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AN INITIAL LOOK AT THE DYNAMICS OF THE MICROSCALE FLOW FIELD WITHIN A LARGE WIND FARM IN RESPONSE TO VARIATIONS IN THE NATURAL INFLOW

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ABSTRACT

This paper discusses some early results from a study to examine the influence of the natural inflow structure on the internal microscale turbulence environment of a large wind farm. Two fully equipped, high-resolution boundary layer measurement systems were employed to document the alteration of the turbulent structure as the flow entered and left a wind park consisting of 41 rows of turbines. These systems collected data continuously for a period of several weeks during the peak wind season in San Gorgonio Pass. In addition, statistical summaries of the inflow and outflow characteristics from a hub-height elevation were recorded prior to, during, and after the detailed measurement period. Results of these hub-height summaries will be discussed and interpreted in this paper.

INTRODUCTION

This program has been initiated to improve our knowledge of the microscale turbulent structure present within a large wind park. This information is vital to the development of more efficient and reliable turbine designs because most machines will operate in such an environment. Further, a knowledge of how the park internal turbulence structure is influenced by the characteristics of the natural inflow will hopefully aid future siting decisions. Thus, the specific objectives of this study are to

- quantify the internal turbulence environment of a large wind park
- describe the dynamics of the internal microscale turbulence structure in terms of variations in the natural inflow
- establish which external flow characteristics have a dominant impact on the park internal turbulence environment.

DESCRIPTION OF THE WIND PARK STUDIED

The wind park used in this study is operated by the SeaWest Energy Group, Inc., and is located approximately 2 km east of San Gorgonio Pass in Southern California. The park consists of 41 rows of turbines with a nominal 7 x 2 rotor diameter spacing arrangement. The rows are oriented perpendicular to a line 100°-280° with respect to true north. The SeaWest park and a neighboring one along its southern border contain well over 1000 turbines. The land the park rests on is generally quite flat with a gentle downslope to the east. There are no wind farms immediately upwind, so the flow can be considered natural and representative of San Gorgonio Pass. Figure 1 is a schematic diagram of the position of the wind park and nearby major terrain features.

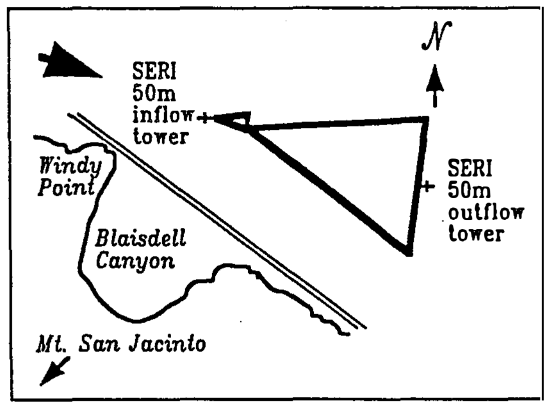

Figure 1. Schematic layout of major features surrounding the SeaWest wind park.

DATA COLLECTION

Two boundary-layer measurement systems were installed on two 50-m towers immediately upwind of Row 1 and downwind of Row 41, as indicated in Figure 1. The linear distance between these two towers was 3.4 km (2.1 mi). The instrumentation complement included fast-response vane and cup wind sensors spaced logarithmically (at 5-, 10-, 20-, and 50-m elevations), a three-axis sonic anemometer at nominal turbine hub height (23 m), absolute dry bulb and dewpoint temperatures at 5 m, the temperature difference between the 50- and 5-m levels, surface barometric pressure, and global solar radiation (insolation). The data were continuously collected at rates up to 50 readings per second by a personal computer-based data acquisition system and recorded on an optical disk. These systems were placed in operation in mid-June 1989 and continued to operate until mid-August.

Beginning in March, a micro data logger began collecting hourly statistics of wind speed and direction from fast-response sensors mounted at the 24-m tower level as well as the dry bulb temperature at the 5-m height. The individual measurements were sampled at a 10 second interval and a series of aggregate statistics were stored in a solid-state memory device once per hour. The recorded statistics included the wind vector means and standard deviations, the peak gust magnitude and time of occurrence, and the mean air temperature. In addition, on-line histograms of the wind direction and speed were also recorded. The wind direction distributions were saved with a 5°-resolution over a range of 235° to 315° true. Wind speeds were quantified in 3 ms^{-1} intervals over a range of 0–33 ms^{-1}. A total of 2714 hours of data was collected simultaneously from both towers over the period from mid-March to early July. The discussions that follow are based on this limited data set.

