AN ABSTRACT OF THE THESIS OF

David R. Wilkinson for the degree of Master of Science

in Atmospheric Sciences presented on May 5, 1978

Title: A Study of Flow Acceleration Over A Coastal Headland

Redacted for privacy

Abstract approved: ______________________________
(Dr. Ernest W. Peterson)

The thesis examines the applicability of a two-dimensional flow acceleration model to describe a terrain-induced flow perturbation as measured at Yaquina Head on the central Oregon coast. The geometry of Yaquina Head together with the upstream wind values were used in estimating hilltop winds. These estimates compare well with the observed wind values.

A second method to estimate the hilltop winds was attempted by developing a mean ratio of Yaquina Head winds to the upstream Yaquina South Jetty winds. This ratio was taken from one winter's data and used to estimate the next winter hilltop winds. The same upstream wind values were used with this method as were used with the geometric model.

Statistical evaluation in the form of regression analysis was performed to determine the ability of the geometric and statistical models to estimate the hilltop wind on Yaquina Head. It was found that both models did reasonably well but that neither model was appreciably better than the other.

A STUDY OF FLOW ACCELERATION OVER A COASTAL HEADLAND

by

David R. Wilkinson

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Completed May 5, 1978

Commencement June 1979

APPROVED:

Redacted for privacy

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Date thesis is presented May 5, 1978

Typed by Tami Denison for David R. Wilkinson

ACKNOWLEDGEMENTS

I wish to thank Professor Ernest W. Peterson for his contributions to the structure, content, and review of this work.

I would also like to thank Professors W. George N. Slinn, Larry Mahrt, Robert W. Boubel, W. Lawrence Gates, and Hasong Pak for their careful review and editing of the thesis.

The tireless and continuous computer programming efforts of Mr. James Buckley have been essential to the development and completion of the data analysis.

Financial assistance from Professor E. Wendell Hewson under grants from the Public Utility District (PUD) Director's Associaiton, and the Lockheed-California Company has also been appreciated.

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A STUDY OF FLOW ACCELERATION OVER A COASTAL HEADLAND

I INTRODUCTION

It is often observed that the wind is stronger on the windward side and top of a hill than on surrounding, flatter terrain. Quantification of this phenomenon, in terms of other easily measured physical variables, would be of great help to many branches of applied meteorology; for example, those associated with architecture, aviation, and air pollution dispersion modeling.

Two different prediction schemes are considered in this study. One method is based on work done by Jackson & Hunt (1975), Taylor & Gent (1974), and Frost et al. (1973). This method characterizes the hilltop flow as a function of the hill height and length and an upstream measurement of the wind speed over level ground (see figure 1). The above mentioned works involve two-dimensional flow models and require many arbitrary assumptions of the flow field and terrain. However, practical models of more realistic complexity are not available. One purpose of this study is to see how well such a model will work in a real world situation.

The second prediction method considered in this study is purely statistical in nature. The"state-of-the-art" of predicting topographical effects on the wind field is primitive. Consequently, if the wind regime is to be specified at a given location, at least some observations of the wind at that location must be made in order to determine the wind statistics. The analytical model discussed above is only valid, at best,

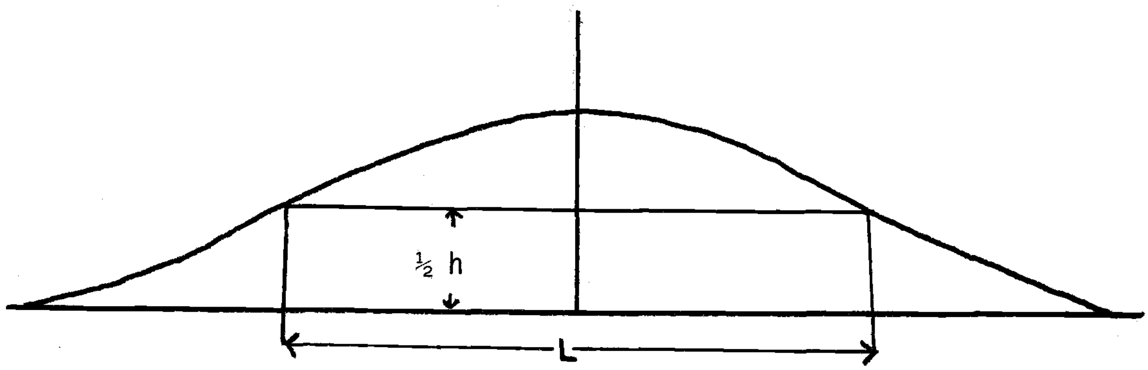


Figure 1

Hill showing parameters of height, h, and length, L for ridges perpendicular to the flow with an approximate logarithmic incident wind profile. On the other hand, a statistical model requires no physical assumptions. Therefore, it is applicable to any combination of terrain features, but is site specific.

Both the analytical model and the statistical model are used to estimate the winds at a hilltop location. The estimates are compared with observation to determine the quality of the models. Then the models are compared to see which of the two is better.

Good results from both models would suggest a two-fold program for predicting the speed-up experienced on a particular hill. First, the analytical model could be used, where applicable, to estimate the expected accelerations. If this estimate suggested good winds for power production, for instance, then a short term instrumentation program would be desired. Data collected could then be used with a nearby permanent instrument to construct a statistical model. Long term records from the permanent instrument would be used with the model to predict the long term nature of the hilltop winds. If this model suggested winds of interest, then a detailed instrumentation program would be justified. In this way, an objective method is developed for predicting wind accelerations. Such a method is needed in view of the cost of detailed instrumentation and the number of hills to be investigated.

II SITE DESCRIPTION

A terrain induced flow acceleration study requires measurement of winds at a minimum of two locations. One instrument should be located upwind of the terrain feature and ideally measures the homogeneous, equilibrium flow ($U = U_\infty$). The other instrument should be located at the top of the hill that is creating the flow disturbance. For testing simplified theoretical models, the hill profile should be a smooth, mathematically continuous function and the hill should be two dimensional. In addition to the above requirements, the two locations must be sufficiently close so that differences in the synoptic scale pressure gradient may be assumed to be zero. The two sites chosen did not fulfill these conditions; however, they were the best combination for which sufficient data were available.

