCIDENCE ANGLES IS UNIFORM OR TRIANGULAR

tions in wind energy for two simple assumed distributions of the incidence angles. For any assumed distribution of directional probability, $p(\theta)$, the mean or expected value of the reduction q is

$$\bar{q} = 2 \int_0^{\alpha} q(\theta)\, p(\theta)\, d\theta \, .$$

The factor 2 enters because $p(\theta)$ is assumed to be symmetrical, and the absolute value of the directional deviation is considered. For the uniform or rectangular distribution, $p(\theta) = 1/2\alpha$ and

$$\bar{q}_{unif} = 1 + (\sin^3 \alpha - 3 \sin \alpha)/3\alpha .$$

This is 6% when $\alpha = 20°$ and 21% when $\alpha = 40°$. More realistic is the triangular distribution, $p(\theta) = (\alpha - |\theta|)/\alpha^2$, for which

$$\bar{q}_{tri} = 1 - (2/9\alpha^2)(7 - 6 \cos \alpha - \cos^3 \alpha) .$$

This is only about half as large: $\bar{q}$ is only 3% at 20° and 11% at 40°. Still more realistic assumptions about $p(\theta)$, such as the von Mises distribution (circular analog of the Gaussian) are less tractable, but their expected relative reductions should not differ much from those of the triangular distribution, which approximates them.

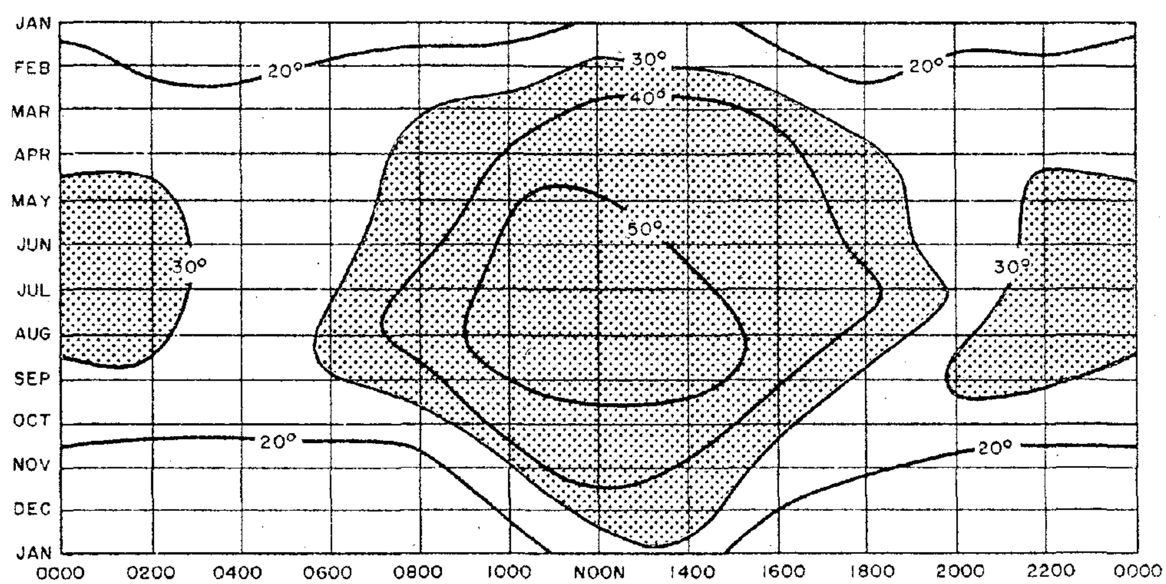

Fig. 2. Average range of directions during 15-min samples, taken each hour, of winds measured each second 75 m above the desert floor at the National Reactor Testing Station in Idaho (from Slade, 1968, Fig. 2.33).

2. RANGES

How much the wind direction changes during intervals of a few seconds to a few minutes has not been studied extensively, but a few measurements are available. Root-mean-square fluctuations of 1-second winds at 2 meters over short grass during eight experiments, each lasting about 3 minutes, in May 1957, ranged from 4.8° to 15.3°, with no relation to mean wind speeds, which were 2.7 to 8.3 m/s (Hay and Pasquill, 1959). At the extremes of their ranges, these rapid fluctuations would cause a net reduction of around 5% in the energy impinging on a wind turbine.

At much finer resolution, Verholek (1978) found that the range, 2α, of wind directions measured at 0.1 second intervals 24.4 m above the desert floor near Hanford WA increased with time, so that during 10 seconds only half the 100 directional values were within 5° of the mean and 5% differed by more than 20°. These data also indicate a maximum reduction of at least 5% in the actual energy normal to a wind turbine blade, which is essentially fixed in orientation during 10 seconds.

Tabulations of directional variations over periods of 10 to 15 minutes are becoming more common, because the maximum widths of the recorder traces of wind direction during 15-minute periods are used in studies of atmospheric dispersion. At the National Reactor Testing Station in northeast Idaho, the average maximum direction variations during 15-minute periods, once an hour, 75 m above the desert floor were always greater than 10°, exceeded 30° during most of the year, and were more than 50° around noon in summer (Fig. 2). Thus a wind turbine at that site, able to follow directional changes much more slowly than the wind itself, would experience only 95% to 25% of the energy estimated from actual wind speeds (Fig. 1).

3. DEVIATIONS

Maximum directional variations are also considered as estimates of the "standard deviation" of wind direction, σ_θ, although a unit vector, such as direction, has two dimensions and a correct measure of its dispersion must also have two dimensions, rather than the single dimension of the standard deviation of a scalar quantity. Computed "standard deviations" of wind direction actually are deviations of the tangent of direction, but over angular variations of only a few tens of degrees the difference is slight, probably less than the error in measuring wind direction.

At six places, the maximum ranges during 15 minutes of wind directions measured every 5 or 10 s, or as averages for intervals of 1 to 15 s, were about six times the corresponding "standard deviations" (Markee, 1963). Thus one-sixth of the 15-minute range in directions sometimes is used as an estimate of σ_θ in diffusion computations. This implies that, if wind direction (actually its tangent) has a Gaussian distribution, the extremes of a 15-minute sample (900 1-s values) will approximate ± 3 standard deviations.

During neutral stability conditions over level ground, σ_θ decreased slightly with height from 8° to 12° at 1 or 2 m to 6° to 8° around 20 m, Slade (1969) showed. But on a 270 m tower 12 km northwest of downtown Philadelphia, where 1 s values were accumulated over 10-minute periods, σ_θ was much larger, 16° to 23° at 12.2 m, depending on wind direction, decreasing to around 10° at 270 m. A wind turbine in a comparable location, with airflow affected by hills and buildings, would encounter a σ_θ at hub height of around 20°; a third of the time the actual wind energy on the blades would be at least 10% less than that inferred from the anemometers.

Sometimes σ_θ is used to indicate the vertical stability of the atmosphere, according to the following typical values:

	STABLE				UNSTABLE		
	Extreme	Moderate	Slight	Neutral	Slight	Moderate	Extreme
σ_θ:	1.7	2.5	5.0	10.0	15.0	20.0	25.0

These correspond to Pasquill categories G to A, respectively (AEC, 1972). Thus estimates of stability can indicate the extent of the directional variability of wind, and the percent reduction in wind energy available to a wind turbine blade; under extremely unstable conditions, one-third of the time the wind direction will be more than 25° away from perpendicular, causing a 25% reduction in apparent energy.

4. CORRELATIONS

Another measure of directional fluctuations would be through their serial correlations, perhaps transformed into a spectrum. While many spectrums are available of wind speeds, none has been found for wind directions. Correlations of simultaneous speeds or directions at horizontal separations of a few tens of meters, covering the span of wind turbine blades, likewise are quite rare. Some correlations and spectrums have been repoted for speeds at various elevations on a tower, but few if any for directions.

For horizontal separations, the best and perhaps only data are those presented by Verholek (1978). Speed and direction were recorded every second on poles simulating the hub and circumference of a 24.4-m turbine (Fig. 3). Directional correlations between the hub and each of the eight peripheral points are shown on the outside of the circle (Fig. 3), those between diametrically opposite points on arrows inside it. The decreases ("decay") in correlation (r) with separation for horizontal, vertical, and diagonal separations are plotted on "correlation transformation" paper in which the ordinate is linear in Fisher's $z' = 0.5 \ln \left[(1 + r)/(1 - r)\right]$.

The smallest correlations are with the lowest point, 12.2 m above ground, suggesting that much of the time it is in the boundary layer. Horizontal correlations and even diagonal correlations were larger than the vertical correlation to the uppermost point. Unjustified extrapolation of the apparent trends hints that correlations reach 0 at 35 to 40 m and at greater distances are negative before becoming slightly positive at separations of 100 to 125 m. A wind turbine with 50-m blades will receive far less wind energy than if winds were uniform over its entire disc.

5. CONCLUSIONS

Winds strong enough to spin a wind turbine at rated speed often blow during unstable conditions, and hence may have directional ranges at one point of 45° to 75° or more. These fluctuations can cause an average reduction of 10 to 30% in the wind energy normally incident on the blades at that point. In addition, wind directions vary with distance away from the point, so that the total energy incident on a large rotating blade is much less than would be assumed from the speed at the hub.

Many more detailed measurements of wind directions, as well as of speeds, at vertical and horizontal separations of tens of meters, are needed for proper assessment of the energy available to a wind turbine.

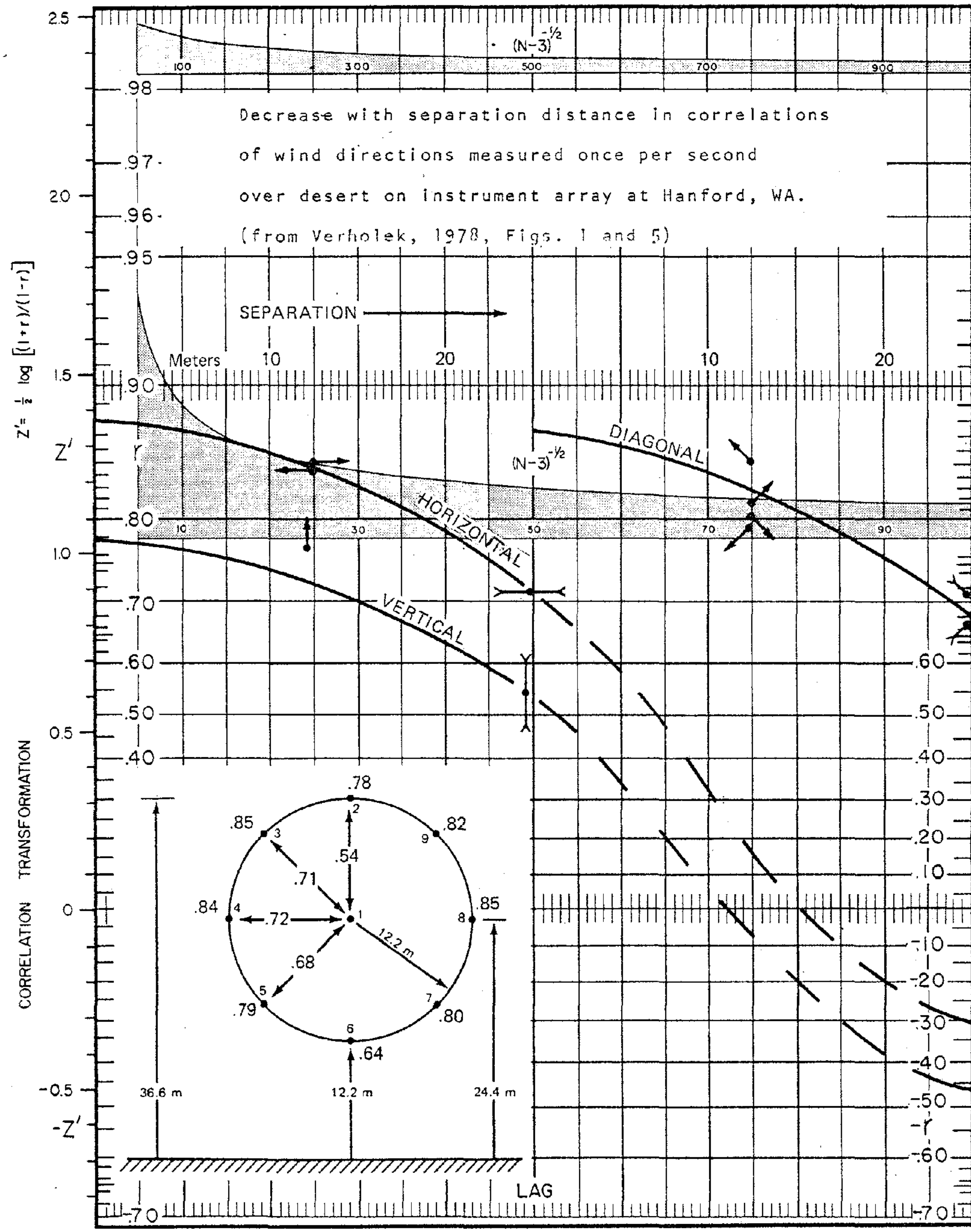
Decrease with separation distance in correlations
of wind directions measured once per second
over desert on instrument array at Hanford, WA.
(from Verholek, 1978, Figs. 1 and 5)
SEPARATION
Meters
HORIZONTAL
VERTICAL
DIAGONAL
$(N-3)^{-1/2}$
$Z' = \frac{1}{2} \log [(1+r)/(1-r)]$
CORRELATION TRANSFORMATION
LAG
36.6 m
12.2 m
24.4 m
12.2 m

Fig. 3

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EVALUATING WIND DATA FOR EXTREME WIND ANALYSIS

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INTRODUCTION

Computing or evaluating extreme wind values from a meteorological data set presents a number of problems. The problems are compounded when the data come from a source outside the United States. Before any analysis of wind data can be accomplished, the analyst must have some further background information about the wind statistic. The following lists these points and then identifies some of the problems associated with them. A discussion of the risk incurred in a specified design life relates the risk incurred with a specified return period when associated with design life. A specific example illustrates how meteorological analysis of the wind data can prevent costly over design of structures and emphasizes the need for meteorological expertise in the evaluation of wind data.

1. SELECTING AND EVALUATING THE DATA

What must an analyst know before he begins computer summarization of wind data? He must have knowledge, understanding, and appreciation of the period of record of the data, location of the wind recording instrument, terrain effects, height of the wind recorder, observation count, frequency of the observations, and type of wind observation which has been recorded. An analyst must be fairly confident that the period of record is long enough to give him a reliable end statistic.

What is a reliable period of record? It should be at least as long as the design life of the proposed structure, preferably 30 years or more, but not less than 15 years. With less than 15 years of data extreme wind values are questionable.

The location of the wind recording instrument has often changed during its history. It could have been on the roof of a building, on the ground near the runway, at a height of 30 feet above the ground or at heights of 50, 80, or 100 feet above the ground. All these changes in location have to be adjusted for in order to make the wind observations compatible over the whole period of record.

The terrain in the vicinity of the wind instrument must also be evaluated as to its effect on the observation.

The analyst must look at the observation count over the period of record. He must determine if the site has a continuous wind recorder or whether wind observations are taken only at specific times, i.e., every 3 hours. If the site is not a continuous recording station, the analyst has a problem. Wind data are not readily interpolated linearly for missing hours. How is one going to be sure the maximum wind has been recorded? An analyst familiar with wind distributions and one who has some expertise in this area is far more capable of evaluating what the maximum wind value might be. Do the wind observations truly describe the wind regime of the site?

All of these questions regarding the quality of the wind observations are even more important when the data is from overseas. The history of the anomometer at most sites is almost non-existent. Often when compairing nearby sites and observing a significant difference in the wind statistics, the difference is the result of either location and its terrain effects or of the difference in height between the instruments.

Another problem is trying to determine just what wind value has been observed. This problem is intensified when the data are from a foreign source. Some sites record a 5-minute average wind, others a 10-minute average. Frequently, one does not know if the maximum wind reported is a sustained wind or a peak gust. Is the wind value observed the fastest mile wind or the fastest observed 1-minute wind?

Performing extreme value wind analysis involves more than summarizing wind values from a magnetic tape of meteorological data.

2. RISK VERSUS RETURN PERIOD

The terms "risk" and "return period" are related to design life. Risk is the chance one is willing to take that a specific event will not be equalled or exceeded, in this case a wind value. It is expressed as a percentage. The term "return period" is frequently referred to in discussing the results of an extreme value analysis. Return period is "an event that happens A times in N trials has a relative frequence of occurrence of A/N, and a return period (RP) of RP=N/A." The return period, or reciprocal of the relative frequency, is therefore the average interval between recurrences of the event in a particular series of trials. This means that a 50-year return period wind value will occur on the average of once every 50 years. When related to design life or desired life of a structure what does this wind value mean?

Oversimplifying the term, one usually thinks of a 50-year return period wind as having a 2 percent chance of occurring. This is relatively true in any one year. But if the assumption is made that since it has only a 2 percent chance of occurring in any single year, that over the life of the structure it has only a 2% chance of occurring, then this is a <u>gross</u> error. Table 1 illustrates this fact. Assume a structure is built to last for 50 years, or in other words the building has a 50 year <u>design life</u>; then, the 50-year return period wind has a 64 percent chance of being exceeded during the 50-year design life, not a 50 percent chance. Is this the risk of exceedance one wants to assume when building to last for 50 years? The design engineer must first set the risk he wants to take in the design life of the building. Then, the value of the design wind can be determined. Such a value is more meaningful than the return period wind in which the risk taken is hidden until you relate it to design life.

3. ANOMOLOUS WIND EXAMPLE

The extreme wind value set for Ellsworth AFB, South Dakota, shows the maximum sustained value is 90 knots and the second highest value is 65 knots. When these values are adjusted for elevation to 30 feet they become 82 and 65 knots respectively. The original observation records verify these values, but synoptic weather map does not warrant such a value. Surrounding stations, especially Rapid City, South Dakota, had maximum values in the 50s at the time of the Ellsworth 90-knot observation. Tables 2, 3, 4, and 5 illustrate what happens when such an anomalous value gets into the data set. Tables 2 and 4 illustrate the extreme value statistics calculated with the 90-knot wind value. Tables 3 and 5 illustrate the statistics calculated with a different period of record so that the 90-knot observation was eliminated from the set. The analyst has to make the decision as to whether or not to use this value and ask the design engineer to design for this increased design wind. Even without including the 90-knot wind in the analysis, the extreme wind values for 1 percent and 5 percent risk in a 25-year design life are greater than 90 knots. Tables 3 and 5 show the sustained wind and peak gust design wind statistics for Ellsworth AFB that should be used.

4. NEED FOR METEOROLOGICAL EXPERTISE.

Much of the information presented here is not new to design engineers. These problems point out the need for the meteorologists who have training and expertise in <u>applied</u> climatology to evaluate, and obtain for you your design winds. The information that comes out of the computer must be evaluated in the light of the problem. The applied climatologist must attempt to understand and appreciate the design problem, but he does not have to be able to work the design problem. Meteorologists should not attempt to play the role of design engineers. Likewise, design engineers should not try to be meteorologists; they should use meteorologists to help them with their design problem.

TABLE 1. RISK THAT OCCURS WITH A GIVEN COMBINATION OF RETURN PERIOD (YEARS) AND DESIGN LIFE (YEARS).

DESIGN LIFE	RETURN PERIOD							
	10	20	25	30	40	50	75	100
1	10	5	4	3	2.5	2	1.3	1
5	41	23	18	16	12	10	6	5
10	65	40	34	29	22	18	13	10
15	79	54	46	40	32	26	18	14
20	88	64	56	49	40	33	24	18
25	93	72	64	57	47	40	29	22
30	96	79	71	64	53	45	33	26
40	99	87	80	74	64	55	42	33
50	99	92	87	82	72	64	49	39

TABLE 2. ELLSWORTH AFB SD MAXIMUM SUSTAINED WIND (KNOTS), 1950-1977.

WIND SPEED FOR SPECIFIED CALCULATED RISK OF BEING EQUALLED OR EXCEEDED AT LEAST ONCE DURING INDICATED DESIGN LIFE (YEARS)

DESIGN LIFE	CALCULATED RISK							
	.01	.05	.10	.20	.25	.40	.50	.64
1	89	75	69	62	60		53	
5	103	89	83	76	74		66	
10	109	95	89	82	80		72	
15	112	98	92	86	83		76	
20	115	101	94	88	86		78	
25	117	103	96	90	88	83	80	
50	123	109	102	96	94		86	83

VALUES ARE VALID AT A HEIGHT OF 30 FT ABOVE GROUND

TABLE 3. ELLSWORTH AFB SD MAXIMUM SUSTAINED WIND (KNOTS), 1953-1977.

WIND SPEED FOR SPECIFIED CALCULATED RISK OF BEING EQUALLED OR EXCEEDED AT LEAST ONCE DURING INDICATED DESIGN LIFE (YEARS)

DESIGN LIFE	CALCULATED RISK							
	.01	.05	.10	.20	.25	.40	.50	.64
1	82	70	65	60	58		51	
5	94	82	77	71	70		63	
10	99	87	82	76	75		68	
15	102	90	85	79	78		71	
20	104	92	87	81	80		73	
25	106	94	88	83	81	77	75	
50	111	99	94	88	86		80	77

VALUES ARE VALID AT A HEIGHT OF 30 FT ABOVE GROUND

TABLE 4. ELLSWORTH AFB SD PEAK GUST WIND (KNOTS), 1950-1977.

WIND SPEED FOR SPECIFIED CALCULATED RISK OF BEING EQUALLED OR EXCEEDED AT LEAST ONCE DURING INDICATED DESIGN LIFE (YEARS)

	CALCULATED RISK							
DESIGN LIFE	.01	.05	.10	.20	.25	.40	.50	.64
1	103	88	82	75	73		65	
5	117	103	96	90	87		80	
10	123	109	102	96	94		86	
15	127	112	106	99	97		89	
20	129	115	108	102	100		92	
25	131	117	111	104	101	97	94	
50	137	123	117	110	108		100	97

VALUES ARE VALID AT A HEIGHT OF 30 FT ABOVE GROUND

TABLE 5. ELLSWORTH AFB SD PEAK GUST WIND (KNOTS), 1953-1977.

WIND SPEED FOR SPECIFIED CALCULATED RISK OF BEING EQUALLED OR EXCEEDED AT LEAST ONCE DURING INDICATED DESIGN LIFE (YEARS)

	CALCULATED RISK							
DESIGN LIFE	.01	.05	.10	.20	.25	.40	.50	.64
1	94	83	78	72	71		65	
5	105	94	89	84	82		76	
10	110	99	94	88	87		81	
15	113	102	97	91	90		83	
20	115	104	99	93	92		85	
25	116	105	100	95	93	89	87	
50	121	109	104	99	98		91	89

VALUES ARE VALID AT A HEIGHT OF 30 FT ABOVE GROUND

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SOME APPLICATIONS OF WIND DATA IN AGRICULTURE[1]

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ABSTRACT

Heat and mass exchanges in plant communities depend upon wind and turbulence. In this paper we discuss some specific applications of wind data in agricultural meteorology. Application of an aerodynamic technique for predicting fluxes of sensible and latent heat and CO_2 requires the measurement of wind speed gradients in conjunction with the gradients of air temperature, humidity and CO_2 concentration. Knowledge of the boundary layer resistance and its dependence on wind speed is essential for estimating large area evapotranspiration by means of resistance models. Resistance models have also been used for evaluating fluxes of ozone and SO_2. Reliable measurements of windspeed profiles within and above crop canopies are needed to fully understand the mechanisms of turbulent transport between crop and air.

Wind velocity information plays an important role in various other agricultural applications, e.g. in (a) determining water distribution patterns from sprinkler irrigation systems; (b) minimizing drift in aerial applications of pesticide; (c) modeling the aerial dispersal of plant pathogens; (d) designing and evaluating windbreaks and shelterbelts and (e) efficient use of wind energy for farm and rural applications.

INTRODUCTION

Information about wind and turbulence is needed to evaluate the exchanges of energy and matter between crop surfaces and the atmosphere. A complete understanding of the processes by which water vapor, carbon dioxide, sensible

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heat, dust, pollen and various pollutants are transported requires detailed knowledge of wind structure in the lower layers of the atmosphere. Windspeed and direction are among the most important variables in agricultural meteorology research. Some applications of wind data in agriculture are discussed below.

APPLICATIONS

1. PREDICTION OF EVAPOTRANSPIRATION, PHOTOSYNTHESIS AND OTHER FLUXES

a. Aerodynamic Technique

The vertical fluxes of momentum, sensible heat, water vapor and CO_2 in the turbulent surface boundary layer can be expressed as:

Momentum flux $$\tau = \rho K_m \frac{\partial U}{\partial z} \qquad (1)$$

Sensible heat flux $$H = \rho C_p K_h \frac{\partial \theta}{\partial z} \qquad (2)$$

Water vapor flux $$E = \rho K_w \frac{\partial q}{\partial z} \qquad (3)$$

CO_2 flux $$F_c = f K_c \frac{\partial c}{\partial z} \qquad (4)$$

where K_m, K_h, K_w and K_c are the turbulent exchange coefficients of momentum, sensible heat, water vapor and CO_2; $\partial U/\partial z$, $\partial \theta/\partial z$, $\partial q/\partial z$ and $\partial c/\partial z$ the vertical gradients of wind speed, air temperature (potential), specific humidity and CO_2 concentration, ρ the air density, C_p the specific heat of air at constant pressure and f is a conversion factor. The above equations can be rearranged:

$$H = \rho C_p k^2 z^2 \left(\frac{\partial U}{\partial z}\right) \left(\frac{\partial \theta}{\partial z}\right) \left[(\phi_m^{-2}) \left(\frac{K_h}{K_m}\right)\right] \qquad (5)$$

$$E = \rho k^2 z^2 \left(\frac{\partial U}{\partial z}\right) \left(\frac{\partial q}{\partial z}\right) \left[(\phi_m^{-2}) \left(\frac{K_w}{K_m}\right)\right] \qquad (6)$$

$$F_c = f\, k^2 z^2 \left(\frac{\partial U}{\partial z}\right) \left(\frac{\partial c}{\partial z}\right) [(\phi_m^{-2}) \left(\frac{K_c}{K_m}\right)] \qquad (7)$$

where wind speed gradient $\partial U/\partial z = u_*/kz\ \phi_m$ with u_*, the friction velocity = $(\tau/\rho)^{\frac{1}{2}}$; ϕ_m = non-dimensional wind shear, $K_m = u_*^2/(\partial U/\partial z) = k^2 z^2 (\phi_m^{-2})(\partial U/\partial z)$, k = von Karman's constant. It is customary to assume that K_c is equal to either K_w or K_h. ϕ_m and $K_{w,h}/K_m$ have been found to vary with atmospheric thermal stability, which is usually expressed in terms of the Richardson number (Ri) or Monin-Obukhov stability parameter (Z/L).

$$Ri = \frac{g\left(\frac{\partial \theta_v}{\partial z}\right)}{\theta_v \left(\frac{\partial U}{\partial z}\right)^2} \qquad (8)$$

and

$$Z/L = -\frac{k\ z\ g\ \overline{w'\theta_v'}}{\theta_v\ u_*^3} \qquad (9)$$

where $\partial\theta_v/\partial z$ and $\partial U/\partial z$ are gradients of virtual potential temperature and wind speed, g = acceleration due to gravity, z is the height of observation, $\overline{w'\theta_v'}$ = covariance of vertical windspeed and virtual temperature fluctuations. These stability correction formuli are available in Dyer and Hicks (1970), Webb (1970), Businger et al. (1971) and Pruitt et al. (1974).

Using equations (5), (6) and (7), the fluxes of sensible heat, water vapor and CO_2 can be computed from measurements of vertical gradients of windspeed, air temperature, specific humidity and CO_2 concentration. Aerodynamic techniques have been used extensively for measuring sensible and latent heat fluxes as well as fluxes of CO_2 (e.g. Harper et al., 1973; Lemon, 1967; Verma and Rosenberg, 1973 and 1976), ammonia (Denmead et al., 1974), nitrous oxide (Hutchinson and Mosier, 1979) and toxic pollutants (Waggoner, 1975). Measurements of horizontal wind speed gradients, in conjunction with individual concentration gradients are needed for such computations. The relationships given above also require sufficient fetch of uniform crop cover and, therefore, wind direction needs to be measured concurrently.

b. Resistance Models for Estimating Large Area Evapotranspiration

Accurate estimates of evapotranspiration over large areas are needed for hydrologic studies, irrigation planning and scheduling and other practices related to efficient utilization of water resources. One approach is the use of a resistance-energy balance model of evapotranspiration, the data for which can be supplied, in part, by remote sensing and in part by National Weather Service observations. This model is described by the following equation:

$$LE = -(H + Rn + S) = -(\rho\ C_p \frac{T_a - T_c}{r_a} + Rn + S) \tag{10}$$

where LE, H, Rn and S are the flux densities of latent heat, sensible heat, net radiation and soil heat, respectively. T_a is the air temperature, T_c the crop temperature and r_a the boundary layer resistance. Rn, S and T_a can be measured routinely. T_c can be measured with a thermal radiometer and/or remotely sensed thermal imagery (Blad and Rosenberg, 1976). r_a can be computed from the procedures outlined in Heilman and Kanemasu (1976) and Verma et al. (1976). Detailed information is needed about r_a over various crops and the functional relationship of r_a with the controlling (primary) meteorological parameter, windspeed. Some typical relationships are given in Verma et al. (1976).

Although several forms of resistance models have been used in the literature for estimating evapotranspiration (e.g. Rosenberg et al., 1975 and Verma and Barfield, 1979) and for estimating ozone and SO_2 fluxes to vegetated surfaces (Wesely et al., 1978 and Wesely and Hicks, 1977), determination of boundary layer resistance and its dependence on wind speed plays an important role in application of this technique.

2. SENSIBLE HEAT ADVECTION AND EVAPOTRANSPIRATION

Evapotranspiration is an energy-consuming process, the energy for which derives orignally from solar radiation. In humid regions this energy consumption rarely exceeds the net radiation and is normally less since the air acts as a sink for both latent and sensible heat (Tanner, 1967; van Bavel, 1961). However, in semi-arid and arid regions the energy content of latent heat flux often exceeds that of net radiation since the crop, if well supplied with water, is a sink for heat. That sensible heat which is consumed is brought to the field by advection from local sources such as adjacent dry fields or from remote sources which are relatively dry. The dry fields or areas become warm with respect to the air passing over and, therefore, transfer heat to the air (Rosenberg, 1969, 1972).

The advection of sensible heat is of major importance in determining the water balance and the moisture stress imposed on crops grown in large parts of the Soviet Union where the so-called "Sukovey" winds prevail with varying frequency (Dzerdzeevski, 1957; Lydolph, 1964). Sensible heat advection is a major component of the energy balance in regions of Australia (Stern, 1967; McIlroy and Angus, 1964) and in the Great Plains of North America (Rosenberg, 1969, 1972; Rosenberg and Verma 1978; Brakke et al., 1978).

At our observatory near Mead, Nebraska in the east central Great Plains, evapotranspiration by such crops as soybean and alfalfa, when well supplied with water, consistently range between 8 and 12 mm. The radiant energy accounts for 6-7 mm of this evapotranspiration. Advection of sensible heat provides the additional energy consumed in the process. Thus the need for wind data in evaluating the magnitude of sensible heat advection is obvious.

3. WITHIN AND ABOVE CANOPY WIND SPEED PROFILES

Windspeed above the crop canopy can be described by the log law:

$$U(z) = \frac{u_*}{k} \left[\ln \frac{z-d}{z_o} + \Psi_m\right] \text{ for } z > h \qquad (11)$$

where d is the zero plane displacement, z_o is the roughness parameter, h is the crop height and Ψ_m is a diabatic correction factor (see e.g. Paulson, 1970). Prediction of wind within crop canopies is quite complicated and eq. (11) is not adequate for that purpose.

Several investigators (e.g. Inoue, 1963; Saito, 1964; Uchijima and Wright, 1964; Allen, 1968; Cionco, 1965, 1972, 1978) have measured windspeed in canopies and developed mathematical relationships. The canopy flow regime can be considered as being divided in three layers[2]: (a) the top layer ($d < z < h$) is the layer that exerts drag on the wind above the crop. The wind speed decreases exponentially with distance down from the top of the canopy in

[2]See Businger, 1974 and Campbell, 1977 for further discussion of this subject.

this layer; (b) in the middle layer ($0.1\ h < z < d$) which is primarily the stem space of the crop, the wind may be unrelated to the wind above the crop; (c) in the bottom layer the wind speed profile is similar in shape to the profile above the canopy (i.e. logarithmic), with the wind speed at the top of the layer matching the wind at the bottom of the middle layer.

To evaluate the energy budget of individual leaves and to fully understand the mechanisms of turbulent transfer of heat and mass, information is needed on wind speed profiles within crop canopies as well as above them.

4. WATER DISTRIBUTION PATTERNS FROM IRRIGATION SPRINKLERS

Uniformity in irrigation water application is important. Nonuniform water distribution results in too little water applied in some parts of the field which reduces crop yield. Too much water applied in other parts may cause deep percolation resulting in loss of nutrients and reduced crop yield.

Water application patterns from irrigation sprinkler systems are affected by wind speed and direction. Wiersma (1955) investigated water distribution patterns from several small-head sprinkler systems operating in varying wind conditions. Shull and Dylla (1976a and b) have reported detailed field tests of wind effects on application patterns with a traveling-gun sprinkler system and a stationary large single nozzle sprinkler. Their tests on a traveling-gun irrigation system indicated that increases in wind speed must be accompanied by decreases in travel lane spacing if an acceptable water application uniformity is to be maintained. Travel lane spacing must be decreased further as the wind direction and travel direction become more nearly parallel. An empirical equation to estimate lane spacing as a function of wind speed, wind direction and system operating pressure was presented.

5. AGRICULTURAL SPRAYING OF PESTICIDES

The volume of liquid dilutant used in aerial spraying is much smaller than that used in ground-based sprayers. It is, therefore, necessary to produce much smaller droplets in order to obtain adequate cover. The concentration of pesticide is also proportionately higher. It is essential in aerial spray operations to minimize or control the drift so as to avoid deposition of the chemical on anything but the intended target. Strict controls, in an effort to avoid deposition on adjacent fields, streams etc., may lead to insufficient deposition on target. Several scientists (e.g. Lomas et al., 1964; Williamson and Threadgill, 1974; Marchant, 1977; Trayford and Welch, 1977 and others) have discussed the physical and meteorological principles which govern aerial applications. Air motion due to natural surface winds and atmospheric turbulence, as well as air currents caused by the motion of the spray vehicles are among the important variables which control the dynamics of spray droplet deposition.

6. AERIAL DISPERSAL OF FUNGAL SPORES

Many plant diseases are spread by wind (Meredith, 1966; Sreeramula and Ramalingan, 1966). The aerial dispersal of fungal spores involves three highly interdependent events: liberation, transport and deposition. Aylor (1978) presents a thorough discussion of how spores are liberated, how turbulence aids their transport in the atmosphere and how they are deposited on the leaves of plant canopies. Aylor and Lukens (1974) made some observation on Helminthosporium maydis and indicated that winds of about 1.0 m sec^{-1} liberated 60 to 75% of the spores and most spores were liberated during periods of high wind variability. Wind and turbulence information is crucial in modeling the airborne spread of plant pathogens.

7. WINDBREAKS AND SHELTERBELTS

Crops are subject to damage from such stress-inducing weather conditions as extreme evaporative demand caused by hot, dry winds. Plants also suffer direct mechanical injury from strong winds. Windbreaks and shelterbelts have, by reducing these stresses, proven beneficial to the growth of crops in the sheltered area. (For a detailed discussion, see Brown and Rosenberg, 1971, 1972; Miller et al., 1973; Rosenberg, 1979). The effectiveness of windbreaks depends on several factors including their height, porosity and length (Caborn, 1957; van Eimern et al., 1964). Wind information is needed for proper selection, adequate design and performance evaluation of windbreaks and shelterbelts.

8. FARM APPLICATIONS OF WIND ENERGY

Several national wind energy assessments (e.g. General Electric Company, 1977; Lockheed, 1977) point out some potential applications of wind energy in agriculture. These reports indicate that energy needs for many farm and rural applications (such as irrigation pumping, crop drying, space and water heating and refrigeration storage) can be met, at least partially, by wind energy conversion systems. A knowledge of wind characteristics within a region can contribute greatly to a more efficient use of the wind energy resource (Renné, 1979). The important wind characteristics include mean annual wind speed, frequency distribution of the wind, seasonal and diurnal variations in wind speed and direction, and the turbulent characteristics of the wind.

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WIND DATA APPLICATIONS AND NEEDS IN ATMOSPHERIC DIFFUSION

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ABSTRACT

Air flow measurements represent a critical parameter in atmospheric dispersion processes. It is essential that careful selection of wind data be made for use in atmospheric dispersion estimates to assure that the complexities of the air flow within the planetary boundary layer are adequately accounted for.

The application of wind data to dispersion modeling are described with specific emphasis on the limitations relative to source characteristics, plume transport, and averaging times. The summary paper also discusses the needs within air pollution meteorology for wind information applicable to various dispersion situations determined by source and terrain configurations.

INTRODUCTION

Representative data on air mass motion constitute one of the basic input parameters in the assessment of atmospheric dispersion of pollutants. This dispersion process is characterized by turbulent diffusion which occur at rates which are orders of magnitude greater than molecular diffusion.

Turbulent diffusion in the atmosphere is a complex phenomenon. However, based on the concept proposed by Reynolds (1), which considers the total wind motion to be composed of a constant, mean part and a fluctuating, or turbulent, part, quantitative approximations of turbulent diffusion are being made from wind observations. In vector notation, the total wind ($\mathbb{V}$) can be expressed as the sum of the mean wind ($\overline{\mathbb{V}}$) and the fluctuating, turbulent part ($\mathbb{V}'$) as:

$$\mathbb{V} = \overline{\mathbb{V}} + \mathbb{V}' \qquad (1)$$

Special three-axis anemometers are capable of measuring the horizontal u (x direction) and v (y direction) components and the vertical w (z direction) components of $\mathbb{V}$ from which the three-dimensional mean flow and the turbulent characteristics of the atmosphere can be evaluated.

The mean wind flow in the lower atmosphere relates directly to the capacity of the atmosphere to dilute pollutants emitted from sources in the boundary layer. In any assessment of the atmospheric dispersion characteristics, it is important to note that the turbulent fluctuation part of the wind has a wide range of periods which must be considered in the averaging time to be used when determining the mean and turbulent parts of the flow.

The requirements of wind data in atmospheric dispersion assessment vary greatly depending upon the specific situation under consideration. This paper summarizes some of the practical applications and needs of wind observations in air pollution meteorology related to the use of mathematical dispersion modeling. The brief summary does not address the theoretical aspects of the subjects of wind structure, wind measurements, and wind averaging methodologies; the readers are referred to excellent treatments of these subjects by Sutton (2) and Slade (3).

1. WIND DATA APPLICATION TO ATMOSPHERIC DISPERSION

The application of wind data to atmospheric dispersion modeling is a function of several factors concerning such categories as source characteristics, transport characteristics, and impact averaging time. Each of these areas require careful consideration in order that proper acquisition and application of wind data be made.

In the following, a discussion is presented of various factors regarding wind applications related to the three categories listed above.

a. Source Characteristics

The choice of wind data in dispersion modeling is very much dependent upon the source. Dispersion assessments for a single emission source at or near the ground require different wind data inputs compared with an elevated, tall stack point source or a low-level line source. For low-level point sources and line sources appropriate atmospheric dilution factors can usually be determined from surface winds, with the provision that for the line sources the angle between the wind direction and the line source be considered. For the elevated, tall stack emission sources the surface wind is no longer applicable without proper adjustment for the vertical wind structure in the planetary boundary layer. Under stable atmospheric conditions the potential for significant wind shear exists which will affect the horizontal plume dispersion as well as the directional transport characteristics.

Plume rise is a critical parameter in all dispersion assessments and is very sensitive to wind speeds, being inversely proportional to the strength of the wind. It is conventional in air pollution meteorology to utilize the mean wind speed at the stack height level for both plume rise and dispersion calculations, since such winds are more readily available. Obviously, the plume rise is affected by the wind through the total depth between stack height and plume level, hence one must be cautious about using the most representative wind speed value where strong wind shears exist. Also, with respect to plume dispersion calculations, Smith, et al.(4), state that there are reasons to believe that one should use a mean wind value representative of the entire layer in which the plume is dispersing. In a low-level atmosphere with strong, vertical wind gradients this condition adds significant complexities to dispersion calculations, but it is usually ignored in practical applications.

b. Transport Characteristics

Again, the nature of the problem dictates the application of wind data to plume transport. Representative single point wind observations are found to be applicable to plume transport where the distance between the source and receptor is relatively short and the terrain is simple. Consideration must be given to the persistency of the wind field over the period of plume transport which becomes a parameter of increasing importance as the travel distance increases.

In fact, with increased plume trajectory distance and terrain complexities, the spatial and temporal distribution of wind observations become increasingly critical. Plume transport in complex terrain often results in meandering trajectories which must be defined in order to make representative plume dispersion estimates. Instead of a single point wind observation for use in wind dispersion flow modeling, the total wind field must be defined, either through conventional streamline and trajectory analysis or through wind field computer model techniques.

c. <u>Averaging Time</u>

The selection of representative averaging time of wind becomes very critical when performing atmospheric dispersion modeling. It must be made with due consideration to the resultant short term (1-24 hr) versus long term (monthly, seasonally, yearly) assessmsents relative to ambient air quality standards.

When continuous wind records are available, hourly mean winds are preferable for use in dispersion modeling of hourly impact values; however, 10 minute peak values are frequently calculated using standard weather service or aviation wind data which are at best averaged over a few minutes. In the assessment of the longer 3 hr, 8 hr, and 24 hr average impact values, it is important to analyze fluctuations in the mean hourly wind directions to determine the actual persistencies and variations in the local flow. Under certain terrain configurations and coastal locations the diurnal variations in the wind may be so regular that extrapolations based on climatological assessments may be valid. However, there is no substitute for detailed wind analyses to establish the true fluctuation in wind patterns for use in making critical impact assessments.

2. WIND MEASUREMENT NEEDS IN AIR POLLUTION METEOROLOGY

The conventional low elevation wind data serve as basic input parameters for streamline and trajectory analysis of low-level airflow and dispersion evaluation. Under ideal meteorological conditions these observations can be extrapolated to higher elevations through standard power functions found applicable for selected air mass stabilities. Whenever the low-level wind observations are augmented with tall tower wind data and free lift balloon (pibal) measurements, added validity is given to the extrapolated winds aloft.

However, too often the wind data base is inadequate to properly evaluate the impact of tall stack emissions. Sufficient continuous wind data applicable to plume levels more than 1000 ft above the ground are seldom available. The desired spatial wind data needed to make representative assessments of plume dispersion usually exceed the budgetary constraints and the analyst must resort to various interpolation and extrapolation methods based on the available information on hand.

Recent advances in remote sensing techniques are helping to bridge the gap in the required wind data base. Traditionally, when acquiring wind data applicable to tall stack dispersion, one relies on tower data from 150-300 ft elevations, augmented with occasional pibal balloon observations, and, at times, "floating" constant volume (C-V) balloons and elevated smoke releases. The resultant data base requires considerable professional analysis in order to combine in situ wind observations from the fixed tower locations with (1) occasional snapshots of the vertical wind profile based on pibal winds which are averaged through finite layers of the atmosphere, and (2) occasional air mass trajectories at quasi-constant elevations based on C-V balloons and visible smoke.

Recent advances in both in situ and remote measuring techniques will hopefully provide significant improvements in the needed data base for elevated plume assessment and complex terrain settings. Instrumented tethered balloons can provide both vertical wind profiles and plume altitude winds over significant time periods. As to remote sensors, the new doppler wind systems are capable of providing continuous measurements of wind and discrete altitudes in the lower planetary boundary layers. Hopefully, the continued improvements in wind measurement resolution will provide not only mean wind data but also the turbulent structure of the wind to accurately and continuously portrait the dispersion characteristics of the planetary boundary layer.

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DISCUSSIONS OF SESSION I

* * *

Hugh Church

Arnold Court mentioned exponents on wind speed of interest as: 3, 2, 1, 1/2, 3/2 . . . to which I suggested we must add -1, as appears in $\chi/Q = K/U$

In determining intensity of turbulence $(\overline{U'^2})^{1/2}/U$, let us seek to obtain this information as a profile through the planetary boundary layer, at least through plume height.

* * *

Question by Einar Hovind: Dr. Peterka identified the need for more research regarding transferability of airport wind data to downtown locations. In his current studies of wind influence upon new structures in downtown areas where existing buildings influence the windfield at significant distances, and where he has to depend on airport winds, what methods are employed in the application of such wind data to downtown locations?

Answer by Jon Peterka: We generally assume that wind characteristics at gradient level are the same at the airport as they are over the city. The effects of individual buildings or hills are accounted for by including them in the wind-tunnel model. The transferability is not always straight forward--for example, in complex terrain.