FOUR BASIC EXTERNAL FLOW REGIMES IDENTIFIED

An extensive examination of the data set was performed in order to identify those inflow regimes in which it could be said with certainty that conditions at Row 41 were definitely related to those at Row 1 (and therefore isolate the impact of the park itself). It was found that, at least for the available record, the SeaWest site is impacted by four distinct external flow regimes. These include two daytime flows and two predominantly nocturnal ones. The strength of the flow coming through the pass is the denominator which separates both the daytime and nocturnal regimes into two sub-classes. The nocturnal flows are dominated by cool drainage flows emanating from Blaisdell Canyon southwest of the site (see Figure 1). The breakdown includes

Daytime hours

- strong winds through pass
- weak winds through pass.

Nocturnal flows

- canyon drainage combining with strong winds in the pass
- canyon drainage combining with weaker winds in the pass.

The daytime inflow regime associated with high winds in the pass is characterized by strong, turbulent winds flowing through the park approximately perpendicular to the rows of turbines. Weak westerly winds in the pass generally bring west-northwest inflows at Row 1 and light southeasterly winds at Row 41. How far west the easterly flow penetrates into the park varies from day to day.

Strong nocturnal flows in the pass are generally characterized by heavy inflow winds from a more westerly direction at Row 1 and somewhat lesser velocity flows with a southwestern component at Row 41. Finally, weaker nocturnal flows in the pass allow the canyon drainage to penetrate at least as far north as the inflow tower, often acting in such a way as to reduce the velocity and vastly increase the turbulence seen there. At the same time, the winds at Row 41 often increase well above those at Row 1 but usually are not as turbulent. Measurements have shown that the drainage winds tend to peak twice each night, once at about 2300 h (LST) and again at around 0400 h. They also appear to reach their highest frequency of occurrence and intensity during the month of June.

EXAMPLE OF INTENSE DRAINAGE-AUGMENTED FLOW

The night of June 6–7, 1989 provides a good example of a reasonably intense drainage-augmented flow episode. Figure 2 plots the hourly mean wind direction and air temperature for the inflow tower upstream of Row 1. As can be seen, the shift in the wind direction towards the southwest (and Blaisdell Canyon) closely follows the decrease in air temperature during the period from 1600 to 0600 h. Figures 3(a) and 3(b) plot the corresponding mean wind directions and speeds for both the inflow and outflow (Row 41) towers.

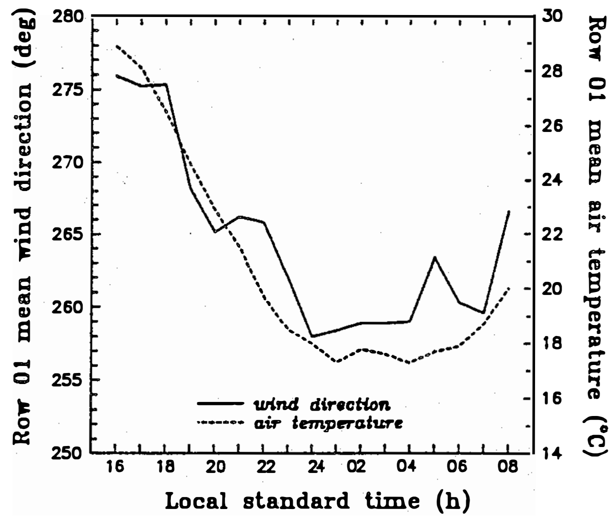

Figure 2. Inflow (Row 1) mean wind direction and air temperature for night of June 6–7, 1989.

The tie-in between the cool canyon drainage and its effect on the conditions at the inflow tower are demonstrated in Figures 4(a), 4(b) and 4(c). The vertical dash lines highlight the temperature dips at 0100 h and 0400 h when the wind was from the southwest. These dips are accompanied by sudden drops in wind speed and dramatic increases in the turbulence intensity and peak gust-to-mean ratio. The two turbulence regimes are further underscored by the plots of the wind speed standard deviation in Figure 5 for Rows 1 and 41. Figure 5 shows that turbines on the west side of the park are operating in very high turbulence levels from 2000 to 0700 h, while on the east, conditions are much more moderate.