The upwind or reference velocity used for this study was recorded on the south jetty of Yaquina Bay, south of Newport, Oregon. The instruments there were installed and are maintained by the Marine Science Center, a research facility of the School of Oceanography, Oregon State University. The instrument is at the top of a seventeen foot mast. The mast is situated on top of a fifteen foot hill. The base of the hill stops at the top of the jetty, then drops fifteen feet to Yaquina Channel for directions 280° through north and continuing eastward to 50°. At the base of the hill, level grassy fields continue outward for directions 60° through 150°. For directions 160° to 170° there is no hill; instead, there is a grass covered ridge line which runs parallel to the beach.

In the directions 180° to 270° is the ocean, and then smooth beach to the base of the ten to fifteen foot hill on top of which the mast is located. An exception is that the beach and hill are especially smooth and gentle at 200°.

Yaquina Head is a rugged east-west oriented peninsula located north of Newport, Oregon. The westward protrusion of this headland is approximately one mile on the south side and one half mile on the north side.

The instruments are on a one hundred foot tower which is at the crest of the hill and about one half mile east of the tip of the peninsula. Anemometers were located at thirty and one hundred feet. The crest of the hill is about two hundred thirty five feet above mean sea level. The vegetation consists of six to twelve inch grass in all directions except east and west. Dense foliage, three to four feet deep, covers the ground to the east and west. In addition, there are some small trees about four hundred feet to the east.

The land slopes downward to flat grassy fields for directions 360° to 70°. For directions 80° to 140°, the land slopes upward to a maximum of three hundred seventy five feet above mean sea level. The land resumes its downward slope for directions 150° to 260°. The topography is rugged and ridge-like for directions 270° to 300°. For the remaining directions, 310° to 350°, the land slopes downward to beach and ocean.

The anemometers were located at the crest of the hill, thus providing optimum exposure to hilltop winds. The requirement posed by the analytical model that the hill profile should be gentle and mathematically continuous is not well met. However, one purpose of the study is to see how well the theory may extend to more rugged terrain.

Failure to meet the requirement of two dimensionality might provide a serious source of error. If this requirement is not met, flow non-perpendicular to the length of the hill can occur. If this occurs, the effective length and shape of the hill would be a function of the angle of attack. Further, the two dimensional assumption requires all of the air to go over the hill. If mass is lost to "along-the-ridge" flow, then the acceleration caused by the ridge will be diminished. In order to minimize this loss, only the flow trajectories approximately perpendicular to the ridge line of Yaquina Head, i.e. northerly and southerly winds, were considered. Further, on the basis of topography alone, the south winds appear more appropriate since the south shoreline lies on approximately a 260° to 80° line. Thus, winds from 190° would seem to be the best for this study. In fact, winds from 185° to 205° are used. Further rationale for choosing this particular direction sector is given later. Refer to figures 2 and 3 for cross-sections of Yaquina Head.