* * *

Einar Hovind

In view of the trend to phase-out meteorological observation stations, it is important that this workshop express the needs of the engineers, air quality meteorologists, agriculture scientists, etc., for improved low-level observation systems to meet the needs of these disciplines.

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SESSION II

WIND DATA COLLECTION AND STORAGE

Chairman: Michael Changery
Rapporteur: Michael P. Gaus

SESSION II: WIND DATA COLLECTION AND STORAGE

SUMMARY

Michael P. Gaus
Michael Changery

Session II focused on the following items:

- Availability of existing data
- Characteristics of existing data
- Characteristics of existing instrumentations used to collect data
- Types of data to be collected in the future
- Characteristics of instruments to be used for future data collection
- Methods required to satisfy the needs of different user groups

1. Availability of Existing Data

Presently known sources of wind data include:

a) National Climatic Center. Approximately 2000 stations currently reporting and archived. Data are aviation oriented. One-minute average, peak gust and fastest-mile are generally available. Five-minute maximum and one hour average are also available prior to 1950.

b) Nuclear Regulatory Commission. Instrumented multi-level towers record one hour data at approximately 100 nuclear facilities. Limited data are available from the NRC. Majority of the data are archived by the respective utilities.

c) Forest Service. Over 1000 sites report and are archived by the Forest Service. One observation/day (1 minute wind) are reported during the fire season only.

d) Environmental Protection Agency. Specialized data collection (one-hour winds) are available through Research Triangle Park, NC.

e) State Agencies. Many state environmental agencies have instrumented sites for pollution-related monitoring. Quantity and quality of data are unknown.

f) Department of Energy. Three years of tower data have been collected at 18 sites for wind energy analysis. An additional 15-20 sites will be instrumented with data loggers recording 2 minute winds.

A recommendation was made to index currently available data from all sources - possibly through a group such as the Wind Engineering Research Council.

2. Characteristics of Existing Data and Instrumentation

The following recommendations were made concerning the use of existing wind data:

a) Publishing of existing station descriptions. Station descriptions, which provide information on anemometer exposure and station environment need to be compiled into a single publication. This publication would aid the user in evaluating the representativeness of the station's wind data.

b) Obtaining more detailed station information. Standard forms which provide detailed information on anemometer location and station environment should be distributed and filled out by all stations taking wind observations. Information on these forms should include: method of observation, anemometer height and location, description of station's immediate environment (e.g., direction and distance of buildings, trees, etc.) and description of location terrain and influences on wind. Some of this information is provided by NWS, FAA, and military sites. A drawing or photograph of the environment around the wind instrument and a topographic map depicting the site's location would be valuable. If the anemometer is located on a structure, a description of the height of the instrument above the rooftop, location on the rooftop and height and width of the structure, and a drawing or photograph of the structure and instrument location should be provided.

c) Obtaining more reliable and representative wind data. Current anemometer locations, maintenance of the sensors and methods of observing the winds should be evaluated for each station. This information should be reviewed and recommendations made for obtaining more reliable and representative wind data at each station.

d) Digitizing of surface weather observations. Stations for which wind data are digitized by NCC need to be reviewed to evaluate how much of this data is useful and to recommend additional stations for which the records should be digitized. For example, some very good data taken in data-sparse areas are not digitized; whereas, in some areas with numerous stations there may be several nearby stations for which the data are digitized. The problem of digitizing hourly vs 3-hourly data also needs to be addressed.

e) Digitizing RAMOS and AMOS data in TD 1440 format. RAMOS and AMOS (automated station) data are often located in data-sparse areas. However, this data is not summarized and is not conveniently available to be summarized and evaluated. Could this data be digitized in same format as the surface weather observations in TD 1440 tape format?

3. Characteristics of Future Instrumentation, Data Types and User Requirements

Problems and opportunities for future collection of wind data were brought out in the discussion. The variety of wind data users must do a better job of communicating their needs for wind information. In addition to the needs of aviation, the following groups should have a voice in formulating wind data collection activities:

- Structural Building Loading and Response
- Environmental Dispersion
- Wind Power
- Agriculture

Although each of these activities may involve some detailed and specialized activities which are unique, there is a common base of data which is needed by each.

It was pointed out that the National Weather Service is proposing to drop some currently recorded information such as fastest mile and that there seems to be a tendency to decrease the amount of information collection concerning surface winds. A primary user of fastest mile data has been the building load group. This has largely been a matter of convenience because of the need for a long sequence of consistent data for predicting extreme effects. There is probably a more staisfactory type of data which should be collected for such purposes, but the important thing is to assure continuity in transitioning from one type of data to another.

A great opportunity exists to formulate a comprehensive plan for widespread collection of wind data in the future due to the introduction of new types of instruments, use of computer based microprocessors in collecting data and new automatic data transmission links. Each interest group should present their data requirements. The need for values such as:

Fastest mile
Peak recorded wind
Fastest minute
One minute average
Ten minute average
Twenty minute average
One hour average
Duration of storm
Directional information
High frequency spectra
Power spectral density
Gradient wind

should be established. Clearly if there is no real need for data it would be too expensive to collect and archive. Questions which need to be addressed are:

- Widescale vs local or more specialized data,
- Long-term permanent installations - how many, where,
- Portable installations to answer research or specific problems. In particular, long-term measurements should be made at heights up to 50m at several airport sites in varied terrain to establish standard wind profiles.
- Calibration of instrument sites with respect to effects of topography, obstructions and ground clutter,
- Future workshop should address consistent units and archiving of data,
- The impact of elimination of state climatologists should be re-assessed with respect to the quality of data collected.

COLLECTION AND STORAGE OF METEORLOGICAL DATA BY THE FOREST SERVICE

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ABSTRACT

The National Fire-Weather Data Library is a collection of more than 1.5 million weather observations maintained by the Forest Service. The library is a computerized meteorological data base that has been made available to users of the USDA computer at the Fort Collins Computer Center (FCCC) at Fort Collins, Colo. This data library is a source of unique data since most of the observations are from forest and mountain locations not covered by the National Weather Service. The weather observations are taken once per day in the early afternoon when the fire danger is highest. Records for many of the stations cover more than 20 years.

INTRODUCTION

The National Fire-Weather Data Library is a collection of computerized historical weather data maintained by the Forest Service (1). The library consists of more than 1.5 million daily weather observations taken at forest and mountain stations across the nation. There are a few year-around stations; however, most of the observations are taken during the fire season. These stations are maintained to provide weather information for use in fire supression planning. The observations are taken once per day during the early afternoon (1300 to 1400 local time) when fire danger is usually the highest. In addition to planning for fire suppression, these data have become useful for other planning efforts such as prescribed fire, and environmental assessment.

This pool of weather data is also a valuable source of information on the climatology and meteorology of forested and mountain areas. The data are available to all agencies having access to the USDA UNIVAC 1100/80 at the Fort Collins (Colorado) Computer Center (FCCC). For agencies not having access to FCCC, requests for data can be made directly to Cooperative Fire Protection, Boise Interagency Fire Center (BIFC), 3905 Vista Ave. Boise, ID 83705.

1. DATA COLLECTION

a. Manned Stations

Federal agencies concerned with fire protection have established a network of fire-weather observation stations because the National Weather Service observation stations were not located where they could monitor weather conditions meaningful to forest fire danger problems. Standard fire-weather station observations include dry-bulb temperature, wet-bulb temperature, maximum and minimum temperature, wind speed and direction, precipitation, and fuel moisture (Figure 1). Maximum and minimum relative humidity are available at a few stations. This fire danger network has grown to more than 800 stations nationwide. Figure 2 shows the locations of fire weather stations in the western United States.

Wind speed and direction are critical in fire protection activities. Wind instruments at fire-weather stations are exposed at a height of 20 feet above open, level ground. This standard height must be adjusted to compensate for height of ground cover, surface irregularities, and nearby obstructions (2).

The primary source of current weather data is a tape prepared by the Administrative and Forest Fire Information Retrieval and Management System, (AFFIRMS) (3) (4). Each participating agency relays to AFFIRMS via computer terminal weather information taken once per day at its fire-weather stations. AFFIRMS computes fire indices and stores the weather information for future retrieval. Data from years past, obtained from a number of sources, have been put in the AFFIRMS format and are also included in the library. Many stations have weather records extending back more than 20 years. The format of AFFIRMS archived fire weather data are given in Table 1.

b. Remote Automatic Weather Station

To provide weather information around the clock and throughout the day in remote mountain areas, automatic weather stations are needed. In 1978 the

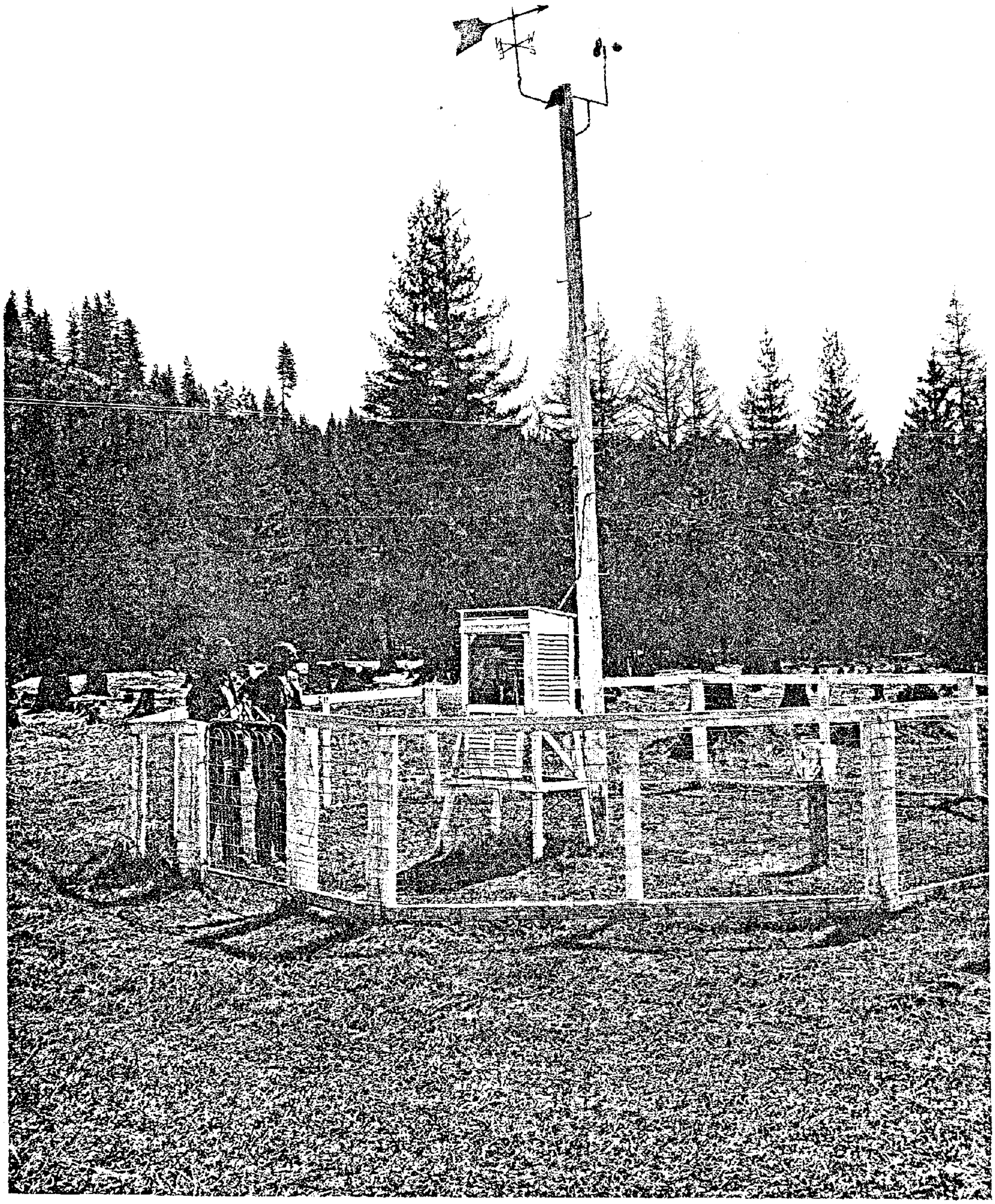

Figure 1. A standard fire-weather station. The anemometer and wind vane are exposed at 20 feet above open, level ground.

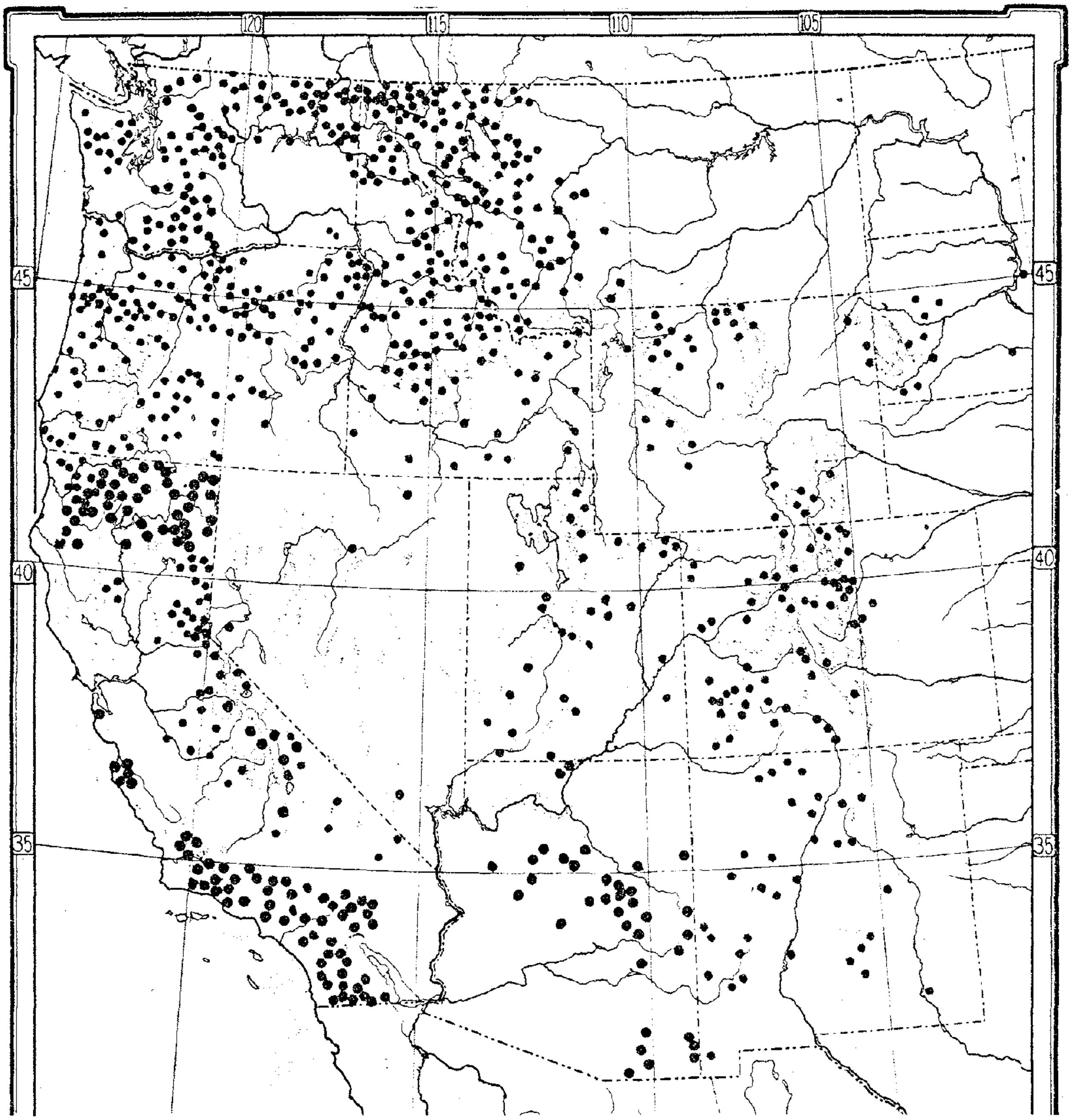

Figure 2. Locations of fire-weather stations in the western United States.

TABLE 1. FORMAT OF AFFIRMS DAILY FIRE-WEATHER DATA

Field Description	Begin Col. #	End Col. #
Station Number	1	6
Year	7	8
Month	9	10
Day	11	12
State of Weather		13
Dry-Bulb Temp. (°F)	14	16
Relative Humidity (%)	17	19
1-Hr-T/L Moist.	20	22
Herb-Veg-Cond (Model 1)	23	24
Man-Caused-Risk	25	27
Wind Direction (8 point)		28
Wind Speed (mph)	29	31
Woody-Veg-Cond (Model 1)		32
10-Hr-T/L Moist. (%)	33	35
100-Hr-T/L Moist. (%)	36	38
Max. Temp (°F)	39	41
Min. Temp (°F)	42	44
Max. R.H. (%)	45	47
Min. R.H. (%)	48	50
Not Used		51
Precip. Duration	52	53
Precip. Amount (in)	54	57
Lightning Act. Level	58	60
Digit "2"		61

Forest Service and the Bureau of Land Management together purchased and installed 20 Remote Automatic Weather Stations (RAWSs) in Hawaii, Alaska, and across the conterminous United States (Figure 3). A RAWS measures air temperature, relative humidity, fuel temperature, wind speed, wind direction, precipitation, barometric pressure and battery voltage every hour on the hour. The wind sensors on the RAWS are at the standard height of 20 feet. These stations operate off 12-volt batteries with solar panel chargers. Every three hours the RAWS transmits the past three observations through the Geostationary Operational Environmental Satellite, (GOES), to Wallops Island, then to NOAA/NESS and on to the Boise Interagency Fire Center. At present the RAWS data are manually entered by computer terminal into AFFIRMS. However, work is progressing to send the RAWS data automatically from the NESS computer to AFFIRMS.

2. DATA STORAGE

a. Screening and Editing

Data arriving at the Fort Collins Computer Center are first screened and edited. This involves checking to see if the particular weather variable is within permissible values. For wind direction this is 0 to 8 (8-point compass) and for wind speed 0 to 99 (mph). In instances when a data record is rejected, an effort is made to salvage it. Usual procedure is to send a list of rejected data to the originating agency and ask for corrections from the source documents. The corrected data records may then be returned to the FCCC and checked again. Checked data are sorted by station number and date and merged into the appropriate collection tape.

b. Collection and Library Tapes

The library system has two main parts, the collection tape and the library tape. The collection tape is updated weekly. As data are received at the Fort Collins Computer Center from AFFIRMS, or as new data are received from other sources, they are screened and edited then sorted and merged onto the collection tape. The collection tape data are current to within a month and are available to anyone having a need for current-year data. In January of each year the collection tape is merged onto the library tape and and a new collection tape is started. The library tape is the repository for all but

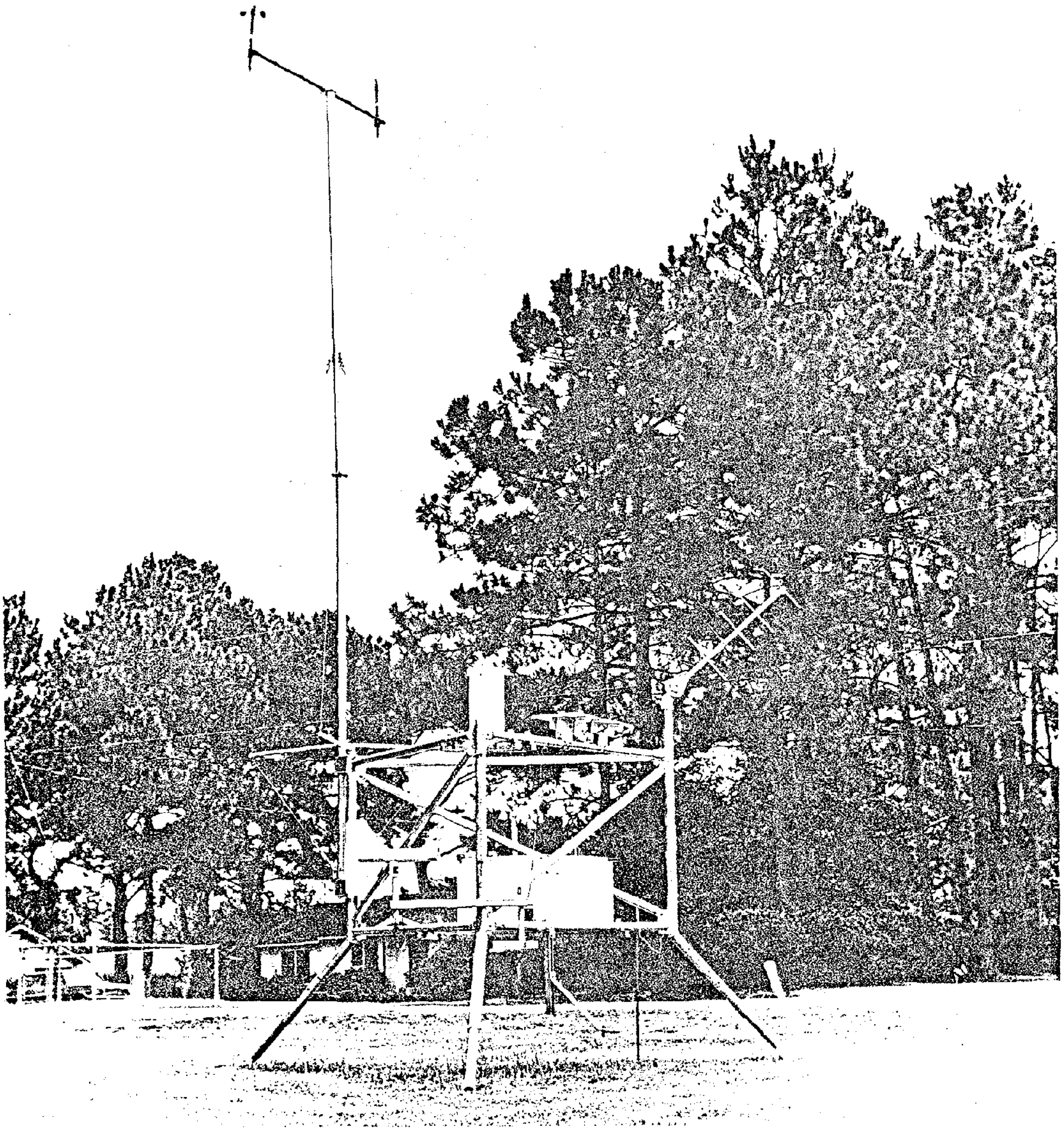

Figure 3. Remote Automatic Weather Station (RAWS). The anemometer and wind vane are 20 feet above ground.

the current year's data and newly acquired historical data. The data in the library are stored on several computer tapes in order by station number and by date. Fire-weather data are available to users from both the library and collection tapes.

3. DATA RETRIEVAL

Retrieval of information stored on the collection and library tapes is facilitated by a collection of routines called GETDATA available to all users. These routines perform the functions of finding the information requested by the user, and transferring it to some storage device (tape, disk, cards). These routines can retrieve large or small blocks of information, such as all the records for a state or a year's data for an individual station.

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DATA COLLECTION AND STORAGE
By the National Climatic Center

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INTRODUCTION

The primary purpose of the National Climatic Center is to collect, process, archive, and disseminate data to satisfy user needs. Data collected by the National Weather Service, military services including the Coast Guard, Federal Aviation Administration, merchant marine vessels and locally operated airfields are routinely sent to the Center, many of whose records begin prior to this century. Although data are available for all levels in the atmosphere, the majority of data are restricted to the layer within 20 meters of the surface. At present, the Center is receiving comprehensive observations of various elements from approximately 2000 locations in the continental United States, Alaska, and Hawaii. These stations take observations of temperature, wind direction and speed, visibility, present weather, cloudiness, pressure, etc., usually once each hour and more often during adverse conditions. The primary network, consisting of approximately 70 stations, takes observations 24 hours per day. The remaining locations take observations during daylight hours, every 3 or 6 hours, or to meet local air traffic requirements.

These hourly data are generally obtained from airport locations and are received in the form of manuscript records. Many stations also furnish contact and/or continuous anemometer recording sheets. Records are currently archived in original manuscript and microfiche form. A limited amount of hourly data is placed on magnetic tape. Instrument type and location are available for the last 25-30 years. Prior to the late 1940's much information is unavailable and/or contradictory.

Limited meteorological data gathered by other government agencies, such as the Forest Service, and by state agencies, research groups, universities, and industrial concerns are not archived at the Center.

1. DATA COLLECTION NETWORK

The earliest data were taken at Weather Bureau City Offices and Army Signal Corp locations and generally consist of only a few observations per day. Traces of wind data (speed only), where available, are presented on register charts. Published hourly wind run (total miles of wind passage) and prevailing direction begins for most stations in the early 1900's. By the late 1920's or early 1930's meteorological data were observed at airport locations near major urban areas and many small stations were developed along established air routes to facilitate data observation for aviation purposes. During hours of operations, observations were made at hourly intervals and when weather conditions required special observations. Concurrent City Offices were gradually phased out during the 1940's at most major cities. Many of the currently operating non-NWS airport locations take observations during daylight hours only or in conjunction with aircraft arrivals and departures.

By the 1930's, comprehensive data were being collected at large Naval and Army-Air facilities. A large number of 24-hour stations were established at relatively remote locations during the early 1940's and were then phased out after the end of WWII. During the 1970's, a decrease in the number of military stations and/or their hours of operation has continued. A major effort to establish 3-hour reporting facilities at Coast Guard locations was begun in the 1960's.

2. NWS INSTRUMENTATION

Although various research instruments are available for sampling the wind speed fluctuations at intervals of seconds or fractions of seconds, the standard anemometer of the Weather Service (and its predecessors - the Weather Bureau and Army Signal Corps) has been the vertical axis rotating cup anemometer. Many modifications were applied to this instrument in an attempt to more accurately record wind speed. The number, shape and strength of the cups, and length of the supporting arms have all been changed. Basically, however, these instruments measure wind passage determined by motion applied to a freely rotating mechanism.

Beginning in 1870, the 4-cup hemispherical Robinson anemometer was introduced by the Army Signal Corps. This was a contact-type instrument which accumulated wind passage in miles and fractions of miles on a dial. Frequently, this instrument was used with a mechanism which allowed a current to flow at each contact and actuate a light or buzzer. The observer reported wind speed by counting the number of contacts per unit time. For the early observational forms, a 5-minute speed converted to miles per hour was used. A more sophisticated mechanism actuated a pen arm at each contact which recorded each mile of wind passage on a clock-driven drum chart called a single or multiple register.

The 4-cup instrument was used exclusively through 1927 when replaced by a 3-cup anemometer with significantly better accuracy. The 4-cup was known to highly overestimate wind speeds - particularly the extreme winds. For example, a 100 m.p.h. observed speed required a minus 24 m.p.h. correction to indicate the true speed. Only the observed speeds were entered in the official records, and all data before 1928 must be corrected by a table of 4-cup corrections. Many investigations during the 1920's demonstrated the superiority of the 3-cup hemispherical anemometer (designated "S" type), and beginning January 1, 1928, the Weather Bureau began using this instrument for official wind measurements. The 4-cup was retained as backup. Observations made with the 3-cup were also entered unchanged in the official records on the erroneous assumption that the anemometer ran so close to the true speed that corrections were unnecessary. It was later determined that the established corrections were in error, and hence the published data must also be corrected to true speed before use. Readings from any 4-cup backup instrument used were corrected to a true speed for entry in the official records. For a few years, beginning in 1932, the 4-cup instrument was again the official station instrument, but at most locations the 3-cup was eventually readopted for official observations. Most importantly, all wind data entered in official records since January 1, 1932, are true speeds with the necessary corrections applied.

Additional investigations in the early 1930's demonstrated that cups with "beaded" edges - produced by rolling the edges outward to form a ring - ran considerably smoother in a turbulent air stream than cups with a straight edge.

Beaded edges were used on 3-cup (semi-conical) small airways contact anemometers (designated "SA") introduced at smaller airports in the 1930's. While beaded cups were found to be advantageous, they were not used on the standard 3-cup ("S") anemometer at major airport stations. However, at selected locations, a special beaded 4-cup experimental instrument was used in the 1930's and 40's. All instruments were contact anemometers, although aviation requirements in the 1930's led to the development of contacts for each 1/60th of a mile of wind passage. Thus the number of contacts per minute was converted directly to a m.p.h. equivalent for observations purposes.

A second type of anemometer employing a different method of recording wind speed was introduced during the 1940's at most major airport locations. This was the direct-reading type (similar to those in current operation) in which the wind-induced rotation governs the magnitude of electrical current generated by a magneto. The current is linearly related to the true wind speed which is determined by dial displacement. At observation time, the observer estimates a 1-minute velocity and any attendant gusts for entry on the observations forms. The direct-reading instrument is frequently connected to a device called a gust recorder which provides a continuous record of wind speed. Direct-reading instruments have generally replaced contact-type instruments at all locations except at approximately 130 major airports which also employ the older-type instrument in recording data on multiple registers.

In the early 1960's, a concerted effort was made to standardize anemometers on an approximately 20-foot mast located near the runway. Prios to this, the airport instruments were mounted on a 6- to 12-foot mast located on the operations building, control tower or nearby hangar. At many locations the mast was located atop a 60- to 80-foot beacon tower. At inner city sites, instruments were frequently mounted on much taller masts in order to reduce or minimize building effects on the air stream.

3. DATA STORAGE

All original manuscript records and charts are currently archived by the Center. Meteorological records can be consolidated into the following basic form types:

a. Meteorological Summary Form

Form 1001 was first used in the late 1800's and initially contained wind observations (5-minute average) made twice daily. By 1939, similar pages containing data for two additional hours were added. Beginning in 1905, two pages of hourly prevailing wind direction and wind run were added for use by stations with recording contact anemometers. In 1923, a page was added for wind - number of miles and length of time from - for each direction. Similar forms were used by military services until the early 1940's when an abbreviated Form 1 was introduced. Form 1001 was discontinued at the end of 1948. Although used initially at City Offices, Form 1001 also contains airport data for many locations transferring their operational programs to airport sites in the 1940's.

b. Airways Forms

Airways reporting forms were used at all locations (some beginning during the 1920's) established as airports. Such records contain the most detailed observations made.

These observations may be made hourly on a 24-hour basis with additional (special) observations taken when weather conditions warrant. However, because of location requirements, many stations took observations (hourly or less frequent) during daylight hours only or at 3 or 6 hour intervals on a 24-hour basis. The initial forms used for aviation purposes was introduced in the late 1920's and was known as form 1130. Columns for reporting wind direction (8 or 16 compass points) and wind speed (m.p.h.) were included. The reported wind was considered to be the representative 1-minute wind measured at the observation time. No correction is made to the observations to correct them to a standard height. Generally a manuscript page includes one day of data; however, for many locations with only a few observations per day, a form page may include several days of data.

Following the installation of direct reading anemometers in the 1940's, many stations included the wind gusts observed at observations times in the remarks column. A gust is defined as a wind speed which exceeds the lowest observed speed by at least 10 knots during the observation interval. By the early 1950's, the observed gusts were included on the observation form in a column (wind character) immediately following the prevailing speed column.

In the mid-1940's, the form 1130 was replaced by the forms WBAN 10A and 10B currently in use. The 10B contains supplementary and summary of day data.

Wind speeds on the 10A are reported in knots beginning in 1955 and wind direction in tens of degrees beginning in 1964.

c. Multiple Register

Recording equipment for contact anemometers was installed at locations as early as 1872. Although current charts contain measurements of sunshine and rainfall, the earliest register charts include wind direction and/or speed only.

These register charts provide a measurement of wind movement by indicating the passage of each consecutive mile of wind. Four 6-hour horizontal traverses are made across the chart with 5-minute time increments indicated by vertical lines. A mile of wind passage is indicated by each pair of short lines drawn parallel to the time lines and at right angles to the lines of pen traverse. The speed is obtained directly by dividing a one mile passage of wind by the elapsed time in hours. Each 6-hour period contains 4 rows labeled N (North), E (East), S (South), and W (West). One dot or tick mark per minute is marked in the appropriate row depending on the wind direction. Two-dot combinations can be used for winds from the Northeast (N and E), Southeast (S and E), etc.

Beginning in the early 1960's the data are recorded on continuous roll charts. Some data, especially that taken at second-order or Coast Guard locations, are difficult to use due to frequent equipment outages and poor quality control.

The number of locations providing these charts has decreased considerably in the past 30 years. Initially used at most Weather Bureau Office (city) locations, multiple registers are currently installed at approximately 130 locations, the majority of which are airports. These charts are also archived for a large number of Army Signal Corp locations equipped during the late 1800's. Fastest mile data extracted from these charts are not quality controlled. Independent evaluations of published data have shown these to be frequently erroneous.

d. Gust Recorders

Continuous trace gust recorders were installed at National Weather Service locations beginning in the 1950's although most locations were not so equipped until the late 1960's. Military stations were instrumented for earlier and longer periods. Many stations established for brief periods during WWII utilized gust recording equipment. Air Force station data have not been sent to the Center for archiving since 1973. FAA stations have not been equipped with recorders. These data have not been quality controlled and there have been problems of calibration, lack of annotation and improper time registration.

e. Digital Records

Surface observations for NWS stations are available on magnetic tape beginning generally in 1948. Through 1964, either 24 obs/day or all available hourly observations were digitized. This includes the reported wind direction and speed but not the gust measurements if reported on the original manuscript. Also not included are special observations taken between the required hourly reporting times. Beginning in 1965, all National Weather Service and other civilian station data were digitized on a 3-hourly basis, although hourly data may be reported on the manuscripts. Many of the military stations operating briefly during WWII have data on tape. Air Force and Navy stations were digitized hourly until December 1970 and February 1972, respectively. Air Force data have not been keyed since 1970 although unedited digitized synoptic sequence data obtained via radio-teletype and continuous wave broadcasts are available.

Most of the NWS and military locations and a portion of the FAA sites will have data on magnetic tape for the complete period ending in 1978. Most FAA sites will have various periods from 5-15 years in length available.

For stations with gust recorders and/or contact anemometer register charts, the daily peak gust and/or fastest mile is included in a summary of day tape. Fastest mile data have been included only since 1965.

Until 1972 data were punched onto standard 80 column cards and transferred onto tape for further processing. Since 1972 data are keyed directly to tape although cards can be generated if required. The Center's computing and processing equipment can accommodate most required tape characteristics. 7 channel tapes up to 800 bpi (BCD) and 9 channel tapes at up to 6250 bpi (EBCDIC and ASCII) can be processed.

Within a few years, with full implementation of the AFOS system, the Center will receive much of it's currently keyed data in digitized format. This would include all hourly and special observations - including Remarks.

A cost estimate to process or furnish data in original, microform or digitized format will be given upon request. Inquiries should be addressed to:

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WIND DATA FROM CONVENTIONAL MEASUREMENT SYSTEMS; THE KNOWN, THE KNOWABLE AND THE UNKOWN

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ABSTRACT

The output of a measuring system used for routine monitoring of meteorological variables can be described in terms of data and information. The data (numbers people are used to seeing) should be qualified by additional information which will tell the user what is needed to match the data to the application. The following discussion will list these items and suggest timely moves toward standardization.

INTRODUCTION

The time has come for action. Over a quarter of a century ago Court (1953) (1) put together the basic considerations for the measurement of wind speed. Sissenwine et al (1973) (2) has updated the Military Standard 210 A which was based on Court's work; and here we are at a Workshop on Wind Climate to talk about application, availability, quality, limitations, generalizations (modeling) and acquisition of wind data for climatological purposes.

We must know by now what we need to do. We certainly know how to do it. Court and others told us why we should do it. I submit that the when to do it is now. Let us at this workshop, at the very least, agree to some standards for measurement and let us all use every opportunity to get the standards implemented. If we succeed at this minuscule objective then maybe a quarter of a century from now we will have a superior wind data base.

This goal needs a consensus agreement on what should be archived in machine processable form. The agreement should include the following:

		Example
Sampling period	- acceptable range	- 20 minutes per hour
Averaging method	- acceptable types	- arithmetic
Units	- acceptable units	- meters per second
Resolution	- acceptable range	- 0.1 m/s
Date-Time	- some standard format (i.e., SAROAD)	
Location	- some standard format (i.e., SAROAD)	
Information	- see below for lists	

The first six items will be the easiest - an immediate goal perhaps. The information which describes the data gathering will take some time to gather enough facts and ideas to reach a consensus agreement.

1. CONVENTIONAL MEASUREMENT SYSTEMS

If one considers all measurements of wind which are made in the United States during a year, there are no conventional systems. If on the other hand one considers only those measurements which become our official climatological data, there are only a few conventional systems.

Since it is our purpose to try and have a larger body of data available we should look at a generalized system for the purpose of discussing differences in elements of the system. Figure 1 from MacCready and Lockhart (1973) (3) divides the system into two parts; atmospheric coupling and data handling. While the sensor-transducer box in Figure 1 suggests a mechanically responding device, the concepts will also fit remote sensors such as sonic anemometers and acoustic dopplers and mechanically passive sensors such as hot wire or hot film anemometers. For this discussion consider the fluidic anemometer as mechanical.

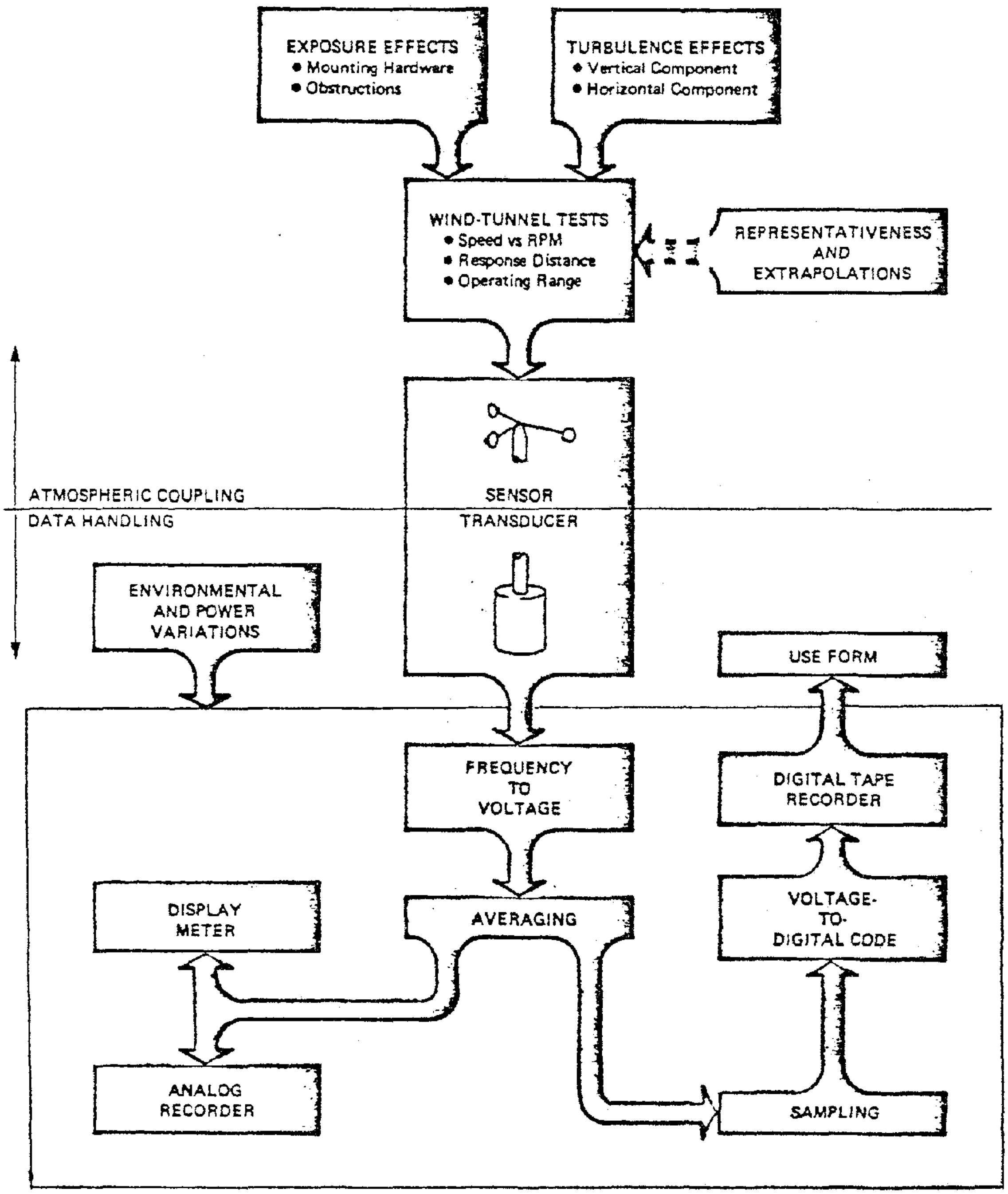

Figure 1. Conventional Measurement System

What then do we now know about our operational systems; what should we know that we can know with relative ease and what is likely to remain unknown. Let us define knowable as something that can be objectively expressed quantitatively with error bars with confidence levels, where appropriate. Let us further require that what we know must be found with the data or descriptive information as easily available as the data and from the same source as the data. The unknown should be recognized and at least an estimate of the impact on the data provided or solicited from the scientific community.

Information and data can be defined as follows:

- Data are numerical values with qualifiers such as units, date-time, sampling period and averaging method and period. Data may be expressed as combined values (i.e., daily averages) but they require the same qualifiers.

- Information includes everything else about the data and the measurement system, including exposure of the sensor, which might have some effect on the data or the use to which it is put.

Some of the items to be considered are listed in Table 1 in a matrix which associates each item with the system shown in Figure 1 and the separation of data and information. A tiny number of items deal with the data from the Data Handling part of the system. The bulk of the items are informational which either describe the measurement coupling or the management (Housekeeping) of the instrument system. The information items may be numerous but they need be described only once or when change or additional information becomes available. Anyone who wants to use the data will probably need to dig up most of the information. For this reason it is recommended that a large header be used to provide it along with the data in machine processable form.

TABLE 1. ELEMENTS OF A MEASUREMENT SYSTEM

ATMOSPHERIC COUPLING		
SYSTEM REFERENCE	DATA	INFORMATION
Exposure Effect		Site Description Roughness (2) Uniformity (2) Major Biases (2) Mounting Description (2)
Turbulence Effects		Reference to Text Results (3)
Representativeness & Extrapolations		Horizontal Profile (3) Vertical Profile (3)
Wind Tunnel Tests		Accuracy and Precision (2) Dynamic Response Characteristics (1)
Atmospheric Tests		Functional Precision (2)
Sensor		Model Number (& Manufacturer)(1) Serial Number (& Change Flags)(1) Location (Longitude & Latitude)(1) Height & Elevation (1) Transfer Function (speed vs RPM) (2)
DATA HANDLING		
Transducer		Transfer Function (RPM vs Output) (2)
Signal Conditioning		Method (2)
Averaging		Method (2)
Sampling	Sampling Period (2)	Method (2)
Output	Speed (Units) (1) Date/Time (1)	Time Definition (2)
Averaging	Speed (Units) (1) Date/Period (1)	Method (2) Period Definition (2)
HOUSEKEEPING		
Responsibility		Organization and Subdivisions (1)
Data Quality Assurance		Inspection Cycle (Data & Instrument) (2) Calibration (Cycle & Method) (2) Calibration Results (Date/Time) (2) Automatic Validity Check Criteria (2) Action Strategy (2)

Key (1) Known
(2) Knowable
(3) Unknown

The following sections will enlarge on the state of knowledge of each item to the extent possible.

2. THE KNOWN

a. Location

This is usually pretty well known for data from NWS and FAA stations. If data from other sources are known to exist, the location of the measurement is at least knowable. Data which gets into the EPA data bank (APTD-0663) (4) must pass some tests and be in the format called SAROAD. The location designation for SAROAD is longitude and latitude to the nearest second of arc (31 m at the equator).

b. Height

This value is also rather easy to find and often associated with the data. One presumes the height is a measure of the distance between the mean ground surface and the plane in which the center of the cups turn or the midpoint of a propeller hub. As will be mentioned later, this does not necessarily mean the effective or equivalent height for rough, complex, or obstructed locations. The elevation of the sensor or the mean ground surface is also important. A convention needs to be established whether to report the station elevation or the sensor elevation which would include the height above ground.

c. Type of Anemometer

Perhaps this belongs in the knowable category. It is easily available but may require an inquiry rather than being a part of the data report. It should include the manufacturer (if knowable), model number and serial number. It might be argued that the model is sufficient given a service and calibration procedure which provides equivalent replacement. If a method can be found which will tie the data to a particular sensor with its service and calibration record, the data will be legally defendable and probably more accurate.

d. Dynamic Response Characteristics

Again this may belong in a knowable category. It is true that any manufacturer will supply the starting threshold, response distance and operating range of his first order rotating type anemometer. Since no standards exist as yet to form a point of reference for definitions and methods for determining dynamic response characteristics, the information must be considered approximate. When standards are available and cited in the information, the characteristics will be known.