This example demonstrates that in a park of this size, large spatial variations in the local turbulence environment occur. There is little doubt that a transition zone exists between the flows represented by conditions at Rows 1 and 41 within the park boundaries. The character of the flow within this zone is undoubtedly very unsteady and turbulent. This example demonstrates how the characteristics of the external flow can have a powerful influence on local environment within a large wind park.

The available record indicates that drainage-augmented flows occurred approximately two-thirds of the time when a wind with a westerly component of 3 ms^{-1} or more was observed at Row 1. These conditions are most typical during the late afternoon to early morning due to nocturnal peaking of the winds in San Gorgonio Pass.

THE MODIFICATION OF THE NATURAL INFLOW BY A LARGE WIND PARK

One of our objectives has been to document the modification of natural inflow by the presence of a large wind park. The tower location downstream of Row 41 was chosen because it is believed

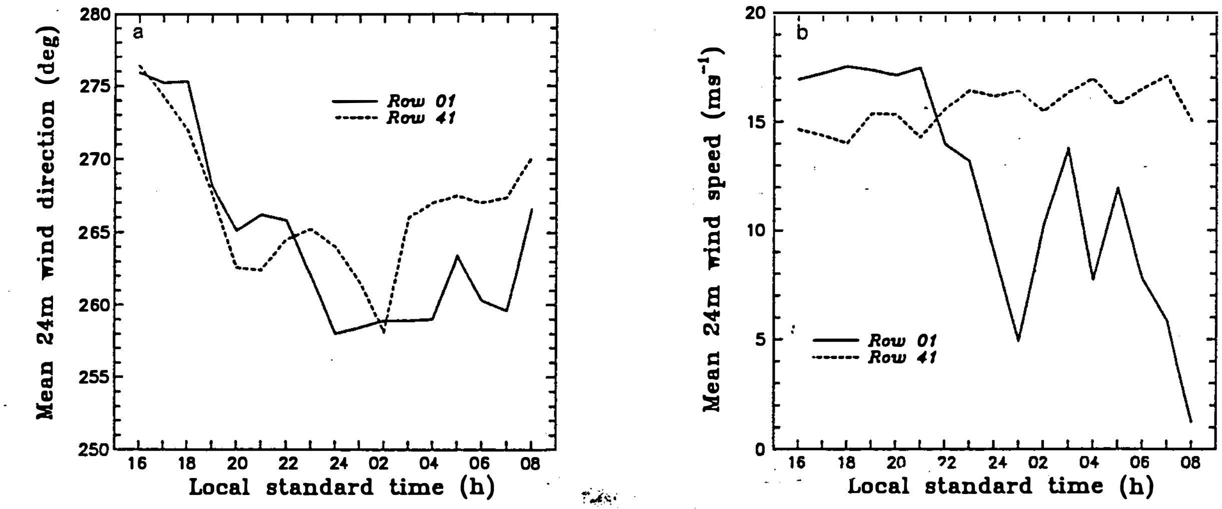

Figure 3. Comparisons of (a) wind direction, and (b) wind speed at Rows 1 and 41.