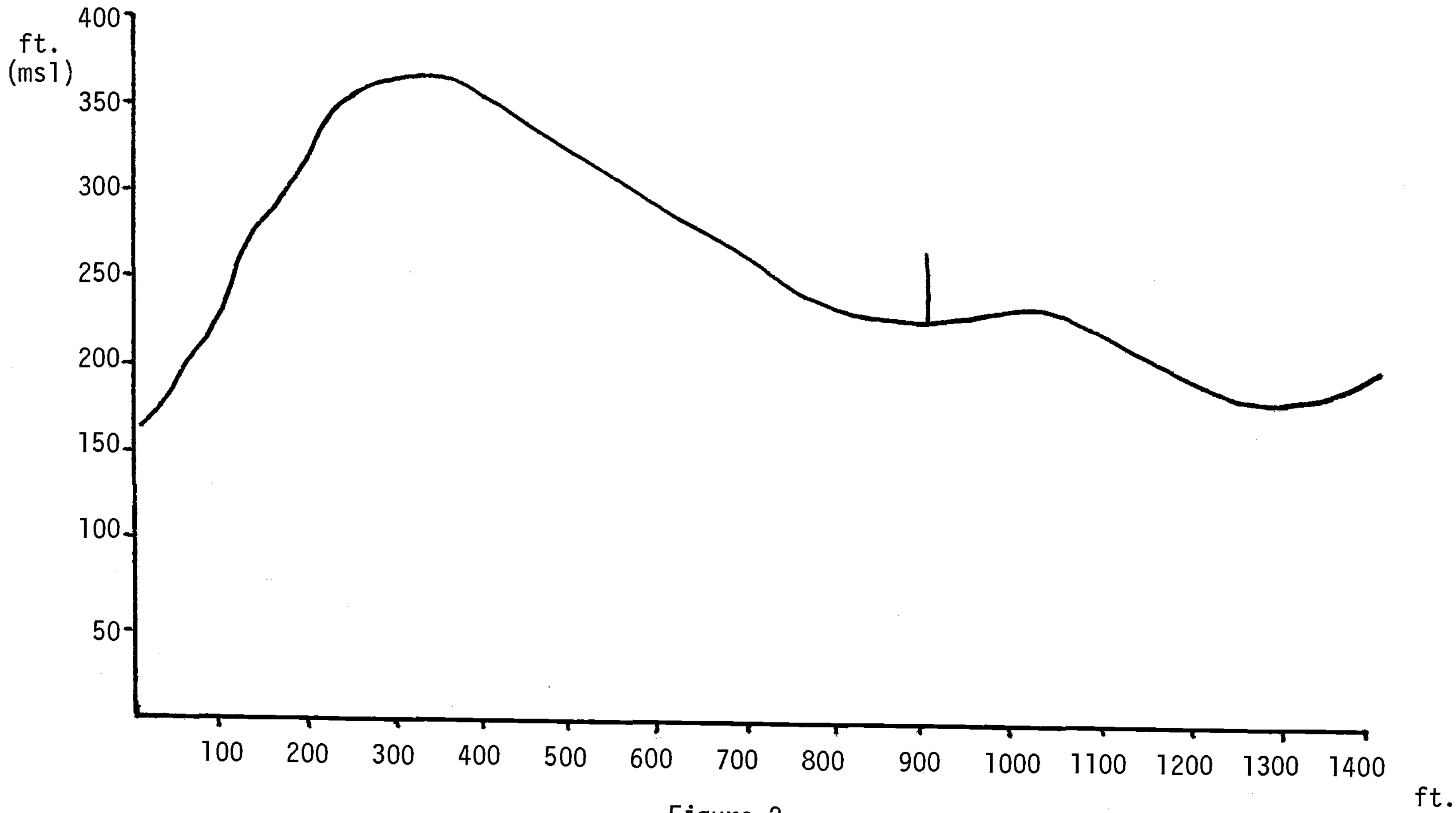


Figure 2

YAQUINA HEAD CROSS-SECTION

on 100° - 280° LINE

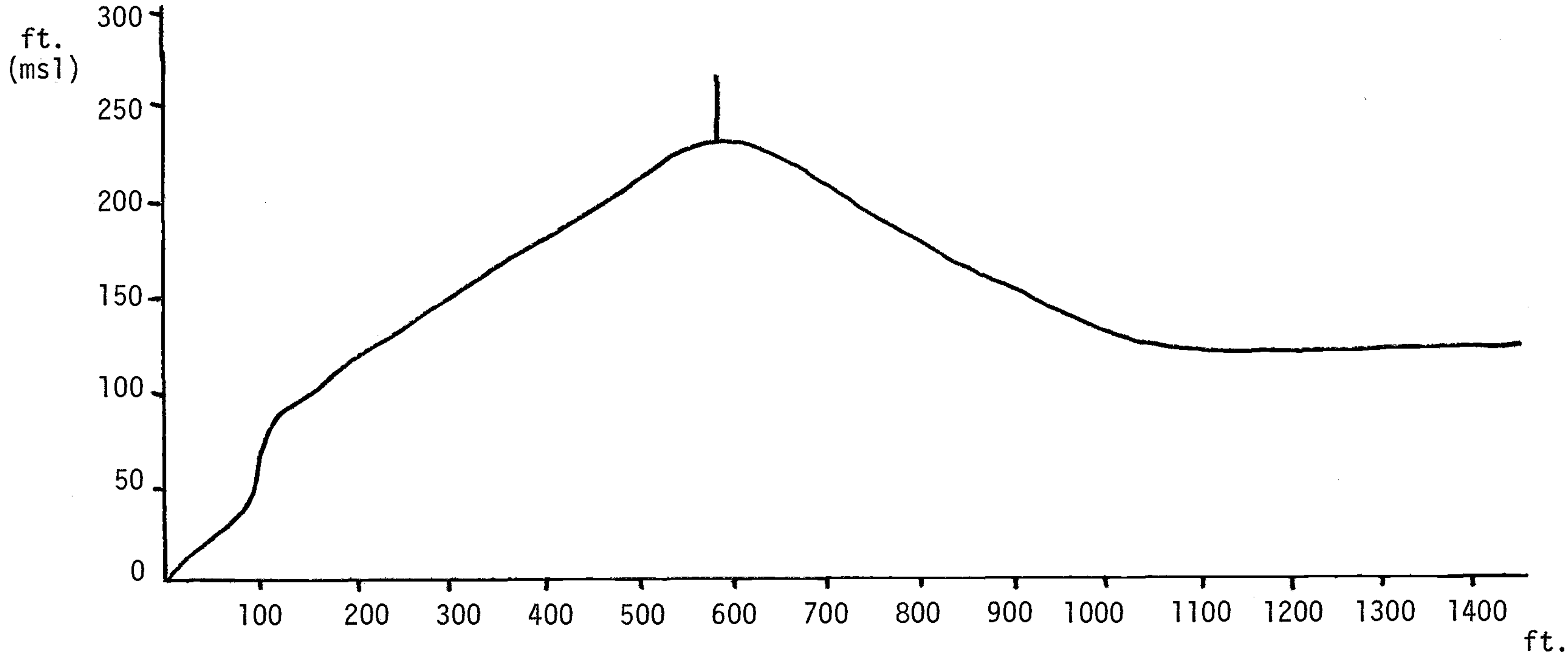


Figure 3

YAQUINA HEAD CROSS-SECTION

on 190° - 10° LINE

III LITERATURE SURVEY

Literature on modeling flow accelerations caused by surface obstructions is not abundant. However, it is expected that the small number of reports is more an indication of the complexity of the situation than a reflection of the need for such knowledge. Modeling studies that have been examined for this study are by Jackson and Hunt (1975), Taylor and Gent (1974), and Frost et al. (1973). These authors consider only the very simplified case of flow over a two dimensional low hill. Further restrictions commonly assumed by these authors include uniform surface roughness, horizontally homogeneous flow, adiabatic lapse conditions, and the requirement that the production of turbulence be balanced by dissipation. Interestingly enough, the attepts by the above authors assume similar initial and boundary conditions with different analytical techniques, yet obtain similar results.

The theoretical model of Jackson and Hunt (1975) provides a simple method of predicting the accelerating effect of a low hill on the incident wind field. The model is a function of the hill's geometry only, although many assumptions of the geometry and incident flow field are inherent in its development. An understanding of the model's derivation, assumptions and limitations is necessary for proper interpretation of its predictions.

The incident flow U_o, is assumed to be logarithmic and dependent only on height;

$$U_o(Z) = (U^*/\kappa) \ln (Z/Z_o) \qquad (1.1)$$

where Z is the vertical coordinate; U^*, the friction velocity; κ is the von Karman constant taken to be 0.4; and Z_0, the characteristic roughness length. Furthermore, the flow field is specified to be two-dimensional, thus, the low hill is actually an infinitely long ridge. The boundary layer is divided into an inner and an outer region. The inner region is a thin layer whose upper boundary follows the hill profile. The horizontal velocity over the hill in this region is, to a first approximation, equal to the upstream velocity at the same elevation. Since the incident velocity profile is specified as horizontal, the vertical velocity, w, in the inner region is only a perturbation induced by the hill.