The same holds true for the more exotic instruments but the schedule for standards is farther into the future. Some flag or footnote could be used to describe the method used to determine the equivalent response characteristic values or a reference given where it is described in the literature.

e. The Data Itself

Each value in the data base is known to the resolution reported and in units identified. What should these units be? The SI answer is meters per second (5), but still used are miles per hour, knots and feet per minute. The proposed NWS metric units are kilometers per hour.

Along with the value is some indication of date and time, either explicit by a number in the record or implicit by a location in a record with start date/time in a header. What is probably not known is the sampling period for the data.

If a series of data are reported in averaged form or as an extreme value of a period, the time period is also stated and the averaging method can be found. Confusion may result if one is not very careful in the interpretation of what is reported as an extreme value. For example, if a fastest mile is reported for a 24-hour period, it is presumed to be the shortest distance (time) between two adjacent event marks recording the passing of a particular mile of air past a cup anemometer. Of all the miles continuously recorded during the 24 hours, one is the fastest. There may have been a faster one which would include a part of a mile on either side of any event.

The fastest minute, on the other hand, is simply the largest recorded observation during the 24-hour period. These observations are presumed to be one-minute averages but they often are not. The fastest minute for a 24-hour (or 30-day) period is <u>not</u> the fastest one-minute average which occurred during the period. It is the fastest one on the observer's form. The two are often used interchangeably as though they were nearly the same which they are not.

f. Responsible Organization and Subdivision

It is usually known in the data what organization took the data. As more organizations are involved in this type of activity, the identity of the source should be maintained. It should be complete enough to describe to an information center of the main organization and get a telephone number of the operating group in response.

3. THE KNOWABLE

Using Figure 1 as a guide the following lists those important specifications or measurement methods or other facts which should and could be known to the data user.

a. Exposure

Some expression of the exposure is possible. The surrounding square kilometer could be characterized by some objective method representing its elevation variability with a resolution of a meter. In addition, the nature of the surface (rock covered, variable grain crops, grass or paving) could be expressed along with some statement about the surrounding tens of square kilometers with the direction toward prominent features. The elevation and height of the highest object within 10 sensor heights of the sensor (and perhaps also 100 sensor heights) might be recorded along with the direction to the object from the sensor.

If the sensor is mounted to a tower, the direction between the sensor and the tower as well as the separation distance is needed. Some physical description of the tower is also needed to assess the direction pie within which the sensor will measure the influence of the tower. If the sensor is on a tripod on a building roof, a complete description of the building, its roof dimensions, where the tripod is located and how high the sensor is above the effective roof height is needed. It would be insufficient to report an anemometer 10 m above the roof of a 90 m building as 100 m above ground elevation.

If the sensor location is near the shore of a large body of water or near a valley wall it would be good to report the principal directional axis of the shoreline or ridge and the perpendicular distance to it.

b. Wind Tunnel Tests

Properly designed wind tunnel tests will provide a measure of the accuracy and precision of the sensor when operating in a wind tunnel flow. To be most useful the tests should be in accordance with a standard method. This becomes most important when calibrations are performed by a variety of test facilities. For wind vanes the dynamic response characteristics should include Delay Distance, Overshoot (damping ratio), Dynamic Vane Bias (bent tail).

c. Functional Precision

If a measure of precision of operation in a turbulent environment is to be defined, Hoehne (1973) (6) suggests the first step is to define the variation between two identical sensors mounted within 10 m of each other. He calls this performance description "functional precision." This would be a starting point for either a measure of representativeness or a co-located field calibration.

d. Transfer Function

This description of what the sensor shaft does (rpm) in a variety of conditions (speeds) results primarily from wind tunnel tests. If a standard expression can be adopted (i.e., $Y = a + b x$ for the best linear fit) in standard units, a means of comparisons would exist with the data. The accuracy and precision data should refer to such an expression.

A second transfer function will describe the transducer output as a function of sensor operation. For instance, if a speed sensor uses a light chopper to convert rate of rotation (rpm) to output frequency (Hz), a 100 slot chopper would calculate the output frequency, F (Hz) from

$$F = 1.667\ Y \qquad \text{where Y is sensor rpm}$$

e. Data Handling

If the signal conditioning provides any change to the performance of the sensor, it should be described. The most common of such effects would be averaging and temperature drift. In addition, averaging may be intentionally used. It is not enough to state a one-minute averaging circuit is used. The time constant (if it is an R-C circuit) must also be disclosed. A one-minute averaging circuit will have a 12-second time constant if a five-time constant definition is used to describe the average. If digital methods are used the method might be described as "the arithmetic average of 60 instantaneous one-second samples."

Sampling may be used rather than continuous operation. If so, the sample period and repetition rate needs to be described. For example, the method might be to sample 20 minutes centered on the hour. A value would be reported as an hourly value but the information would identify it as being an average of the period H ± 10 min.

The method of averaging data must be reported. There are a variety of methods appropriate to a variety of applications (Lockhart, 1979) (7). Either a description of the averaging method used or a flag identifying some one of a standard list might be used.

f. Housekeeping

This part deals with the quality of the data or the validity criteria. Some inspection cycle will likely be used for both the data from the field and for the instrument itself. The frequency of this cycle should be declared.

Calibrations will be scheduled. The method used, the frequency and the results of date-identified calibrations should be part of the information content of the data header. Any action taken on the data as a result of a calibration must be declared.

Some organizations use automatic computer data validity checking systems. If so, the criteria chosen for action and the nature of the action must be described. This is particularly important if the data are changed or deleted as a result of some test. If flags are used to draw attention to criteria violators it is not as important.

4. THE UNKNOWN

a. Turbulence Effects

The performence of a mechanical wind sensor can be defined partially by wind tunnel tests. There will be some difference when the sensor is in turbulent flow and the difference is likely to vary as the intensity and wave length of the nonlaminar flow (see MacCready, 1966) (8). It may be impossible to generalize this effect on the data but if relevant references do exist, a listing of them will help the dedicated user.

b. Representativeness

There needs to be an objective method to characterize the size of the plane which can be represented by a point measurement. This question when addressed at all is given expert subjective judgement. The application too often dictates the range of representativeness given to the data. This is perhaps the most important unknown and one which can be moved to knowable in reasonable time.

c. Vertical Profile

This site specific unknown should be moved to the knowable. Methods for measuring a profile are known. Some caution is advisable when generalizing a profile shape to be sure a single layer is being described and to be sure the data averaged for a profile statement do not come from different meteorological conditions. For example, an average profile calculated from 24-hourly profiles each day for a month will probably not represent either the nocturnal profile or the mid-day profile.

5. CONCLUSION

In terms of items it may appear that much more is known or knowable than unknown. One must realize however that the known and knowable needs immediate attention to organize them in a framework of practical standardizations for the knowledge to benefit the user as it can and should. Furthermore, while the number of items listed as unknown (and there are probably more) are few, they represent the greatest potential for erroneous application conclusions of all parts of the measurement system. It is here that future progress will be made from research. This progress will come faster if the easy part is standardized.

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ADJUSTMENT AND ANALYSIS OF DATA FOR REGIONAL WIND ENERGY ASSESSMENTS

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ABSTRACT

An assessment of the wind energy resource for the Northwest region of the United States has been completed. Techniques were developed for identifying, screening, adjusting, and analyzing the existing wind data. Anemometer height and location and site exposure were evaluated for selected stations. Mean wind speeds and power densities were adjusted to 10 m and 50 m reference levels for presentation of the wind resource. An examination of long-term mean wind speeds and powers at airport locations at which the anemometer height was changed and at tower sites with multiple levels of anemometry indicated that a power law exponent $\approx \frac{1}{7}$ is applicable to sites characterized by good exposure and low surface roughness. Mean wind speeds at airfields were found to be significantly higher than mean wind speeds at nearby rural and urban sites.

Climatological adjustment (i.e., using long-term records to adjust short-term records at other stations) was not found reliable. Thus, no attempts were made to adjust mean wind speeds based on short periods of record (e.g., one year).

In the spatial analysis, techniques using qualitative indicators of wind energy were developed and applied to deduce the wind energy in data-sparse areas. The wind data and qualitative indicators were combined to analyze the geographical distribution of the wind energy.

INTRODUCTION

Rapid commercial utilization of wind as a source of electric power is the principal goal of the Federal Wind Energy Program. Assessments of the

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wind resource play an important role in achieving this goal, because utility planning, wind turbine manufacturing and marketing of wind energy conversion systems depend on detailed descriptions of the wind resource. However, previous national-scale assessments and their synthesis (1) have not displayed the geographical and temporal detail needed to effectively plan a strategy for tapping wind as a viable source of energy.

The wind energy resource of the United States and its territories must be described in adequate detail to meet the needs of a variety of users. To meet these needs, the Wind Characteristic Program Element, managed for the U.S. Department of Energy (DOE) by Pacific Northwest Laboratory (PNL), developed, applied and tested techniques using existing wind information to assess the wind energy potential of the Northwest region. This assessment included Idaho, Montana, Oregon, Washington and Wyoming.

The Wind Energy Resource Atlas for the Northwest (2) is the first of twelve such atlases. The other atlases will cover eleven other regions of the United States. To produce the Northwest Atlas in a timely fashion, only existing relevant data were used. Atlases for other regions will be produced using comparable data sets, analysis techniques and presentations to ensure the compatability of the wind resource assessments. The wind resource is presented and discussed on three space-and-time scales: regional, state, and station; annual, seasonal, and daily, respectively.

This paper will focus on the techniques developed and applied in adjusting and analyzing the wind data used in the wind energy resource assessment. The three primary aspects to be addressed are: (1) vertical adjustment of the mean wind speed and power; (2) climatological adjustment of short-term records; and (3) spatial analysis of the wind energy resource over different classes of landform. Methods used in identifying and screening the data and for evaluating the wind power are described in the Northwest wind resource atlas.

1. VERTICAL ADJUSTMENT OF MEAN WIND SPEED AND POWER

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

$$\frac{\overline{V}_r}{\overline{V}_a} = \left(\frac{Z_r}{Z_a}\right)^{\alpha_s} \text{ or } \frac{\overline{P}_r}{\overline{P}_a} = \left(\frac{Z_r}{Z_a}\right)^{3\alpha_p} \qquad (A.4)$$

where

$\overline{V}_{a,r}$ and $\overline{P}_{a,r}$ = the mean wind speed or wind power density at heights $Z_{a,r}$ (the anemometer and reference level, respectively)

α_s and α_p = power law exponent for mean wind speed and mean wind power density, respectively.

Because the shape of wind speed distribution may change with height, α_s may differ from α_p.

Values of α_p have been calculated and are shown in Table 1 for certain airport stations with anemometer height changes and for meteorological towers with multiple levels of anemometry from locations throughout the United States.

TABLE 1. POWER LAW EXPONENTS α ESTIMATED FOR AIRPORTS AT WHICH THE ANEMOMETER HEIGHT WAS CHANGED AND FOR DOE AND NUCLEAR POWER PLANT TOWER SITES WITH MULTIPLE LEVELS OF ANEMOMETRY

	No. of Stations	Mean α_p	Range of α_p	Comments
Airport Stations				
Northwest	8	0.157	0.106-0.224	Periods $\geq$ 5 yrs and $\geq$ 7 m difference in anemometer height
East and Gulf Coast	11	0.159	0.100-0.215	Periods $\geq$ 3 yrs and $\geq$ 7 m difference in anemometer height
Florida	4	0.078	0.065-0.091	
DOE Meteorological Towers				
Instrumented at 9.1 and 45.7 m levels	11	0.141	0.037-0.233	Low roughness sites
Instrumented at 18.3 and 45.7 m levels	5	0.246	0.137-0.386	High roughness sites (i.e., wooded)
Nuclear Power Plant Sites	21	0.201	0.129-0.318	Sites with >50 w/m^2 and >2.5 m/s at 10 m

The mean α_p for airport stations in the Northwest agrees well with the α_p estimated for East and Gulf Coast airports (3). However, Florida stations showed significantly lower α_p.

At the Department of Energy meteorological towers, located in various regions of the United States and Puerto Rico, the mean α_p is 0.141 for sites instrumented 9.1 and 45.7 m and 0.246 for sites instrumented at 18.3 and 45.7 m. All sites had from 12 to 17 months of data. Tower sites where the lower level of instrument was placed at 18.3 m to get above trees or obstructions are called "high roughness sites". Sites instrumented at 9.1 m are called "low roughness sites;" however, one site (Block Island, Rhode Island) has an α_p of 0.233. At all the other sites instrumented at 9.1 m, α_p is less than 0.18. For the five Great Plains sites, the mean α_p is 0.137; thus, $\alpha_p = 0.14$ or $\frac{1}{7}$ appears to be a reasonable value for low roughness sites. This corresponds to a wind power at 50 m that is approximately double (1.99) the power at 10 m. A comparison of α_s and α_p shows that, on the average, α_s is greater than α_p. The mean $\alpha_s = 0.159$ for the 11 low roughness sites (compared to $\alpha_p = 0.141$), and for the five high roughness sites $\alpha_s = 0.268$ (compared to $\alpha_p = 0.246$). At three of the 16 sites, $\alpha_s - \alpha_p$ is greater than 0.05. This difference in α_s and α_p results from the change in the shape of the wind speed frequency distribution between the lower and upper levels.

Wind summaries have been compiled for 104 nuclear power plant meteorological towers throughout the United States (4). Fifty-five sites have summaries at more than one level. The α_p has been evaluated for 21 sites where the 10 m level wind power exceeds 50 w/m^2 and the wind speed exceeds 2.5 m/sec. The mean $\alpha_p = 0.201$ and $\alpha_s = 0.258$. Thus, as with the DOE meteorological towers, α_p is significantly less than α_s. Table 2 described the site environments which have the highest and the lowest values of α_p. The two sites with the greatest wind shear are both located on the shores of the Great Lakes; however, the inland environment consists of high surface roughness features (e.g., buildings, woods, etc). The two sites with the least wind shear are located in a low surface roughness environment of mostly sagebrush and grasslands.

TABLE 2. COMPARISON OF NUCLEAR POWER PLANT TOWER SITES WHICH HAVE THE HIGHEST AND LOW VALUES OF α_p

Site Locations	α_p	Site Description
<u>High Roughness Sites</u>		
Bailly, Indiana	0.318	South shore of Lake Michigan. Industrial and residential areas in other directions.
Perry, Ohio	0.262	Southeast shore of Lake Erie. Light to heavy woodland and farm-land in other directions. Tower is 1130 m inland.
<u>Low Roughness Sites</u>		
Pebble Springs, Oregon	0.129	Desert sagebrush and grasslands environment.
Hanford WPPSS, Washington	0.143	Desert sagebrush and grasslands environment

Variations in surface roughness over a region make it difficult to portray an average wind power at 10 m. In the Northwest wind energy assessment, the wind power analyses represent well exposed sites of low surface roughness such as airports and large clearings. The most desirable clearings are elongated in the directions of the prevailing power-producing winds. Wind power was adjusted to 10 m and 50 m using an exponent of $\frac{1}{7}$ in the power law, which was shown to be very reasonable for low roughness sites. Depending on the location of roughness features relative to the prevailing wind directions, wooded and suburban sites may have 30% to 70% less wind power at 10 m than nearby airports and cleared areas. Even at 50 m, the wind power may be 10% to 40% lower in partially wooded, wooded, and urban areas than at airports and large fields. A major problem is that the local site exposure is not known at many of the sites with wind data; thus, heavy reliance must be placed on those airports and sites where the local site exposure is known and/or where wind data at higher levels (e.g., 50 m) exist.

2. CLIMATOLOGICAL ADJUSTMENT

Large interannual variations in wind speed were found at many stations with long periods of record. For example, the interannual variations in annual average wind speed at Great Falls International Airport are shown in Figure 1. The anemometer height and location were changed in 1959. During the 5-year period from 1965-69 the annual mean wind speeds were significantly lower than the long-term mean. In another 5-year period from 1972-76 the annual mean wind speeds were significantly greater than the long-term mean.

Many locations used in the Northwest wind energy resource assessment had less than 5 years of data at constant anemometer height and location. Because the wind power in a given year may differ by up to 50% from the long-term mean power, the feasibility of using long-term data to adjust the winds speeds at stations with short-term data was explored.

Z IS THE ANEMOMETER HEIGHT; $\overline{V}$ IS THE LONG-TERM WIND SPEED

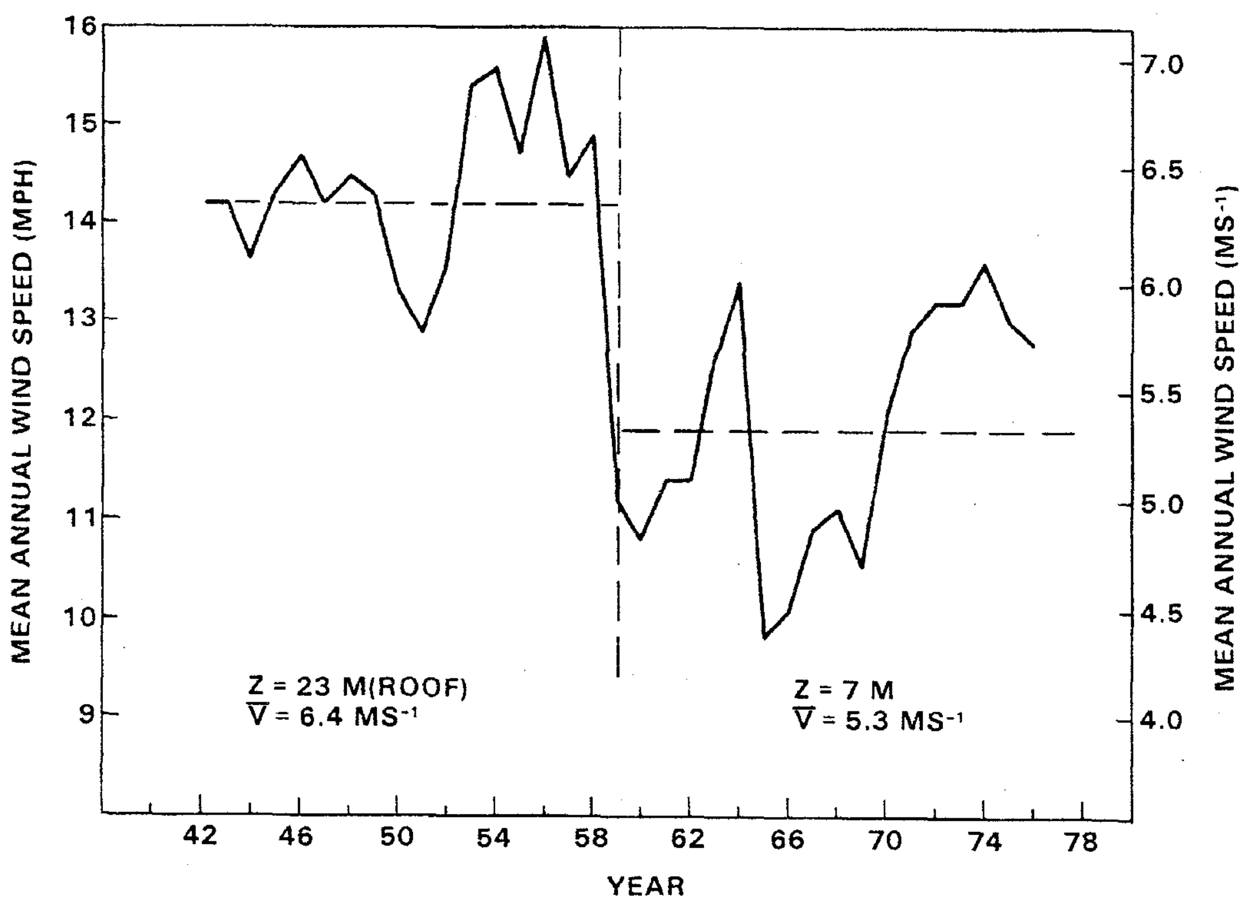

Figure 1. Interannual Variations in Annual Average Wind Speed at Great Falls, Montana

However, the correlation between interannual variations in mean annual wind speeds at nearby stations has been found to be poor. An examination of interstation correlation of mean annual wind speeds from stations in the Northwest and similar studies by Justus, et al. (5) show that climatological adjustment does not appear to be reliable and, hence, was not used in the Northwest assessment to adjust short-term data. Corotis (6) has done statistical studies on the reliability of the mean wind speeds based on short periods of record. His studies indicate that one year of data gives ± 10% of the mean long-term wind speed with 90% confidence.

3. SPATIAL ANALYSIS

The wind power at a given site may be representative of a large area (e.g., 100 km^2) or it may only be representative of the site itself and its immediate surroundings. An important part of the wind data analysis was an evaluation of the representativeness of a station's wind power estimate. Four items were found useful for determining how well a site represents the wind characteristics of exposed locations in the region:

1) Description of the site location with respect to the surrounding terrain; e.g., hilltop, flat plain, ridge crest, valley, etc.
2) Determination of the character of the local environment surrounding the site; e.g., airport, urban, forest, shoreline, etc.
3) Evaluation of exposure of the site with respect to the wind; e.g., poor, acceptable, excellent.
4) Determination of exposure of the anemometer at that site; e.g., tower, rooftop, etc.

Much of the information needed for these evaluations is in National Climatic Center indexes and station histories and on topographical and sectional aeronautical charts.

a. Reliability of Wind Data

The reliability of the accuracy of the wind power estimates at the site is difficult to assess. This depends on factors such as the accuracy of the wind speed measurements, the method of observing and recording the wind data, the period of record, the frequency of observations, and the type of wind summary. No attempt was made to adjust the estimates for any of these factors; however, wind power estimates based on data with large uncertainties were used with caution. In areas with abundant data, only the most representative and highest quality data were used in the assessment. However, in data-sparse areas even the very limited data were used to serve as an indicator of the wind power.

b. Reliability of Areal Estimates

The reliability of the wind power estimates over a large area is primarily a function of the data density and complexity of the terrain. Over large flat plains where mean wind speeds are fairly uniform, the wind power analysis based on just a few stations may be quite reliable. However, in coastal, hilly, and mountainous areas where the effects of local terrain and differential heating can cause large variations in wind power over short distances, a wind power analysis of high reliability would require an unwarranted station density. Nevertheless, in data-sparse areas, techniques using various indicators of wind energy can be applied to infer the wind power with confidence. These techniques included the use of meteorological and topographical features (7), vegetation features (8), and eolian landforms (9). Of these, the meteorological and topographical indicators were of greatest benefit to the Northwest regional assessment.

c. Analysis of Wind Power

The production of mean wind power maps, such as the one shown in Figure 2, depended on the coherent synthesis of information from annual and seasonal wind power estimates adjusted to 10 and 50 m for the surface stations; mountain summit and ridge crests estimates (based on upper air climatology supplemented with existing data); descriptions of location and representativeness of wind power estimates at each site; qualitative indicators of wind power; topographic relief maps; and surface landform maps (10). Underlying the synthesis process was the goal of presenting wind power density values representing sites exposed to the prevailing power-producing

Figure 2. Annual Average Wind Power for the Northwest

winds. In forested or wooded areas, the estimates are representative of large clearings with good exposure to the prevailing winds. The map values shown in Figure 2 generally represent terrain features that are favorably exposed to the wind, as indicated in Table 3. However, because of the large spatial scale of the regional assessment, the map values can only represent major terrain features. For example, isolated hilltops and mountains in open plains, such as the Snake River Plain in Idaho, are not depicted. Shaded relief maps (1:500,000 scale) were used to identify and outline the mountainous areas and major terrain features. In mountainous regions, the analyses also reflect major valleys.

TABLE 3. TERRAIN FEATURES WITHIN A GIVEN LANDFORM CLASS REPRESENTED BY MAP VALUES IN THE REGIONAL WIND ENERGY RESOURCE ANALYSIS

Surface Landform	Map Values
Plains	Plains
Plains with Hills	Open Plains
Plains with Mountins	Plains Ridge Crests and Mountain Summits (shaded areas)
Tablelands	Tablelands
Open Hills	Hilltops and Uplands
Open Mountains	Broad Valleys and Basins Ridge Crests and Mountain Summits (shaded areas)
Hills	Hilltops and Uplands
Mountains	Ridge Crests and Mountain Summits (shaded areas)

4. CONCLUSIONS

The one-seventh power law appears reasonable for adjusting long-term mean wind power estimates to 10 m and 50 m at airports and other low roughness sites. Climatological adjustment does not appear reliable and was not used to adjust short-term data.

Wind data alone are not adequate for assessing the geographical distribution of the wind energy resource. The spatial analysis of the wind resource and the production of the wind power maps depended on the coherent synthesis of a variety of techniques. Techniques developed by PNL appear to yield reasonable wind resource assessments when applied to the Northwest. Maximal use of available wind data and use of indirect indicators of wind speed allow the space and time resolution to be much improved over previous national scale assessments.

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DISCUSSIONS OF SESSION II

*   *   *

Arnold Court

Once an hour wind speed reports from a 1/60-mile contacting anemometer provide unbiased estimates of wind passage during the hour. At Huron, SD, during 1941, the two measurements agreed within 3 mph on 95% of the 730 hours beginning at noon and midnight. Hourly passage came from the "triple register" record of miles of wind passage, speed reports from the flashes or buzzes during one minute of a 1/60-mile contact in the same anemometer.

*   *   *

Harold Crutcher

1. ALL data presentations should include error bars and confidence bands. Unless such confidence parts are used or presented, there may be arguments as to which model may or may not be the better one. Unless the period of record is long, one model may be said to be better when in statistical parlance it may be different from the others, but may not be necessarily better.
2. With regard to speeds, there appears to be a change in apparent better fit of models with the east to west (or west to east and north to south or south to north) traverses.
3. Assessment of gradient winds and relationship to surface winds:
    a. There is a distinct relationship between the two as influenced by the inertial wind.

b. High winds will induce higher recorded pibal speeds due to turbulence keeping balloon near the ground.

c. Pibal records may offer potential, not yet totally used, to determine relationship.

4. There seems to be some need to observe (sense) and record wind variance in the vector sense, as well as the mean wind and speed. With microprocessors becoming available, perhaps it is not too late to influence the establishment of NWS system output to EDIS.

*　　　*　　　*

Dennis L. Elliott

Publishing of existing station descriptions: Station descriptions, which provide information on anemometer exposure and station environment need to be compiled into a single publication. The publication would aid the user in evaluating the representativeness of the station's wind data.

Obtaining more detailed station information: Standard forms which provide detailed information on anemometer location and station environment should be distributed and filled out by all stations taking wind observations. Information on these forms should include: method of observation, anemometer height and location, description of station's immediate environment (e.g., direction and distance of buildings, trees, etc.) and description of local terrain and influences on wind. A drawing or photograph of the environment around the wind instrument and a topographic map depicting the site's location would be valuable. If the anemometer is located on a structure, a description of the height of the instrument above the rooftop, location on the rooftop and height and width of the structure, and a drawing or photograph of the structure and instrument location should be provided.

Obtaining more reliable and representative wind data: Current anemometer locations, maintenance of the sensors and methods of observing the winds should be evaluated for each station. This information should be reviewed and recommendations made for obtaining more reliable and representative wind data at each station.

Digitizing of surface weather observations: Stations for which wind data are digitized by NCC need to be reviewed to evaluate how much of this data is useful and to recommend additional stations for which the records should be digitized. For example, some very good data taken in data-sparse areas are not digitized; whereas, in some areas with numerous stations there may be several nearby stations for which the data are digitized.

Digitizing RAMOS and AMOS data in TD 1440 format: RAMOS and AMOS data is often located in data-sparse areas. However, this data is not summarized and is not conveniently available to be summarized and evaluated. Could this data be digitized in the same format as the surface weather observations in TD 1440 tape format?

Obtaining wind profiles from airport sites: Since airport data is evidently used for numerous applications and is usually adjusted to different heights, we need more information on the height variation of wind speed and direction at airports. Tower data from locations such as power plant sites, are usually not applicable to airport sites. Mean wind speeds are significantly higher at airports because of lower surface roughness in the direction of the prevailing winds. Long-term wind measurements at heights up to 50 m should be taken at several airport sites located in a variety of different geographical environments in order to evaluate the wind profiles.

Including scalar mean speeds on upper air summaries: Upper air wind summaries (WBAN 33) should also include mean scalar wind speeds in addition to mean resultant speeds.

* * *

Question by Kishor Mehta: What is approximately the response time or response distance of the standard three-cup anemometer currently in use?

Answer by Thomas Lockhart: The most common anemometer in current use by the National Weather Service (NWS) is designated as F420C. It is the three-cup anemometer, a splayed-tail wind vane set commonly seen along runways at airports. The specification for this instrument contains no requirement for response distance but H. H. Crouser, 1967 (Notes on wind measurement, ESSA Tech. Memo WBTM-EDL-2) reports the distance constant to be 8 m (26.2 feet). This represents a (1-1/e) recovery from a step-function change in a wind tunnel environment. At wind speeds of 40 m/s (89 mph or 131 fps) the response distance can be expressed as a response time of 0.2 s. Such performance is adequate for the proposed 2 s peak wind speed at speeds above about 12 m/s.

Data on response distance of the old four-cup or the newer three-cup "S" type anemometer used for fastest mile recording is not readily available. Since response distance is a function of mass and size it is likely that these anemometers have a much larger response distance than the F420C.

*   *   *

Hugh Church

The coming National Weather Service AFOS system should be able to integrate and calculate winds for any specified interval. We should make our recommendations to that system now.

It is desirable to obtain proper averages of wind speed and direction. In order to obtain these quantities averaged over a period of time, it is necessary to convert the instantaneous values into two vector components and average these components. Robert Akins (1978) has provided an excellent discussion and methodology to accomplish this.

Akins, Robert E. (1978), Wind Characteristics at the Vawt Test Facility, Sandia Laboratories Energy Report, SAND78-0760, September 1978.

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SESSION III

CLIMATIC MODELLING AND WIND DATA ANALYSIS

Chairman: David Surry
Rapporteur: Phil Landers

SESSION III: CLIMATIC MODELLING AND WIND DATA ANALYSIS

SUMMARY

David Surry
Phil Landers

The papers presented in this session reviewed present capabilities for analysing and modelling the wind climate with emphasis on defining outstanding shortcomings, particularly in terms of wind data requirements. Attention was directed towards strong wind events. Several important areas were brought forward for discussion, many echoing those delineated in earlier sessions. These included the advantages of the gradient-level wind approach, the importance of wind direction, the need for careful analysis of mixed wind climates, and the special problems associated with relatively local severe storms such as tropical cyclones, tornadoes and thunderstorms.

Considerable discussion centred around extrapolation of predicted wind speeds to very long return periods, i.e. very small risk levels. This was stimulated by Simiu's Monte Carlo results which indicate a plateau in the predicted wind speeds for very long return periods. It was suggested that this phenomenon may well be a property of the particular approach utilized and that, although some physical limit on wind speed must exist, this limit seems well beyond those speeds of practical interest. Nevertheless, extrapolation of data to long return periods must be done with care, as Vickery's mixed climate examples illustrated, and an error band should be estimated together with extrapolations.

Some discussion followed up the suggested need for more frequent measurements of wind speed directly above the friction layer (at a height referred to by wind engineers as "gradient" height"), say at about 500 meters. Such measurements not only can characterize the wind climate over large areas but also can be used to "calibrate" surface measurement stations. For example, over a relatively short term, correlation of surface and gradient speeds (the latter taken using portable equipment, perhaps) could define the gradient/surface wind speed ratio as a function of direction for strong winds, allowing better interpretation of historical surface data to account for local-surface-induced biases. Acoustic Doppler systems were suggested as possible candidates for such gradient height measurements, offering about 1 meter per second accuracy at 500 meters (an off-the-cuff estimate). Meteorological towers, such as described in Gaynor's paper, offer the capability of checking the technique, as well as providing basic information on wind structure.

The importance of wind direction was also discussed in detail. While some use is made of this information for particular design studies, more effort is required to determine how best to introduce it into codes. At the moment codes specify wind speeds independent of direction and hence penalize structures whose aerodynamic characteristics are directionally sensitive.

The problems of collecting data to characterize severe storms of relatively small size were discussed. Measurements made at hourly intervals can miss some severe short duration events. Thus continuous data monitoring is needed. Time of day also needs to be maintained with the wind data measurements so that diurnal effects can be identified. The problems of identifying the type of storm leading to a high wind event were also discussed. This is difficult for historical records and should be recognized when designing future data collection systems.

The importance of wind profile measurements in severe storms was also discussed. This relates to the appropriateness of conventional power or logarithmic laws used in code models and wind tunnel simulations when velocity profiles in such storms may deviate appreciably from these. There is a need for improved wind profile measurements in all local severe storms including hurricanes, thunderstorms and line squalls, and tornadoes.

In discussion following the contributions on tornadoes, a number of requirements for furthur research were identified, including 1) improved wind speed determination, 2) direct measurement of tornadic core pressures using minimum pressure sensors, 3) improved correlation between damage and wind speed and 4) better tornado warning systems.

Several general requirements were also identified for data collection. These included a general call for the return of the state climatologist to oversee equipment replacement and related data quality control duties (including review and improvement of anemometer system designs so that they will not be destroyed during strong wind events); a need to upgrade historical data records for improved risk assessment; and a detailed cost/benefit analysis of the suggested improvements in the wind data collection network.

Many of the points made above are echos of requirements cited in previous sessions and were reiterated again in the final session which led to the final recommendations adopted by the workshop.

MODELLING THE WIND CLIMATE: An 'Over' View

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ABSTRACT

Current approaches to predicting wind climate for wind engineering purposes are briefly reviewed. Attention is drawn to the wind climate and wind structure as being major sources of uncertainty in the determination of response to wind. For well-behaved wind climates, parent distributions of wind speeds are suggested as important resources for wind climate definition, both for problems primarily concerned with common events and as alternative routes to extreme values. The advantages of determining such parent distributions at gradient height just outside the boundary layer are discussed in terms of reduced variability and improved description of wind directionality. The importance of this latter aspect is discussed in detail. The climatology of non well-behaved storms, such as tropical cyclones, tornadoes and thunderstorms, is discussed briefly in order to direct attention towards areas requiring further effort. Recommendations for improvements in the basic wind data on which all modelling depends are also made.

INTRODUCTION

The problem of modelling the wind climate is inherently entangled with the eventual application of the model and with the data base on which it is built. In some cases this results in special approaches to special problems: such as for the hurricane and the tornado, to which we shall return later. There is, however, a large geographical area over which the winds are relatively 'well-behaved'. The majority of this paper will deal with such situations. A few preliminary general comments can be made.

First, it is usually worthwhile to carefully distinguish between wind climate and wind structure, although their separation is not always distinct and can be made in differing ways. By "wind climate" we normally mean those characteristics of the wind determined over many years by the general weather patterns, as distinct from those wind characteristics dependent on the local environment. It has been reasonably established that for sites in homogeneous terrain, wind fluctuations having periods of less than twenty minutes or so are associated with mechanically or convectively generated turbulence and hence are part of the wind structure, whereas longer period wind fluctuations are associated with mesometeorological processes. This appears to be a reasonable distinction between climate and structure; however, difficulties arise in ascribing to one or the other the mean characteristics inherent in the wind due to nonhomogeneous local effects, for instance differing surface roughnesses or topographical effects such as hills or valleys. Here, such characteristics will be considered as components of wind structure, which is consistent with a broader view of wind climate to be discussed later. Regardless of terminology, such local effects exist and there is often good reason to clearly separate them as suggested. We will return to this point again.

A second general comment is that almost all models of the wind *climate*, within the foreseeable state-of-the-art, are likely to be statistical. As is evident by most of the contributions to this session, attention is often focussed on predicting extreme wind speeds; partly because they constitute critical design cases and partly because they often represent the most difficult climatic statistic to predict. Such extremes are associated with the definition of overall strength, durability and risk-of-failure of structures. On the other hand, the parent distributions for the wind climate should not be neglected. Not only are they important in determining serviceability of buildings (acceleration levels, pedestrian-level wind speeds etc.), but also they are of critical importance to the definition of wind energy potential. These areas of interest are essentially sensitive to the common event rather than the rare one. Furthermore, the parent distribution provides an alternative route to the extreme values which can be beneficial both as a verification procedure, and as a means of providing more rational approaches to some problems than can be offered by the exclusive use of extreme wind speeds; an example to be discussed later is the inclusion of the effects of wind direction.

A third general comment is that the definition of wind climate is only one part of any design process. Each part has elements of inaccuracy and uncertainty. The definitions of wind climate and structure often represent the largest sources of uncertainty. The chosen *model* of the climate represents only part of that uncertainty and may well be overshadowed by the lack of reliability of the source data itself. Thus it is always worthwhile to keep in mind the overall process for which the model is intended. As an example, it is instructive to look at the wind loading process, which has been conceived (1) as a chain of interconnected components, as shown in Figure 1a. This analogy is a useful reminder that the adequacy of the entire design process is, like the chain, determined by the adequacy of the weakest link. There is little point in embellishing one of the links at the expense of the others.

This wind loading chain can be adapted to the prediction of a variety of responses ranging from those causing serious damage to those associated with unserviceability. It is interesting to note that these actions must be assessed in terms of adequate criteria; a mismatch could be unfortunate. These criteria (breaking strength, deflection limitations, sensitivity to motion) also can often only be expressed conveniently in statistical terms, reflecting our uncertainities. Convolutions of the statistics of these criteria with the statistics of the responses due to wind determine the safety and reliability achieved.

FIG. 1a THE WIND LOADING CHAIN

FIG. 1b THE WIND ENERGY CHAIN

Several studies (2,3,4,5), some in embryonic form, have indicated that it appears to be the variability in the definition of the wind *climate* that dominates the reliability of the wind loading chain. An example illustrates this:

The wind load W is defined by the Canadian Code as $W = q\,C_e\,C_g\,C_p$, where q is a reference wind pressure, C_e is an exposure factor to adjust for height and terrain type, C_g is a gust factor and C_p is a pressure coefficient. q essentially represents the climatic component, while C_e and to some extent C_g represent wind structure. The total variance associated with the determination of the load W is approximately given by:

$$V_w^2 = V_q^2 + V_{C_e}^2 + V_{C_p}^2 + V_{C_g}^2$$

Crude estimates of these variabilities have been made and are displayed in the table below for loads determined by code approaches and wind tunnel tests.

Type of Climate	V_q	V_{C_e}	V_{C_p}	V_{C_g}	V_w
		Code Design			
Hurricane	.35				.44
		.20	.15	.10	
Extratropical	.25				.37
		Wind Tunnel			
Hurricane	.35				.36
		.05	.05	.05	
Extratropical	.25				.26

This illustrates the dominant role of the climatic component, V_q, in determining the final variability of the design load.

As indicated,the wind structure is another large source of variability for many problems, only some of which can be resolved by wind tunnel techniques (6,7,8). Some of these problems of wind structure bear closely on the problems of climate. Examples for which a reliable description of the mean wind structure is a prerequisite are: transferring a well-defined climate at one specific locality, say at an airport, to another location – perhaps a hill crest for wind energy purposes, or a downtown site for structural purposes; reduction of the variability associated with model studies and code requirements; and the unification of data bases from different sources in order to increase reliability of overall predictions.

Before leaving the chain concept it is worth noting that it can easily be adapted to other design processes as well. For example, Fig. 1b illustrates the analogue for the production of available wind energy. Others may wish to comment on the relative predictability of the links of this chain.

From the basis of these preliminaries then, there are many standpoints from which to present an overview. The 'over' view of this paper is 'over the boundary layer' – a view generally characterized by its freedom from minor disturbances far below. The objective is to point out the advantages of the definition of wind climate models defined just outside the boundary layer at so-called gradient height. Such models offer the potential of reducing the uncertainty in the modelled wind climate and enable more reliable wind direction information to be included. Inclusion of wind direction statistics can be an important component of rational design, as we shall discuss later. Generally, such a gradient height approach tends to put more emphasis on definition of the parent process, from which both common events and extremes may be predicted, in contrast to direct determination of extreme value distributions. There is no suggestion, however that this should be an exclusive approach. In estimating wind climate, it is best to utilize all the tools at one's disposal.

The remainder of this paper presents some examples of such a gradient level approach and illustrates the potential importance of including wind direction in the description.

1.0 WIND CLIMATE PREDICTIONS AT GRADIENT HEIGHT

This approach to the definition of wind climate allows us to avoid at least two somewhat spurious effects. The first is the influence of terrain roughness, which may be highly irregular and locally varying; the second is the incursion of turbulent fluctuations which are secondary to the main features of the flow. The gradient level model (typically taken at about 500m) essentially removes these elements into the domain of wind structure. Inherent in such a model is the smoothing associated with the physical reality that the upper level wind climate must be a slowly-varying function of geographic location. It is also a convenient circumstance for model testing that gradient winds correspond to the free stream speed above the wind tunnel's boundary layer.

The correspondence of gradient winds with the free stream wind tunnel speed has further significance in that it bears directly on the concept of the gradient wind itself. In the context of this work, the gradient speed is that speed which would be realized under the action of the atmospheric pressure gradients if the surface friction were not present. Gradient height is primarily a parameter which arises from fitting the variation of the ratio of the mean speed in the friction or boundary layer to the gradient speed. As in the wind tunnel, it is only one of a number of measures of boundary layer depth. The fact that it is a consistent and useful concept has been well borne out; however, Figure 2 from references 9 and 12 is a reminder of its widespread applicability for strong winds. Figure 2 includes some of the original data used in establishing graph B. In spite of the city anemometer being in all cases higher than that at the airport, the wind speed is lower.

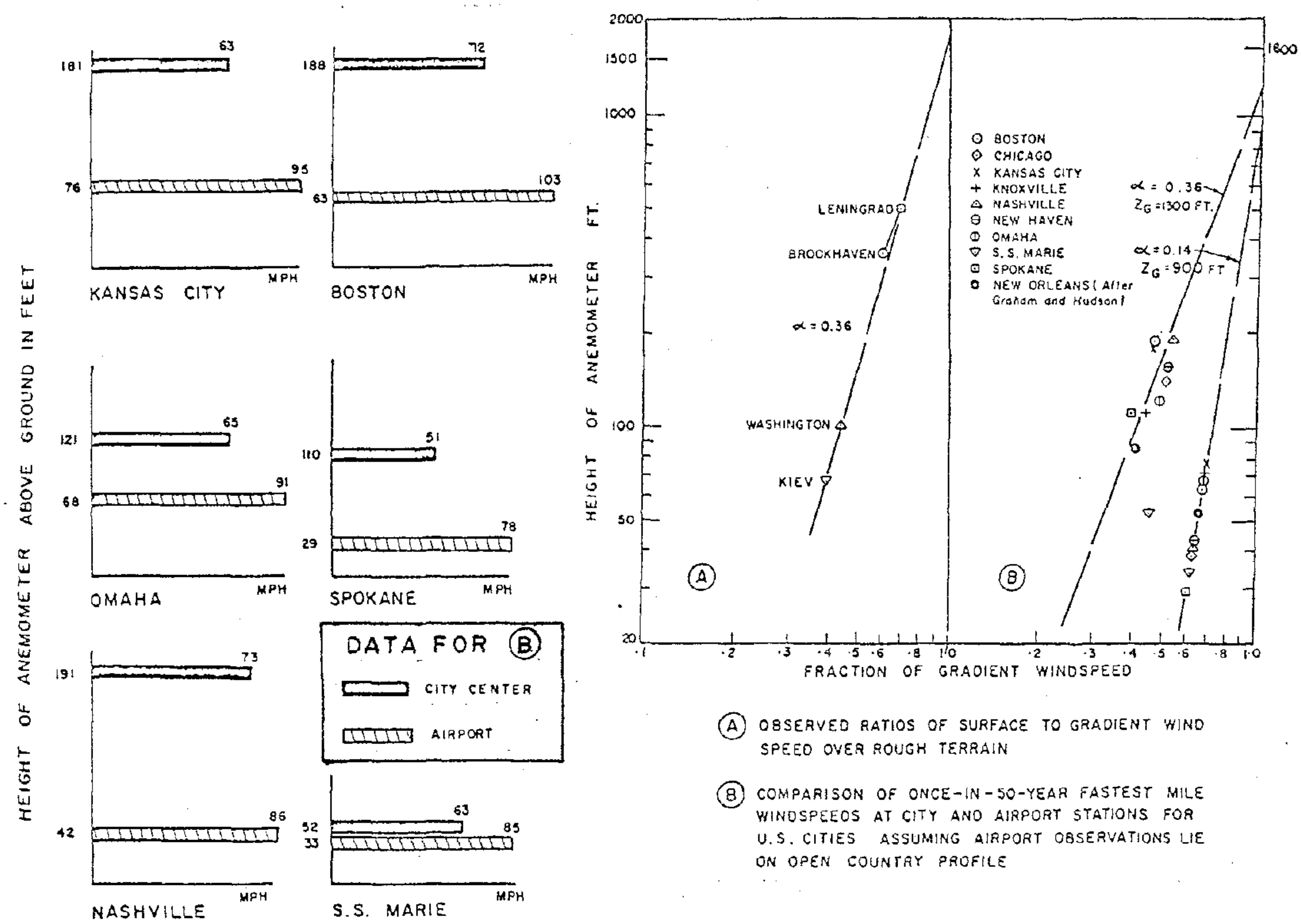


FIG. 2 COMPARISON OF SURFACE AND GRADIENT MEAN WINDSPEED

1.1 Predictions of Wind Speeds at the Surface and at Upper Level

As we have noted, the prediction of wind speeds is the cornerstone of any prediction of response to wind. It is an area where battles can easily be won or lost. Historically, predictions of extremes have relied on long term surface anemometer records. The records are analyzed statistically using extreme value analysis to predict speeds with certain recurrence intervals such as 50 or 100 years. These speeds then form the basis for design.