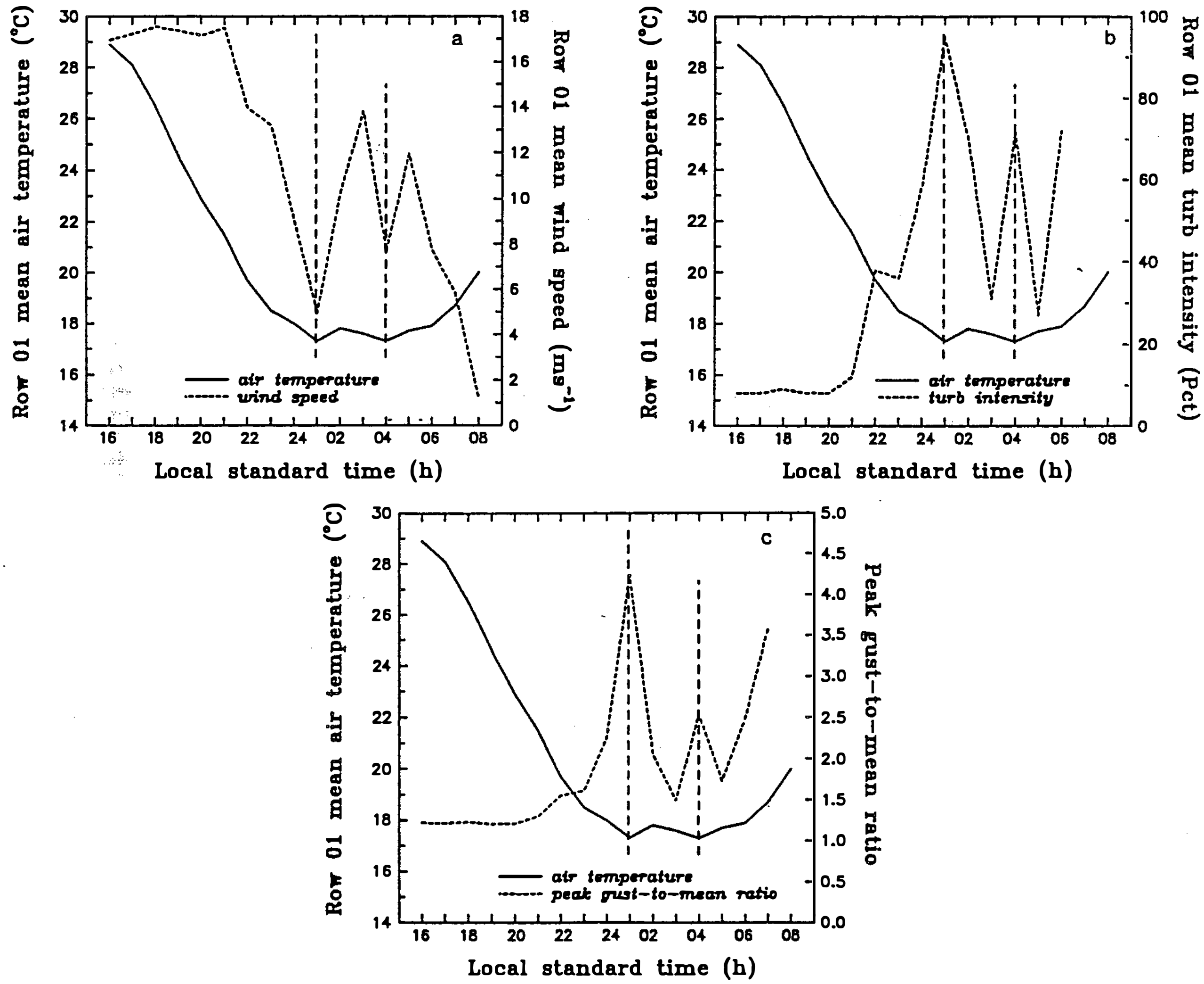

Figure 4. Comparisons of Row 1: (a) wind speed, (b) turbulence intensity, and (c) peak gust–to–mean ratio vs. air temperature.

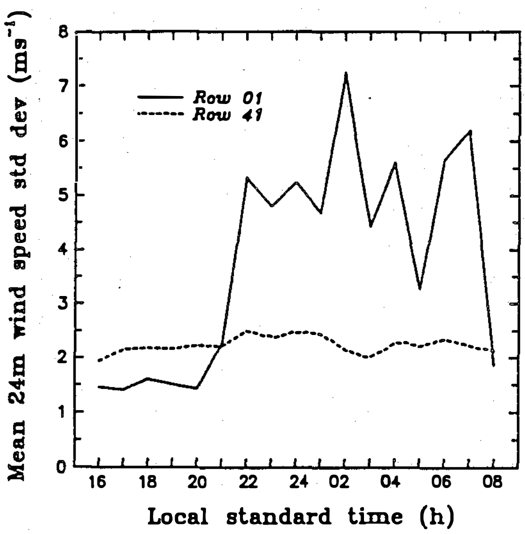

Figure 5. Comparisons of mean wind speed standard deviations for Rows 1 and 41.

that the conditions have reached a quasi-steady state. In order to minimize the influence of the canyon drainage which introduces the large spatial variations within the park, we chose the daytime period of 0900 to 1800 h when the wind direction at Row 1 was between 260°–290° and within 10° of Row 41. Further, an inflow speed threshold of 9 ms^{-1} was applied. A total of 660 hours of data was available for this portion of the characterization.