It is assumed that the outer region flow possesses the same horizontal incident velocity profile as the inner region. The vertical velocity perturbation from the inner region is continuous through the outer region. Mass continuity considerations suggest a corresponding horizontal velocity perturbation, ΔU, in the outer region such that

$$\frac{\partial \Delta U}{\partial X} + \frac{\partial W}{\partial Z} = 0 \qquad (1.2)$$

At some height sufficiently far from the surface, the effects of the hill are not seen. Thus the upper boundary condition ($Z \rightarrow +\infty$) is ΔU and $W \rightarrow 0$.

Another assumption of the flow field is that the mean horizontal pressure gradient $\partial P/\partial X$ is constant. However, the outer region velocity perturbation, ΔU, induces a perturbation pressure, ΔP, which is continuous through the inner and outer regions. Since the perturbation pressure is continuous, there exists a perturbation pressure gradient, $\partial \Delta P/\partial X$.

The perturbation pressure gradient then drives a perturbation velocity, $\Delta\hat{U}$, in the inner region. The purpose of the analysis is to solve the two-dimensional momentum equations of the inner and outer regions for ΔU, $\Delta\hat{U}$, W, and ΔP.

The method for obtaining these solutions is to write the momentum equations for the inner and outer regions separately. Then perform the appropriate scaling to eliminate the least significant terms, i.e. leaving a balance between the acceleration, pressure gradient, and Reynolds stress terms. The equations are further simplified by assuming a homogeneous, or no-hill condition so the perturbation shear-stress is proportional to the perturbation velocity gradient.

$$\tau_{12} = 2\kappa \; \Delta \; Z \; \partial\Delta\hat{U}/\partial Z.$$

Here, ΔZ is the displacement above the surface.

When the shear-stress is written in terms of the velocity gradient, the equations can be solved for ΔU, $\Delta\hat{U}$, W, and ΔP. Before the complete solution can be given the following boundary and matching must be specified:

ΔU, W, $\Delta P \to 0$ as $Z \to \infty$

$W \to 0$ as $Z \to 0$

ΔU, $\Delta\hat{U}$, $W \to 0$ as $x \to \pm\infty$

$\Delta U = \Delta\hat{U}$ at the boundary interface

An interesting conclusion of the analysis is that the horizontal velocity perturbation, ΔU, is greatest at the common boundary of the inner and outer regions. A convenient parameterization of the horizontal velocity perturbation, ΔU, is the fractional speed-up ratio, ΔS, which is defined as:

$$\Delta S = \frac{U_2 - U_1}{U_1} \qquad (1.3)$$

Where U_1 is the horizontal velocity at the upwind station and U_2 is the horizontal velocity on the hilltop, measured at the same height above the surface as U_1. When expressions for U_1 and U_2 are substituted into Eq. 1.3, ΔS is found to be most sensitive to the ratio h/L, where h and L are the scaled height and length of the hill respectively. When typical values for roughness length, displacement height, and the depth of the inner region are substituted into the expressions for U_1 and U_2, it is found that $\Delta S \simeq 2h/L$.

Jackson and Hunt used wind measurements from a low hill which were taken by Berlyand, Genikhovich, and Kurenbin (1968) to test their model. The hill was 50m high and the horizontal length was 500m, thus giving h/L = 0.1. At 1m above the surface, ΔS = 0.2 to 0.3. Wind tunnel simulation of the flow over this hill by Zrajevsky, Doroshinko, and Chepik (1968) gives ΔS = 0.24 at 1m.

Estimates of wind accelerations over Lowther Hill in southern Scotland by Hardman et al. suggest $\Delta S \doteq 1.0$. A low estimate of h/L for Lowther Hill is 0.34. This suggests $\Delta SL/h \doteq 2.7$.

In summary, the Jackson and Hunt analysis predicts a fractional speed-up ratio, $\Delta S \simeq 2$ h/L. Experimental results, which consist of wind tunnel simulations and rough estimates of wind speeds of over real hills, suggests ΔS is closer to 2.5 h/L.

Taylor and Gent (1974) attempted to describe the flow over a two-dimensional hill using numerical techniques. Their approach was quite different from that of Jackson and Hunt (1975). However, the conclusions from both methods are similar.

Taylor and Gent assume similar equilibrium upstream conditions, but choose a coordinate system conforming to the hill profile. They further limit the hill size to "gentle topography - defined as not giving rise to mean flow separation". This is a more stringent restriction than Jackson and Hunt (1975) specify for their hill. The convenience provided by such a restriction lies in the fact that the streamlines coincide with lines of constant vertical coordinate. This conformal coordinate system matches the rectangular coordinate system in the limits for zero and infinity for both vertical and horizontal coordinates.

The method of analysis taken was to write the equations of motion in terms of the conformal coordinate system. Two different approximations were used to close the equations: one, the simple mixing length hypothesis, and the other making use of the turbulent energy equation. Both models were solved via computer using iterative techniques.

Velocity profiles produced by both models are comparable. These results suggest that three-dimensional effects would become much more important if the hill were steeper. An interesting result is that the "speed-up" predicted by this analysis supports that of Jackson and Hunt.

Frost et al. (1973) do not consider a low hill as the other authors do; instead, they use a semi-elliptical cylinder on a flat plate and study the effects on the flow produced by altering the ellipse's aspect ratio. The aspect ratio, k, is defined as the ratio of the length of the major axis, which is parellel to the ground, to the height of the ellipse which is one-half of the minor axis. In general, their conclusions are:

1. The wind maximum occurs directly above the top of the hill.
2. An increase in aspect ratio causes a decrease in the maximum flow acceleration.
3. A decrease in the aspect ratio influences the flow field in the same way as an increase in the surface roughness.

These three papers express a need for an atmospheric boundary layer model which satisfactorily includes topographical effects. They also demonstrate that the construction of that model is a nontrivial problem. In general, the conclusions from these three analyses are mutually supportive and do not produce contradictory results. Specifically, the result from these analyses that is tested here is the relationship $\Delta S = 2h/L$. Good results from this test would give more credence to the analytical methods and physical assumptions used to derive the model.