This extreme wind speed distribution is generally described by the Type I extreme value distribution.

$$P_v(V) = 1 - e^{-e^{-a(V-U)}}$$

which expresses the probability that a velocity V will be exceeded. U and $1/a$ are the mode and dispersion of the distribution with units of wind speed. The speed corresponding to a return period of r (years) can be written:

$$V(r) = U - \frac{1}{a} \ln[-\ln(P)]$$

$$\approx U + \frac{1}{a} \ln r$$

Values of U and $1/a$ are derived from fitting available data.

In contrast to most countries, the practice in the United States has been to follow the alternate Type II distribution. A recent study by Simiu and Filliben (10) has however concluded that the Type I distribution is in fact more appropriate.

This approach, straightforward as it may seem, presents a number of difficulties if not idiosyncrasies. First,the standard wind speed measure varies widely from country to country and even from time to time. In the U.S.,the "fastest mile of wind" has been a long standing reference speed; in Canada the reference has been the mean hourly speed (the average wind speed during an hour) and latterly the hourly mean speed (the average wind speed during a minute or two taken every hour); in the U.K. it has been the mean hourly speed and the fastest gust speed recorded by the Dines pressure tube. The previously-mentioned argument separating wind climate and structure leads to the suggestion of a 10 to 15 minute average as optimum.

All of these measures of wind speed differ by significant factors, which have to be allowed for. There are other factors which make the use of surface anemometers awkward. Often during their life they have been moved both horizontally and vertically, often with inadequate documentation as to their type,or to the location of nearby aerodynamic influences, or to the adequacy of their calibrations. Furthermore, the character of the terrain surrounding the anemometer has often been modified by urban sprawl or city growth. All these factors affect the exposure and apparent windiness of the site. These effects are difficult to correct for. Their presence leads to additional apparent variability in the wind climate and to exaggerated predictions of extreme speeds. These problems are further compounded by the difficulty of correcting for surface roughness effects when it is required to translate these wind speeds to other neighbouring localities.

Gradient wind speeds avoid some of these problems. These winds are by definition only weakly affected by surface roughness and topography and should be broadly consistent over large stretches of country. For taller structures these wind speeds are also more relevant. This suggestion, when initially put forward by Davenport (11) used extreme annual surface winds to predict extreme annual gradient wind speeds over the United Kingdom as shown in Figure 3a. To do this required an evaluation of the surface roughness at the anemometer sites and extrapolation using profiles of the mean wind speed appropriate to the roughness of the anemometer stations.

More recently it has become apparent that this technique can be supplemented using direct measurements of upper level wind speed (12,13). These are recorded several times daily by observation of pibal or rawinsonde balloons at major airports and observing stations. Unfortunately it is difficult to estimate extremes from such data directly. Recently,Caton (14) published the 1% quantile of gradient wind over the U.K. at 900 m. from the distributions of balloon wind speeds. These are shown in Figure 3b.

It is apparent that the patterns of the two wind speed statistics – the mode of the annual extreme and the 1% quantile – in Figures 3a and 3b are similar. In fact, there is a connection between them which has been demonstrated by Davenport (1). In order to do so, it is first necessary to determine a suitable form of the statistical distribution of wind speed.

There are, in fact, good reasons (12) for believing that the distribution of wind speeds tends towards a Rayleigh distribution with the cumulative distribution function (probability of exceeding speed V)

$$P_v\ (> V) = e - V^2/2\sigma^2$$

in which σ is a parameter of the distribution. The degree of adherence to this form can be judged from Figures 4a and 4b in which distributions of mean wind speed over several minutes from two very tall towers (15) are plotted and compared with the Rayleigh form. Davenport then demonstrates that the mode $U \simeq 4.1\,\sigma \simeq 1.37\ V_{.01}$ and $1/a \approx 0.26\,\sigma \simeq 0.62\ U$.

The resulting numerical values have been added to Figure 3b. The dispersion is somewhat less than the value $1/a = 0.1\ U$ suggested in Figure 3a. Since the latter is based on the variability of surface winds, this is not surprising.

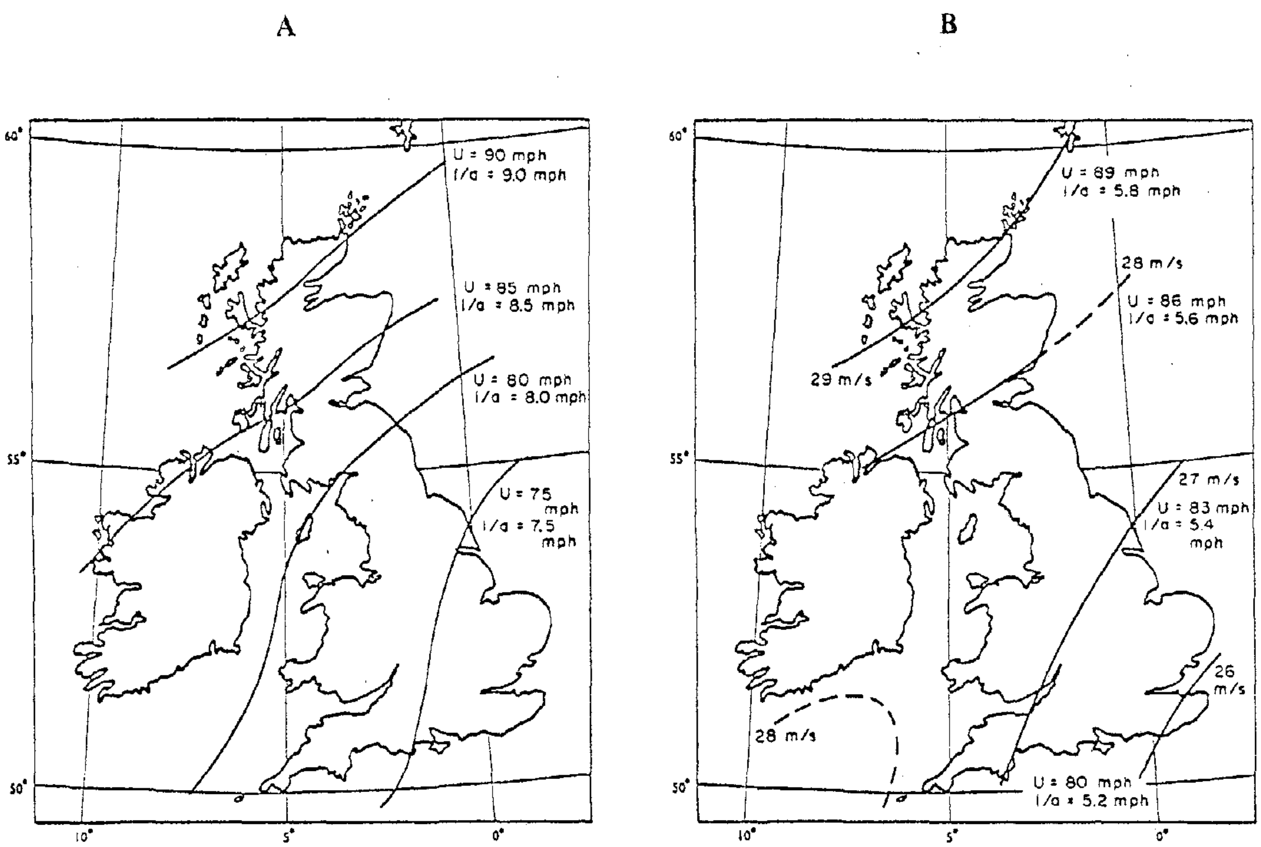


FIG. 3 COMPARISON OF EXTREME ANNUAL GRADIENT WIND SPEEDS OVER THE UNITED KINGDOM PREDICTED A) FROM EXTRAPOLATION OF SURFACE OBSERVATIONS AND B) FROM 1% CONTOURS AT 900 m

The purpose of this exercise is to demonstrate that there may be solid grounds for developing the design wind speeds on the basis of upper level winds, using the resources of both surface and upper level observations. A study of this kind was made by Davenport and Baynes (16) to map gradient winds in Canada and the northern United States. Values of σ from this study are shown in Figure 5. The values of U and $1/a$ can be assessed from the equations given above. More detailed relationships between parent and extreme value distributions can be found in references 17 and 18.

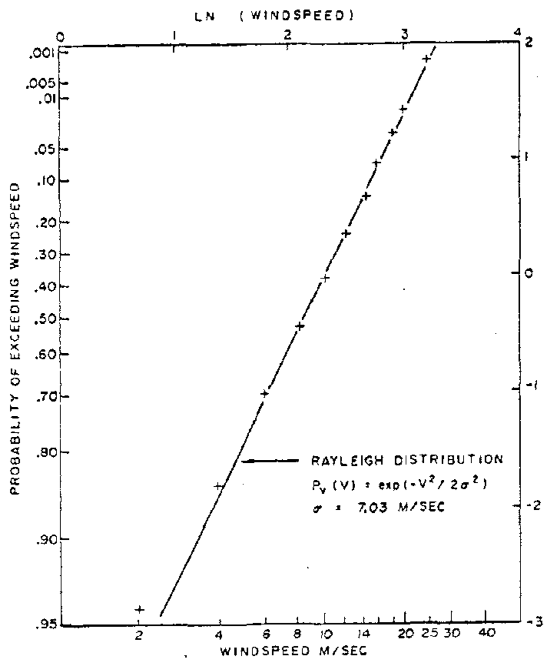


FIG. 4a Eiffel Tower at 305 m (1890–1895)

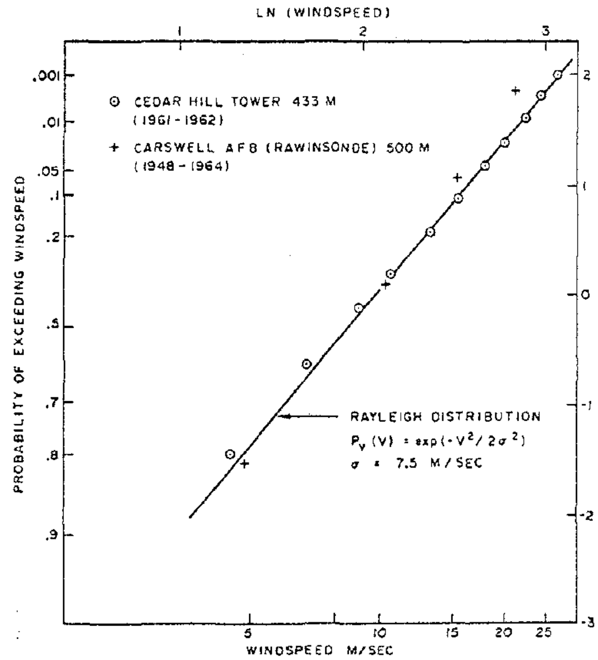


FIG. 4b Cedar Hill Tower, Texas

FIG. 4 OBSERVATIONS OF THE MEAN WIND SPEED DISTRIBUTION FOR TWO TOWERS SHOWING COMPARISONS WITH THE RAYLEIGH DISTRIBUTION

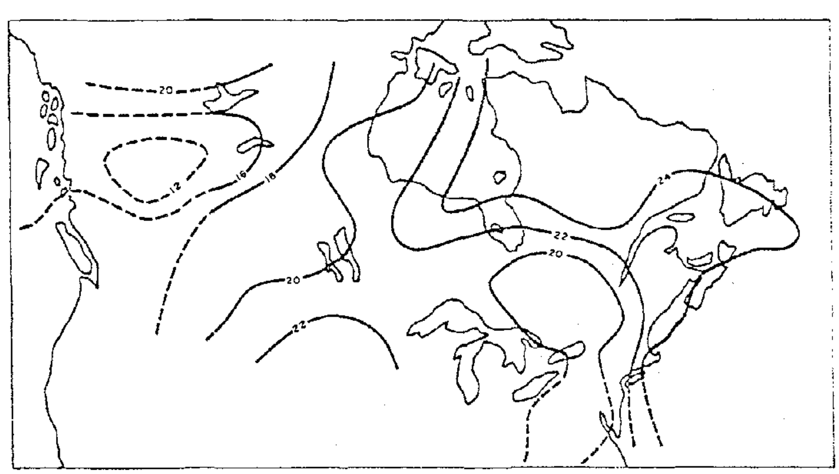


FIG. 5 CONTOURS OF STANDARD VECTOR DEVIATION OF WIND SPEED, σ AT 500 m, OVER CANADA. For Extreme Annual Gradient Wind Speeds $U \approx 4.1\ \sigma$; $1/a \approx 0.26\ \sigma$ (Units mph)

1.2 The Influence of Wind Direction

The importance of the inclusion of wind direction in the modelling of wind climate can be seen from reviewing some typical types of responses taken from the structural loading domain. Two examples of model test results are illustrated in Figs. 6 and 7 representing respectively the variation in response with azimuth of the peak suctions measured at a point on a structure, and the torsional response of a suspension bridge. Both are shown in conjunction with their respective aerodynamic response boundaries where the wind speed (at gradient level), and not the response, is the dependent variable. These are found by asking the question, "What wind speed is required from a given azimuth, a, to produce a certain response R?" This wind speed is denoted $V_R(a)$. These response boundaries are found by inverting the aerodynamic data mapped for wind speed and direction.

If for example we refer to the peak pressures of Fig. 6, then

$$V_{\check{p}}(a) = \sqrt{2\check{p}/[\rho\, C_{\check{p}}(a)]}$$

The response contour corresponding to the suctions at this tap location is shown in Fig. 6a for the value of $p = 30$ psf. This shows that for the critical east wind, the wind speed required is comparatively low.

A similar contour diagram has been drawn in Fig. 7b for the suspension bridge response. This shows the penetration of the contours into low wind speed regions near the critical perpendicular directions. Similar response contours can be drawn for aeroelastic responses of buildings. These can often be simplified by the use of power law dependencies such as

$$\hat{R} = D(a)\, V^{n(a)}$$

$$V_R(a) = [\hat{R}/D(a)]^{1/n(a)}$$

where the important point to note is that, unlike pressures for which $n(a) = 2$, in many cases of aeroelastic response, $n(a)$ is often in the range 2.5 to 3.5 and sometimes greater.

It is clear from the above that the basic problem in predicting the likelihood of occurrence of any given response is to predict the likelihood of the wind speed crossing the boundary defined by the response contour. These boundaries, as we have seen, can vary greatly with wind direction and in instances of severe dynamic response can be closely packed.

To attack this problem with any degree of completeness, the description of the wind must be more sophisticated than simply being the extreme speeds in a given time interval. Such wind speeds may not occur from a critical direction and may pass by harmlessly.

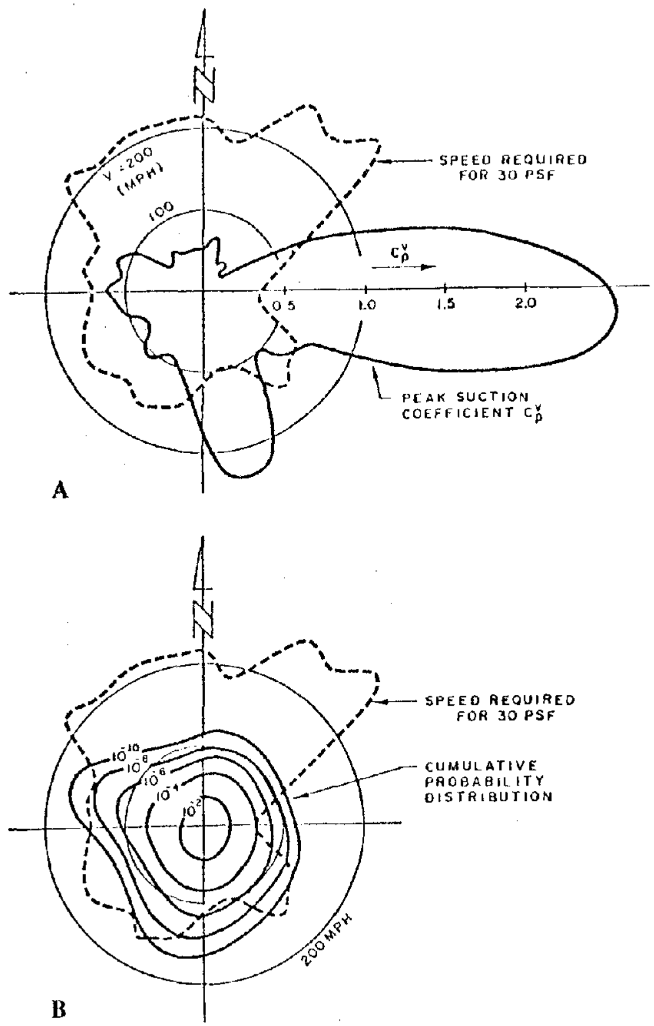


FIG. 6 SYNTHESIS OF AERODYNAMIC RESPONSE WITH WIND STATISTICS:

A SPEEDS REQUIRED TO EXCEED A SELECTED PRESSURE;

B PROBABILITIES OF EXCEEDING THESE SPEEDS

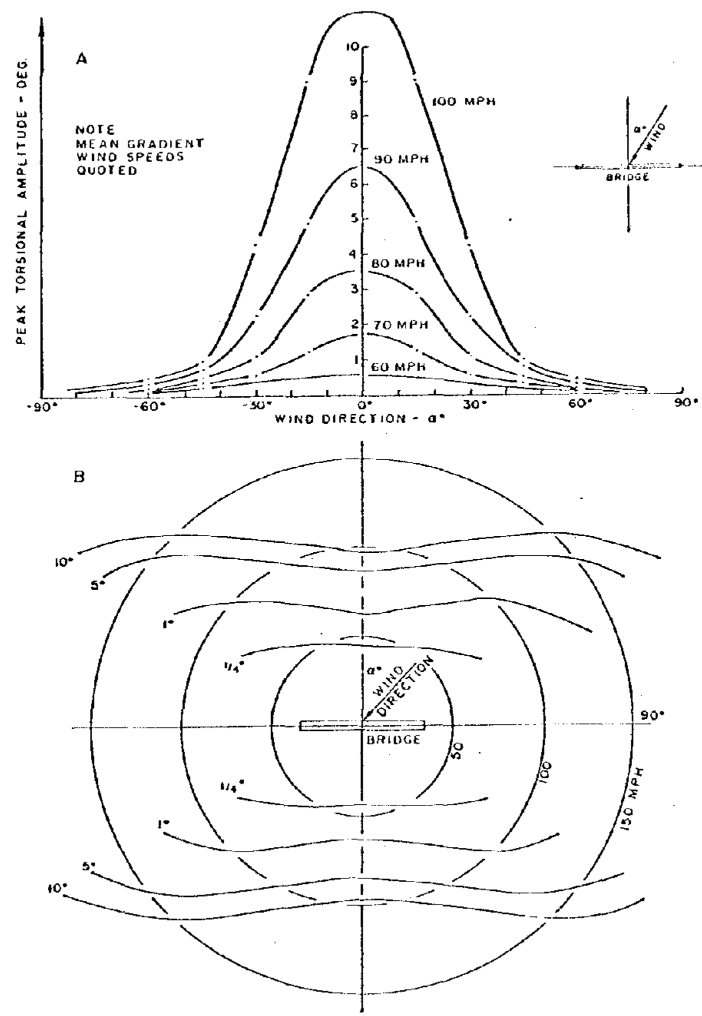


FIG. 7 A. VARIATION OF PEAK TORSIONAL RESPONSE AMPLITUDE OF SUSPENSION BRIDGE WITH WIND DIRECTION

B. DEVELOPMENT OF RESPONSE BOUNDARIES

The basic requirement for describing the wind climate then becomes the probability distribution of wind speed and direction, preferrably at gradient height. This relies on meteorological observations of all winds and is not confined to the extremes. A typical plot of such a distribution is shown in Fig. 7b, discounting for the moment the dashed line representing the 30 psf response boundary. In this plot, radial distances indicate wind speeds in mph. Each contour represents those speeds which, on average, are equalled or exceeded for a specified fraction of time within a 22.5^{o} sector of a chosen azimuth angle. Such a plot is obtained by fitting mathematical expressions to the data and extracting the contours.

Generally speaking, these distributions display directional characteristics belonging mostly to the prevailing winds. (Some of the directional effects, however, may be spurious; i.e. due to sampling and extrapolation). These directional factors clearly have a significance in relation to the directionally sensitive responses discussed above.

Directional effects may become even more pronounced when related to surface conditions. This is illustrated in Fig. 8. The upper diagram refers to the amplification of wind speed over water at the site of a long bridge (relative to that in fairly homogeneous terrain). The lower diagram shows the reduction in wind speed on the coast due to the screening by the buildings in a large city. Both of these imply that surface wind speeds and directions can be profoundly affected in certain situations by the roughness. Again these must play a part in the directional response to wind. Conversely, these diagrams also indicate the potentiality for bias due to surface roughness inherent within surface measurements. They are examples of variation in what has been defined as wind structure. These would be largely taken into account automatically within a wind tunnel test program by the analogue nature of the wind modelling.

Having established the probability distribution of wind speed and direction, it is now possible to relate this to the response. Consider the relationship between the probability distribution and the 30 psf pressure contour of Fig. 6b. Denoting the cumulative wind speed and direction distribution by $P_{V,\,a}(V, a)$ and the response boundary by $V_R(a)$, then the probability that R (= 30 psf) is exceeded is

$$P_R(R) = \int_0^{2\pi} P_{V,\,a}(V_R, a)\, da$$

i.e. the integral on the contour.

This defines the total fraction of time that R is exceeded. It does not, however, indicate how often this happens, whether for a single long period or many short periods. For this, we must examine the crossing rate of the response contour.

The one dimensional crossing rate has been discussed by Rice (19). The extension to the two-dimensional situation is shown conceptually in Fig. 9. Fig. 9 depicts a process (in this case the wind vector) which moves randomly in x and y. The possibility that the process crosses a typical element of the boundary in an outward direction has been considered in detail by Davenport (15). The result is that the average rate of crossing, $N(R)$, of the boundary R (denoted here as $V_R(a)$) can be determined in terms of the joint probability *density* function $p_{V,\,a}(V_R, a)$ as:

$$N(R) = \sqrt{2\pi}\,\nu\,\sigma \int_0^{2\pi} \sqrt{1 + \left(\frac{1}{V_R}\frac{dV_R}{da}\right)^2}\; p_{V,\,a}(V_R, a)\, da$$

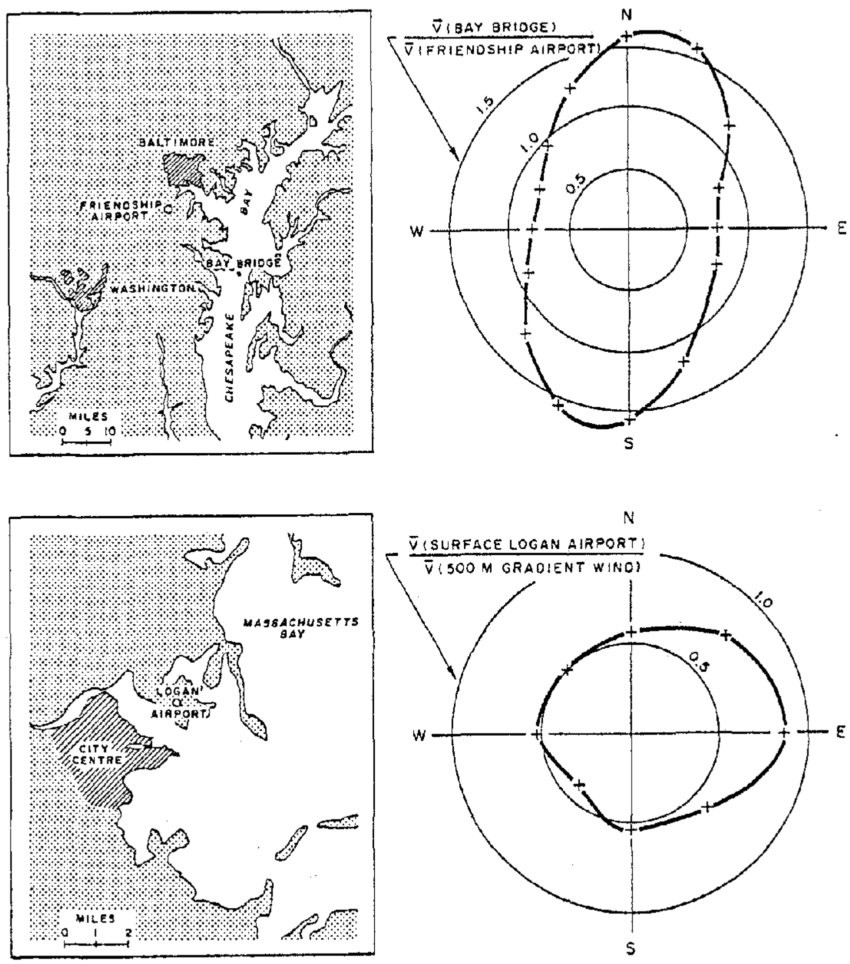


FIG. 8 INFLUENCE OF TERRAIN ROUGHNESS ON SURFACE WIND SPEEDS AND DIRECTION

In this expression ν is the mean cycling rate of the process. This latter term can be evaluated from the spectrum of the wind velocity. For several sites the value of ν turns out to be of the order of 1–2 cycles per day.

If these crossings of the boundary are rare, independent events, their distribution will be Poisson and the cumulative probability distribution of the largest value of R in time T is

$$P_{\hat{R}}(R) = 1 - e^{-N(R)\,T}$$

From results such as those portrayed in Figs. 6 and 7, the distribution of the extreme responses can now be determined from the previous equations, if necessary numerically.

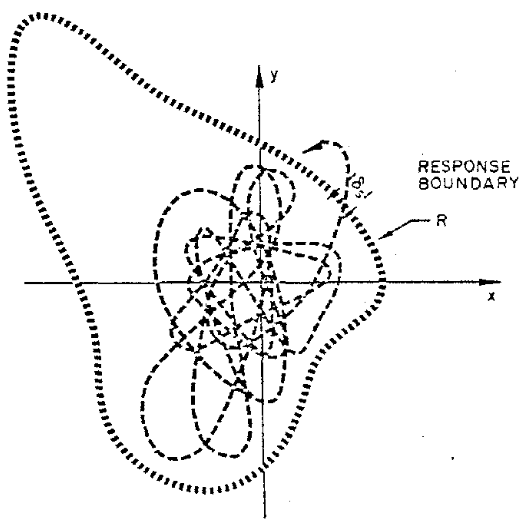


FIG. 9 THE INTERCEPTION OF A RESPONSE BOUNDARY

The directional effect embodied in this approach can have an appreciable effect on the final result. If the critical direction of response coincides with the prevailing direction of the wind, the extreme prediction will differ significantly from situations in which it does not.

The above clearly provides a workable approach to the prediction of directionally-sensitive response in particular design studies; it has been used more or less routinely in the Boundary Layer Wind Tunnel Laboratory. For more general applications, such as for codes, there are clearly differences which arise. In particular, even if the directional responses are generally understood the orientation of any building to the prevailing wind will not be known.

This is equivalent to saying that the orientation of the wind is offset by some unknown angle β. Assuming buildings will have no preferred orientation, then the expected rate of crossing of a boundary R for all such buildings is

$$E\{N(R)\} = \int_0^{2\pi} N(R/\beta)\, p_\beta(\beta)\, d\beta$$

where $p_\beta(\beta) = \dfrac{1}{2\pi}$

from which

$$E\{N(R)\} = (2\pi)^{-1/2}\, \nu\, \sigma \int_0^{2\pi} \sqrt{1 + \left(\frac{1}{V_R}\,\frac{d V_R}{d a}\right)^2}\; p_V(V_R)\; dx$$

This now expressly depends on the distribution of wind speed only, not wind speed and direction. This simplifies the problem in an interesting way and allows us to consider some idealized responses in order to determine the potential importance of the directional effect. Consider the responses shown in Fig. 10(i), which are assumed governed by the response relationship

$$R = 1/2\, \rho\, V^2\, C(\theta)$$

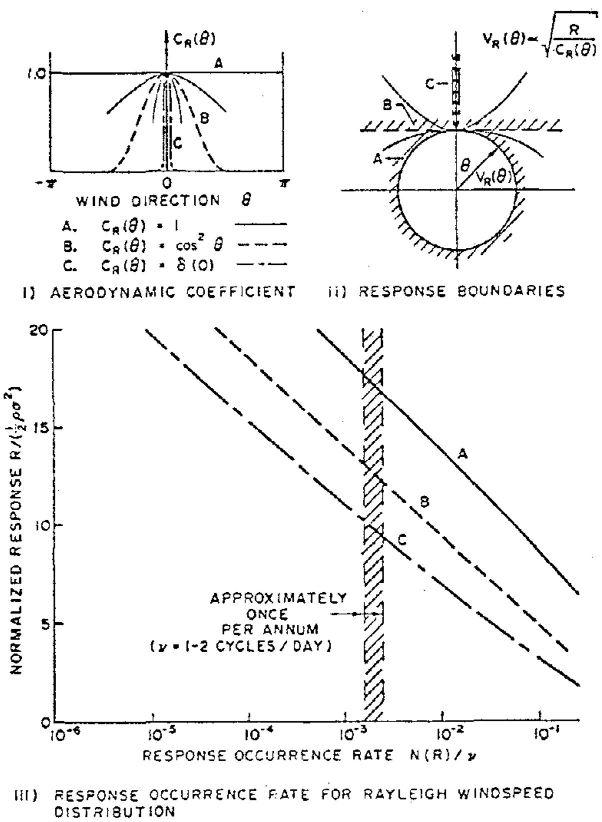


FIG. 10 DEVELOPMENT OF THE RATE OF OCCURRENCE OF RESPONSES FOR VARIOUS DIRECTIONALLY DEPENDENT RESPONSES

In this, $C(\theta)$ is the directional variation of the aerodynamic coefficient. For illustrative purposes three cases of $C(\theta)$ have been considered (15), corresponding to "1/2 power bandwidth" of infinity, $\pi/2$ and 0.

Case A.	$C(\theta)$	=	1	
Case B.	$C(\theta)$	=	$\cos^2\theta$	$-\frac{\pi}{2} < \theta < \frac{\pi}{2}$
		=	0	*elsewhere*
Case C.	$C(\theta)$	=	$\delta(\theta)$	*(Dirac delta function)*
				$C = 1$ *when* $\theta = 0$
				$= 0$ *elsewhere*

Case A corresponds to a completely homogeneous response such as the scalar deflection of a circular structure. It also corresponds to the assumption frequently followed in practice, i.e. that the worst response occurs no matter what the direction of the wind. This represents a 'norm' against which other responses can be compared. Case C is the other limiting case in which the response is extremely sensitive to direction and is simply a spike. Assumption B lies in between the two limiting cases A and C. It is a response corresponding to a simple cosine law. This law, for example, more or less describes the horizontal force on a transmission line cable in an oblique wind.

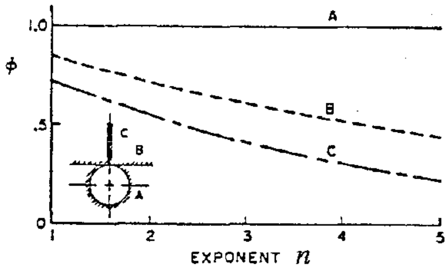
By introducing the previously established Rayleigh distribution, these responses enable the crossing rates to be evaluated in closed form in certain cases. (See reference 15). The results are shown in Fig. 10 (iii). What is important to note is that for a given crossing rate, or recurrence interval, the response amplitude is significantly reduced as the response bandwidth narrows. Davenport also shows that the directional effect primarily affects the mode of the extreme value distribution; the dispersion is constant.

Using case A as a norm, the ratio of the mode values in case B and case C to the mode in case A indicates what will be defined as the *wind direction reduction factor*, denoted Φ. Φ is 11.8/16.4 = 0.72 and 9.1/16.4 = 0.56 for cases B and C respectively. These reductions are obviously significant.

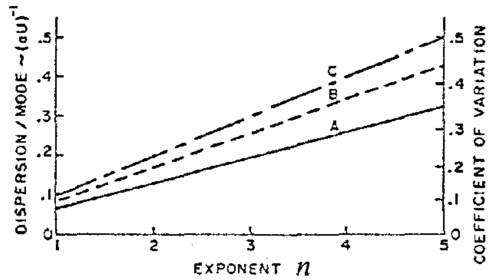
As pointed out earlier, the sensitivity of the response to wind speed also has a strong influence. To examine this, Davenport has considered the general form $R \propto V^n$. As previously pointed out, values of $n > 2$ are frequently characteristic of dynamic responses.

Using the same procedures as before, the wind direction reduction factors can be determined for various values of n. These are plotted in Fig. 11(i). It is seen that the wind direction reduction factors fall off progressively for the more sensitive responses.

This trend is accompanied by another trend in the variability (Fig. 11 (ii)). This is indicated by the dispersion to mode ratio $1/(a\,U)$; the latter is roughly equal to the coefficient of variation. It is evident that higher wind speed exponents (n) produce higher coefficients of variation, as well as more significant wind direction reduction factors.



I) WIND DIRECTION REDUCTION FACTOR ϕ
ϕ = (MODE CASE i ; i = A,B,C) / MODE CASE A



II) MEASURES OF VARIABILITY OF DISTRIBUTION OF ANNUAL EXTREMES

FIG. 11 DEPENDENCE OF THE PROPERTIES OF THE EXTREME DISTRIBUTIONS ON THE WIND SPEED EXPONENT (n) FOR THREE DIRECTIONALLY DEPENDENT RESPONSES

1.3 Applicability of Gradient Wind Models

The approach we have discussed above is most applicable to temperate latitudes in which the winds are dominated by the West to East migration of large scale pressure systems and the wind climates are comparatively well-behaved.

When such methods are used in a design process, the effects of small random errors in the measured response contours and in the description of the wind climate tend to be diminished because the predicted responses arise largely through procedures involving integrations. However, a sufficiently reliable description of the wind climate is at times difficult to obtain due to practical limitations of the data. The observation methods used by weather services were primarily designed for weather forecasting and, in some cases, to provide information for aircraft operations. Instrumentation and observation sites have been developed from these viewpoints and are subject to various difficulties such as those associated with site location and averaging times as mentioned previously. Also, routine reduction of the very large quantities of meteorological data to a useable format has been underway only for a few years since the advent of large computers. Thus the length of record that is easily accessible is usually relatively short. A criterion for acceptability of a wind climate model is that the data base includes a representative sampling from the type of storms likely to produce high winds at a site. Satisfaction of this criterion will depend on the length of record used and the nature of storm systems that frequent an area.

Within large regions of North America, the weather systems dominating the wind climate have a characteristic size of 500 miles–1,000 miles and a frequency of occurrence of the order of 75 per year, as indicated in Table 1. Using data based on radiosonde and pibal observations, which are taken either two or four times a day, depending on the station, a 30 year summary of data will include of the order of 22,000 observations. Of these, approximately 5,000 will have been taken during extratropical cyclones, i.e., during a large-scale storm likely to produce widespread strong winds. Thus for such a region, a 20-yr data base can be expected to include enough observations of storm winds for each of the 16 wind directions normally used to give a reliable description of the wind climate.

TABLE 1: APPROXIMATE REPRESENTATION OF VARIOUS STORM SYSTEMS WITHIN UPPER LEVEL OBSERVATIONS (Assumed Taken at 2 Observations/day–4 Observations/day)

Type of system	Characteristic size, in miles	Characteristic frequency per year	Approximate number of observations during passages—20 yr period	Average number of observations within each of 16 wind directions
Extratropical cyclone (low)	1,000	75	5,000	375
Convective storm (thunderstorm)	10	20	400	25
Severe tropical cyclone (hurricane)	300	0.6	50	3

Even in regions where local convective storms which are often imbedded in the larger scale systems contribute significantly to the wind climate, a 20-yr record can be expected to give at least some estimate of their extreme wind statistics, although this may be arguable in regions frequented by sudden thunderstorms and squall lines.

A positive comparison of extremes predicted near Dallas from annual surface data and from an upper level parent distribution is shown in Fig. 12 taken from reference 20. The upper level data were again derived from the Cedar Hill Tower of Figure 4b. The agreement is surprisingly good considering the short record length from the tower (2–3 years), although it has only been used here to predict overall speed. Its definition of directionality is not as good. The balloon data led to somewhat lower predicted speeds as can be inferred from Figure 4b. This is likely to be due to the inherent limitations of the balloons in sampling the higher wind speed components of the climate which suggests that biasing the parent fitting process to the lower speed data in some cases may be worthwhile. Nevertheless, the fundamental approach through the parent distribution at upper level seems to be in good agreement with the annual surface data, implying that both (or neither!) approaches are including the primary effects of intense local storms. Vickery discusses this subject further in another contribution to this workshop and in previous work (21).

However, some storm types are not amenable to this type of approach. Along the Gulf

Coast and the south-eastern coast of the United States, the highest wind speeds are due largely to tropical cyclones. Such storms are quite small in a meteorological sense, being of the order of several hundred miles in diameter, with a region of very high winds restricted to even smaller dimensions. Also for a particular geographic region, tropical cyclones are relatively rare events. For example, the coastline within about 160 miles either side of New Orleans is frequented by only about 30 tropical cyclones of hurricane intensity per century (22). Assuming that reliable radiosonde or pibal observations could be taken during such storms at normal frequencies (an assumption not valid for intense storms) there would be approximately 50 such observations during a 20-year period for a place such as New Orleans and even fewer for localities on the east coast. As indicated in Table 1, there would then be only a few observations per wind direction representative of such storms and these would be buried by the very large number of routine observations. There is the additional difficulty with sampling hurricane force winds in that instruments frequently fail and on occasion whole observing sites are completely destroyed by the passage of an intense storm. This need to separately identify the distribution of hurricane winds was recognized earlier by Thom (23) in his analysis of extreme surface wind in the United States and is the subject of further discussion by Simiu and Vickery in this session.

These difficulties lead to Monte Carlo approaches which utilize two complementary characteristics of the tropical cyclone; namely, its well-defined structure and the availability of more broadly-based statistics governing the major parameters of that structure.

Tentative steps along these lines have been taken in more or less parallel studies by Tryggvason, Surry and Davenport (24) who studied Gulf Coast and Atlantic hurricanes and by Gomes and Vickery (25) who studied Australian cyclones. Both of these owe their impetus to Russell (26) who suggested the use of Monte Carlo simulation of these storms with slightly different ingredients and objectives in mind.

The Monte Carlo computer technique aims to simulate a representative set of hurricanes which would be expected to affect a particular area over a time period of the order of thousands of years. The physical characteristics of the hurricanes – which determine their intensities and their particular paths relative to the site in question – are chosen randomly but are constrained to have the same statistics as hurricanes observed over a much larger geographic area. In this way more reliable statistics are used as the basis for the simulation, and the simulation in turn provides a large enough set of data at the particular site to form a reliable basis for that site's particular hurricane-induced wind climate. Details are provided in the aforementioned references.

In practice, the statistics required to form the basis of the simulation are those defining the strength of the storm – its central pressure and its radius to maximum winds – and those defining the path of the storm – its track angle relative to north, its distance of closest approach, and the storm's overall speed over the earth's surface. Each of these parameters can be well-defined statistically based on observations such as those compiled by the Hurricane Research Centre in Coral Gables, Florida. Within the computer simulation, a value of each of the parameters is chosen randomly but according to its long-term statistics. The resulting storm is then followed in the computer as it passes the vicinity of the site in question, and the resulting time history of wind speed and direction is recorded. Such time histories can be used in two ways: first, to define the probability distribution of both the speed and direction associated with hurricane-induced winds at the site, which can then be used to predict response as discussed previously; or second, the wind-tunnel derived aerodynamic characteristics can be incorporated within the simulation to develop directly time histories of structural response and their associated statistics.

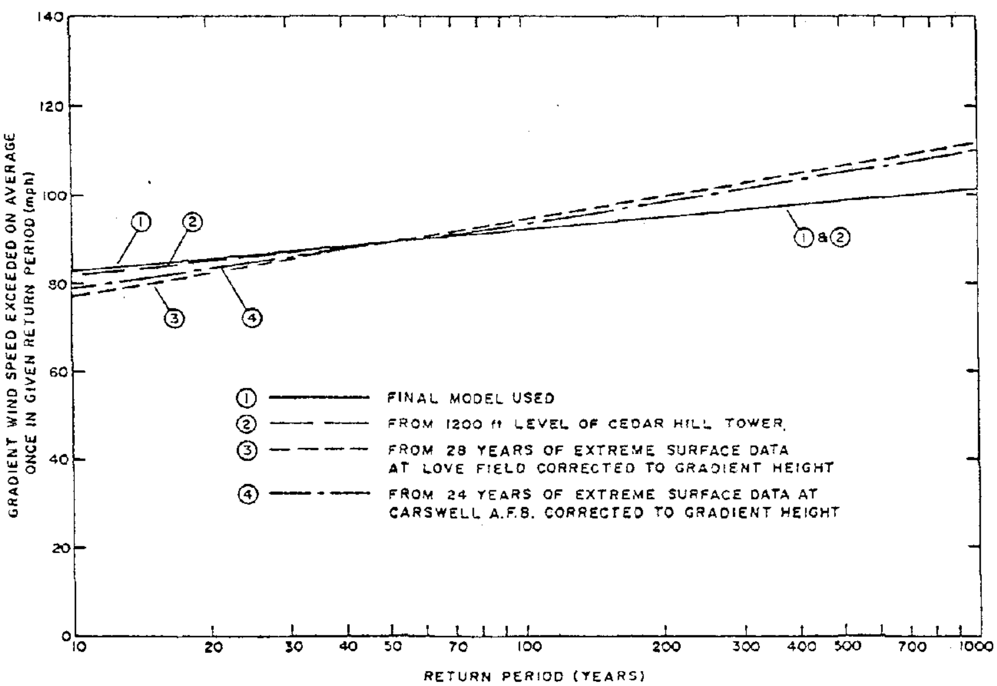


FIG. 12 PREDICTED GRADIENT WIND SPEEDS FOR SEVERAL DATA SETS NEAR DALLAS, TEXAS

The resulting extreme value distribution for hurricane winds at New Orleans is shown in Fig. 13. These are compared to the distribution of winds due to extratropical storms. In this case the recurrence interval has been taken as 50 years, thus representing the range of largest wind speeds likely to be encountered in a building lifetime. While the average values of the wind speed are comparable, the spread of the distribution of hurricane winds is much broader. This strongly indicates the need, effectively, for higher load factors on expected 50 year winds to deal with extreme occurrences.

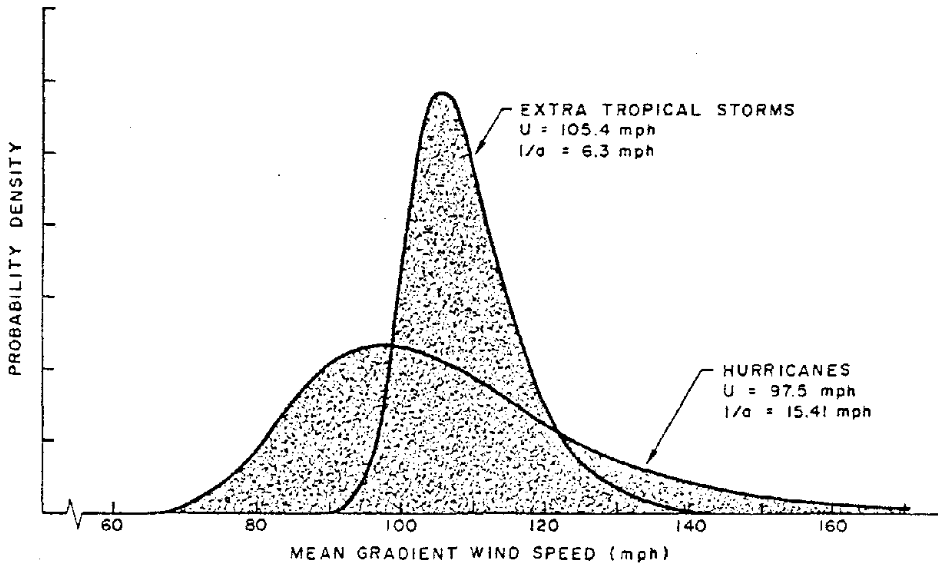


FIG. 13 COMPARISON OF 50 YEAR EXTREME WIND SPEEDS IN NEW ORLEANS COMPUTED FROM TROPICAL STORMS AND EXTRATROPICAL STORMS

The advantage of this approach is that the data base is much broader than the isolated anemometer records. The experience gained in the studies by Russell and by Tryggvason et al to Atlantic hurricanes, by Gomes and Vickery to Australian cyclones, and recently to unpublished studies of Hong Kong typhoons and Mauritius cyclones suggest this approach is important in establishing the climate of these severe storms.