The extent of the wind field modification is delineated in the following figures in which pertinent flow parameters are represented as functions of the mean inflow wind speed. Figure 6 indicates, for example, that the expected velocity deficit approaches 30% at an inflow speed of 8 ms^{-1} and 22% at 22 ms^{-1}, while the turbulence intensity increase averages nearly 80%.

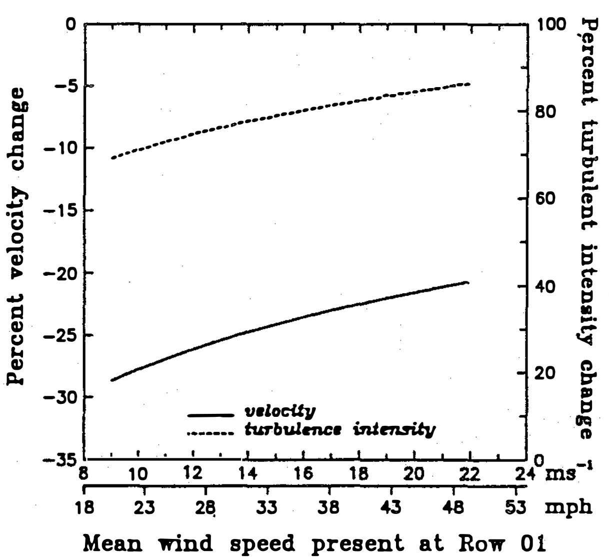

Figure 6. Percentage change of velocity and turbulence intensity at Row 41 as referenced to Row 1.

Figure 7 depicts the actual turbulence levels as described by the wind speed standard deviation. The influence of the park here is immediately obvious. Figure 8 displays the same information as local turbulence intensity. Similarly, Figure 9 plots the change in the wind direction standard deviation. The ratio of the observed peak gust magnitude to the local mean is plotted in Figure 10. The relationship between the peak gusts at Row 41 and those observed at Row 1 is shown in Figure 11.

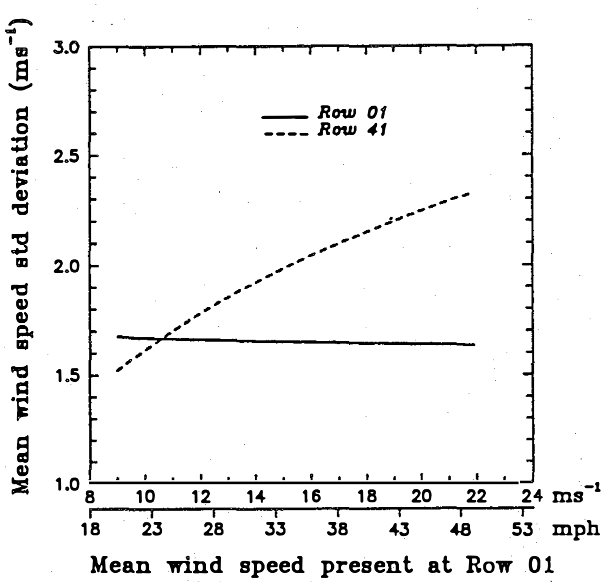

Figure 7. Comparison of wind speed standard deviation of Rows 1 and 41 vs. wind speed at Row 1.

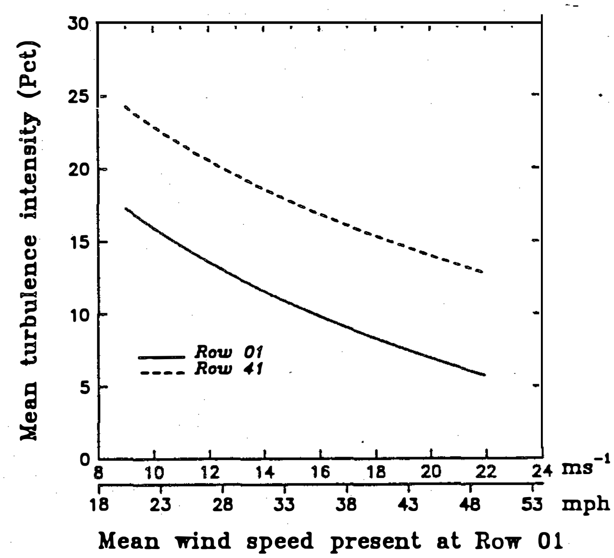

Figure 8. Comparison of turbulence intensity of Rows 1 and 41 vs. wind speed at Row 1.