IV THE STATISTICAL MODEL

The second model examined in this study is based on a statistical relationship between wind speeds at two different locations. The purpose of developing such a model is to see if a small number of observations (of order 100) can be used to predict future winds speeds. The necessary data for such a scheme is composed of long term wind records from the South Jetty at Newport, and approximately fifteen months (from September 1975 to March 1977) of data from Yaquina Head. The model is developed by taking the average ratio of the hourly observations from the two stations for September 1975 to March 1976. The statistical model is then $E(V_2) = C\ V_1$ where C is the mean ratio, V_1 is the known upstream wind, and $E(V_2)$ is the expected value of the predicted hilltop wind, V_2. The model is used with wind data from the South Jetty, V_1, to predict winds at Yaquina Head, V_2, for the same seven months of 1976 and 1977. Real time observations are compared with predicted values to test the model.

Wind speed ratios used to determine the model were calculated for incremental speed classes. Ratios calculated from low wind speeds (below 10mph) were found to fluctuate from values less than one to values near two for a given direction. Mean ratios calculated for higher speeds ($\geq$ 10 mph) at five mph speed class increments typically varied one tenth from one class to another (See Tables 1 and 2). Since flow patterns are not so well organized at low wind speeds, the larger flucuations are to be expected. Furthermore, winds below ten mph are not useful for power production, do very little damage, and can disperse

Table 1

Mean Ratio of Yaquina Head Wind, V_2, to Yaquina Jetty Wind, V_1 by Speed Increments for 175° to 184° and 185° to 194°

Directions 175° to 184°

Speed Class (mph)	Observations	Mean Ratio $(\overline{V_2/V_1})$	Std. Deviation
1 - 4	2	0.80	0
5 - 9	10	1.97	1.15
10 - 14	17	1.65	1.07
15 - 19	18	1.75	0.67
20 - 24	25	1.68	0.83
25 - 29	10	1.68	0.57
30 - 39	15	1.65	0.35
40 - 49	8	1.39	0.09
50 - 59	0	0	0

Directions 185° to 194°

Speed Class (mph)	Observations	Mean Ratio $(\overline{V_2/V_1})$	Std. Deviation
1 - 4	2	0.60	0.28
5 - 9	12	1.12	0.64
10 - 14	32	1.57	0.85
15 - 19	25	1.65	0.46
20 - 24	36	1.50	0.50
25 - 29	22	1.49	0.30
30 - 39	43	1.53	0.20
40 - 49	46	1.57	0.28
50 - 59	29	1.48	0.20

Table 2

Mean Ratio of Yaquina Head Wind, V_2, to Yaquina Jetty Wind, V_1,

By Speed Class Increment for 195° to 204° and 205° to 214°

Directions 195° to 204°

Speed Class (mph)	Observations	Mean Ratio ($\overline{V_2/V_1}$)	Std. Deviation
1 - 4	0	0	0
5 - 9	21	1.05	0.23
10 - 14	30	1.72	1.08
15 - 19	18	1.50	0.32
20 - 24	22	1.60	0.50
25 - 29	16	1.37	0.17
30 - 39	25	1.52	0.20
40 - 49	12	2.81	4.09
50 - 97	6	1.41	0.08

Directions 205° to 214°

Speed Class (mph)	Observations	Mean Ratio ($\overline{V_2/V_1}$)	Std. Deviation
1 - 4	3	0.57	0.23
5 - 9	6	1.70	1.42
10 - 14	4	1.30	0.16
15 - 19	10	1.27	0.26
20 - 24	6	1.17	0.51
25 - 29	11	1.37	0.29
30 - 39	9	1.33	0.16
40 - 49	4	1.45	0.06
50 - 97	0	0	0

less pollution than winds with speeds greater than ten mph. For these reasons, the low wind speeds were not used.

V ANALYSIS OF THE DATA

The methods used to analyze the data were determined by not only the desired information, but also the characteristics of the data itself. Because of this, a discussion of the raw data might be desirable. A logical, if not chronological, narrative of the analysis is presented to give better insight to the significance of the results.

Two wind vector data sets were collected on essentially the same type of sensor and recorder combination. The recorders were Bendix 141 units and the sensors were Aerovanes. The raw data is in the form of continuous strip charts with separate traces for speed and direction.

The values were read manually at two mph intervals for speed and ten degree intervals for direction. Values of speed and direction were averaged hourly. The advantage of taking hourly rather than, say, fifteen minute averages is that most of the turbulence with a space scale smaller than the distance between the two anemometers, is thereby filtered from the data. Also, time synchronization error between systems is minimized. The data were then transferred to punched cards for easy access to subsequent computer analysis.

A library of computer programs has been accumulated to satisfy the various data analysis needs. The first of these was to determine whether or not the flow field encompassing the two instruments was approximately homogeneous. In other words, to determine if the two instruments measured approximately the same flow regime. To ascertain this, a program was designed to plot a frequency distribution of the wind direction measured at one location as a function of the wind direction measured at the other location. Figure 4 shows results of this analysis for the southerly directions of 180°, 190°, 200°, and 210°. Northerly flow was not well organized, having a characteristic wide spread distribution. Eastern and western directions are not suitable for further analysis because of terrain complications. Refer to Figure 5.

Consideration of the southerly sectors shows good agreement in wind directions. Winds from directions 170° and 180° were not well organized, but directions 190° and 200° show good flow agreement between stations. Although the distributions show a marked preference for flow from 200°, it must be remembered that instrumentation orientation could be in error by as much as ±10°. This inaccuracy renders inconclusive the determination of direction shifts of 10° or less.

Since the wind direction is in approximate agreement at the two stations, when from 190° to 200°, it may be reasonable to assume that differences in wind speed between the two stations can be described as accelerations. In contrast, when the two wind directions are not in agreement, differences in wind speed may be attributed to measuring two different flow regimes and not accelerations. The conclusion drawn from this observation is that winds from 190° and 200° are the only acceptable winds to consider for a flow acceleration study at this site.