The basic ideas discussed above may also have validity in attacking the question of tornadic winds. Some of the data required is available through studies of hazard probabilities such as reported in reference 27; however, it is likely that the basic storm parameters would have to be inferred indirectly. This would be an interesting area for discussion.

2.0 DIFFICULTIES AND DIRECTIONS

Returning to the starting point of this paper, the models can only be as good as the data on which they are based. Several improvements in the data base can be suggested from the wind engineering point of view:

i) An extension of the program of direct measurement of upper level winds, potentially incorporating recently-developed techniques to facilitate more frequent measurements and data collection during severe storms.

ii) Consideration should be given for 'calibrating' selected surface stations by the use of portable upper level wind measuring equipment so that such surface data could be more reliably interpreted – either in upper level terms, or "equivalent" surface data over a standard terrain.

iii) A return towards longer averaging periods for surface stations, such as the five minute maximum or the hourly mean speed, along with continuous records so that gust fronts would be sampled. The fastest-mile recorder remains a fairly good measure of wind speed, although the extraction of the fastest mile data from the charts bears improvement.

iv) For surface stations, details of the station histories and of the siting of anemometers (including a description of their aerodynamic environment) are often crucial in the final judgement as to the reliability of the data. These factors should be better documented and more easily available.

These are a few of the improvements in the basic data collection which would make it easier to provide better climatic models.

Many examples are possible of residual uncertainties left by the available data base – some of which end up being insoluble. Two examples may serve to illustrate the origin of the above requirements.

First, a recent study of the Calgary wind climate illustrates difficulties with biased surface data. The closest available data source, at Calgary itself, comprises only surface measurements. These are highly biased in direction due to a large hill with a height of about 500 ft directly upstream in the prevailing wind direction. The closest upper level station, at Edmonton (about 180 miles away), provides a good picture of the upper level winds there. Extreme speeds, from both surface and upper level stations at Edmonton and from the surface data at Calgary are in remarkable agreement, as indicated in Table 2. However, particularly with the proximity of the site to the mountains, the question remains as to what the directionality is really like for Calgary. To further complicate the issue, other apparently unbiased surface stations in the surrounding area indicate a general shift in the prodominant wind directions from north-westerly to south-westerly as one proceeds south from Edmonton. Several of these are illustrated in their geographic context in Fig. 14. Obviously, many of the interpretative problems for this site would have been avoided if direct upper level measurements had been available at Calgary itself.

As a second example, during an intensive study of the wind climate in and around the Boston area, many anomalies in the data base were discovered. The analysis of the data became as much an exercise in evaluation of data quality as determining best methods of prediction. Many items of interest in the station history, such as details of the anemometer types, responses, and aerodynamic environments were never fully established; however, some of the entries in the official records did little to instill confidence (such as one period where it was recorded that the anemometer was subject to spurious gusts caused by the propwash from taxiing aircraft!). During this exercise, the data illustrated in Figure 8 was also derived indicating the strong overall biases introduced by the nearby city. Such biases can be traced as they change in line with city growth in numerous cases. As previously mentioned, such factors generally lead to overestimation of extremes.

Fulfillment of the four items recommended above would be a major step in improving the overall data base. Other measures may be equally important; this workshop provides an excellent forum for suggestions.

TABLE 2

100-YEAR RETURN PERIOD WIND SPEEDS FOR CALGARY AND EDMONTON

( ) = estimate

Station	Mean Hourly Surface Speed (mph)	Factor Relating Surface to Gradient	Mean Hourly Gradient Speed (mph)
Calgary International Airport (1953–1976)	51.6	(1.80)	(92.9)
Edmonton Stony Plain Station (1966–1976)	51.7*	1.78	91.8
Edmonton Industrial Airport (1961–1966)	42.5*	2.27	96.4
Edmonton Industrial Airport (1957–1976)	42.6	(2.27)	(96.7)
Edmonton International Airport (1961–1967)	51.2	(1.80)	(92.2)
Edmonton Combined Upper Level (1961–1976)	(51.7)	(1.80)	93.1

* These values were estimated from the surface readings associated with the upper level data taken at these sites.

This section would not be complete without recognition of the many difficulties posed by the special or rare events. Hurricanes have been discussed above; however, details of the wind structure within such storms – particularly the mean wind speed profiles – remains an important unresolved question. The mean wind speed profile assumed significantly affects the loading of a tall building, where extrapolation is taking place upwards from surface estimates. Likewise,

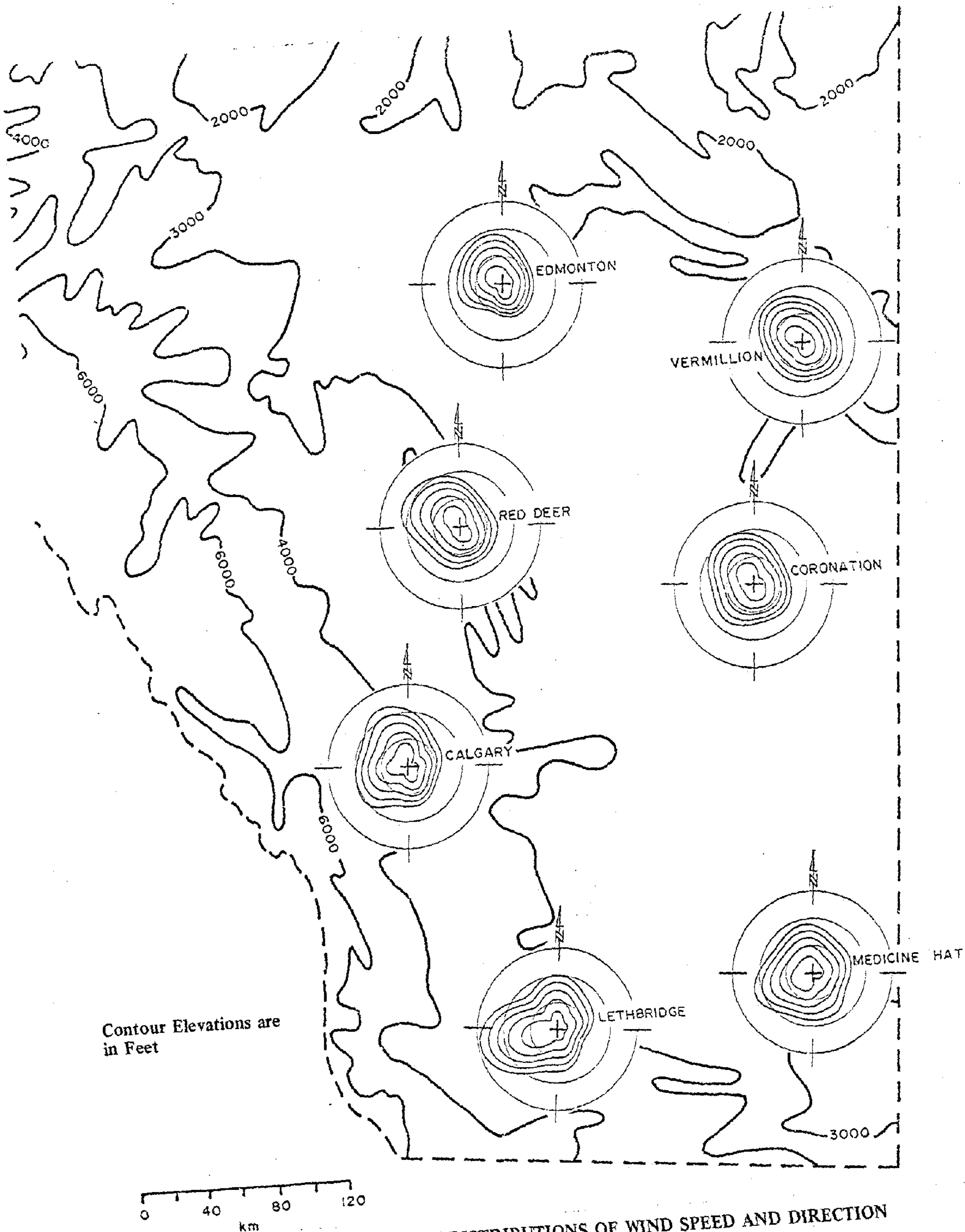


FIG. 14 SEVERAL PROBABILITY DISTRIBUTIONS OF WIND SPEED AND DIRECTION IN THE SOUTHERN ALBERTA AREA

the detailed structure of tornadoes is also at a very early stage of understanding. In the case of tornadoes, the overall climatology also bears improving. For both such severe storms, the questions of wind structure also have important implications as to the appropriate loading coefficients to be utilized, since these are themselves dependent on wind structure.

Between these well-identified special storms and the well-behaved extratropical winds lie several types of wind which have not been sufficiently studied as to their influence on wind climate predictions. These are such things as squall lines, thunderstorms, downbursts, downslope winds etc., – which are often characterized by their severity and their relatively small size and short duration. Many of the severe wind incidents associated with such events are so local and of such short duration that they slip through the conventional wind-measuring system. For these storms, it is important to determine better climatology and better structure. A good means for this may be through the use of well-instrumented towers in regions prone to such events. At the moment, their presence can add substantial uncertainty to the predictions of speeds for regions where they are an important occurrence.

3.0 CONCLUDING REMARKS

In reviewing some current approaches to predicting wind climate for wind engineering purposes, the following major points have been made.

i) The concept of a gradient wind model for well-behaved extratropical wind climates offers the possibility of increased reliability in the resultant predictions of extreme events. Within this concept, the parent distribution also offers some advantages.

ii) Maintaining the wind direction within the statistical model for the wind is an important ingredient for many problems, including those involving directionally-sensitive structural loads, wind energy determination and pollutant dispersal.

iii) The climatology of tropical cyclones is becoming reasonably well-known; that of tornadoes less so. The structure of the winds in both types of storm requires further research.

iv) Intense local events, such as thunderstorms, line squalls, etc. remain a thorn in the side of both data gatherers and data analysers. Much work remains to be done in these areas.

v) Several suggestions have been made to improve the quality of the available data for future wind engineering purposes. These include more and better upper level wind data, calibration of surface stations (in terms of expected wind profile parameters), and improved documentation of measurement stations.

ACKNOWLEDGEMENTS

Much of the information presented in this paper was excerpted from references 1, 15 and 24. The authors are also indebted to their colleagues at the Boundary Layer Wind Tunnel Laboratory who have inevitably participated in the development of the ideas presented here. In particular, Dr. N. Isyumov, Prof. B. J. Vickery and Mr. B. V. Tryggvason deserve special mention. Special thanks also go to D. Bailey, M. Mikitiuk, K. Norman and J. Surry for their assistance in the preparation of this paper.

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ON THE ESTIMATION OF EXTREME SPEEDS IN MIXED WIND CLIMATES

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ABSTRACT

Techniques for the estimation of extreme speeds in mixed wind climates are discussed and exemplified by reference to a study of extreme speeds in Australia. In essence, the method involves the breakdown of the available data into winds associated with the different storm types under consideration and analysing each data set by the most appropriate method. The extreme distributions derived from each data set are then combined to produce a composite extreme wind speed description. The method eliminates many of the well recognized dangers of the "conventional" approach of fitting an extreme value distribution to observed annual maxima and, in addition, permits the use of a much wider data base.

The method is applied to a number of Australian cities and the extreme speeds so determined are compared with values derived using the conventional approach applied to synthesized collections of annual maxima. The comparisons clearly illustrate the difficulties of working from annual maxima in situations where the extremes are derived from two or more storm types.

INTRODUCTION

The potential dangers of estimating extreme winds from a collection of annual maxima are well recognized and these dangers increase as attention is directed, as is the case in limit state design, towards very low probabilities of occurrence. In tropical and sub-tropical regions where tropical cyclones or hurricanes are severe but infrequent the prediction of extremes from even moderately lengthy collections of annual maxima can be highly misleading. This has been recognized and other techniques, discussed in further detail in Section 2, are now being employed to deal with the problem. While the situation in regard to tropical cyclones is receiving attention, similar problems exist in all cases where a particular storm type dominates the "tail" of the extreme value distribution but does not contribute strongly to its "body".

Many of the difficulties arising when dealing with mixed distributions can be avoided by first subdividing the data set. In the Australian context there were three major storm types considered to be of interest; the tropical cyclone or hurricane, the thunderstorm and large scale extratropical pressure systems. In other situations it might be necessary to include tornadoes and/or winds due to local topographic effects as additional classes. If low probabilities are of interest then, even in Australia, the tornado may contribute significantly to the distribution and in parts of the U.S.A. there is no question that, at return periods of the order of 1000 yrs, the tornado must be considered in the evaluation of extreme winds. The data concerning tornadoes in Australia is, however, very limited and this fact, together with the knowledge that they occur primarily in sparsely populated regions prompted their omission as a significant storm type.

One of the major advantages of analysing the winds due each phenomenon separately is that the method of analysis most suited to that data set can be employed. In particular, it permits the extremes to be evaluated from the parent distribution and thus greatly expands the data base and hence the reliability or, conversely, it permits the use of shorter records. Separate analysis of the significant phenomena also enables their different forms of destruction to be taken into account if this is significant.

The techniques as developed for the analysis of extreme wind speeds in Australia have been described in considerable detail in a number of reports and papers[(1)–(6)] and, in this paper, they are presented in outline only. The stations for which analyses were made are shown in Fig. 1 but only those locations named in Fig. 1 are referred to in the present paper. Four of the latter group are in regions subject to tropical cyclones (Onslow, Townsville, Brisbane and Darwin). For the remainder, the main storm types are the thunderstorm and E.P.S.

1. ANALYSIS OF THUNDERSTORMS

Before discussing the method of analysis for thunderstorms it should be noted that the significance of a particular storm type is, to some extent, influenced by the measure of wind speed adopted. In Australia it has been the practice (primarily because of the manner in which the wind measurements are made and recorded) to concentrate on the statistics of the peak 2-3 sec. gust at 10m in open country. On this basis of measurement the thunderstorm is a significant phenomenon at virtually all locations but this would not be the case if hourly means were the subject of attention. If "fastest mile" records were studied the roles of the thunderstorm would again change. This point is demonstrated in the two anemographs presented in Figs. 2 and 3 and from data gathered at a Sydney station. The two anemographs clearly demonstrate that if the maximum mean hourly speed were chosen as a reference value neither of these extremely severe storms would be of any great significance. While the peak gust exceeds 50 m/s in both cases the hourly means of about 10 m/s are both substantially below the expected annual maximum mean hourly speed of around 25 m/s. The timewise resolution of the anemographs does not permit an estimate of the fastest mile but it does appear that this would, in both cases, be substantially less than 50 m/s.

Data from the Observatory Hill station in Sydney indicates that roughly 25% of the annual peak gust maxima are associated with thunderstorms and yet a detailed study of 18 years of mean hourly annual maxima showed that in no case did the thunderstorm contribute, all were associated with E.P.S. storms. It is not intended to discuss the structural significance of short duration gusts in any detail but if thunderstorm gusts possess a reasonable degree of spatial correlation then a duration of a few seconds on even one second is sufficient to achieve or even exceed the equivalent static effect.

The analysis of thunderstorm gusts presented the least difficulties of the three storm types, although in order to make use of the readily accessible data on magnetic tape some liberties had to be taken. The data on tape included a notation as to whether thunder was heard (a "thunderday") or not and a record of the peak gust for the day. It was therefore assumed that a "thunderday" corresponded to a single thunderstorm and that the peak gust for the day was in fact due to that storm. To evaluate the influence of these assumptions the daily log and continuous wind chart were examined for each thunderday and the necessary corrections made to the data. This time consuming check was made for one station only but it did show quite conclusively that the errors induced had no significant effect on predicted extremes.

Using the data available on magnetic tape the probability distribution of the peak gust for all thunderstorms was determined as was the distribution of the number of thunderdays per year. Sample distributions for each of these parameters are shown in Figs. 4 and 5. The distribution of gust speeds was fitted by a Type I extreme value distribution and that for the number of thunderstorms by a Weibull distribution. A month by month analysis showed that although the number of storms per month varied markedly, the distribution of peak speed remained essentially unaltered and that all storms could be considered as members of one population. From these two distributions of speed and frequency of occurrence the extreme value distribution was evaluated. It was noted that the distribution of frequency of occurrence was not significant and a mean value could be adopted; since the parent distribution of peak speed was well fitted by a Type I the annual extremes were also of this form but with a different mode.

2. TROPICAL CYCLONES (Hurricanes)

The extreme values of the peak gust speeds associated with tropical cyclones were estimated using a Monte Carlo approach similar to that suggested by Russell and Schueller[7]. This approach, or development of it, have been used by Tryggvason et al[8] and Batts et al[9] in studies in the U.S.A. and by Martin [10] and Tryggvason[11] in studies in Australia. The features of the approach are described in the above references and by Gomes and Vickery[5] and will not be discussed here in any detail. The essential requirements are the definition of a wind field model and the determination of the relevant statistics such as those concerning central pressure, radius to maximum winds, frequency of occurrence, paths etc.

Two of the more significant distributions (central pressure and advance speed) are shown in Fig. 6 for a region near Onslow, both of these have been fitted by log-normal distributions. These statistics, together with other relevant data, are then used to synthesize annual maxima which can then be fitted by a suitable distribution. Fig. 7 shows the distribution of 500 synthesized annual maximum gust speeds for Onslow and, as can be seen, these are well fitted by a Type I extreme value distribution.

As was the case for the thunderstorm analysis, the chief advantage of this approach is the great expansion of the data base and the consequent improvement in reliability. Gomes(1) examined the influence of errors in the various input parameters on the estimated speed at a return period of 50 years. Gomes concluded that variations up to the 95% confidence limits of each input variable would produce an error of 10% in the 50 yr. gust speed. This estimate is somewhat more encouraging that the coefficient of variation of about 10% suggested by Simiu(12) in another paper at this workshop.

It might be noted that the analysis included all tropical cyclones, and was not restricted to those having hurricane force winds. This extension increases the data base and, consequently, the reliability. This point has been recognized by Simiu(12) who concluded that the coefficient of variation improved (reduced) by 2% or 3%.

3. TORNADOES

As mentioned in the introduction, tornadoes were not considered in the Australian study but are certainly worthy of attention in many parts of the U.S.A. Provided the necessary probability distributions of path length, path width, speed etc. are available the most satisfactory approach to the estimation of extreme speeds due to tornadoes would be a Monte Carlo method similar to that described for tropical cyclones. Studies of this type by Wen and Chu(13) indicate that, for a mid-western site in U.S.A., the tornado had significant influence on extreme speeds at the 500 yr. level and was dominant above 1000 yrs. Since the work of Wen and Chu was published further studies have been made concerning the basic probability distributions (e.g., Schaefer and Kelly(14)) and a further investigation of the role of the tornado in determining extreme wind speeds at low probability levels is probably justified.

4. EXTRA-TROPICAL PRESSURE SYSTEMS

The final storm type considered was the E.P.S. although in reality it would be better described as A.O. (any other) since the method of separation was one of elimination of the storm types previously analysed. The method of analysis adopted was that of applying Rice's "Crossing-Rate Equation". This method requires the estimation of a rate parameter together with a knowledge of the probability distribution of the parent population. The rate parameter can be estimated from long term spectra such as that shown in Fig. 8 for Sydney. Due to the comparative insensitivity of the estimates of extreme values to the rate parameter the spectrum was evaluated at Sydney only. It might be noted, however, that the estimate of 750 cycles/year agreed well with the estimate of 880 cycles/year determined from the spectrum derived by van der Hoven[16] from Brookhaven (New York) data. A typical probability distribution of wind speed is shown in Fig. 9, again for Sydney.

The crossing rates predicted from the spectrum and the probability distribution are shown in Fig. 10 together with observed crossing rates. Of the two theoretical lines shown, the broken line takes account of the non-stationarity of the data. The influence of non-stationarity is, however, small and was ignored in the analyses of other stations. Although the application of Rice's equation yields an extreme value distribution which is a little "softer" than the Type I the predicted extremes were fitted by a Type I distribution. Since the slope/mode ratio for EPS storms is small the slight change in the form of the distribution does not significantly change the estimates of extreme speeds. Extreme speeds estimated from each of five one year records are shown in Fig. 11. The shaded area corresponds to the theoretical 80% confidence limits for 1 yr. records and is centred upon the estimates from the complete five year record.

The analysis outlined above used mean hourly speeds and the gust speeds were estimated by the application of a gust factor appropriate to a height of 10m in open country. Working with the mean hourly values virtually eliminated the thunderstorm influence but even if this were not the case, the estimates of extreme speeds are not significantly changed by the failure to eliminate either thunderstorms or tropical cyclones. The estimates of extremes determined using Rice's equation are those associated with the body of the parent distribution and this is not changed significantly by either thunderstorms or tropical cyclones which influence, typically, only 0.2% of total record length.

Although the results presented in this paper all apply to ground level (10m) winds the same method was applied using balloon data to predict upper level extreme winds and the directional distribution of these winds. The upper level climate determined in this manner is representative of EPS storms only and must be modified if other storm types are significant.

5. RELIABILITY OF ESTIMATES OF EXTREME WIND SPEEDS

The reliability or accuracy of the estimates obtained by the methods described herein is, of course, a function of the station in question and the length and quality of the data bank. The accuracy was studied for tropical cyclones at Onslow, EPS storms at Sydney and for thunderstorms at all stations. The results are summarized in Table 1. The values quoted are the 80% confidence limits on the 100 yr. extreme, for tropical cyclones the errors include both sampling and model-line errors while for the other two storm types the errors quoted are due to sampling and the fitting of distribution functions. In no case is the instrumental error included and, in the case of the thunderstorm and EPS storms this is probably the most significant error source. The

TABLE 1: ESTIMATED 80% CONFIDENCE LIMITS

Storm Type	Errors Examined	Date Base	80% Confidence Limit on Estimated 100 yr. Extreme
Tropical Cyclone	*Sampling Modelling Fitting*	*64 cyclones*	$\pm$ 9%
Thunderstorm	*Sampling Fitting*	*50 years 1300 storms*	$\pm$ 1.5%
EPS	*Sampling*	*T years*	$\pm \frac{10}{\sqrt{T}}$ %

marked improvement in accuracy over "conventional" approaches stems primarily from the expanded data base. In Sydney, for example, the thunderstorm statistics were derived from 51 years of records and over 1300 storms. In contrast, an analysis of annual maxima for the same period would be based on 51 observations of which perhaps 12 might be thunderstorms and yet it is the thunderstorm which dominates at return periods above about 5 years. For thunderstorms, the estimated 80% confidence limits for the 100 yr extreme ranged from about ± 1.5% [84 years, 3000 storms] to about ± 4% [10 years, 125 storms].

6. SELECTED RESULTS

The modes and slopes of the Type I distributions fitted to each storm type are given in Table 2 for 10 stations of which the first four are in regions subject to tropical cyclones. In an attempt to compare estimates based on an analysis of annual maxima with those determined by the methods

TABLE 2

ERRORS IN 1000 YR SPEED PREDICTED FROM 30 YRS OF ANNUAL MAXIMA

Station	Mode/Slope E	Mode/Slope T	Mode/Slope C	Spread of Central 80% About Best Estimate of 1000 yr. Speed Type I	Type II
Onslow	21 / 1.5	26 / 5.2	25 / 9.1	+11 -17	+32 -17
Townsville	22 / 1.4	19 / 3.2	20 / 8.4	+13 -35	+38 -22
Brisbane	21 / 1.6	24 / 3.6	14 / 8.7	+ 4 -35	+26 -30
Darwin	21 / 1.6	23 / 3.1	24 / 6.9	+14 -22	+35 -18
Adelaide	28 / 2.0	27 / 4.5	–	+10 -10	+21 -10
Perth	26 / 2.0	24 / 4.1	–	+13 -13	+21 -11
Sydney	27 / 2.2	25 / 4.0	–	+11 -11	+21 -10
Melbourne	28 / 2.3	25 / 3.9	–	+11 - 8	+21 - 8
Launceston	26 / 2.0	23 / 4.2	–	+10 -15	+19 -13
Canberra	26 / 1.9	22 / 3.6	–	+11 -11	+19 -11

destribed herein the following procedure was adopted. For each station the modes and slopes defined in Table 2 were used to generate or synthesize 30 data sets each with 30 annual maxima. These sets were then fitted by the method of least squares by Type I and Type II extreme value distributions. The results are presented in graphical form for four stations and in tabular form for all ten. In Table 3, estimates are given for the 1000 yr. gust speed. Values presented are:

i) the "best" estimate as derived from a combination of the individual storm type distributions,
ii) the value given by fitting a Type I distribution to actual recorded maxima,
iii) the bounds of the central 80%, (i.e., central 24 samples, each of 30 years) of the synthesized data fitted by a Type I distribution, and
iv) as for (iii) but using a Type II distribution.

The bounds of the central 80% of the synthesized data are also included as percentages of the "best" estimate in Table 2.

In reviewing the percentage discrepancies in Table 2 it might be noted that the estimated 80% confidence limits of the "best" estimate are about ± 10% for the first four stations which are dominated by tropical cyclones and about ± 4% for the remainder which are dominated by thunderstorms. With these figures in mind it is clear that neither the Type I nor the Type II distribution produce satisfactory estimates, and that the Type II produces consistently poor overestimates. The inadequacy of the Type II distribution in this respect is also referred to by Simiu[12] in his paper at this meeting. The discrepancies are partly due to sampling errors but are enhanced by the poor fit yielded by the Extreme Value Distributions when these are applied to mixed data.

In terms of wind load as opposed to speed the ranges of the central 80% determined from the better Type I fit are, typically, 2.5:1 for stations influenced by tropical cyclones and 1.6:1 for stations influenced by thunderstorms. The 1000 yr. speeds determined from actual recorded maxima using a Type I distribution are consistently low. This result is not unexpected since the record lengths are short and, in many cases, would contain very few maxima associated with the storm type dominant at large return periods. The case of Darwin is an extreme example. In this instance the twelve years happen to include not one annual maximum due to a tropical cyclone. The 1000 yr. speed determined from the 12 years of data (46 m/s) does, however, agree remarkably well with the best estimate for thunderstorms alone (44.5 m/s).

The information contained in Tables 2 and 3 is, for four of the stations, reproduced graphically in Figs. 12 to 15. The central 80% shown hatched, is for a Type I fit to the synthesized data. In the case of Brisbane (Fig. 14), which is seldom influenced by tropical cyclones, the

TABLE 3

ESTIMATES OF PEAK GUST SPEED (M/S)
WITH A RETURN PERIOD OF 1000 YRS

Station	From Analysis of Storm Types	Direct From Annual Maxima (2)	Central 80% as Estimated From 30 Synthesized 30 Yr Records: Type I	Type II
Onslow(1)	88	98 (30)	67–100	73–116
Townsville(1)	78	65 (25)	51–88	61–108
Brisbane(1)	74	66 (11)	48–77	52–93
Darwin(1)	72	46 (12)	56–82	59–97
Adelaide	58	55 (17)	52–64	52–70
Perth	53	49 (11)	46–60	47–64
Sydney	53	45 (20)	47–59	48–64
Melbourne	52	43 (12)	48–58	48–63
Launceston	52	46 (15)	44–57	45–62
Canberra	47	43 (13)	42–52	42–56

(1) Dominated by Tropical Cyclones

(2) Fitted by Type I over ( ) years

lower bound to the central 80% almost coincides with the thunderstorm line. This result is not surprising since it can be deduced from the individual storm statistics that roughly 5% of all sets of 30 yr. maxima would have no members associated with tropical cyclones.

7. CONCLUSIONS

A technique for the determination of probability levels of extreme gusts in mixed wind climates climates has been presented and discussed. The technique requires the separate analysis of each significant wind type and, as a result, requires substantially more effort than "traditional" methods. This extra effort is, however, rewarded by the substantially enhanced accuracy, particularly at low probability levels. Whether such an approach is warranted in all situations is a matter for debate but clearly there are many instances where such an approach is essential and many more where the improved accuracy is highly desirable.

ACKNOWLEDGMENTS

Much of the study described herein was conducted by Dr. L. Gomes who, at the time was a doctoral student under the supervision of the Author. Support for this part of the work was provided by the Australian Research Grants Committee. Mr. P.N. Georgiou of The University of Western Ontario, assisted in later developments which were supported through a research contract with the Electric Power Research Institute and a grant from the National Science and Engineering Research Council, Canada.

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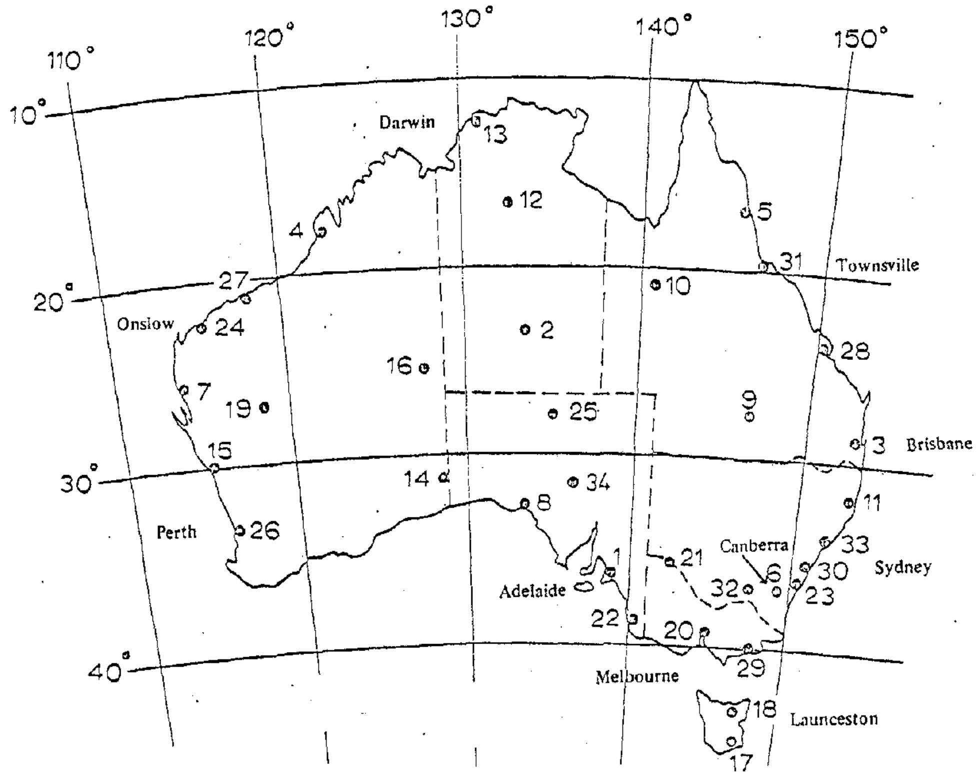


FIG. 1: LOCATION OF METEOROLOGICAL STATIONS

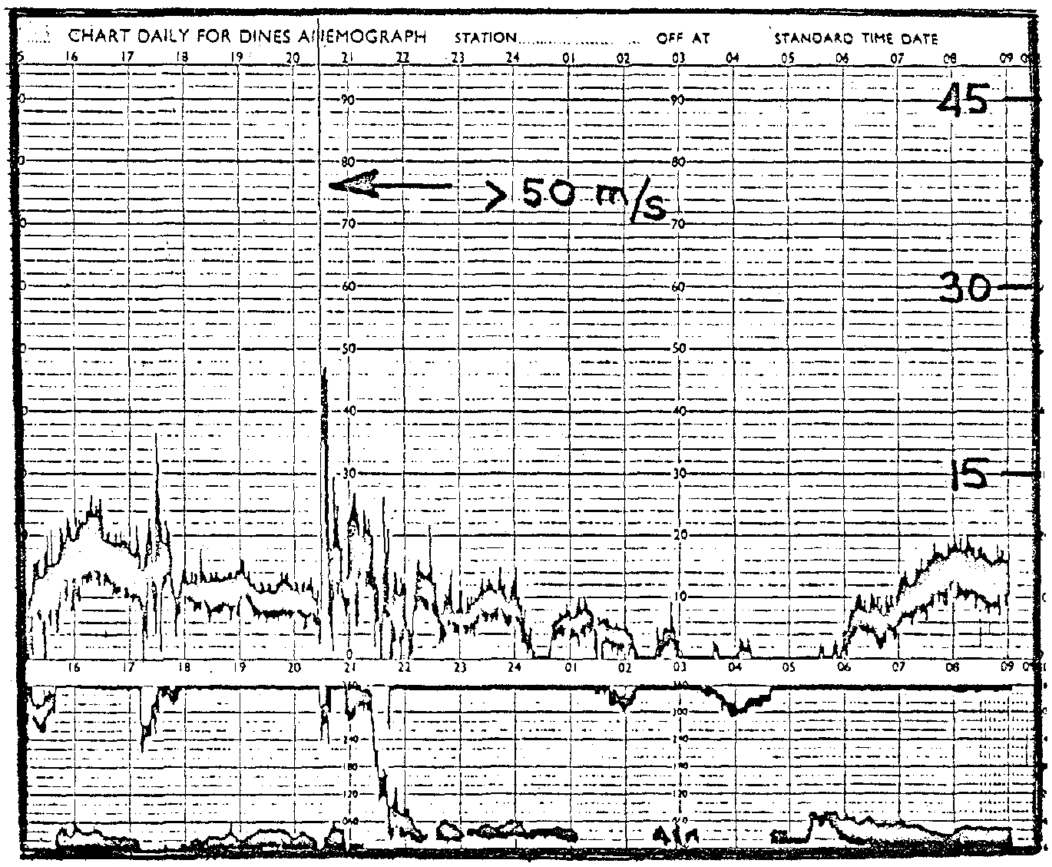


FIG. 2: THUNDERSTORM ANEMOGRAPH, AUSTRALIA, 1961

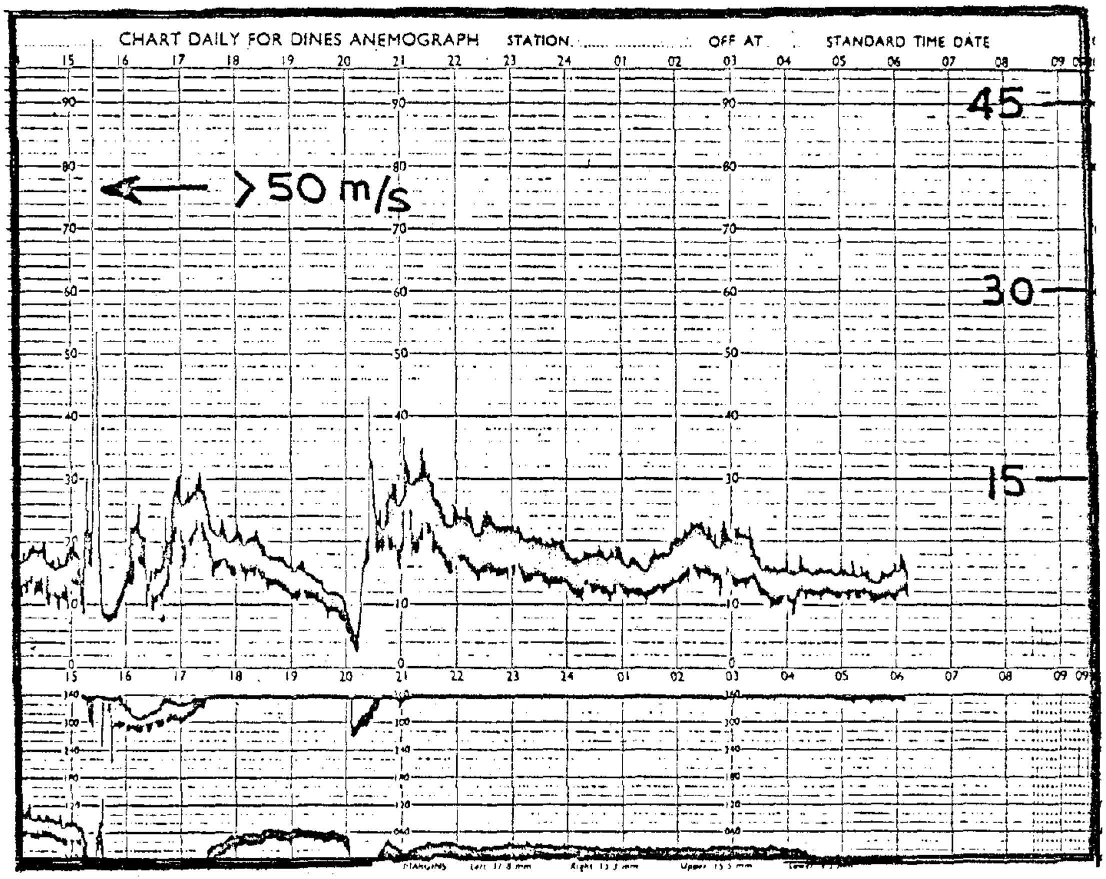


FIG. 3: THUNDERSTORM ANEMOGRAPH, AUSTRALIA, 1959

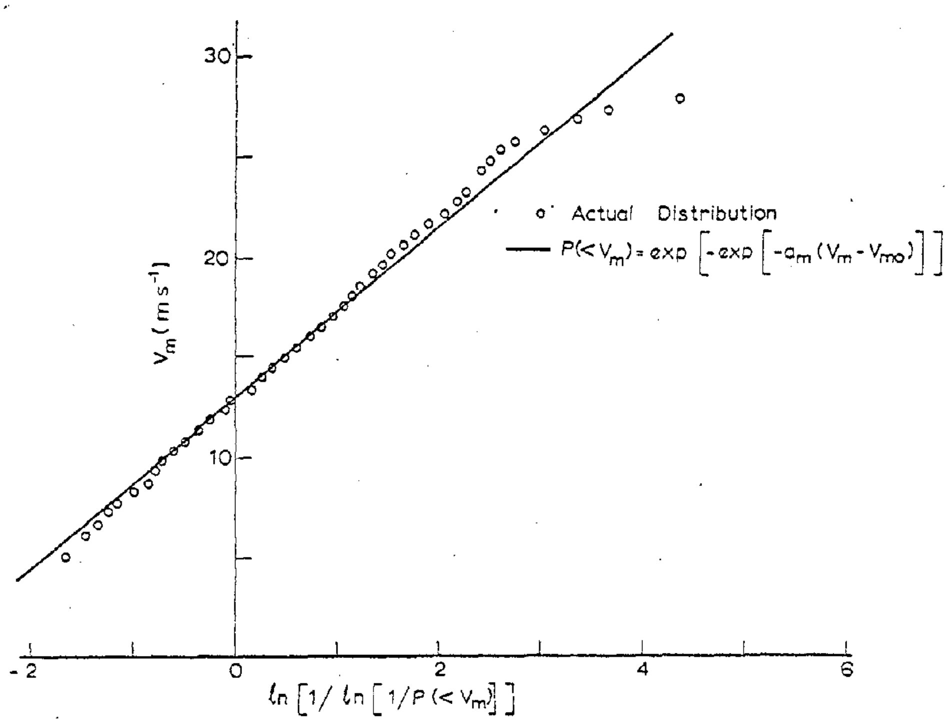
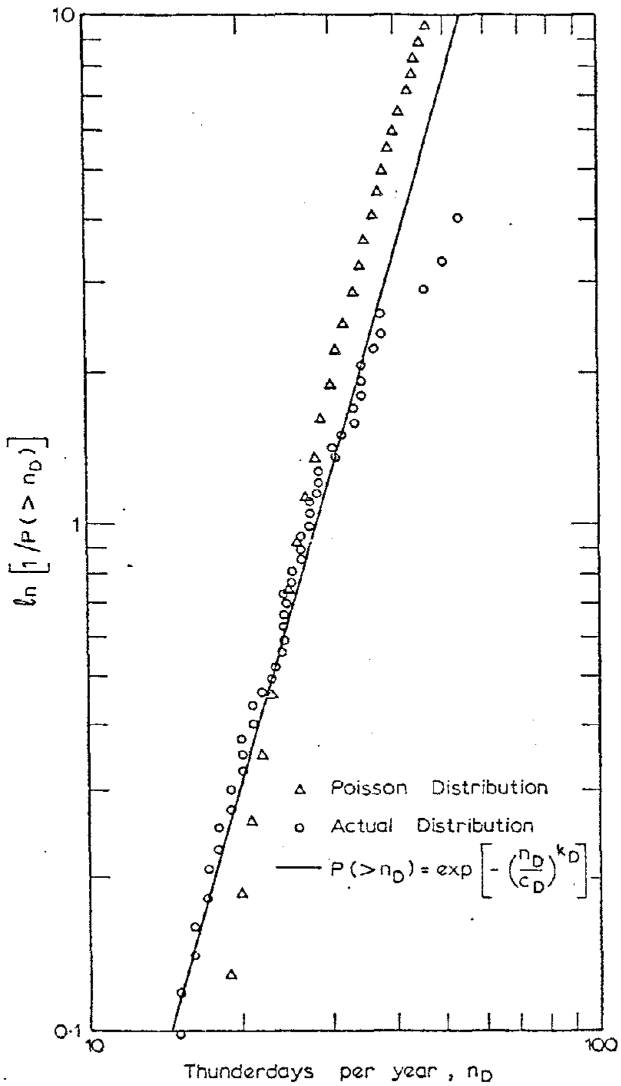


FIG. 4: PROBABILITY DISTRIBUTION OF PEAK THUNDERSTORM GUST SPEED (SYDNEY)

FIG. 5: PROBABILITY DISTRIBUTION OF NUMBER OF THUNDERDAYS PER YEAR



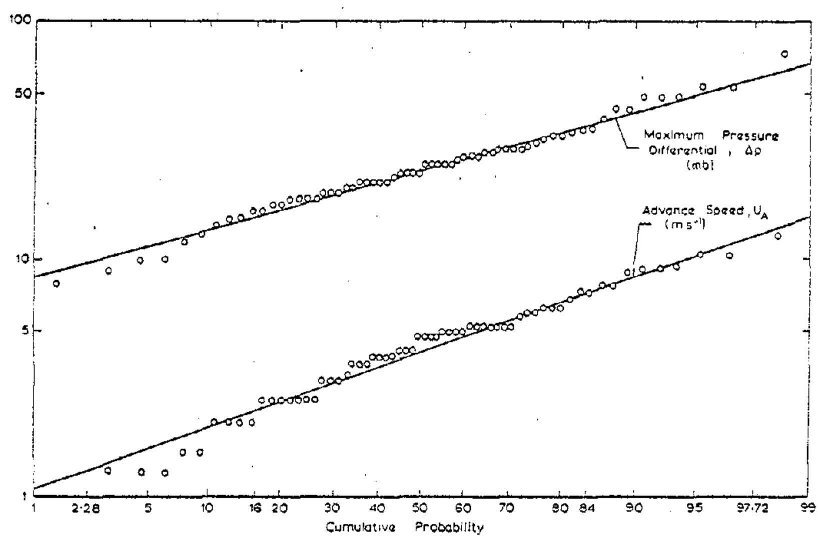


FIG. 6 PROBABILITY DISTRIBUTIONS OF CENTRAL PRESSURE AND ADVANCE SPEED OF TROPICAL CYCLONES NEAR ONSLOW

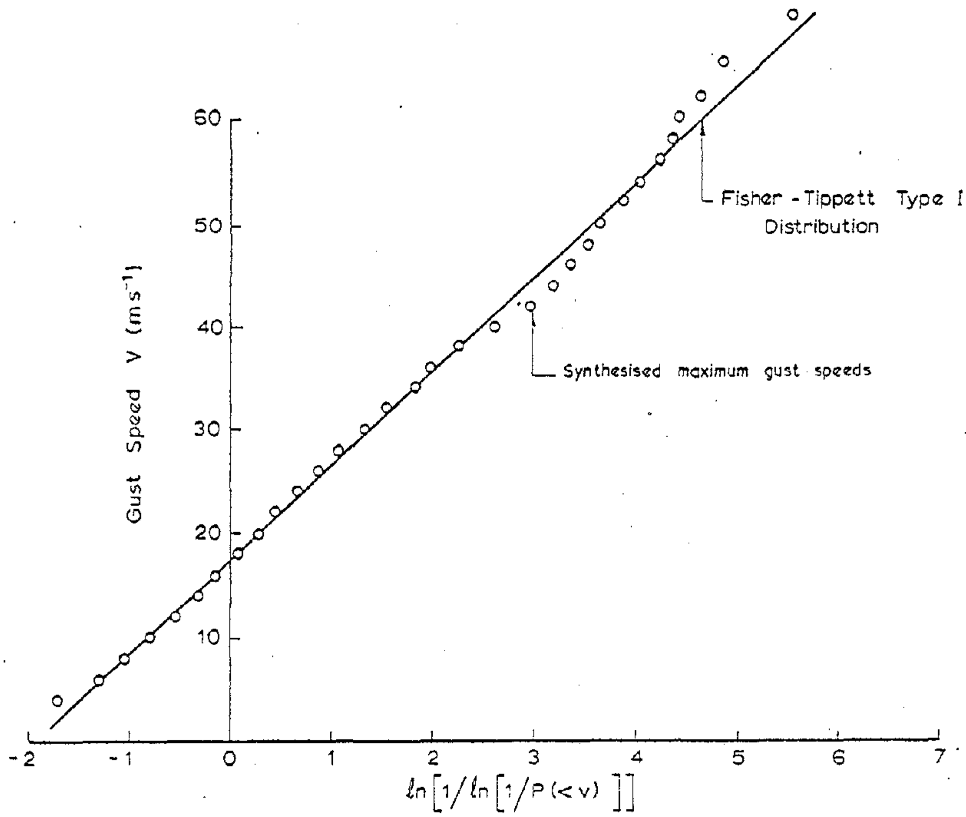


FIG. 7: PROBABILITY DISTRIBUTION OF SYNTHESIZED ANNUAL MAXIMUM GUSTS DUE TO TROPICAL CYCLONES (ONSLOW)