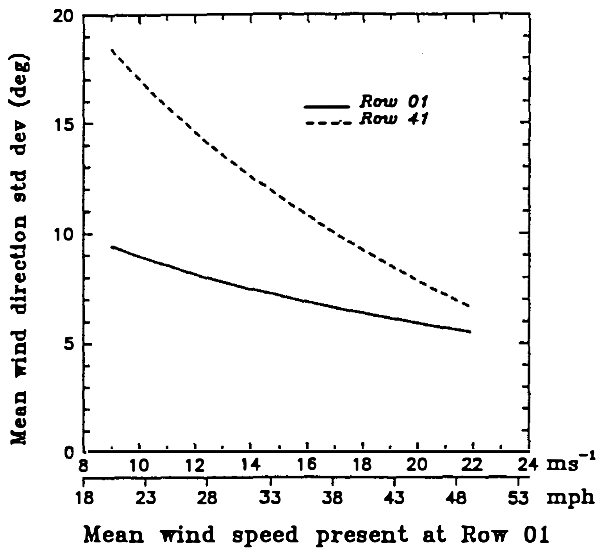

Figure 9. Comparison of wind direction standard deviation of Rows 1 and 41 vs. wind speed at Row 1.

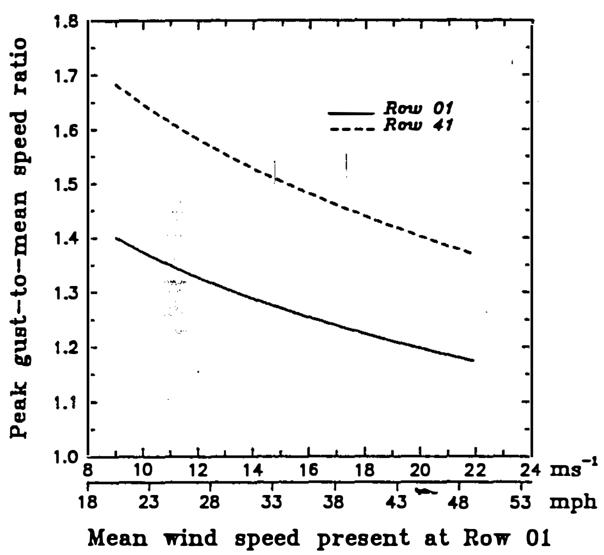

Figure 10. Comparison of peak gust-to-mean ratio of Rows 1 and 41 vs. wind speed at Row 1.

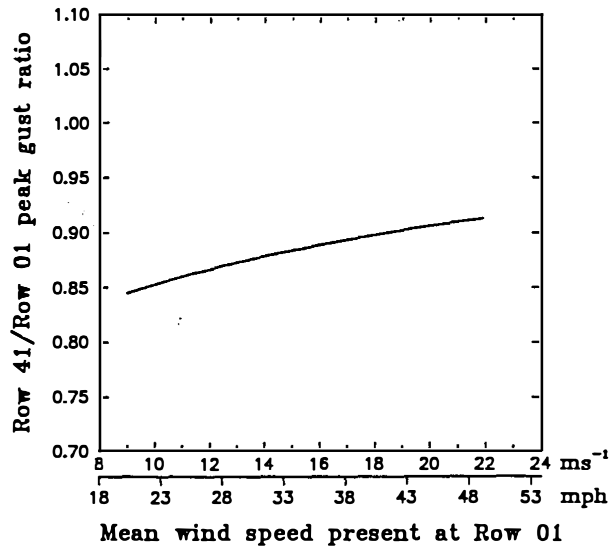

Figure 11. Ratio of peak gust velocities at Row 41 to Row 1 vs. wind speed at Row 1.

CONCLUSIONS

The results so far have clearly demonstrated the importance of external flow characteristics to conditions within a large wind park. Conditions prevalent during the late evening to early morning hours at this location can be very rigorous, a consequence of the large elevation variations associated with the topography surrounding the site. It is abundantly evident that future testing of new turbine and component designs should include conditions such as these in order to insure the widest range of possible operational scenarios.

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