Design and construction of the statistical model provided the next need for programmable data analysis. The data set has been selected on the same basis as for the direction comparison analysis. Next, the problem of organizing the data to get representative results occurs. The statistical model, $E(V_2) = CV_1$, relies heavily on the mean ratio of winds at the two stations. There are at least three ways to obtain

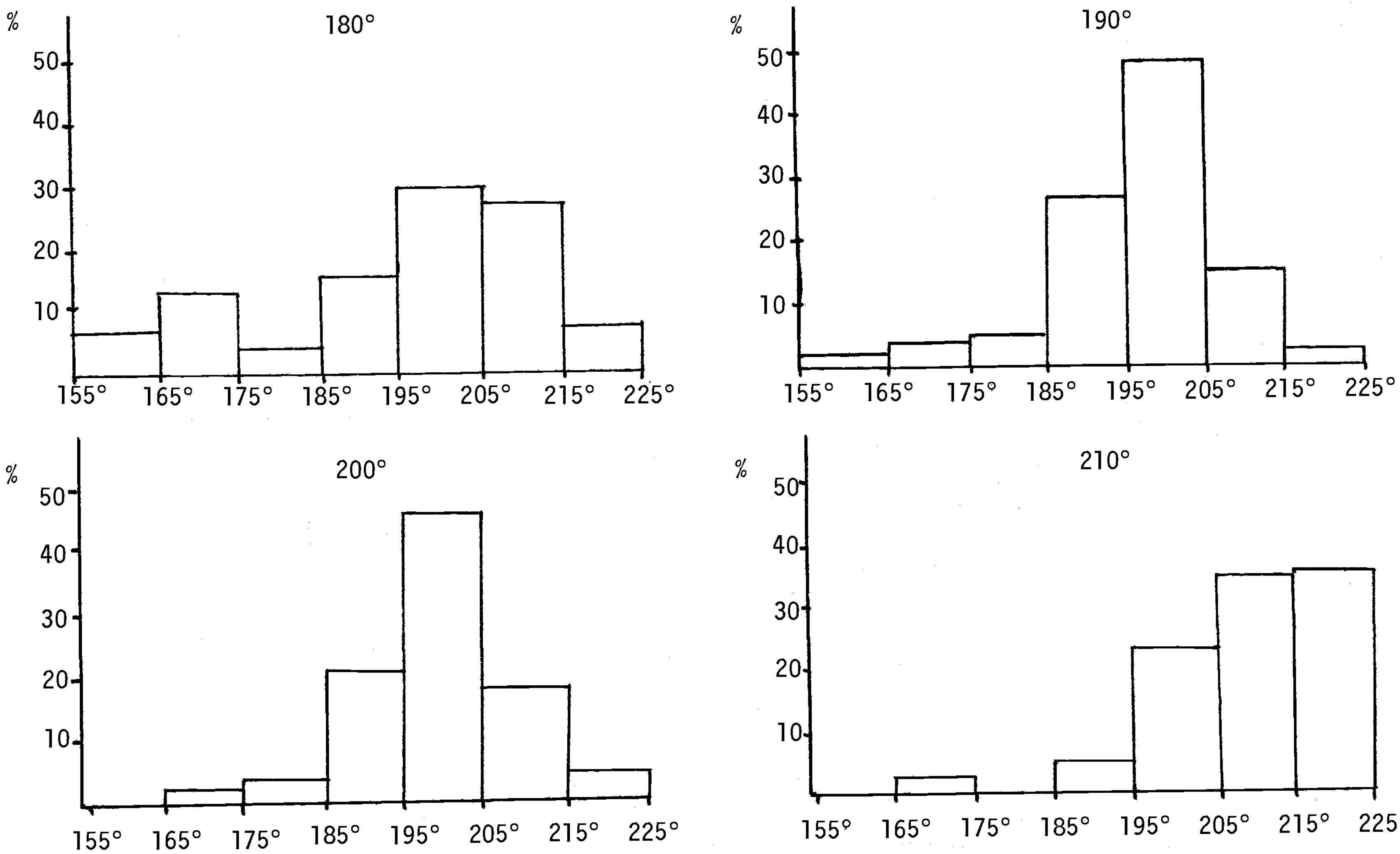


Figure 4. DIRECTION DISTRIBUTIONS AT YAQUINA SOUTH JETTY
FOR THE YAQUINA HEAD 10° DIRECTION SEGMENTS
180°, 190°, 200°, 210°