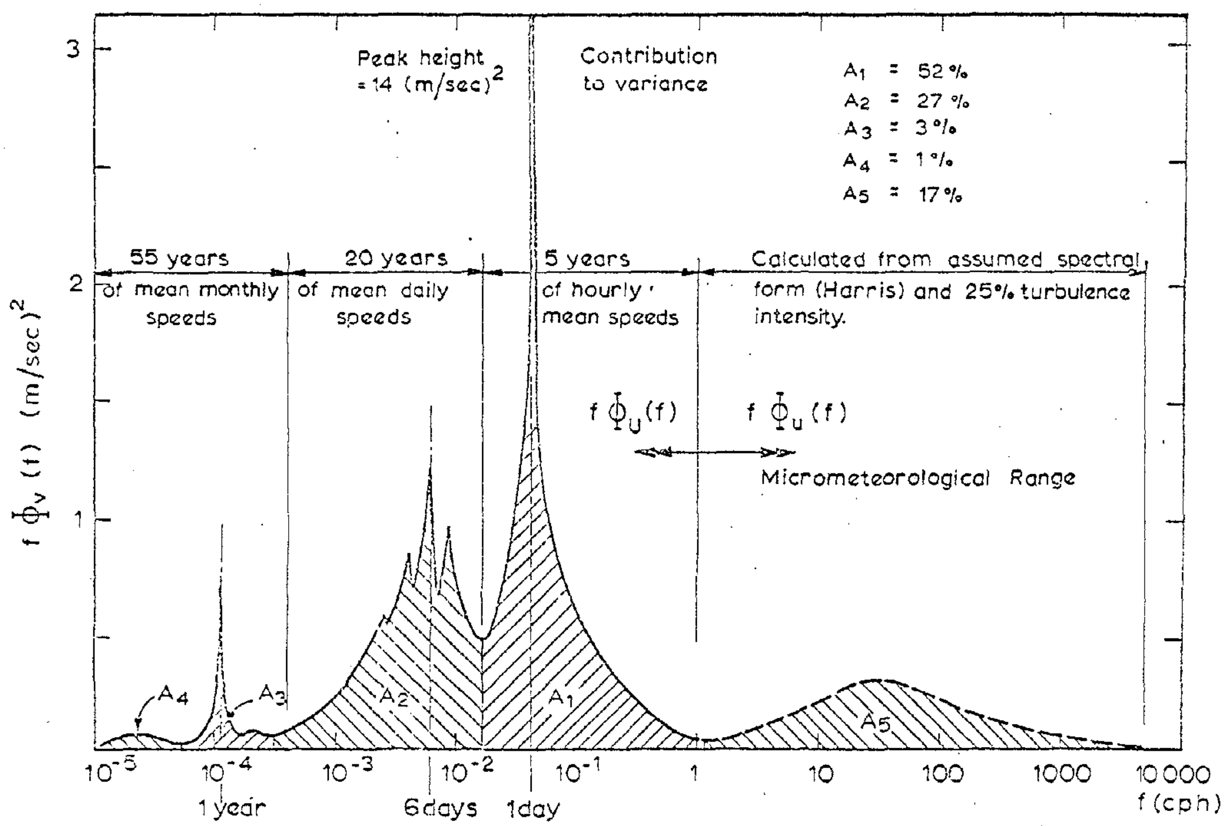


FIG. 8: COMPOSITE WIND SPEED SPECTRUM (SYDNEY)

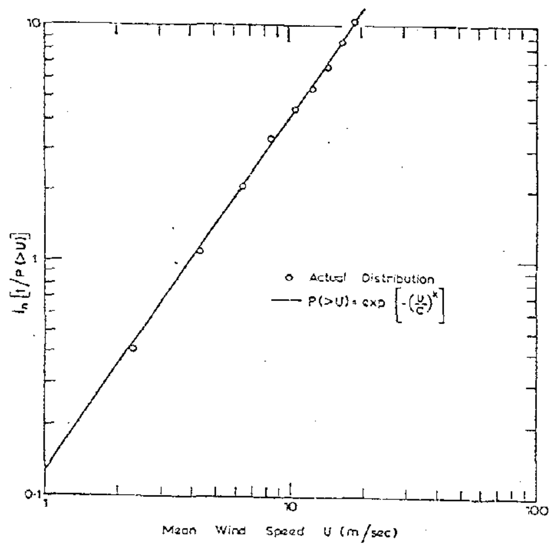


FIG. 9: PROBABILITY DISTRIBUTION OF MEAN HOURLY WIND SPEEDS (SYDNEY)

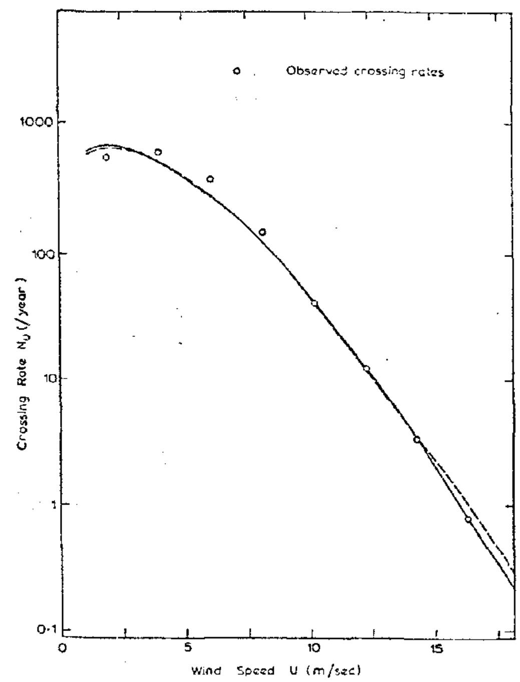


FIG. 10: PREDICTED AND OBSERVED CROSSING RATES (SYDNEY)

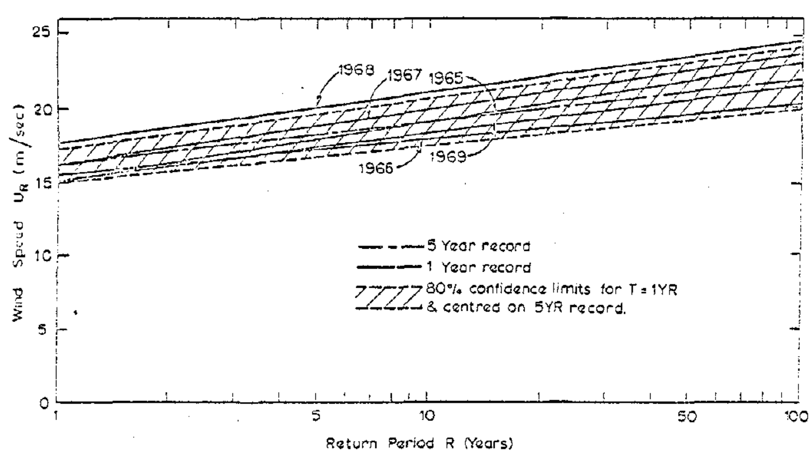


FIG. 11: EXTREME SPEEDS DERIVED FROM ONE AND FIVE YEAR SAMPLES OF THE PARENT DISTRIBUTION (SYDNEY)

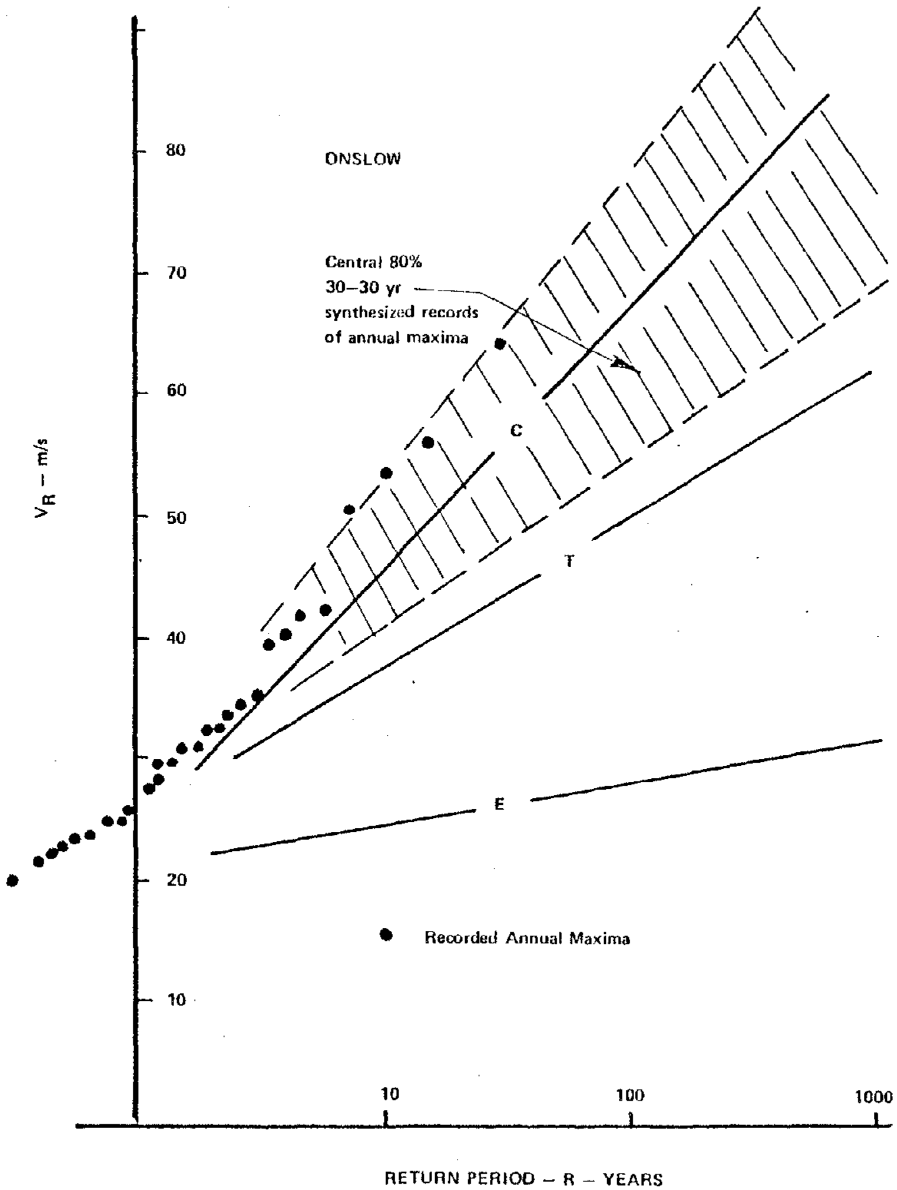


FIG. 12: DISTRIBUTIONS OF EXTREME WIND SPEEDS (ONSLOW)

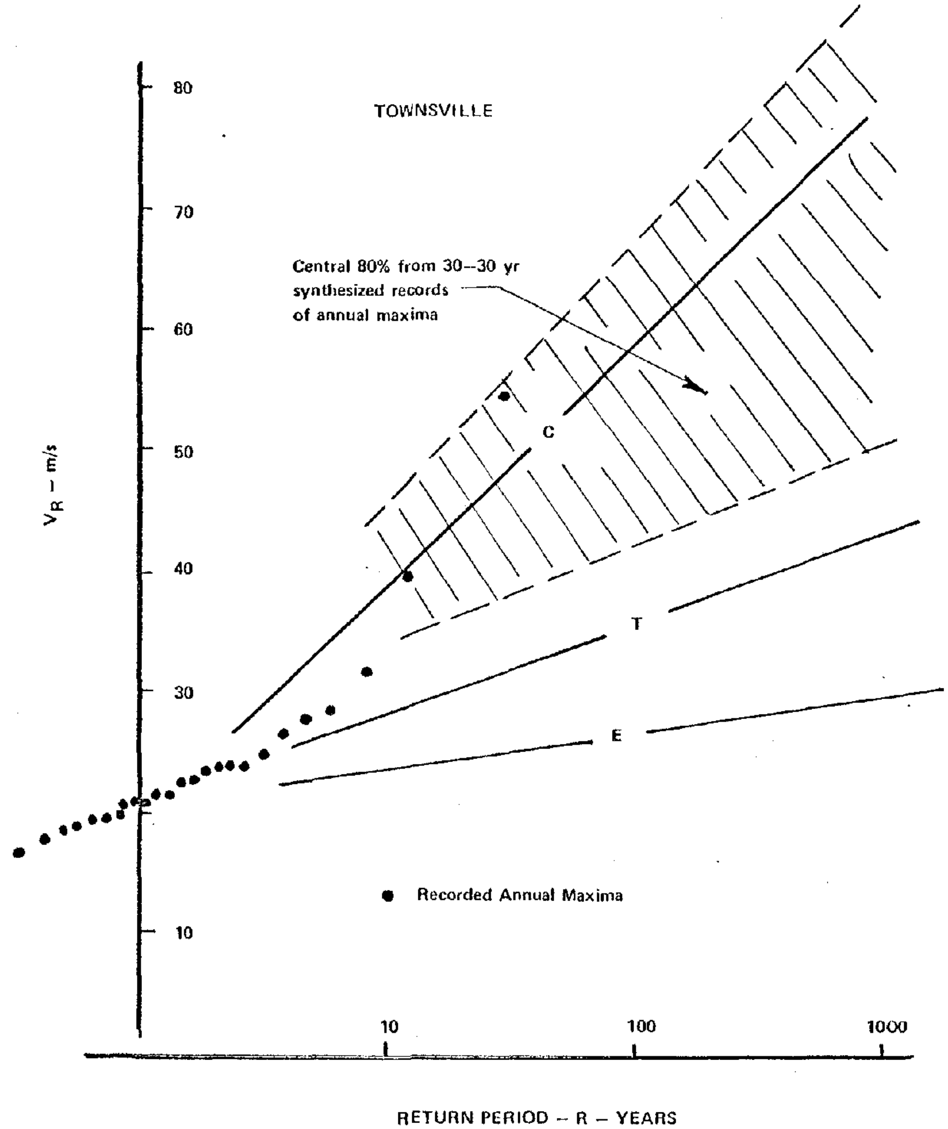


FIG. 13: DISTRIBUTIONS OF EXTREME WIND SPEEDS (TOWNSVILLE)

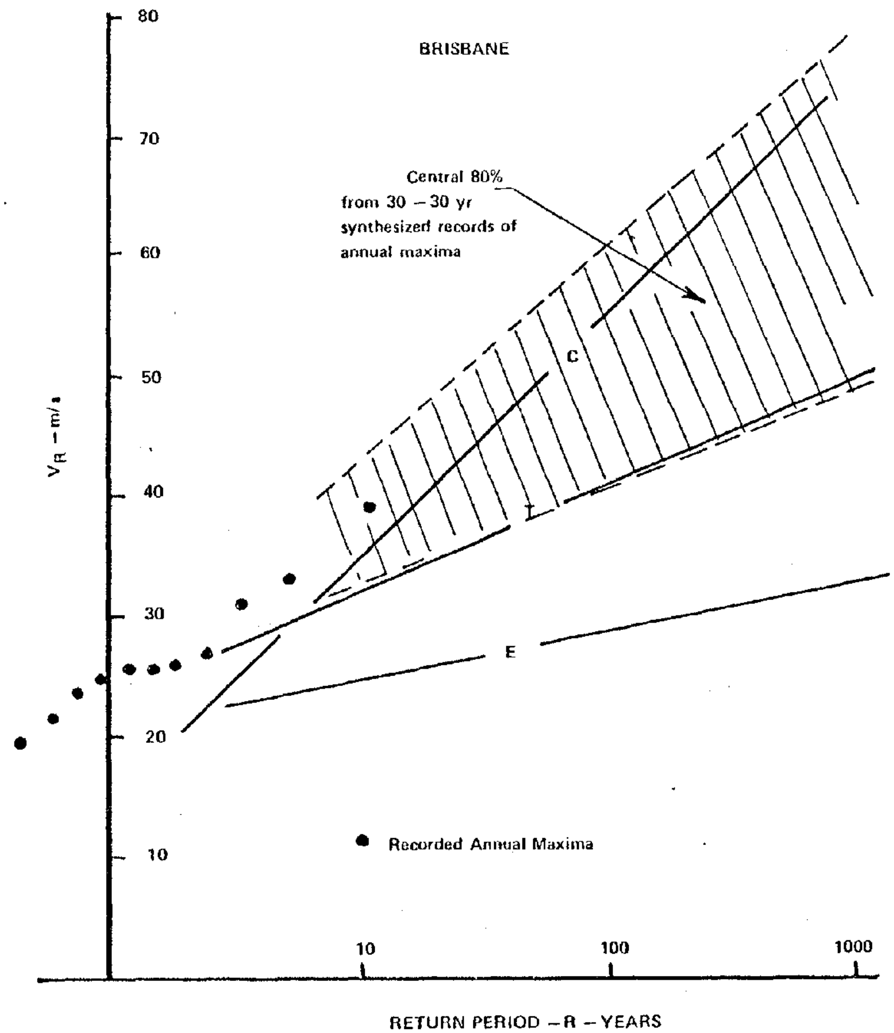


FIG. 14: DISTRIBUTIONS OF EXTREME WIND SPEEDS (BRISBANE)

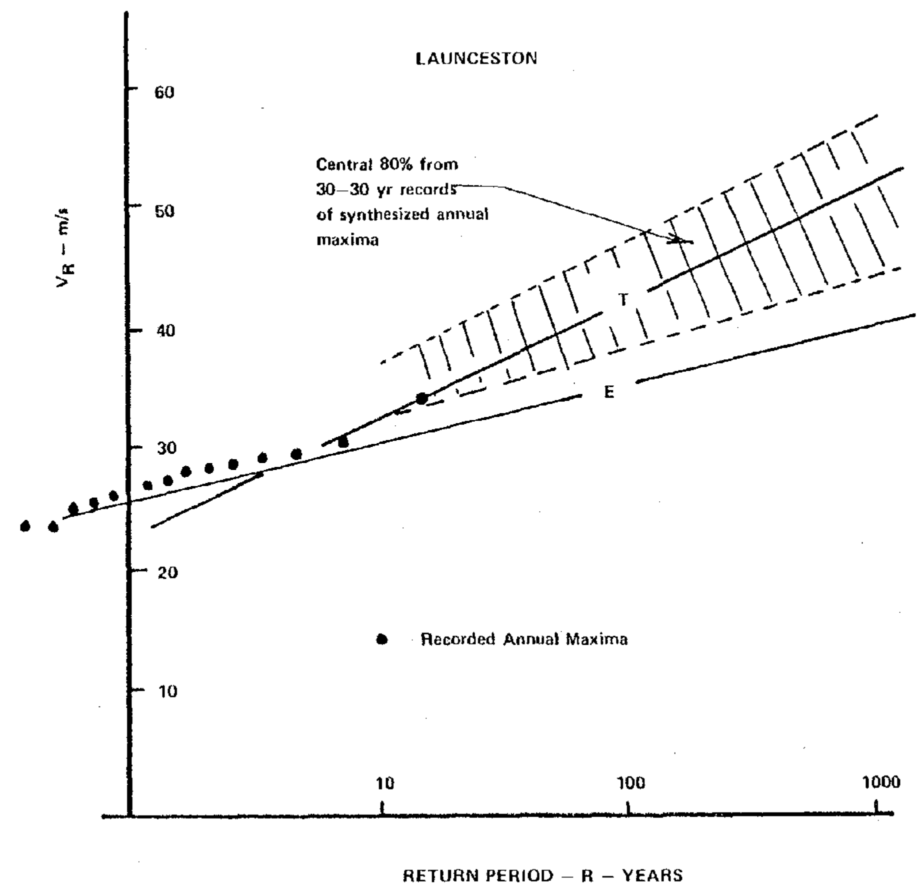


FIG. 15: DISTRIBUTION OF EXTREME WIND SPEEDS (LAUNCESTOW)

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ESTIMATION OF EXTREME WIND SPEEDS

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ABSTRACT

Results of recent statistical studies are reviewed, which suggest that at a majority of U.S. weather stations extreme wind speeds corresponding to large mean recurrence intervals (such as are of interest in structural reliability calculations) are considerably lower than those based on the assumption that an Extreme Value Type I distribution holds. Also presented are results of a preliminary study on the estimation of extreme wind speeds from weekly or monthly data taken over periods of the order of three years or so. Finally, results of a recent study are reported on estimates of hurricane wind speeds on the Gulf and East Coasts of the United States.

INTRODUCTION

Let the acceptable probability that a given structure will fail in any one year under the action of wind loads be denoted by P_f. The task of the extreme wind climatologist is to provide the structural engineer with information on the magnitude of wind speeds with probability of occurrence in any one year smaller than P_f (assuming the wind speed to be the dominant factor).

How large should P_f be? Assume for the sake of argument, that $P_f = 1/50$ in any one year. For a structure with a life of 50 years, it can be easily shown that to this value of P_f there would correspond a probability of failure of the structure during its lifetime of approximately 0.63. Clearly, a more than even probability that an inhabited structure would fail during its 50-year life would be unacceptable, at least in our society. Indeed, even a probability of failure during its lifetime of the order of 0.063, corresponding to a value $P_f \simeq 1/500$ in any one year, appears to be exceedingly large to be acceptable to the average building occupant: risks of such magnitude may not be acceptable even to the reckless motorcycle driver. Without attempting to be very precise, it may be stated that P_f should not exceed one in a few thousand in any one year.

The task of the extreme wind climatologist, then, would be to estimate wind speeds corresponding to mean recurrence intervals of the order of a few thousand of years or so. Unfortunately, this task is so difficult that, to the writer's knowledge, no climatologist has ever attempted it for non-tornadic winds. Indeed, climatologists have at their disposal wind speed data covering periods of a few tens of years at most; accordingly, they do not feel that it is possible to estimate extreme wind speeds with mean recurrence intervals exceeding 100 years or so.

However, as previously stated, because engineers design structures that should not fail, they need some information on wind speeds with mean recurrence intervals of the order of thousands of years. In the absence of any such information from climatologists, engineers have proceeded to obtaining it themselves. In effect, and in simplified terms, it may be stated that according to the engineers-turned-climatologists-by-default,

$$v_N \simeq 1.25\ v_{50} \qquad (1)$$

where v_N and v_{50} = wind speeds corresponding to mean recurrence intervals N = at least a few thousand years and 50 years, respectively, and 1.25 is a coefficient representing the square root of the load factor for wind loads (the load factor being in effect a component of the well-known safety factor).

This informal approach to the climatology of extreme winds with very large mean recurrence intervals has worked fairly well in the past. However, it has become apparent that the adoption of the constant multiplying factor $\simeq 1.25$ may lead to inconsistencies from a structural reliability viewpoint: indeed, if v_N is calculated by Eq. 1, to different wind climates there might well correspond different values of N and, therefore, of the probability of failure P_f. Thus, some structures would be overdesigned (i.e., would be safer than necessary), while others would be underdesigned. The clamor has therefore increased, on the part of structural reliability specialists, for more scientific methods of estimating v_N (or, alternatively, the "correct" value of the load factor for wind loads).

If v_N is estimated by assuming that the extreme winds are described probabilistically by an Extreme Value distribution, structural reliability calculations lead to the result that the safety level inherent in current building code provisions is about one order of magnitude less for structural members subjected to wind loads than for members subjected to gravity loads.

In view of the rather satisfactory behavior of most types of structural members (as opposed to cladding components or roofs) under wind loads, it is legitimate to question the validity of this result. It may be the case, for example, that Extreme Value probabilistic models do not provide a realistic description of the extreme winds. Results supporting this view will be described in the first section of this paper.

Estimating extreme wind speeds with very large mean recurrence intervals is a luxury when, as is frequently the case, even information on wind speeds with mean recurrence intervals of the order of 50 years is not available. This paper will therefore also deal with methods of obtaining such information. The estimation of extreme wind speeds with various mean recurrence intervals will be dealt with separately for regions subjected to hurricane winds and for regions where hurricanes are not expected to occur. In particular, for the latter, the question of estimating extreme winds from short-term records will also be dealt with herein.

1. EXTREME WIND SPEEDS IN WELL-BEHAVED WIND CLIMATES

Infrequent winds (e.g., hurricanes) that are meteorologically distinct from and considerably stronger than the usual annual extremes are referred to herein as extraordinary winds. Climates in which extraordinary winds may not be expected to occur are referred to as well behaved. In a well-behaved wind climate, at any given station a random variable is defined which consists of the largest yearly wind speed. If the station is one for which wind records over a number of consecutive years are available, then the cumulative distribution function (CDF) of this random variable may be estimated to characterize the probabilistic behavior of the largest annual winds. The basic design wind speed is then defined as the speed corresponding to a specified value P of the CDF, or equivalently, to a specified mean recurrence interval $N = 1/(1 - P)$ [1]. It is recalled that the largest yearly wind speed data used in the statistical analysis must constitute a micrometeorologically homogeneous set with respect to averaging time, height above ground, and roughness of surrounding terrain.

a. Extreme Type I and Rayleigh Distributions as Probabilistic Models of the Largest Yearly Wind Speeds

It is assumed in the American National Standard A58.1-1972 that the largest yearly wind speed data in well-behaved wind climates are best fitted by Extreme Value Type II distributions. However, subsequent research has shown that this assumption is not warranted (2,3), and that the Extreme Value Type I distribution - which is less severe than the Type II distribution - provides in general a better fit to the extreme yearly wind speed data.

Nevertheless, as previously mentioned herein, structural reliability calculations have shown that estimated probabilities of failure inherent in current building code provisions are higher for members subjected to wind loads than for members subjected to gravity loads, even if it is assumed that wind speeds are fit by a Type I, rather than Type II distribution (4,5). The question thus arises whether in reality a probabilistic model that is milder than the Type I distribution is not warranted for the description of the extreme yearly wind speeds.

In an attempt to answer this question, an analysis was conducted of extreme yearly data sets recorded at over 100 U.S. weather stations and published in Ref. 3. This analysis has shown that at a majority of the stations the data were best fit by Rayleigh distributions or by Weibull Distributions with tail length parameter $\gamma > 2$ (6). [Recall that the Rayleigh distribution is a Weibull distribution with tail length parameter $\gamma = 2$.]

The significance of this result from a structural reliability standpoint will be illustrated by the following example. At Moline, Illinois, the mean and the standard deviation of the extreme yearly fastest-mile speeds at 10 m above ground in open terrain recorded in the period 1944-1977 are $\overline{X} = 24.49$ m/s (54.78 mph) and s = 3.46 m/s (7.73 mph) [see Ref. 3, p. 73]. Assuming that the Moline largest annual fastest-mile wind speeds are best described by the Rayleigh distribution, the estimated wind speeds corresponding to the 50-yr and 1000-yr mean recurrence intervals are $\hat{V}_{50}^{R} = 32.65$ m/s (73.04 mph) and $\hat{V}_{1000}^{R} = 37.50$ m/s (83.89 mph). If an Extreme Value Type I distribution were assumed, then $\hat{V}_{50}^{I} = 33.88$ m/s (75.79 mph) and $\hat{V}_{1000}^{I} = 42.31$ (94.67 mph). Note that the difference between $\hat{V}_{50}^{I}$ and $\hat{V}_{50}^{R}$ is relatively small (of the order of 3%). However, the difference between $\hat{V}_{1000}^{I}$ and $\hat{V}_{1000}^{R}$ is significant (of the order of 15%).

Assume now that a structure is designed to attain the yield stress under the action of a load proportional to 1.6 $(V_{50}^{I})^2$ (the coefficient 1.6 represents the load factor for wind loads). At Moline, the wind speed which will induce the yield stress is then $(1.6)^{1/2} V_{50}^{I}$ = 42.85 m/s (95.87 mph), to which there corresponds a mean recurrence interval of 1,600 years if the Type I distribution is assumed, and of <u>70,400 years</u> if it is assumed that the Rayleigh distribution holds. If the mean recurrence interval of the wind speed that induces the yield stress is regarded as an index of the nominal safety level of the member under wind loads, it is seen <u>that the difference between nominal safety levels corresponding to the assumptions that a Type I and a Rayleigh Distribution holds is of almost two orders of magnitude</u>.

It would thus appear that, at a large number of geographical locations - if not throughout the U.S. territory - safety levels for structures designed in accordance with current wind loading provisions might be higher than was heretofore believed to be the case.

For convenience, expressions for the estimation of extreme wind speeds, $\hat{V}_N$, corresponding to a mean recurrence interval, N, are given below. These expressions are based on the method of moments.

If a Rayleigh distribution is assumed

$$\hat{V}_N = \overline{X} + s\,[2.16\,(\ell n N)^{1/2} - 1.91] \qquad (2)$$

If an Extreme Value Type I distribution is assumed

$$\hat{V}_N \simeq \overline{X} + 0.78\,s\,(\ell n N - 0.5772) \qquad (3)$$

In Eqs. 2 and 3, $\overline{X}$ and s are the sample mean and standard deviation of the extreme wind speed data. It is noted that differences between estimates based on Eqs. 2 and 3 and estimates based, e.g., on the least squares method have been verified to be generally of the order of 0.5% to 2%.

b. Estimation of Extreme Wind Speeds from Short-Term Records

The question has been raised in the literature (see, e.g., Ref. 7) of whether short-term records could provide useful information on extreme wind speeds. If this were the case, short-term records could be used successfully, e.g., for wind climate microzonation purposes. A preliminary investigation into this question was therefore conducted at NBS. The following results were obtained.

First, the best fitting distribution was determined for sets of maximum weekly data and of maximum monthly data taken at seven locations (Washington, D.C.; Denver, Colorado; Great Falls, Montana; Bismarck, N.D.; Chicago, Illinois; Syracuse, New York; Detroit, Michigan). The length of record was three years in all cases. It was found that the sets of weekly data were best fitted by Rayleigh distributions or Weibull distributions with tail length parameter $\gamma > 2$ at five locations, and by the Extreme Value Type I distribution at two locations (Syracuse and Detroit). The same results were obtained for the sets of monthly data.

Second, extreme wind speeds with mean recurrence intervals of up to 1,000 years were estimated at the same seven stations using Eq. 2 and data sets consisting of (a) the largest weekly and (b) the largest monthly wind speeds over three years of record. In all cases it was found that the estimates based upon the weekly data differed insignificantly, for practical purposes, from those based upon the monthly data. The same result was obtained when Eq. 3 was used for estimating the extreme wind speeds.

Third, a comparison was made at 15 stations between estimates of extreme wind speeds based on (a) three-year sets of maximum monthly wind speeds and (b) long-term (i.e., approximately 30-year) sets of maximum yearly wind speeds. At 12 of the 15 stations the differences between estimates based on three years of monthly data on the one hand, and about 30 years of yearly data on the other hand, were relatively small for practical purposes. For example, the estimated 1000-year wind at Detroit based on Eq. 2 was 29.1 m/s (65 mph) if inferred from the maximum monthly speeds recorded in 1968-1970, and 30.4 m/s (68 mph) if inferred from the maximum yearly winds recorded in 1934-1977. The estimated speeds obtained by using Eq. 3 were 32.2 m/s (72 mph) and 34.4 m/s (77 mph), respectively. However, at three of the 15 stations, i.e., Birmingham, Alabama; Burlington, Vermont; and Chicago, Illinois; differences between estimates of the 50-year wind based on the short-term and the long-term records were unacceptably large (of the order of 20% or so).

Such discrepancies are not surprising: indeed, inherent in the estimates are sampling errors which express the fact that any one sample of data taken from a population may not be representative of that population. This may be true even for samples of data covering periods of tens of years. In the case of three-year data samples, the sampling errors may in certain cases be so large as to render the estimates of the extreme wind speeds useless for practical applications. In conclusion, the writer believes that extreme caution is in order if inferences on the extreme wind climate are attempted on the basis of short-term records.

2. EXTREME WIND SPEEDS IN HURRICANE-PRONE REGIONS

A team including M.E. Batts, M.R. Cordes, J.R. Shaver and E. Simiu, all of the National Bureau of Standards, in cooperation with L.R. Russell of L.R. Russell & Associates, who provided the computer program, recently applied Russell's well-known procedure described in Ref. 8 to the estimation of hurricane wind speeds on the Gulf and East Coasts of the United States. The procedure was used in conjunction with data on climatological characteristics of hurricanes given in Ref. 9, and with physical models for the hurricane wind field consistent with Refs. 10 and 11. The results of the NBS calculations are given in Fig. 1 as a function of location along the coast, expressed in nautical miles as shown in Fig. 2.

Inherent in the estimates of Fig. 1 are physical modeling errors, probabilistic modeling errors, observation errors, and sampling errors. On the basis of an error analysis, it is suggested in Ref. 12 that at locations south of Cape Hatteras, the coefficient of variation of the physical modeling, probabilistic modeling, and observation errors is of the order of 10%. However, these errors could be significantly larger at locations north of Cape Hatteras, owing to the possible inapplicability at these locations of some of the physical models used in Ref. 12. Sampling errors, i.e., errors inherent in the fact that the available data may not constitute a representative sample, were estimated using statistical techniques described in Ref. 13. The coefficient of variation of these errors was found to be of the order of 6% to 10%. It is also shown in Ref. 13 that the precision of the extreme wind speed estimates is increased by about 2% to 3% if tropical cyclone, in addition to hurricane data are taken into account in the analysis.

The probability distributions that were found to provide the best fit to the hurricane wind speed data generated by Monte Carlo simulation are of the Weibull type with tail length parameter $\gamma \geq 4$. It is recalled that these distributions have relatively short tails: for example, the increase in the estimated values of the N-year winds was found to be negligible as the mean recurrence interval increased beyond 2,000 years or so.

Finally, it is mentioned that, at locations south of Cape Hatteras, the effect of non-hurricane winds upon the magnitude of the estimated extreme speeds is negligible for winds with mean recurrence intervals exceeding 25 years or so.

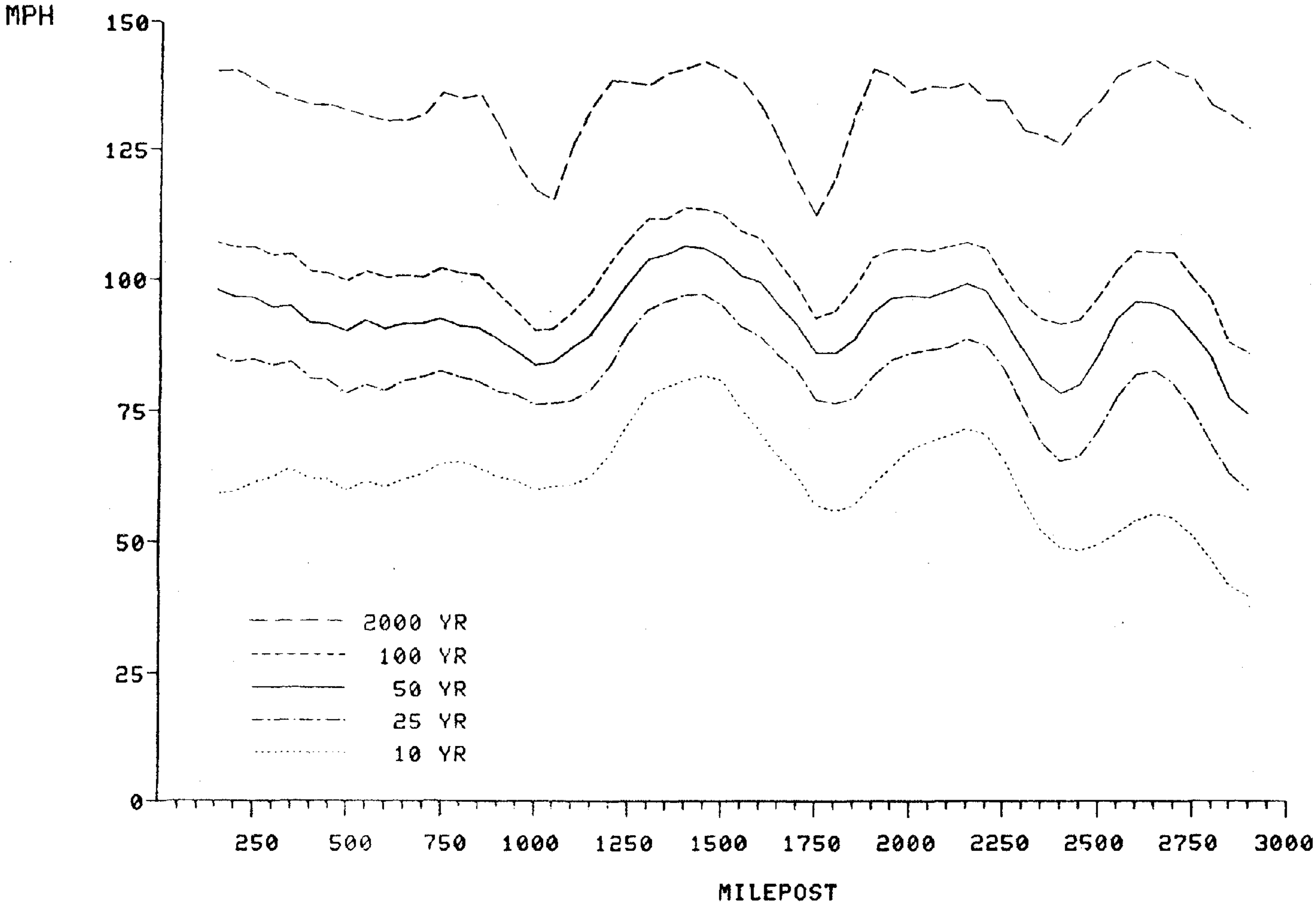

Figure 1. Estimated Fastest Mile Wind Speed Near Coastline at 10 m Above Ground in Open Country, Gulf and East Coasts.

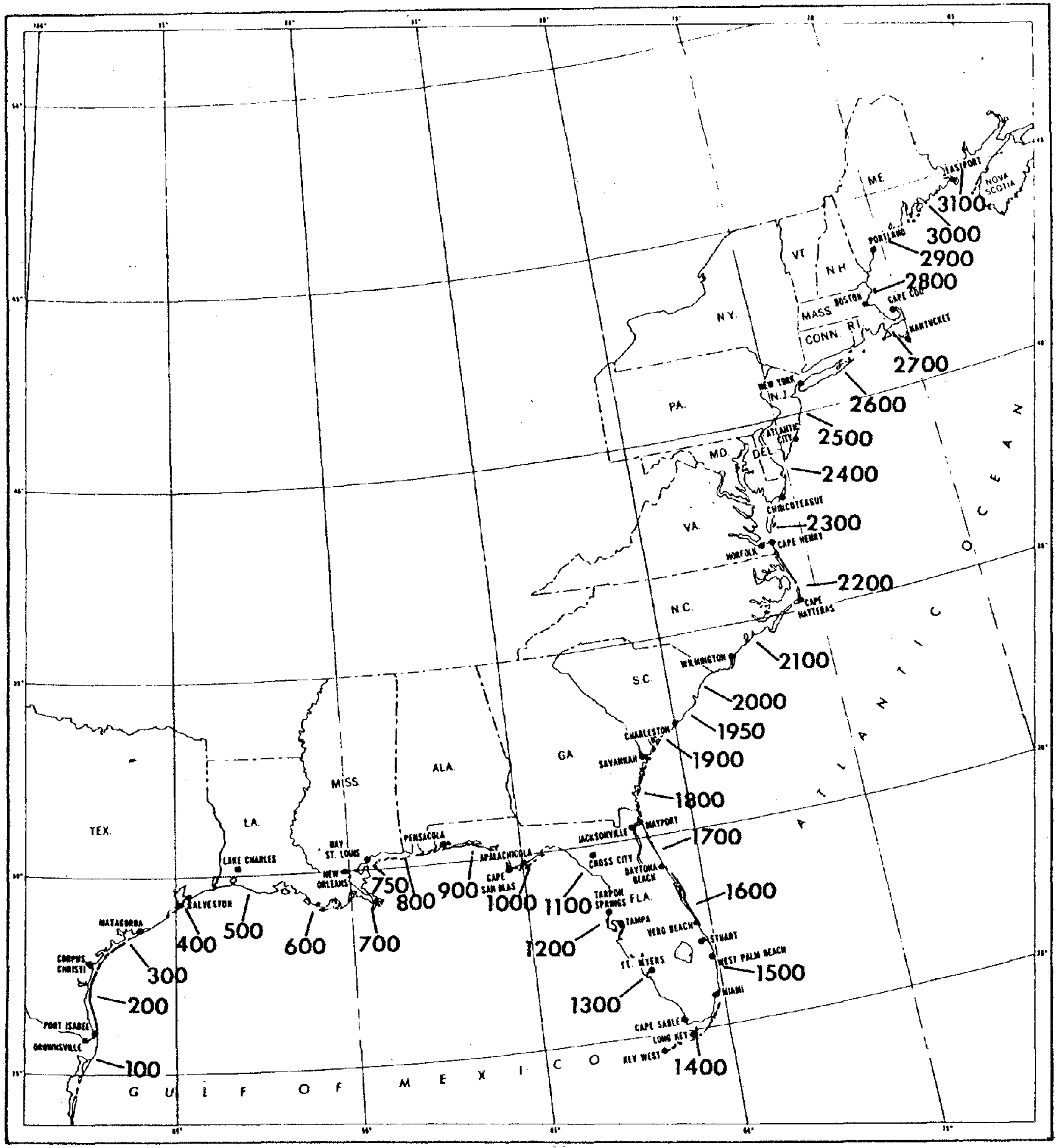

Figure 2 Locations of Mileposts

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METEOROLOGICAL TOWER DATA ARCHIVING AT THE BOULDER ATMOSPHERIC OBSERVATORY

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ABSTRACT

The Boulder Atmospheric Observatory (BAO) located on rolling terrain 30 km (18.6 mi) north of Denver, Colorado, and 25 km (15.5 mi) east of the foothills of the Rocky Mountains provides an atmospheric boundary layer data set for wind climatology assessment. With its 300-m (984 ft) high meteorological tower instrumented with three-axis sonic anemometers, propvanes, slow and fast response temperature sensors, and dew point hygrometers at eight fixed levels, along with an optical triangle for measuring surface winds and divergence, the BAO data are useful for both detailed short-term experiments and longer term wind statistics. The fast-response instruments are computer sampled at 10 Hz and the slower response instruments at 1 Hz. Data are averaged for 20 min; these means and variances and covariances are printed out on a line printer. The 20-min and 10-s averaged data, 10-s grab samples, and spectra are also recorded on magnetic tape and disk storage. The efficient storage of large quantities of data allow quick graphical displays and statistical analysis. The nearly continuously archived wind data, with its relative ease in accessability, adds to wind climatology information in the atmospheric boundary layer.

INTRODUCTION

Although limited by their high cost, height, and fixed location, well-instrumented meteorological towers, because of their detailed data (in the vertical and in time) and continuous operation, can be important for wind climate assessment information. We concentrate here on the Boulder Atmospheric Observatory (BAO) located about 30 km (18.6 mi) north of Denver, Colorado (Fig. 1). BAO is jointly owned by NOAA's Wave Propagation Laboratory and the National Center for Atmospheric Research. The centerpiece of the BAO, a 300-m (984 ft) high tower instrumented at eight fixed levels and built solely for atmospheric research in the boundary layer, provides the major data set for wind climatology at the BAO.

Continuous data acquisition and archiving began at BAO in October 1979, following three major boundary layer experiments and numerous smaller ones during the previous year and a half. The boundary layer winds at BAO are representative of those in the lee of the Rocky Mountains and above gently rolling terrain, for which data have been lacking in climatology studies. Both the quality of the instruments on the tower and the quantity of the data makes the BAO well suited for wind climate studies. Coupled with these is the relatively easy access to the data, both for the purposes of graphical displays or data analysis.

1. INSTRUMENTATION

Table 1 summarizes the standard BAO instrumentation including the wind-measuring instruments. Figure 2 shows the heights of the fixed-level instrumentation and a summary of the measured parameters. (A more detailed account of all the tower instruments is given in (1).) The fast-response sonic anemometers are located near the ends of 4.3-m (14-ft) long booms extending in a direction 26° east of south (SSE) from the tower, and the slower response propeller-vane anemometers (propvanes) are on similar booms to the NNW. With two wind-sensing instruments at each tower level on each side of the tower, we do not lose data when the wind blows through the tower structure into the instrument. We simply use the data from the upwind instrument. We carefully monitor the various data channels for quality and calibrate the instruments when necessary.

Non-standard or visitor sensors may tie into the tower cabling at any fixed level. Also, an instrument carriage with a boom provides connections for the standard fixed level instrumentation and/or other instrumentation. The carriage can be placed at any level or provide profile information.

2. DATA ACQUISITION AND INITIAL PROCESSING

All the data channels are sampled and averaged by a PDP 11/34 minicomputer located in a building about 600 m (2000 ft) from the base of the tower (Fig. 2).

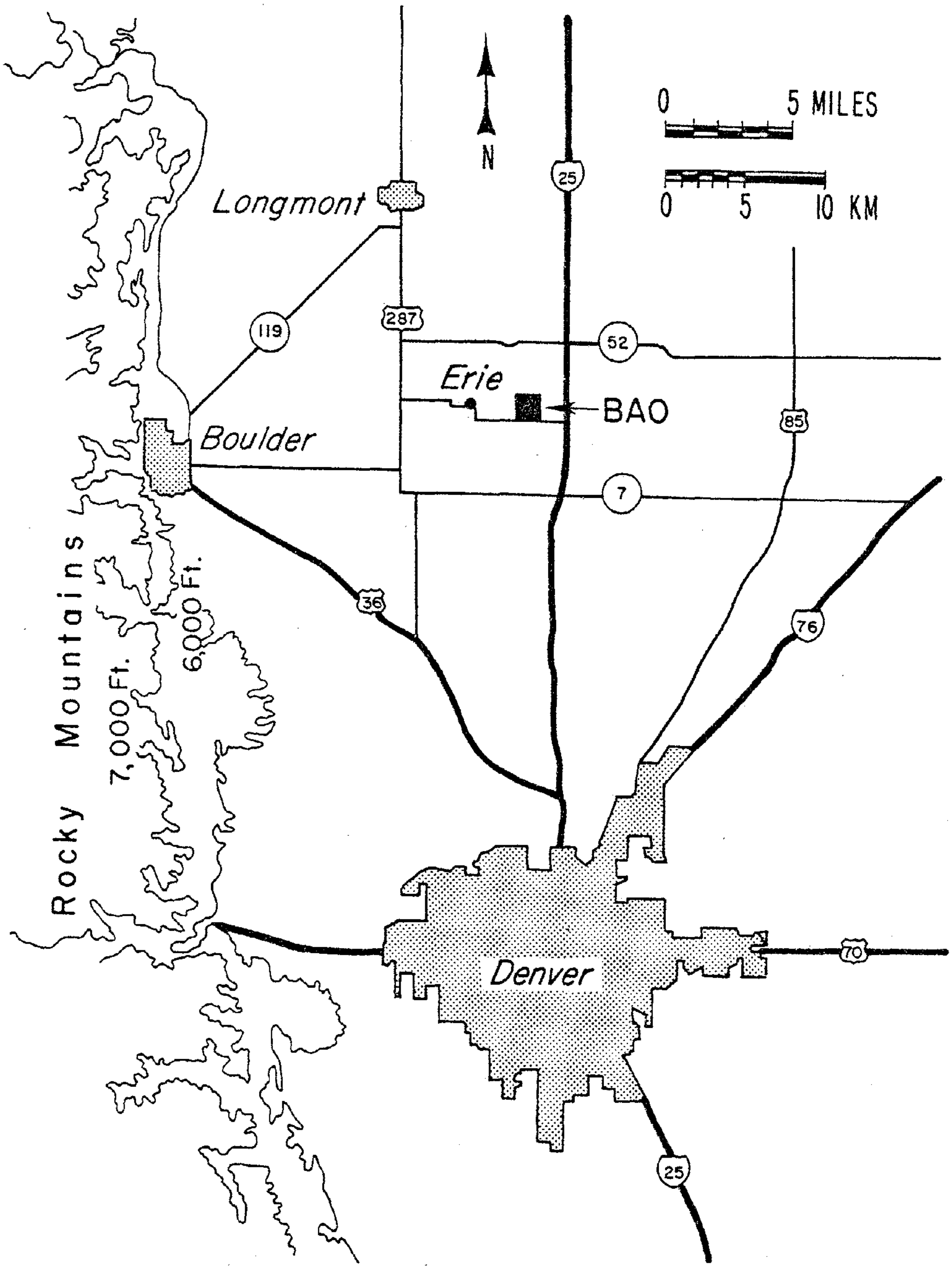

Figure 1. Map showing the location of the Boulder Atmospheric Observatory (BAO) relative to Denver, Boulder, and the Rocky Mountains.

TABLE 1. STANDARD BAO SENSORS

No.	Sensor	Parameter(s) measured	Response characteristic	Rate at which sampled	Location
1	Sonic anemometer	u,v,w	0.05 block-average	10 Hz	SSE boom (all levels)
2	Propeller-vane anemometer	S,D	2.4-m distance constant	1 Hz	NNW boom (all levels)
3	Platinum wire thermometer	θ	5-10 Hz cut-off	10 Hz	SSE boom (all levels)
4	Quartz thermometer	T	1-min time constant	1 Hz	SSE boom (all levels)
5	Cooled-mirror hygrometer	T_d	1-s cycle time	1 Hz	NNW boom (all levels)
6	Absolute pressure	P		1 Hz	Surface (below van)
7	Fluctuating pressure	p		1 Hz	Surface (at 5 locations)
8	Optical triangle	S,D Conv, C_T^2	Spatial average over 450 m equilateral triangle	1 Hz	Surface (outer anchor points)
9	Solar	R	about 5 min	1 Hz	Surface

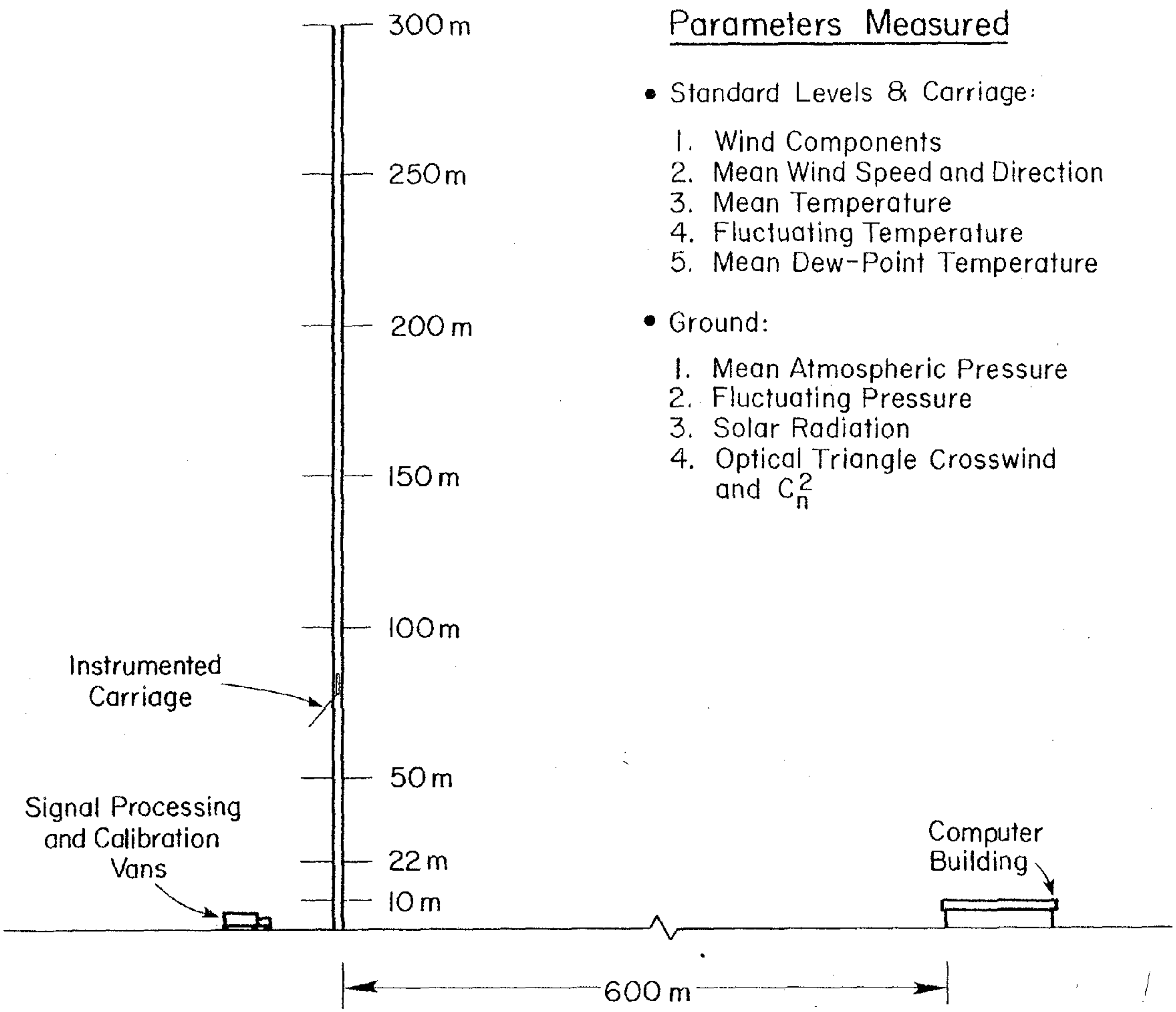

Figure 2. Schematic of the instrumented levels on the tower and the parameters measured at BAO.

The 11/34 software is also able to handle special data channels. Beyond data acquisition, the 11/34 handles the initial processing of the data. For example, the sonic anemometer wind data are converted to standard meteorological NS and EW wind components and horizontal wind speeds and directions. Also, the second moments (variances and covariances) and Obukhov lengths for stability information are calculated every 20 min. The 20-min means of all the data channels at each level and the moments are summarized after each averaging period, providing the user with a nearly real-time look at the data. Table 2 lists and defines the items on the summary sheet.

The PDP 11/34 performs a fast Fourier transform (FFT) on some of the data channels which are sampled at 10 Hz (sonic anemometer and platinum wire thermometer) to calculate spectra of w, the vertical wind component, and temperature, along with the cospectra of w and temperature every 20 min at each level. A 1024-point FFT is computed every 102.4 s, and eleven successive spectra are averaged in time. The resulting spectrum is block averaged over non-overlapping frequency intervals to provide roughly equal spacing of center frequencies on a logarithmic scale. The schematic of this "high frequency" spectrum is presented in Fig. 3. The frequency range is from 9.8×10^{-2} Hz to 4.4 Hz, containing 22 spectral estimates.

The 11/34 also calculates 10-s averages of all channels and 10-s "grab" samples (a data point every 10 s) for the fast response channels. This information, along with the 20-min means, moments, and spectra, is recorded on magnetic tape and also sent over a high-speed data link to a PDP 11/70 multi-user minicomputer at the Wave Propagation Laboratory in Boulder. Figure 4 summarizes the acquisition and initial processing of the data.

3. ARCHIVING AND FURTHER PROCESSING

The data sent to the 11/70 are recorded on magnetic disks. Because of the limited disk space, only the latest two weeks of data are stored on the disk. For long-term archiving, the data are recorded on magnetic tape. The tapes from the 11/34 at BAO are used mainly as backup in case the 11/70 or its data link with BAO is disrupted.

TABLE 2. SUMMARY DATA EXPLANATION

1. AVERAGED PARAMETERS

VWES	Horizontal wind component from west (sonic).
VSOU	Horizontal wind component from south (sonic).
W	Vertical wind component (sonic).
VH	Horizontal wind speed (sonic).
AZ	Horizontal wind direction (sonic).
PVS	Horizontal wind speed (prop-vane).
PVD	Horizontal true wind direction (prop-vane).
T	Temperature (quartz thermometer).
TD	Dew point (dew point hygrometer).
L	Obukhov length.

2. 2nd MOMENTS

UU, VV, WW, TT, UV, UW, UT, VT, UW, WT

where:

U	(=u)	Longitudinal wind component (sonic)
V	(=v)	Lateral wind component (sonic)
W	(=w)	Vertical wind component (sonic)
T	(=θ)	Temperature (platinum wire)

3. OPTICAL TRIANGLE

V	wind speed
AZ	wind direction (CW)
CONV	convergence
CN-SQR	structure parameter for refractive index x 10^{12}

(from measurements along legs of an equilateral triangle, 450 m on each side, centered on tower.)

4. RMS PRESSURE VALUES

STN 1, STN 2, STN 3, STN 4, STN 5.

(from Δp pressure stations around the tower.)

5. PRESSURE

mean surface pressure

6. SOLAR RAD

mean solar radiation (direct and diffuse)

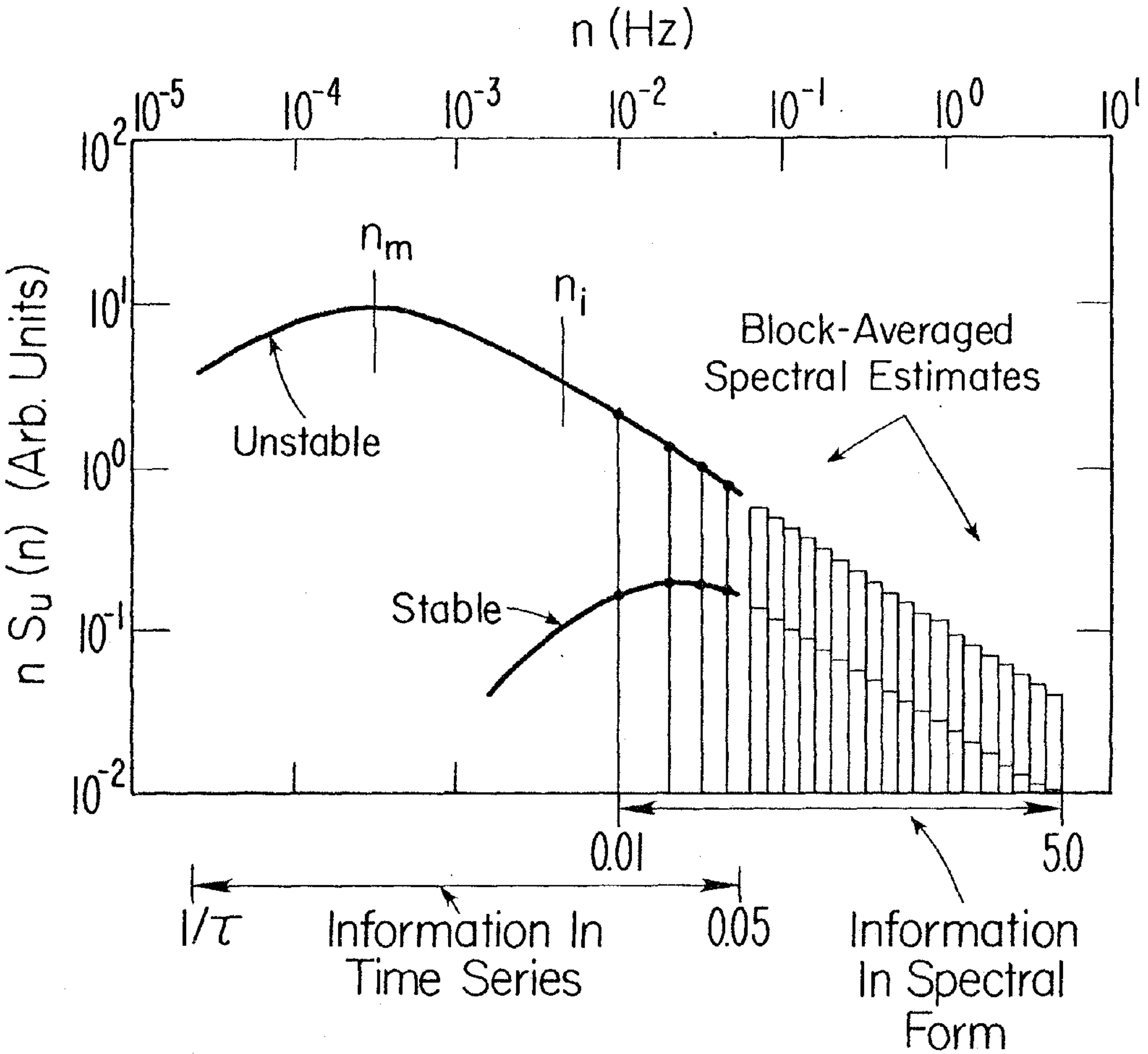

Figure 3. Spectra showing the bandwidths of the averaged high-frequency spectral estimates and the block-averaged time series. The frequencies n_m and n_i correspond to the spectral peak and the onset of the -5/3 inertial subrange, respectively (Courtesy of J. C. Kaimal.).

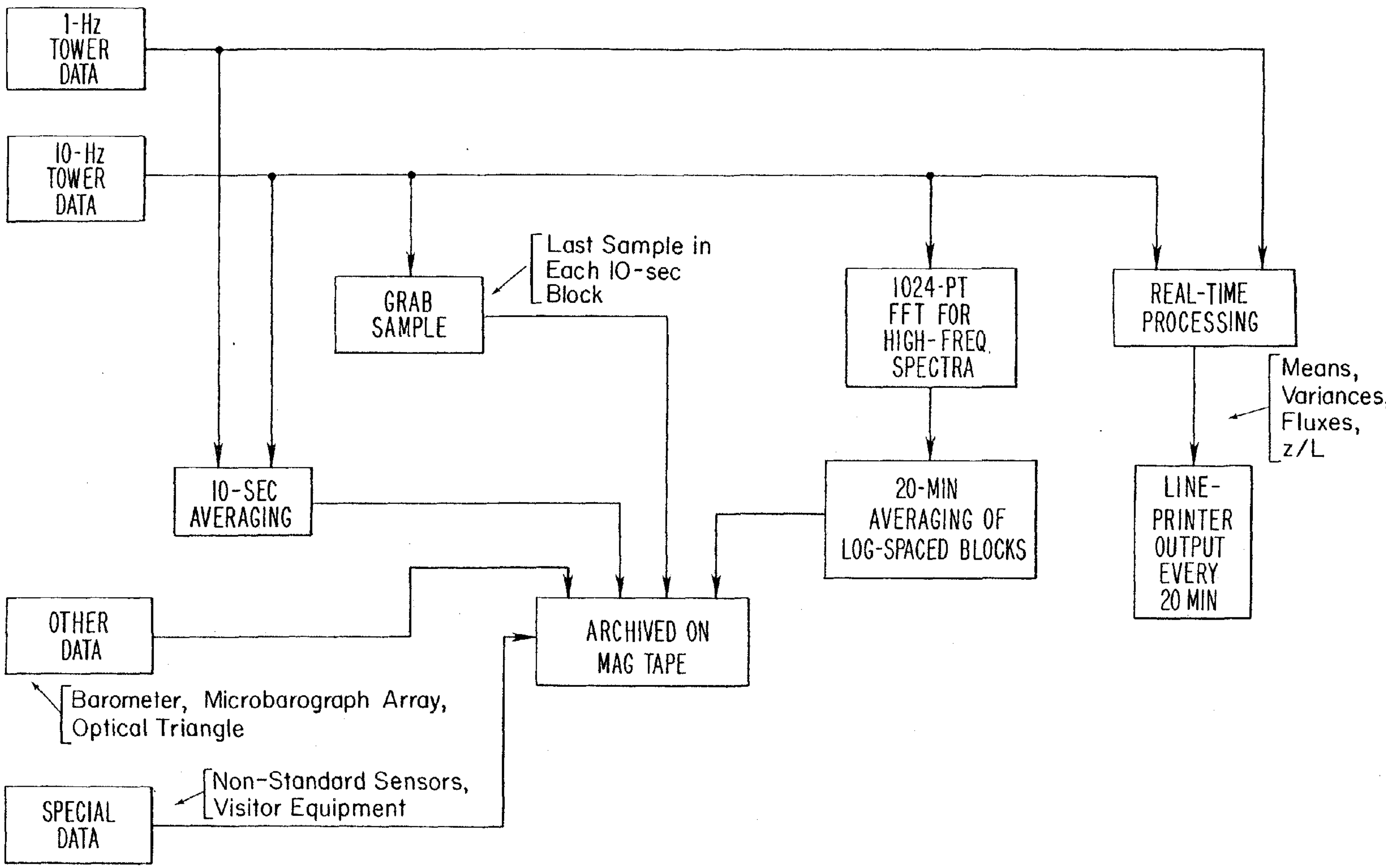

Figure 4. Schematic of the acquisition and initial BAO data processing.

The 11/70 at WPL provides many users with easy access to BAO data through dedicated terminals or phone lines. Plotting and statistics programs are available or the user may write his/her own processing or data analyzing software. An example of such a program is one that computes the spectra from the archived 10-s mean data and combines this with the real-time calculated high frequency spectra. To compute the low frequency spectra, the 10-s data are first zero filled to total 512 points for the FFT. A time series from 40 min to 100 min can be spectral analyzed. Because the 100-min time series totals 600 points, two overlapping FFT's are averaged for the spectra. The full spectrum is schematically illustrated in Fig. 3. The low and high frequency sections of the spectrum are combined between 0.024 and 0.029 Hz. Two smoothed spectral estimates each are lost from the low and high frequency spectra making a total of 35 points for the full spectrum. We also present the difference in spectra expected in an unstable and stable boundary layer in Fig. 3.

Figure 5 shows a plot of the frequency distribution of the 10-s averaged longitudinal component of the wind (u) from the sonic anemometers for all the levels combined. This is an example of a result from a statistics program available on the 11/70 and represents data gathered during an experiment during September 1978. Notice the nearly Gaussian distribution in this case.

To aid in the access to BAO data, the 11/70 disk contains data descriptor information. These descriptor files contain the 20-min mean data only, with less resolution than that on the detailed data files described above. The descriptors allow us to store very large quantities of data recorded over many months time and are useful for "quick-look" analysis. Also, within the descriptor files are data flags that warn of defects, e.g., wind blowing through the tower, or instrument failure which can produce spikes in the time series or kinks in the profile. More detailed information on data storage and retrieval in the context of a particular experiment in September 1978 can be obtained in Chapters 2 and 17 of (2).

Between October 1979 and October 1980, BAO data will be continuously archived. We hope to remain in the archiving mode even longer, but even if this does not occur, many BAO data will be available for many years to come for wind climatology assessment.

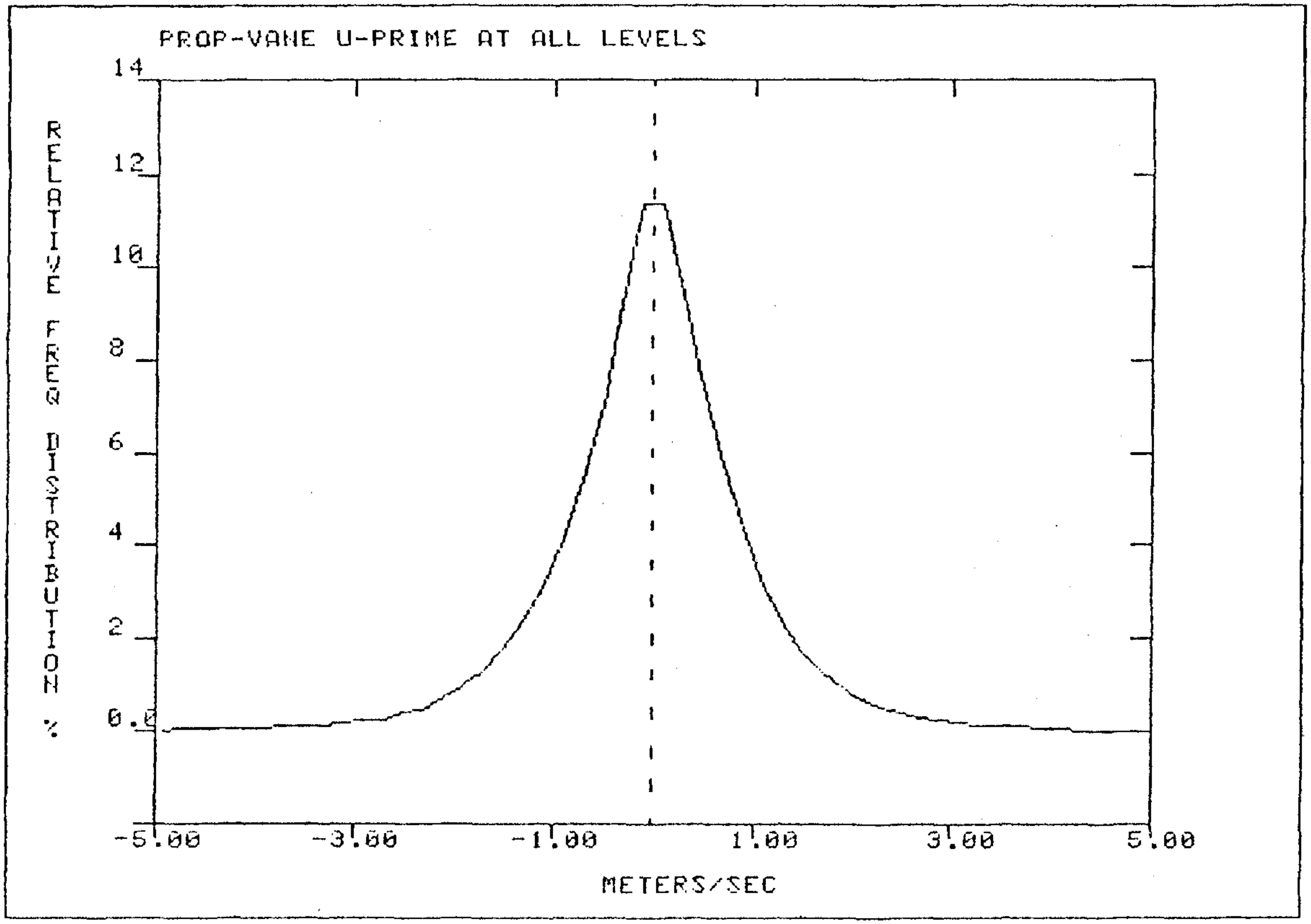

Figure 5. An example of the frequency distribution of the 10-s averaged longitudinal wind component, u, from the sonic anemometers for all tower levels combined.

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ASSESSMENT OF WIND CLIMATE FROM INDIRECT ESTIMATES

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Certain types of wind phenomena are difficult to measure by anemometers because of their short life and rare probability of occurrence. These wind phenomena include dust devils, waterspouts, tornadoes and downbursts. Both indirect and remote methods are used to measure and characterize these phenomena. Indirect methods are defined here as those which use damage or debris patterns as indicators of the wind character. Other measurements are made by remote means or by photogrammetric analyses of movies or photographs.

INDIRECT METHODS

Structural analysis has been used for estimation of tornado windspeeds by a number of researchers (Segner, 1960; Mehta, et al., 1976, 1978). Calculations based on components that have failed give lower bound windspeeds to cause the damage. Undamaged components that survive high windspeeds give upper bound values.

Windspeed estimates from damaged structural components require knowledge of material properties, construction details and resultant wind pressures created by the winds. Careful documentation of the damage is required if accurate measurements are to be obtained.

Besides structural components, numerous other elements have been used for windspeed estimates. They include missiles, tombstones, transmission towers, signs and utility poles. The validity of the windspeed estimates depends primarily on the "sensitivity" of the member to the dynamic effects of the wind. Mehta (1976) developed a "credence factor" for judging the reliability of a windspeed estimate. Structural components, such as cladding, roof slabs or roof support members, have relatively high natural frequencies compared to the wind gust frequency.

Windspeed estimates based on these components have a relatively high credence level. Flexible members, such as signs, light poles and transmission lines, have natural frequencies in the same range as the wind gust frequencies. Their credence levels are relatively low.

Ground marks left in loose soil, cultivated fields or the fall direction of trees are used to determine characteristics of the near ground winds. Cycloidal ground marks and convergent tree fall are indicative of tornado flow patterns near ground level (Fujita, et al., 1967). Divergent patterns near the ground are indicative of downbursts (Fujita, 1978).

REMOTE METHODS

Remote measurements are used because of difficulty in obtaining anemometer measurements. The devices used are capable of determining windspeed magnitude, as well as certain flow characteristics.

Doppler Radar has been used to identify potential vortical flow. In addition, Fujita used Doppler Radar in Project NIMROD to obtain basic information on downbursts. Doppler Radar holds promise for tornado prediction and detection, also.

Doppler Lidar, mounted on both land-based and aircraft equipment, has been used to study dust devils and waterspouts. Like Doppler Radar, the Lidar is capable of identifying wind flow characteristics.

Aircraft probes to date have not been used to study tornadoes, but have been used effectively to study waterspouts. A probe attached to the aircraft wing contains instrumentation for measuring various meteorological parameters.

PHOTOGRAMMETRY

The first significant attempt at photogrammetric analysis of a tornado movie was done by Hoecker (1960) on the Dallas tornado of 1957. Results from this analysis have been used by numerous researchers as a basis for identifying a suitable tornado model for engineering applications. Since 1960, a number of other films have been analyzed by personnel at the National Severe Storms Laboratory and the University of

Chicago (Golden and Davies-Jones, 1975; Fujita, et al., 1976; Zipser, 1976). Although there are definite limitations on photogrammetric analysis, it gives significant information on wind flow in the surface of the visible funnel.

FUTURE NEEDS

All of the methods mentioned above can be used effectively to gain more information on wind phenomena. Additional information is needed on windspeed versus appearance of tornado damage. The Fujita scale (Fujita, 1971), which is used to rate tornadoes according to intensity, needs verification by windspeed measurements which can be either indirect or remote.

The phenomena, for which Fujita coined the name "downburst", has been blamed for several aircraft accidents. The appearance of crop and tree damage has been used to identify downbursts. Additional research is needed to further document and verify the downburst concept.

The measurement methods described above all have potential for defining and identifying certain wind characteristics. In addition, we need to continue to improve statistical records of the phenomena. Reliable statistics are needed in order to make better risk analyses, especially for tornadoes.

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CLIMATOLOGY OF TORNADO PARAMETERS

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ABSTRACT

A tornado data base containing information about 18,545 tornadoes is examined. It is found that path length, width and area are not log-normally distributed. Using empirical methods, an estimate of tornado hazard potential is obtained.

INTRODUCTION

Models of tornadic wind effects have historically suffered from the lack of a climatological data base from which to work. In an effort to overcome this problem, the National Severe Storms Forecast Center and the Nuclear Regulatory Commission have established a tornado data base containing the characteristic parameters (time, touchdown point, retraction point, length, width, severity, etc.) of the 18,545 confirmed tornadoes that occurred between January 1, 1950 and December 31, 1977 in the coterminous United States. From these data, it is possible to make quantitative assessments of tornado risk as a function of either time of day (1,2) or geographical location (3).

GEOGRAPHIC DISTRIBUTION

The geographic distribution of tornadoes can be constructed by tabulating the touchdown point of each tornado within a 2° Marsden (latitude - longitude) square. To account for the spherical earth, these totals are then normalized by area and by year. Such a presentation, with numbers printed at 1° latitude/ longitude intervals is shown in Figure 1.

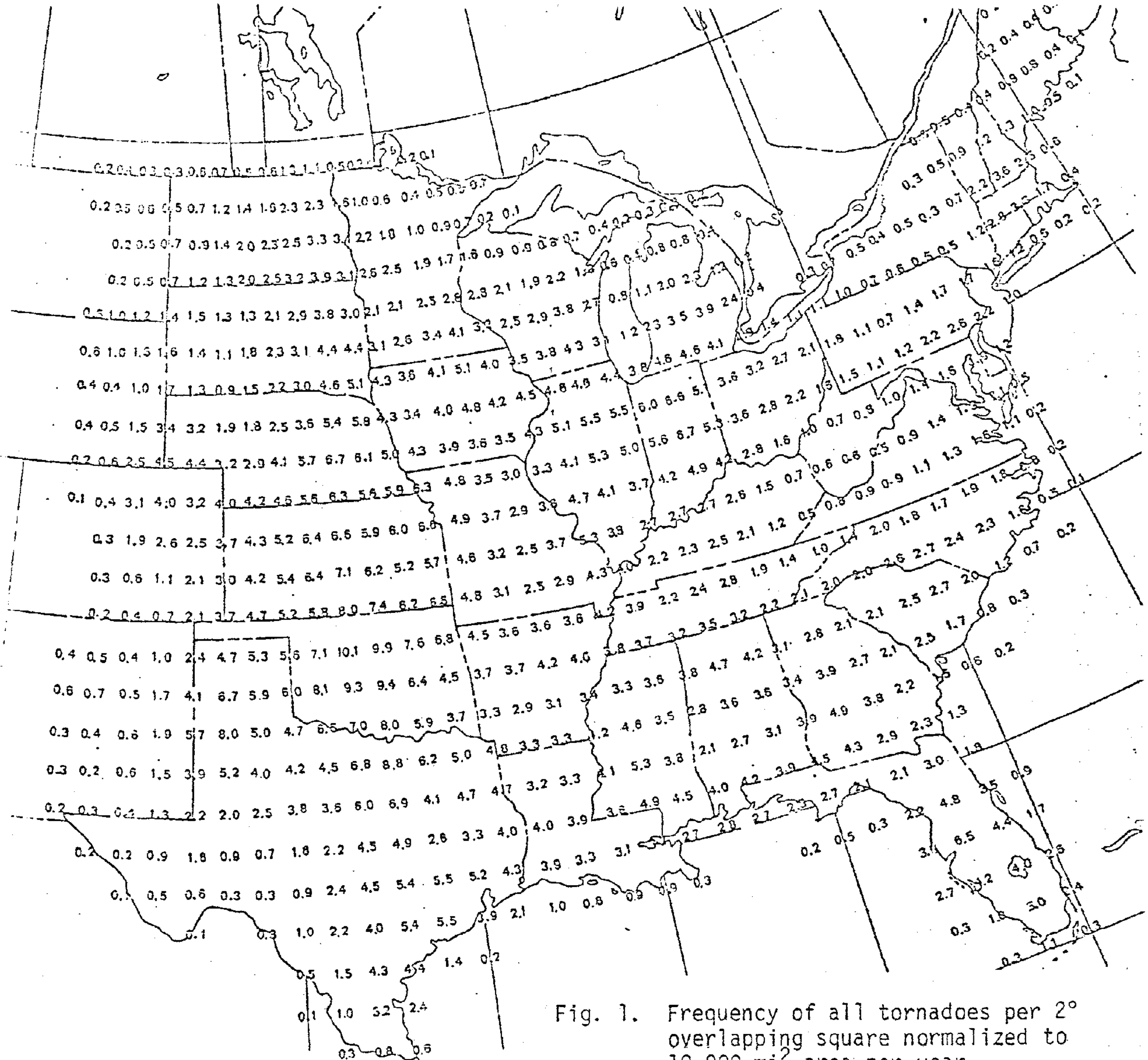

Fig. 1. Frequency of all tornadoes per 2° overlapping square normalized to 10,000 mi² area per year.

"Tornado Alley" running between 97 and 98° W is quite apparent. Also a secondary axis of increased tornado activity, curving from southwest to northeast starting at the Caprock escarpment of west Texas, passing through northwest Missouri and ending in north central Indiana can be seen.

When possible, the estimates of the tornado intensity, path length and path width have been categorized via the FPP (4) classification system (Table 1). Of the recorded tornadoes, an F index could be assigned to 16,709 of them and all indices could be computed for 10,204 storms. The assignment of an F-scale rating to a tornado is made by qualitatively assessing the degree of the worst damage it produced. Recent studies indicate that the wind speeds associated with F4-5 tornadoes may be too great (5).

TABLE 1: Ranges of wind speed, path length and path width included within F, PL, PW and A indices (4).

Scale	F(mph)	PL(mi)	PW(yards)	A(mi^2)
0	<72	<1.0	<17	<0.001
1	73-112	1.0-3.1	18-55	0.001-0.009
2	113-157	3.2-9.9	56-175	0.010-0.099
3	158-206	10-31	176-556	0.100-0.999
4	207-260	32-99	0.34-0.9*	1.000<9.999
5	261-318	100-315	1.0-3.1*	10.00<99.99
6	319-380	316-999	3.2-9.9*	100.0<999.9

*miles

Violent tornadoes are defined as those in categories F4 and F5. Since 1950 only 340 such tornadoes have been reported. Because of the small number of storms, the isotorn map of violent tornadoes (Fig. 2) is statistically questionable. Of the four separate incidence maxima that are evident, two can be directly attributed to one or two tornado outbreaks.

Contoured fields of other tornado features are also possible. A tornado's path length is directly related to the probability of damage associated with that storm. As the path length increases, the odds of a given storm hitting a heavily populated area increase. In the data base, 325 tornadoes had "long tracks" (PL 4 and 5). Two favored zones are evident (Fig. 3). One corresponds to tornado alley, while the other stretches from east-central Texas east-northeastward. This second path is often referred to as the "Dixie alley".

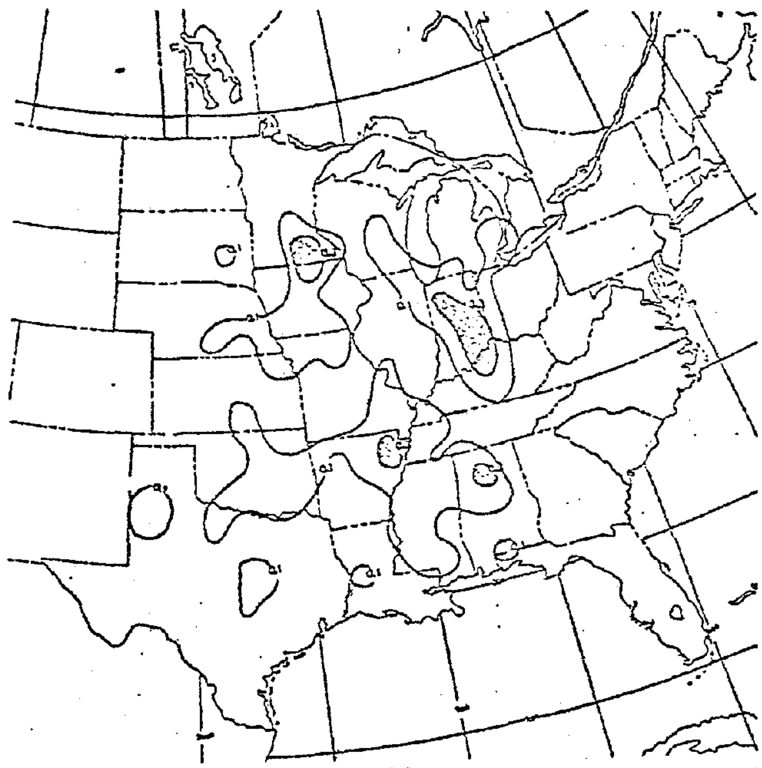

Fig. 2. Frequency per 2° overlapping square for violent tornadoes normalized to 10,000 mi^2 area per year.

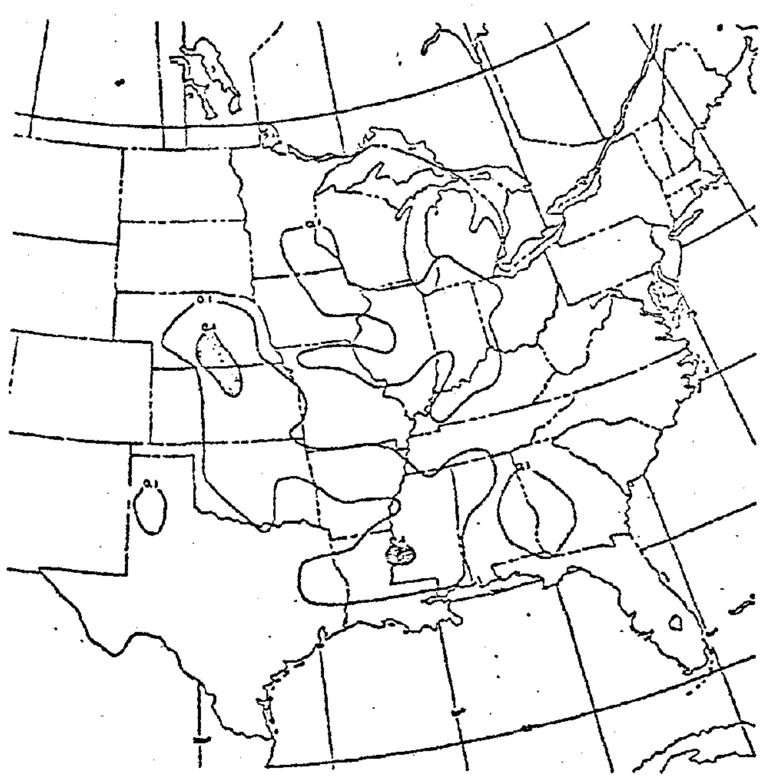

Fig. 3. Frequency per 2° overlapping square of long-path tornadoes normalized to 10,000 mi^2 area per year.

CORRELATION BETWEEN LENGTH, WIDTH, AREA AND INTENSITY

Various tornado hazard models are based upon postulated correlations between tornado parameters. To determine if any strong correlations exist, the actual reported length and width of the tornadoes in the data base were examined (Table 2). Path length has only a 0.25 ± 0.03 correlation to track width. Thus only 6% of the variance can be explained by a linear correlation of a tornado's track width to its path length. The correlation coefficient increases to 0.53 when a logarithmetic relationship is used.

TABLE 2: Correlation Coefficients

	Length to Width		Length to Area		Width to Area		Sample Size
	Actual	*Log.*	*Actual*	*Log.*	*Actual*	*Log.*	
All Tornadoes	0.25	0.53	0.68	0.92	0.57	0.82	10,826
Weak Tornadoes (F0&1)	0.17	0.48	0.62	0.91	0.57	0.80	5,903
Strong (F2&3)	0.16	0.38	0.63	0.89	0.59	0.75	3,987
Violent (F4&5)	0.09	0.25	0.74	0.86	0.53	0.71	314

Since damage area is the product of length and width, stronger correlation is possible between length and area or width and area than is obtained for length to width. Indeed, there is a 0.68 correlation between length area and a 0.57 correlation between width and area. Using a logrithmatic transformation, both of these correlations become extremely strong; however, it is the correlations between the actual measurements which are important. When logarithms are considered, small numerical deviations lose significance.

Heuristically, it seems reasonable to argue that more intense tornadoes have more organization and thus their length and width should be more closely related than in lesser storms. In reality this does not occur. In fact, as the storm intensity increases, there is a slight tendency for the length-width correlation to decrease. However, the variation of the correlation coefficient with intensity is not significant at the 2.5% level. In general, relationships between track parameters are not better defined statistically for more intense tornadoes.

DISTRIBUTION OF LENGTH, WIDTH AND AREA

For the 10,826 tornadoes for which an area could be computed, the average path length is 6.0 miles with a standard deviation of 12.2 miles. While a logrithmatic distribution of these data (Fig. 4) appears to approximate normality, a log-normal distribution is rejected at the 1% level by both the X^2 and the Kolmogorov-Smirnov tests. This rejection results from both the skewness and leptokurtic nature of the distribution. The abnormally high frequency of reports in the lowest length category accounts for the skew and is possibly the result of a tendency to report lengths in decimal increments, with 0.1 mile generally being the shortest path recorded.

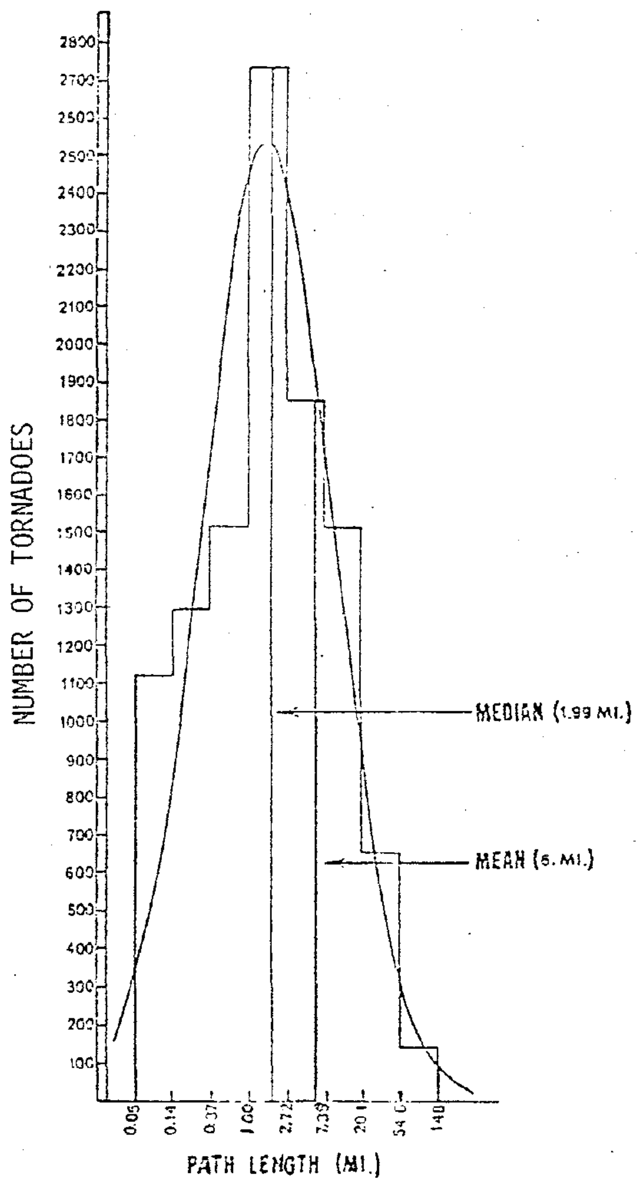

Fig. 4. Distribution of path length.

Perhaps a sizable proportion of the lengths in the 0.05 to 0.14 mile increment should really be in a smaller category. Shifting them would decrease the mean and reduce the skewness. However, this would result in increasing the standard deviation and aggravating the leptokurtic condition. Conversely, if long-track reports are dismissed as erroneous, the observed distribution approaches a log-normal one. While this approach appears in the literature, such a cavalier rejection of data is questionable. Wilson and Morgan (6) have shown that a small but significant proportion of tornadoes have paths greater than 100 miles.

Log-normality is also not found in either the track width (Fig. 5) or area distributions (Fig. 6). This is in agreement with the findings of Twisdale (7)

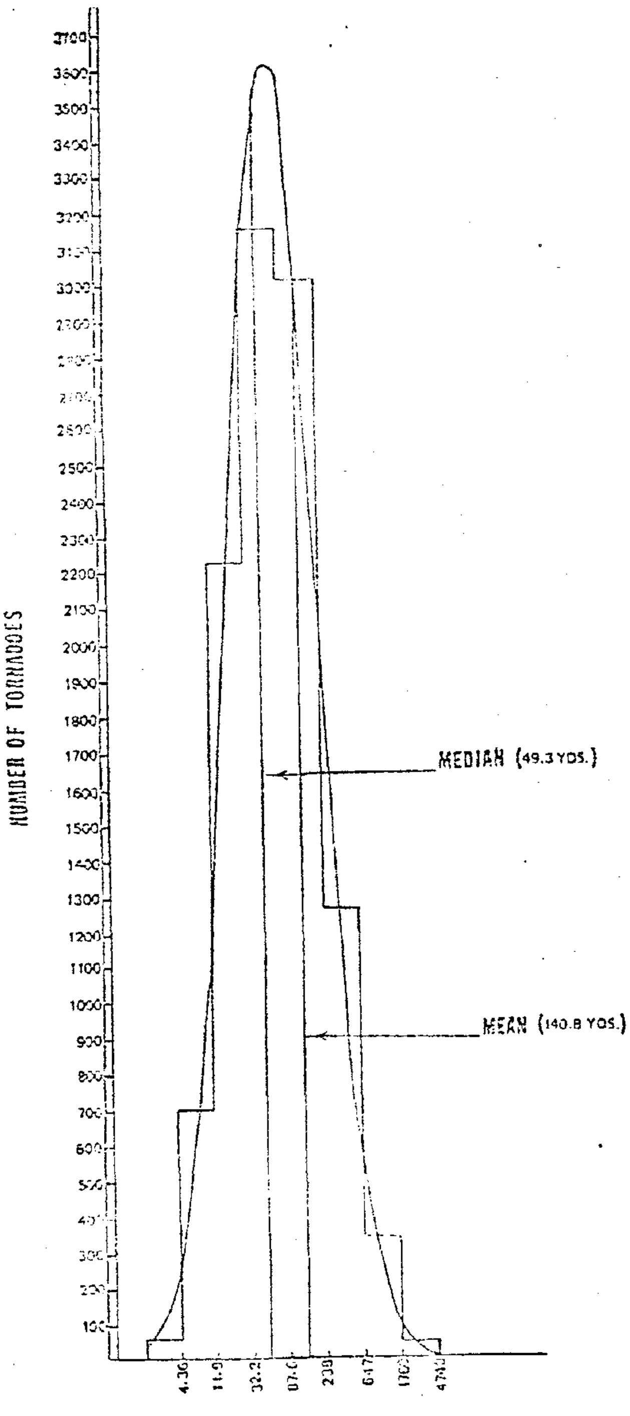

Fig. 5. Distribution of path width.

who considered FPP indices for a considerably smaller sample.

The characteristics of tornado parameters as computed from the NSSFC-NRC data are summarized in Table 3. Other commonly cited values are also given. Emphasis must be given to the fact that mean area does not equal the product of mean length and mean width. This would only be true if there were no correlation (ρ=0) between the length and width measurements. Because the distributions are skewed, the median tornado characterizes the typical tornado and has a length of 1.99 mile, width of 49.3 yards and devastates an area of 0.06 mile^2.

TRACK PARAMETERS VERSUS INTENSITY

The mean and standard deviation of the length, width and area as a function of tornado intensity are listed in Table 4. In contrast to the correlations, there is a definite tendency for the means to increase as the storm's intensity increases. Further, by using the central limit theorem of statistics, it can be shown that these trends are significant at the 5% level. Thus, the mean violent (strong) tornado is longer, wider, and devastates a greater area than the mean strong (weak) one.

There has been speculation that tornadoes follow a two-dimensional normal distribution between the A (area) and F (intensity) indices of Table 1 (11,12).

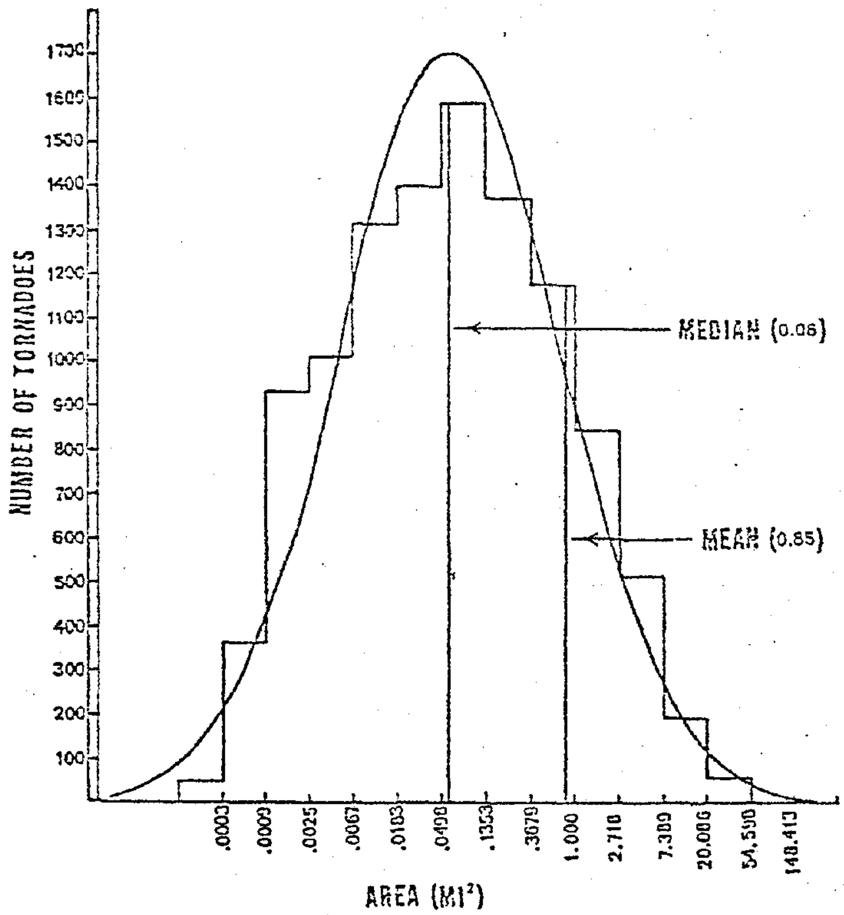

Fig. 6. Distribution of track area.

TABLE 3: Estimates of Expected Tornado Length, Width and Area

SOURCE	LENGTH (mi.)	WIDTH (yd.)	AREA (mi^2)
Mean	6.0	140.8	0.85
Expected Log-Normal	6.72	134.4	1.50
Thom (10)	10.94	259.87	2.82
Howe (11)	4.7	165.0	0.96
Skaggs (12)	-	-	1.82
Hart (13)	-	-	1.66
Garson *et al.* (14) (Model)	3.64	98.6	0.47
Garson *et al.* (14) (histogram)	3.30	107.0	0.36
Brown and Roberts (9)	-	176.0	-

TABLE 4: Mean tornado parameters as a function of storm intensity.

		Length (mi.)		Width (yd.)		Area (mi^2)	
INTENSITY	*Sample Size*	*Mean*	*Standard Deviation*	*Mean*	*Standard Deviation*	*Length*	*Standard Deviation*
All Tornadoes	10,826	6.00	12.20	140.80	221.80	0.85	3.18
Weak	5,903	3.06	6.89	88	140.80	0.24	0.91
Strong	3,978	8.93	1.43	193.60	264.00	1.35	3.74
Violent	314	25.72	27.80	422.40	369.60	6.65	10.2

This distribution is given in Table 5. The mean A is 2.78 with a standard deviation of 1.156 while the mean F is 1.90 with a standard deviation of 0.997. The correlation between A and F is 0.54.

TABLE 5: Distribution of 10204 tornadoes by force and area indices.

5	–	–	–	4	18	19
4	–	3	16	61	150	43
3	3	29	144	365	363	64
2	39	326	874	1208	527	45
1	196	998	1514	1086	286	9
0	320	827	452	177	38	–
F / A	0	1	2	3	4	5

From these statistics, the joint-normal distribution can be calculated. The maximum normalized difference between observed and expected cell frequency is less than 0.025. However, the distribution fails the normalcy tests at the 5% significance level. Too many tornadoes occur when both A and F are low or high and too few occur at mid-values for the postulated joint-normal distribution to be valid.

ASSESSMENT OF TORNADO HAZARD

When the area of each Marsden square is divided by the annual average tornado-affected area, an estimate of the tornado hazard is obtained. If a quasi-continuous distribution of this field is assumed, an isopleth chart (Fig. 7) can be drawn. Primarily this chart shows the geographic variance of the number of square miles which will contain one square mile of tornado damage in an average year.

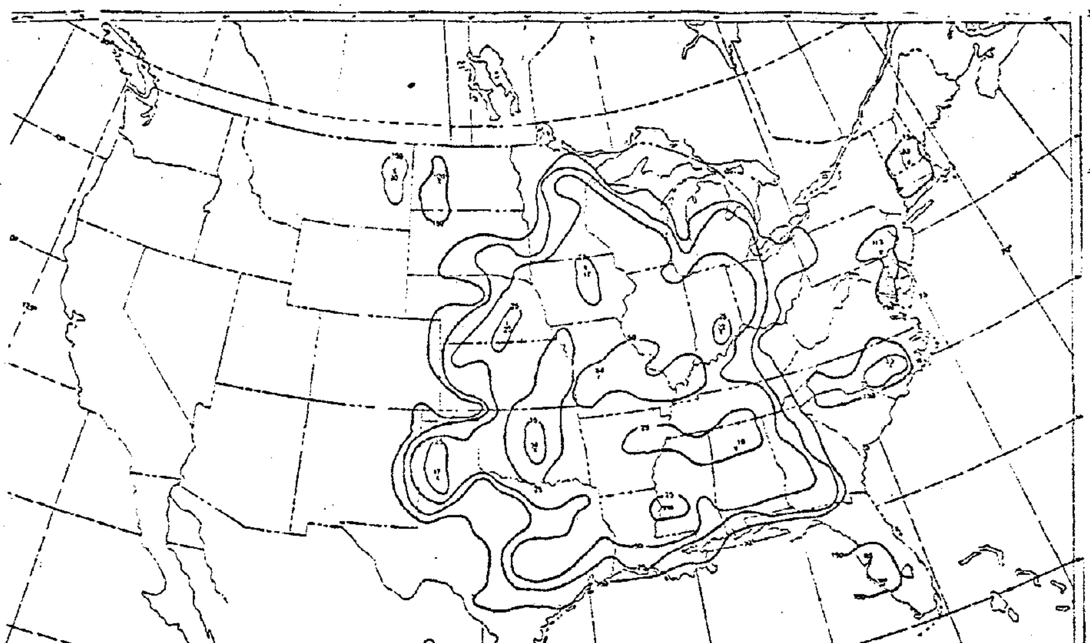

Fig. 7. Isopleths (mi^2-century) of the area-time product which will in the mean encompass 1 mi^2 of tornado damage.

By further assuming that tornado paths do not overlap or intersect, this chart can be interpreted as showing the mean recurrence interval (MRI) of tornado strikes. It must be emphasized that since the area of tornado damage has been calculated in miles, the MRI is valid only for a one square mile area (circle of radius 0.56 mi) surrounding a point. However, for sites larger than 1 mi^2, an MRI estimate can be estimated from the area-time data. Consider the Kansas City metropolitan area (1,643 mi^2). The Marsden square which contains Kansas City has 1 mi^2 of tornado damage for every 1,827 mi^2 per year. Thus, there will be 1 mi^2 of tornadic damage for every 1,643 mi^2 in 1.1 years or a mean recurrence interval of 13 months.

If the MRI is multiplied by 0.69 (see ref. 8), the median tornado occurrence period is found. This is the time span during which there is a 50% chance of a given 1 mi^2 area being devastated by a tornado. Thus from Fig. 7, it can be found that a site in central Oklahoma has an even chance of a tornado strike in 966 years. The MRI can also be used to determine the probability, P, of a tornado strike over a span of N years. The formula is $P\{N\} = 1-(1-1/MRI)^N$. Again over central Oklahoma, it is found that the probability of a tornado strike in 50 years is 3.46%.

SUMMARY

A brief overview of the potential information content of the data collected in the joint NSSFC-NRC project has been presented. While it is still possible to upgrade further the quality of the tornado record, the bias in the historical data set has been considerably reduced.

In closing, we would like to echo the conclusion of a classic paper in tornado climatology (9). "*It might be said at this point that it is not the* purpose of the paper to criticize other than constructively and to indicate a possible better method of handling difficult material or data. These statistical studies are to be used as signposts indicating possible lines of research from which the origin and causal conditions of these phenomena may be derived."

ACKNOWLEDGEMENTS

This work was performed under Interagency Agreement AT49-25-1004 between the Office of Nuclear Regulatory Research and the National Severe Storms Forecast Center, National Weather Service, NOAA. Special gratitude is owed to Beverly Lambert who prepared the manuscript. We would like to express our appreciation by giving a lagniappe to our colleagues in Techniques Development Unit (Drs. C. Doswell, R. McNulty, and Mr. L. Lemon), to the forecasters in the SELS Unit (particularly Messrs. J. Galway and R. Williams) and to Mr. Allen Pearson, Director, National Weather Service Central Region. Without their assistance, this work would not have been possible.

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DISCUSSIONS OF SESSION III

* * *

B. J. Vickery

The recently published report by Simiu, Changery and Filliben presents extreme speeds (fastest-mile at 30 ft. in open country) for 129 stations in the contiguous U.S. These speeds were, in the main, determined by fitting Type I distributions to observed annual maxima. A question raised at the Workshop was whether thunderstorms played a significant role in these maxima and whether separation of the data into storm types would produce significantly different estimates. The data necessary for an analysis of the type adopted in Australia is not immediately available but some of the Australian observations can be used as a basis for comparison. Significant features of the Australian data were;

i) both EPS and thunderstorm maxima are, individually, well fitted by Type I distributions.

ii) the modes of the two distributions are generally comparable.

and iii) the slope of the thunderstorm distribution is roughly twice that of the EPS.

If the distribution at a particular station does exhibit the above characteristics the composite extreme value distribution (i.e. that used by Simiu et al) will be mixed and will exhibit a break in slope with the slope roughly doubling. The Australian data suggests that the break might occur at low values of R (about 2, say).

With these observations in mind the writer reviewed the data of Simiu et al with the aim of identifying distributions exhibiting the characteristics described above. Not all stations were examined and attention was limited to the fifteen stations for which the distributions were given in graphical form. It is emphasized that this is not a representative sample as many were presented in this form to demonstrate a departure from a Type I distribution. This cursory review indicated that seven of the fifteen did indeed exhibit a marked break in slope and two of these are shown here as Figures 1 and 2 [Grand Rapids, Michigan and Minneapolis, Minnesota].

If we assume that the break is indeed associated with a mixed distribution of thunderstorms and EPS storms then Type I distributions can be fitted to each section. Extreme speeds predicted from these can then be compared with those derived by Simiu et al. The separate Type I distributions fitted "by eye" are shown in Figures 1 and 2 together with the single distribution used by Simiu et al. The resulting predictions of the extreme speeds at 100, 1000 and 10,000 years are given in Table 1. The differences between the two methods are undoubtedly significant.

The method employed here in dealing with the apparent mixed distribution is not adequate and an approach using the parent distributions of the storm types is essential if an acceptable level of reliability is to be attained. The only point that the writer wishes to make is that there is evidence that more than one storm type is contributing at some U.S. stations and that the problem should be studied further before estimates of extreme speeds derived from a simple Type I fit are incorporated into codes of practice. Failure to examine this question more closely could lead to significant underestimates of the speeds associated with low probabilities of occurrence..

TABLE 1: COMPARISON OF EXTREME SPEEDS

Station	R Years	Extreme Speed Assuming Overall Type I (Simiu)	Extreme Speed Assuming Mixed Distribution
Grand Rapids	100	82	92
	1,000	100	117
	10,000	119	143
Minnesota	100	70	86
	1,000	83	109
	10,000	97	132

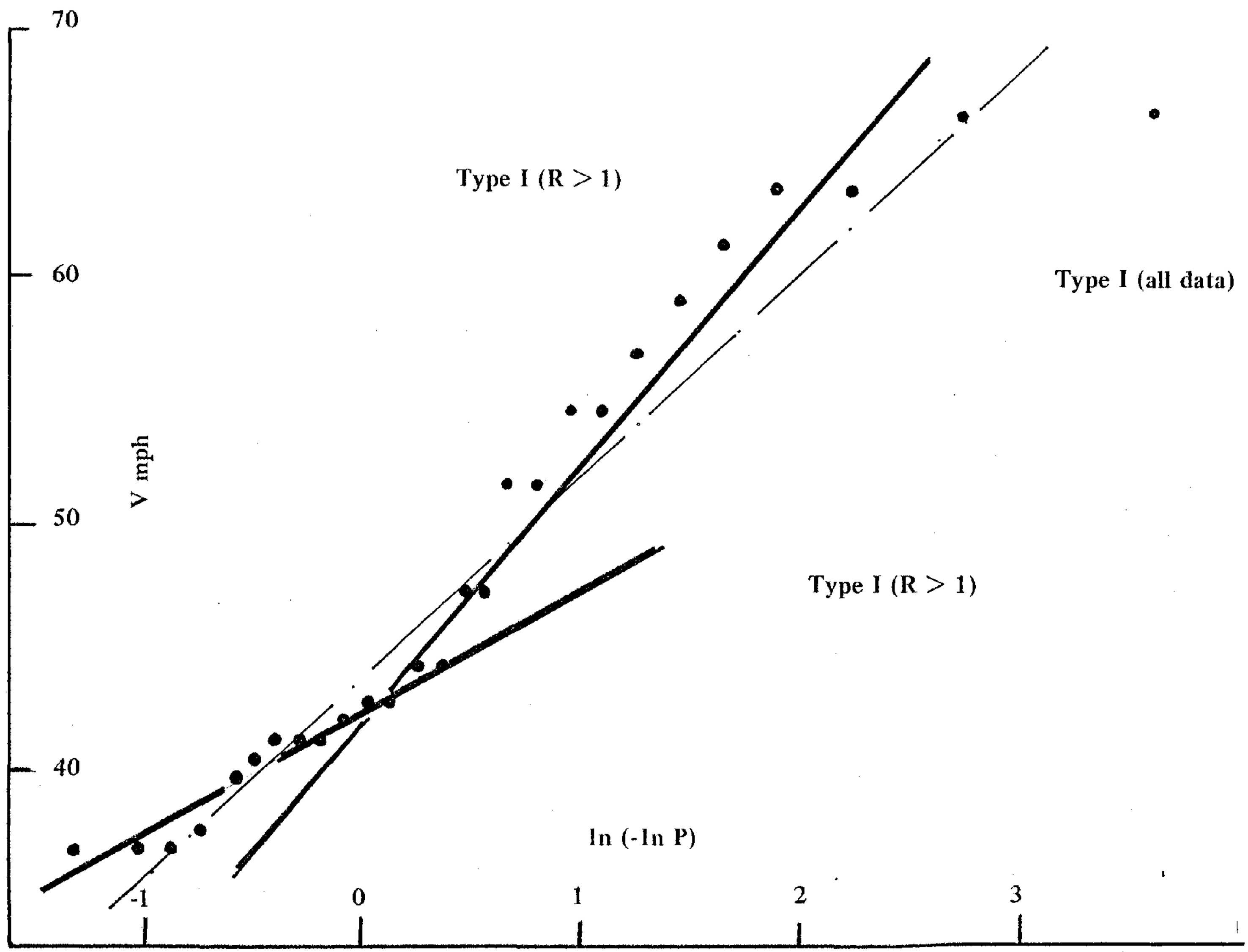

FIG. 1 ANNUAL MAXIMUM WIND SPEEDS – GRAND RAPIDS

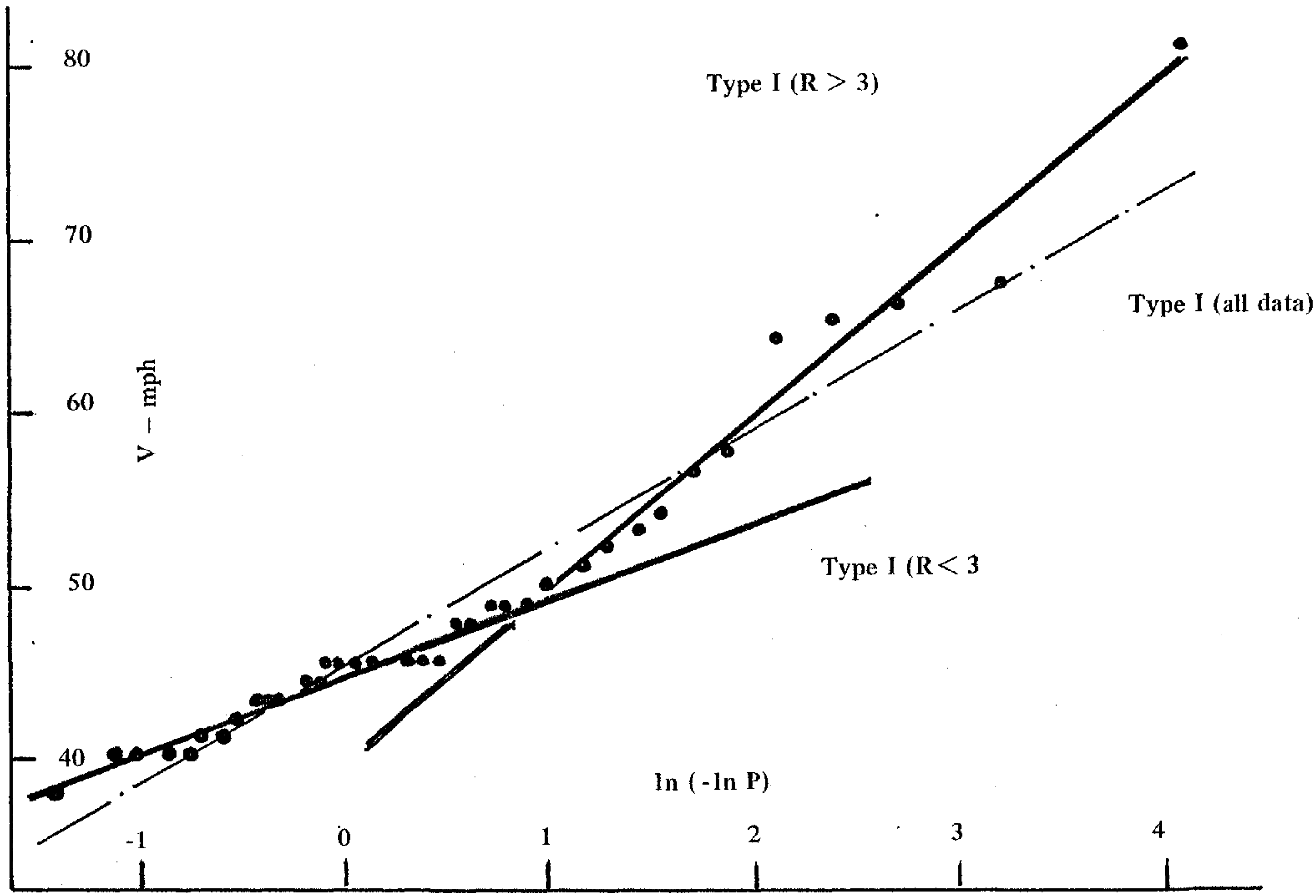

FIG. 2 ANNUAL MAXIMUM WIND SPEEDS – MINNESOTA

* * *

E. Simiu

I fully agree with Vickery that investigations into the climatology of thunderstorms should be carried out in the future. There are two interrelated aspects to such investigations:

1. Structure of thunderstorm winds. Thunderstorms differ significantly from large-scale extratropical storms in several respects. First, the mechanism of their generation is typically associated with the spreading on the ground surface of a cold air downdraft. Thus, the notion of gradient wind has no meaning in the case of thunderstorms. Second, thunderstorm winds cannot be modeled by a stationary time series, as the duration of strong winds in thunderstorms is typically small, of the order of minutes, rather than of one hour. Third, and most important, the spatial extent of the zone of powerful winds in thunderstorms appears to be typically very small (of the order of one thousand meters or even less).

2. Statistical description of thunderstorm winds. Should such a description be obtained by fitting a probability distribution to extreme wind speed data recorded at one station, as in the case of large-scale tropical storms, or should an approach similar to that used for hurricanes and tornadoes be employed? This question is legitimate because the area covered by strong thunderstorm winds is relatively small. For this same reason, caution is in order when attempting to fit a probability curve to thunderstorm wind speed data and extrapolating such a curve to long recurrence intervals. I remember that such an attempt made with hurricane wind speed data led in one case to estimates of the 1000-year wind of 1400 mph!

   Even assuming that it is in order to fit probability curves to recorded thunderstorm speeds at a station, should this probability curve be Extreme Value Type I? Looking, for example at Fig. 1 of Vickery's discussion it is seen that the three strongest winds refuse to fit the straight Extreme Value Type I line drawn for thunderstorms. Maybe a Weibull distribution with large tail length parameter is more appropriate for thunderstorms than the Extreme Value Type I? This is quite possible, as suggested by results reported a somewhat different context in the paper I presented at this workshop.

The problem of thunderstorm winds has been on the minds of code writers for a long time. The 1955 ANSI A58.1 Standard specified design wind speeds based on the following judgment: "the unusually high wind speeds recorded at Wichita and other parts of the Mississippi Valley basin can be attributed to an unusually high frequency of tornadoes and a high frequency of severe thunderstorms. Winds following tornadoes are similar to tornadoes in that they generally strike in short, narrow paths. Thus, the probability that any particular building or structure will be hit is comparatively small, and these winds may be partially discounted. This type of reduction is not unreasonable for Wichita, Kansas. The same conditions apply to Evansville, Indiana; Indianapolis, Indiana; and Omaha, Nebraska." (G.N. Brekke "Wind Pressures in Various Areas of the United States," Building Materials and Structures Report 152, National Bureau of Standards, Washington, D.C., 1959).

The first priority, in my opinion is to be able to devise simplified engineering models of thunderstorm wind structure that would help answer the first question raised in item 2 above. Until this is done, statistical analyses based on curve fitting carried out as in Vickery's Figs. 1 and 2 will not rest on a firm enough foundation to allow confident estimates of extreme winds to be made, especially for long mean recurrence intervals. I believe that, for the time being, the 1955 ANSI A58.1 approach as enunciated by Brekke is a reasonable one. It is this approach that is implicit in the estimates of the NBS-NCC report "Extreme Wind Speeds at 129 Stations in the Contiguous United States."

* * *

Hugh Church

Study of extreme winds by generating storm category may be irrelevant. An extension of Vickery's work by storm or climate type on resulting extreme wind statistical characteristics may be enlightening in this regard.

Vickery's wind speed spectra for Sydney would probably approach Van der Hoven's classic spectra if the diurnal cycle were removed.

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Arnold Court

Wind representation and description has been among my major interests in climatology for more than 40 years, even before I became a Weather Bureau observer in 1938. First I sought methods to determine whether two wind regimes differed significantly, a search which eventually led, a decade later, to the von Mises and other circular distributions. Then came wartime development of RABAL techniques using artillery radar, and the question of the reliability of stratospheric wind reports.

After the war, work on wind design criteria for military structures and equipment led to the concept of calculated risk. After almost 30 years, this methodology has become fairly well recognized in hydrology, but not so much so in other branches of engineering. In a straightforward application of probability principles, it seeks "the design return period whose corresponding event has not more than a given probability of occurring within the desired lifetime" of a structure (Court, 1953, p. 44).

The return period T of an event (flood, strong wind, royal flush) in a stationary series is the average interval between occurrences; in climatology an occurrence usually is an exceedance; rains of 25 mm or more in a day, winds of 80 knots or stronger, etc. The T-year event has probability 1/T of occurring in any given year, so the probability is $1 - 1/e = 0.632$ that the T-year event will recur in less than T years (days, draws, etc.). For a calculated risk U that an untoward event will not occur during a desired lifetime of N years, a structure should be designed to withstand the event having a design return period $T_d = N / [- \; n (1 - U)]$ (Court, 1952, p. 59). For a 5% calculated risk, a structure should be designed for the extreme having return period T_d = N/0.05.3 = 19.5 N , that is for the event with return period 19.5 times greater than the desired lifetime N .

All this, of course, assumes that the process is stationary, i.e. that climate isn't changing appreciably. In the last quarter-century this assumption has become untenable, so we should no longer speak of return periods. Instead we should use their reciprocals, the probabilities of occurrence in any one year. However, climate changes sufficiently slowly that these procedures may be valid for lifetimes of 25 or even 50 years.

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Correlations of winds at two places, two levels, or two times arose in studies of the CEP (circular error probable) of ballistic missiles 25 years ago. Three kinds of correlations were in use, the true vector correlation and the so-called stretch and turn correlations. How correlations decrease with vertical or horizontal separation, or with time, became an important problem, not yet fully solved, and led to the development of correlation transformation paper, used in my Fig. 3 yesterday. To describe the vertical profile of the winds over a point, a complex Fourier series was fitted to observed hodographs.

Description of surface winds, always of interest, is offered by the sector wind rose, in which area, not radius length, is proportional to frequency. In such a diagram, the arcs of the various sectors can be smoothed into a continuous curve by balancing areas, so that the area inside the curve within a sector equals that inside the arc. For any arbitrary sector, the process can be reversed to obtain the best possible estimate of the wind frequency from that direction. Instead of one curve for all winds, several can be constructed for different wind speed groups, as in the more familiar Baillie windrose.

Also of interest in surface winds is the different behavior of winds during rain and in dry weather. This goes back 30 years ago to the House Beautiful project to present climatic information for architects, an effort far before its time but which was revived last winter at a conference in which Mr. Quinlan participated. Because I needed a map of tornado occurrence for an article on United States climate, a decade ago I tracked down all the maps of tornadoes ever published, and finally compiled my own. In the process, I strongly urged our weather officials to report tornado occurrence not by states for various periods, or even by 1° or 2° quadrilaterals, whose areas decrease northward, but <u>per year per unit area</u>, such as 25,000 square kilometers or 10,000 square miles--first used by Cleveland Abbe in 1888. Thus I'm glad to see that later today Mr. Schaefer will present tornado occurrences in this way, but I urge him to present area damaged as of greater significance. Similarly, need for a map of thunderstorm occurrence brought the discovery that official maps use all occurrences since station establishment, even though reporting rules have changed drastically. So I obtained the needed data and prepared maps based on a full 25 years, 1951-1975, for all stations.

Wind energy studies, which became important five years ago, have revealed several problems, one of which I discussed yesterday. Another is the diurnal variation of wind speeds. For a century we have known that in most places winds are strongest after noon, but at 1 km and higher in the free air are strongest around midnight. This is explained as the coupling of the surface layers to the upper gradient flow through convective turbulence by day, and the decoupling of the two under stable or inversion conditions. Because winds atop Mount Tamalpais, north of San Francisco, were strongest at night, some people assumed that such would be the case on all mountains. Thus mountain top wind turbines would spin while those in valleys were becalmed, and vice versa. Continuous wind records on mountains are rare, but none of those available shows a nighttime maximum of wind strengths; most exhibit diurnal cycles similar to those of flatland stations.

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Statistical models of wind behavior are needed for many purposes. Wind is primarily horizontal--only in thunderstorms and tornadoes is the vertical component more than a few percent of the horizontal--and often can be described by a bivariate Gaussian model. Dr. Crutcher, who was present Monday, has applied this model to upper winds and to hurricanes with great success.

If wind components, west-east (zonal) and south-north (meridional), do indeed have a bivariate normal distribution, then scalar wind speed, regardless of direction, must have a chi distribution. This is also called "Rayleigh" by engineers, although Lord Rayleigh, who used it in 1882 for vibrating strings, was at least the fifth person to develop it, apparently independently of Bravais in 1842, Maxwell in 1859, Schols in 1874, and Helmert in 1875.

Some engineers feel that, with only one parameter, the chi or Rayleigh distribution isn't sufficiently flexible, and insist on fitting wind speeds to a two-parameter Weibull distribution. This reduces to the

Rayleigh when one parameter is 2, to which it usually is very close. Others use gamma distributions, and of course the ubiquitous log normal. Thus I'm gratified that Dr. Surry has "good reasons for believing that the distribution of wind speeds tends toward a Rayleigh distribution. . ." and that Dr. Simiu finds that this distribution fits the wind speeds at most of his 129 stations. If indeed wind speeds have Weibull or log normal distributions, the bivariate distribution of their components is a horrible mess.

Equally controversial is the proper model for extreme winds--and even the proper wind extremes to use. When I began developing design criteria for military equipment, which eventually became MIL STD 210, then 210A, now 210B, I discussed the problem at length with Dr. Gumbel, chief developer of the statistical theory of extreme values. He explained the three asymptotic distributions, first identified by Fisher and Tippett and now called, respectively, Gumbel, Fréchet, and Weibull.

The first distribution applies to unbounded variables, or at least those that do not come close to any theoretical limit. Wind speed may have an upper limit at Mach 1, the speed of sound, but we're really not sure about that. Even if it does, the strongest known winds, in tornadoes, are only about half that speed, so for practical purposes wind speed is unbounded above; of course, the lower limit is zero. Hence all our work was with the Gumbel distribution, and I saw no reason then, or now, for using any other.

In 1948, two sets of daily wind extremes were available for United States stations: the strongest winds during a 5-minute period, and the fastest mile speeds. The fastest mile is hard to interpret physically or structurally; values for the U.S. range from around 45 to 120 mph, or for periods of 30 to 75 seconds. Structures, even portable Army shelters, respond to somewhat longer intervals, so we used the maximum winds during 5 minute periods. I've never been able to understand why later workers fitted Fréchet distributions to fastest mile winds, unless in an effort not to repeat my work.

My paper on wind extremes was rejected by the Transactions of the American Geophysical Union because, the referee said, the discussion of how winds were estimated after the instruments blew away was not pertinent and should be deleted. I thought the details of the strongest wind "on record" were important, and sent the paper to the Journal of the Franklin Institute, where W.J. Humphreys published frequently. But few people seem to have seen it, at least for several years.

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"Mixed distributions" are encountered in many contexts, but usually some objective criterion is available to separate the elements. One mixture already mentioned is that of winds on wet and dry days, where the separation criterion is rain, not wind. Procedures are also available to disaggregate elements from two or more distributions, if each is normal with different means and variances. But difficulties arise in trying to separate a sample of annual extreme wind speeds into two or more categories, as Dr. Vickery proposes. How close must the hurricane eye come for a station's extreme wind to be classed as hurricane-caused? Being on the edge of a hurricane's wind field may be like being just a little bit pregnant. Without a rigorous separation independent of the actual wind speeds, this interesting procedure may cause serious under-design.

Dr. Simiu's work is a milestone in the analysis of wind extremes, even though he was misled into using fastest mile data. The illustrations of wind records providing such data, that Mr. Changery presented yesterday, show clearly that any such estimates must have a margin of error of several miles per hour. Yet observers dutifully apply the proper instrumental corrections to such readings. But no corrections are applied to the estimated 1-minute readings (in knots) from the same anemometer for the hourly airways reports, which go onto the data tapes of hourly, or 3-hourly, readings analyzed so elaborately.

Even these corrections are questionable. So far as I know, anemometers are not recalibrated after installation. They are inspected, lubricated, and adjusted--but assumed to maintain forever their original calibrations--if indeed they were ever calibrated. In years past, only a few instruments from each batch were actually put into a wind tunnel, and the rest merely assumed to perform identically.

"Fastest mile" reported wind speeds actually are underestimates, because they are based on the intervals between fixed mile markers on the anemometer, as Mr. Lockhart pointed out yesterday. At some time during the passage of the "fastest mile" the one-second wind speed was greatest, and a faster mile may have started or ended in the middle of the mile actually measured. The maximum rainfall in 60 minutes, starting at any time, is about 13% greater than the 1-hour maximum, starting "on the hour." Some similar relation must apply to the reported "fastest mile" speeds, but not to the 5-minute maximum, which is for any period, not forced to start at a fixed time.

Despite these uncertainties, we find the mean "fastest mile" speed expressed to four significant figures, multiplied by a two-digit influence coefficient (or its square root to four significant figures) to obtain a result with four significant figures! That's not the way the freshmen were taught in Engineering Measurements. Although the meteorologist may apologize profusely for inadequacies and uncertainties of his data, they are probably the most precise part of the engineer's computations. But they still can be improved.

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In his excellent discussion of what's known, or should be known, about wind measurements, Mr. Lockhart didn't mention some things. One is that instrument height should be indicated both in summer, above the ground, and in winter, above the snow; at many stations, the winter height is only half the summer value. Another is the need to specify both the air volume whose motion is measured and the time interval of the measurement. For half of a century the trend has been to smaller anemometers with faster response times, and slower starting speeds. The old 4-cup anemometers sampled the motion of perhaps 0.1 m^2 normal to the air flow, while the new tiny 3-cup anemometers measure over perhaps only 0.02 m^2. On the other hand, standard winds aloft data come from balloon motions through layers half of a kilometer thick, usually for two minutes, but attributed to the midpoint of the layer--or interpolated to standard heights every kilometer or thousand feet. Acoustic doppler soundings, still experimental or developmental, can provide virtually instantaneous motions, which can be averaged for any desired time period, but for volumes of at least cubic meters at specific heights.

Obtaining more of these grossly smoothed "gradient wind" observations for extrapolation down to the surface, as proposed by Drs. Cermak and Vickery, may not lead to safe design. The winds aloft data cover too much space and, at least for balloons, time, to show the range of speeds and directions found from anemometers and wind vanes at the surface or on towers. Obviously, the extreme wind speed increases as the volume decreases, and also as the time interval is reduced. The many diverse users of wind information need speeds for different intervals: Mr. Hovind yesterday indicated needs in air quality studies for averages and extremes for hours, days, and longer periods, while my paper used measurements at 0.1 second to estimate effects on a wind turbine.

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Finally, some fundamentals of statistical analysis, especially as applied to estimation of extremes, need restating. Statistical procedures are based generally on the assumption that the available data are a random sample from a defined population. In such case, the observations needn't be consecutive in time or adjacent in space; in fact, the assumptions are better met if they're not. The main caveat is that data should not be missing from the sample because of the attribute being measured: we can't skip a year because the anemometer blew away. But if politics caused a station to close for a few years, without regard to weather, the gap is no reason to omit the record.

Extreme value analysis applies to a large sample of extremes, each the extreme of a large sample, all from the same population. The "fastest mile" of a week is the maximum of a sample of seven days, a little small for theory. Even so, the closeness of Dr. Simiu's estimates based on weekly extremes to those from annual values is quite gratifying.

However, we still have the nasty assumption of stationary or invariant climate, which isn't fully satisfied. A decade ago I found that next year's temperature or rainfall or cloudiness is estimated with minimum error by the median of the corresponding values for the preceding dozen or so years. No exact period can be determined, because it varies from month to month and station to station. Nevertheless, this reinforces the notion of slow fluctuation in climate, and the fallacy of relying on long records for greater precision.

The precision of any estimate, such as the probability of a rare event, depends on sample size, so the statistician, blithely assuming stationarity in mean and variance, seeks a long record. More realistic estimates of climatic extremes (winds, rainfalls, temperatures) may be attained through combining short records, no more than 25 years, for several stations in a single homogeneous region. This may be all the more appropriate because the estimates are to be used for the whole region; rarely are they desired for the very location of the weather station. As yet, no application of this procedure has come to notice.

Much of what is already known about wind measurement and behavior is yet to be applied by engineers, architects, agronomists, and others. But much more is yet to be learned about wind.

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September 4, 1979

Revised 10/2/79

PROGRAM

WORKSHOP ON WIND CLIMATE

November 12 & 13, 1979

Great Smokies Hilton
Asheville, N.C.

November 11 (Sunday)

6:00 pm to 7:30 pm - Get Acquainted Cocktail Hour (no host)

November 12 (Monday)

SESSION I. APPLICATION OF WIND DATA AND DEFINITION OF NEEDS
8:00 am to 12:00 noon

Chairman: Jack E. Cermak, Fluid Mechanics and Wind Engineering Program, Colorado State Univ., Fort Collins, CO.

Rapporteur: Kishor C. Mehta, Dept. of Civil Engineering, Texas Tech Univ., Lubbock, TX.

8:00 Introduction and Administrative Remarks: Kishor C. Mehta

8:15 Overview: Jack E. Cermak

8:45 Application in Developing ANSI Standard: Hugh Church Environmental Research Div., Sandia Lab, Albuquerque, NM.

9:00 Application to Building Loads: Jon Peterka, Dept. of Civil Engineering, Colorado State Univ., Fort Collins, CO.

9:15 Application to Wind Energy Assessment: Arnold Court California State University, Northridge, CA.

9:30 Discussion

10:10 Coffee Break

10:30 Application to Risk Around the World: Oscar Richard, Engineering Meteorology Section, Scott Air Force Base, IL.

10:45 Application to Agriculture: Shashi Verma, Center for Agricultural Meteorology & Climatology, Univ. of Nebraska, Lincoln, NE.

11:00 Application to Atmospheric Diffusion: Einar L. Hovind, Air Quality Division, North America Weather Consultants, Santa Barbara, CA.

11:15 Discussion

12:00 Adjourn

WORKSHOP LUNCHEON: 12:00 noon to 1:30 pm.

SESSION II WIND DATA COLLECTION AND STORAGE
1:30 pm to 5:15 pm.

Chairman: Mike Changery, Applied Climatology Branch, National Climatic Center/NOAA Asheville, N.C.

Rapporteur: Michael P. Gaus, Directorate of Applied Science and Engineering, NSF, Washington,D.C.

1:30 Overview: Mike Changery

2:00 Data Collection and Storage by NRC: Robert Kornasiewicz, Office of Standards Development, USNRC, Washington, D.C.

2:15 Data Collection and Storage by Forest Service: Morris H. McCutchan, Rocky Mountain Forest & Range Experiment Station, Fort Collins, CO.

2:30 Data Collection and Storage by NCC: Mike Changery

2:45 Discussion

3:25 Coffee Break

3:45 Instrumentation for Data Collection: Tom Lockhart, Meteorology Research Inc., Altadena, CA.

4:00 Collection of Data for Wind Energy Assessment: Dennis Elliott Battelle-Pacific NW, Richland, WA.

4:15 Discussion

5:15 Adjourn

November 13 (Tuesday)

SESSION III CLIMATIC MODELLING AND WIND DATA ANALYSIS
8:00 am to 12:00 noon

Chairman: Dave Surry, Boundary Layer Wind Tunnel Lab, Univ. of Western Ontario, London, Canada

Rapporteur: Phil Landers, Electric Power Research Institute, Palo Alto, CA.

8:00 Overview: Dave Surry

8:30 Mixed Wind Climates Including Thunderstorms and Tropical and Extratropical Cyclones: Barry J. Vickery, Dept. of Civil Engineering, Univ. of Western Ontario, London, Canada

8:45 Analysis of Extreme Wind Data: Emil Simiu, Center for Building Technology NBS, Washington, D.C.

9:00 Importance of Meteorological Tower Data in the Assessment of Wind Climate: John Gaynor, Wave Propagation Lab, Environmental Research Lab, NOAA, Boulder, CO.

9:15 Discussion

10:10 Coffee Break

10:30 Assessment of Wind Climate from Indirect Estimates such as Damage: James R. McDonald, Dept. of Civil Engineering, Texas Tech Univ., Lubbock, TX.

10:45 Climate Models of Tornadoes and Their Meteorological Requirements: Joseph T. Schaefer, National Severe Storms Forecast Center, Kansas City, MO.

11:00 Discussion

12:00 Adjourn

WORKSHOP LUNCHEON
12:00 - 1:30 pm

SESSION IV WRAP-UP
1:30 pm to 3:00 pm

1:30 Wrap-up Discussions: Chairmen and Rapporteurs of the Sessions

3:00 Adjourn

3:00 pm to 4:30 pm Tour of the National Climatic Center conducted by the NCC staff (Transportation will be provided)

WORKSHOP ON WIND CLIMATE

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