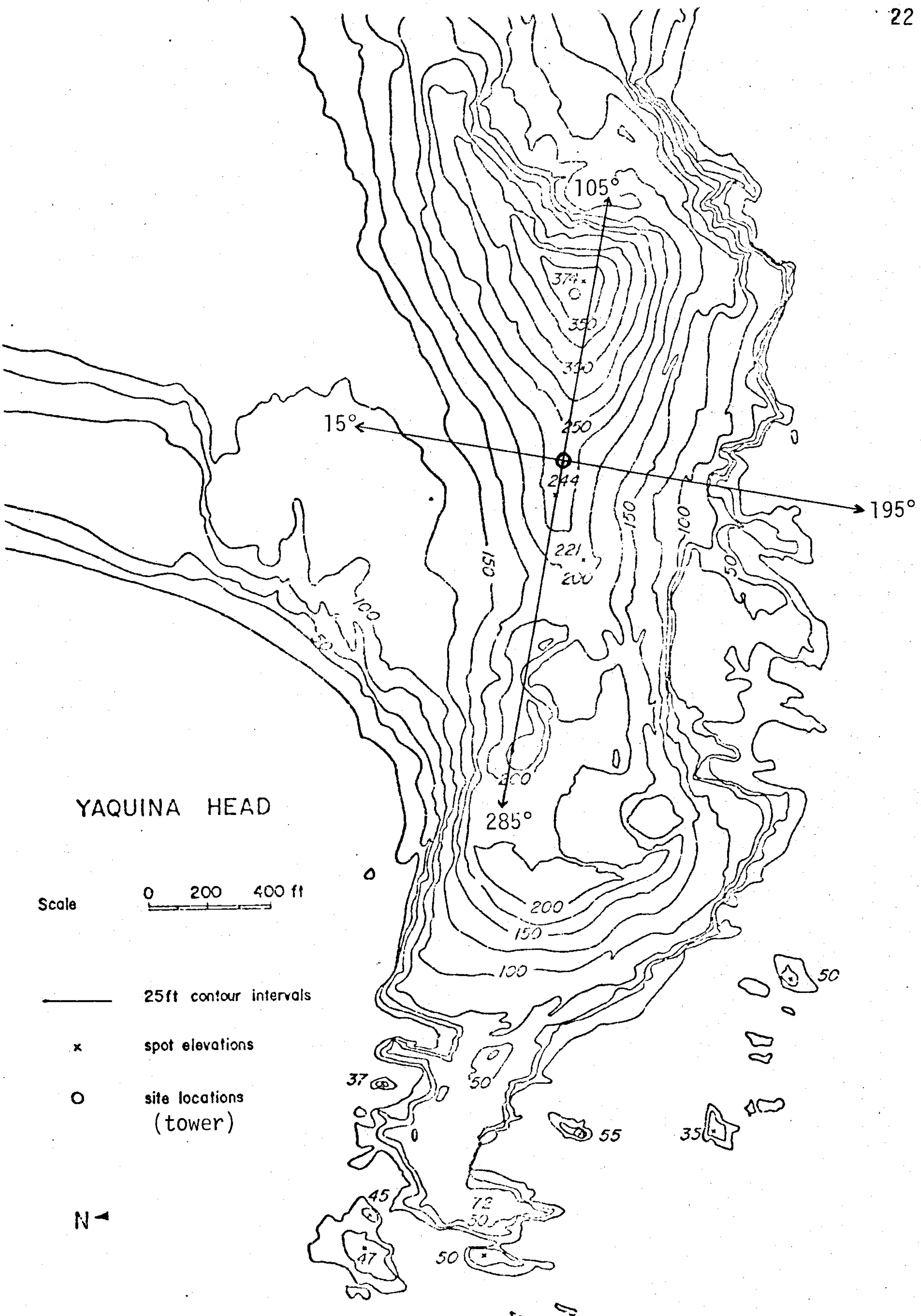

YAQUINA HEAD
Scale
0 200 400 ft
25ft contour intervals
spot elevations
site locations
(tower)
N
105°
15°
195°
285°
374
350
300
250
244
221
200
150
100
50
0
37
55
35
45
72
47

FIGURE 5

this mean. The best method depends on how the variance, $\sigma^2(V_2)$, is related to the velocity, V_1, if the desired mean ratio is $(\overline{V_2/V_1})$. The three methods are described algebraically as:

If $\sigma^2(V_2) \propto V_1$ then $(\overline{V_2/V_1}) = \Sigma V_2/\Sigma V_1$ (2.1)

If $\sigma^2(V_2) \propto V_1^2$ then $(\overline{V_2/V_1}) = \frac{\Sigma(V_2/V_1)}{N}$ (2.2)

If $\sigma^2(V_2)$ is constant with respect to V_1 then $(\overline{V_2/V_1}) = \frac{\Sigma(V_1-\bar{V}_1)(V_2-\bar{V}_2)}{\Sigma(V_1-\bar{V}_1)^2}$ (2.3)

Thus, the next programming chore was to compute $\sigma^2(V_2)$ as a function of incremental values of V_1.

Figures 6 and 7 show $\sigma^2(V_2)$ vs. V_1 and V_1^2. It is obvious that $\sigma^2(V_2)$ is neither constant or increasing with V_1 so equations 2.1 and 2.3 were not used. From Figure 7 it is not clear that equation 2.2 should be used. However, since equation 2.2 is a straightforward method for obtaining a mean ratio, it was chosen for obtaining $(\overline{V_2/V_1})$.

Consequently, a program was written to select, from the data, wind vectors having the desired values of speed and direction, and to compute the mean ratio $(\overline{V_2/V_1})$. The data used to calculate this ratio was taken from August, 1975 through March, 1976.

The next step in the analysis was to use the mean ratio, $(\overline{V_2/V_1})$ and the "parameters" h and L with the South Jetty winds, V_1, to predict Yaquina Head winds, V_2 for data from September 1976 through March 1977.

The statistical model and the geometric model must be expressed in the same sense. This is done as follows. The fractional speed-up is defined as:

$$\Delta S = (V_2-V_1)/V_1$$

$$\Delta S = V_2/V_1 - 1 \qquad (2.4)$$

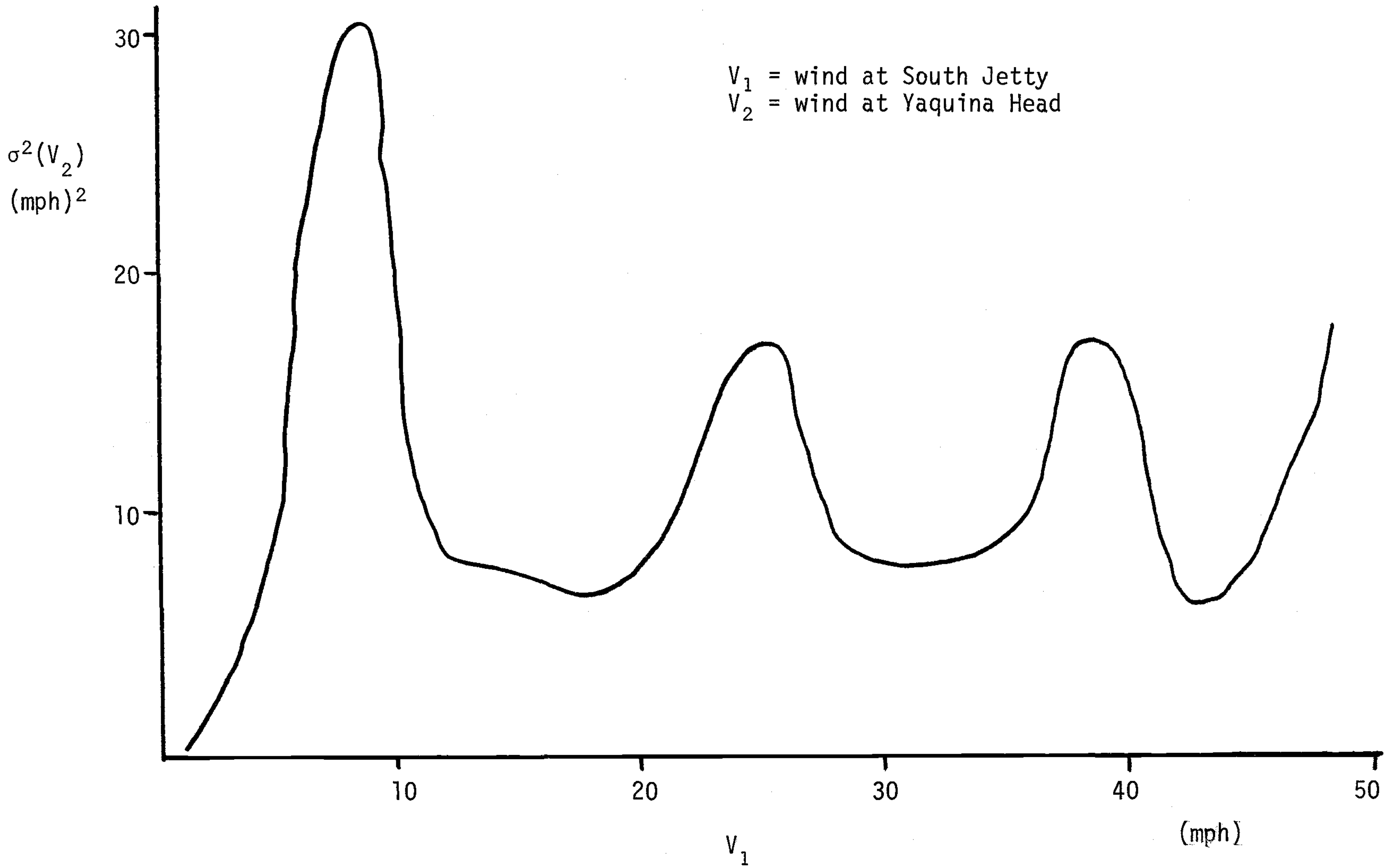
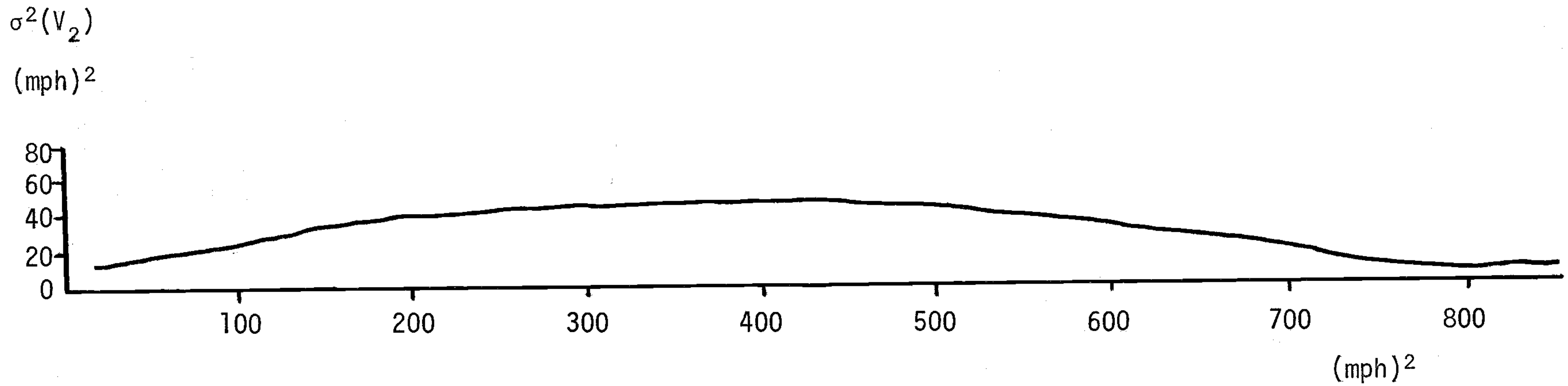


Figure 6

$\sigma^2(V_2)$ vs. V_1



$V_1^{\,2}$

Figure 7

$\sigma^2(V_2)$ vs. $V_1^{\,2}$

$1 + \Delta S = V_2/V_1$

Thus, the geometric model becomes $C_g = 1 + 2h/L$, and the statistical model is expressed as $C_s = (\overline{V_2/V_1})$ so the respective prediction equations are:

$$\hat{V}_{2g} = (1 + 2h/L)\ V_1 = C_g\ V_1 \qquad (2.5)$$

$$\hat{V}_{2s} = (\overline{V_2/V_1})\ V_1 = C_s\ V_1 \qquad (2.6)$$

where $\hat{V}_2$ is the predicted value of V_2; V_1 is taken from the August 1976 through March 1977 data set. Thus, for each value of V_1 there are two predicted values of V_2, i.e. $\hat{V}_{2g}$ and $\hat{V}_{2s}$.

The program that computes V_2 for each model outputs the four column vectors V_2, $\hat{V}_{2g}$, $\hat{V}_{2s}$, and V_1. These variables represent, respectively, the observed values of V_2 for August 1976 to March 1977; the predicted value of V_2 from the geometric model; the predicted value of V_2 by the statistical model; and the observed value of V_1 for August 1976 to March 1977.

The statistical analysis consisted of the construction of scatter diagrams, providing the visual comparisons; and single and multiple variable regression analysis, for least squares fitting of linear regression models to the data.

The scatter diagrams were created to show the relationships between the predicted and observed values of wind speed at Yaquina Head (see figures 8 and 9). Closer examination of the statistical and geometric prediction models was possible by regression analysis and related analysis of variance tables. The choices for the regression models were

$$\hat{V}_2 = \alpha_0 + \alpha_1 V_2$$

or

$$\hat{V}_2 = \alpha_1\ V_2$$

The hypothesis tested was

$$H_0: \alpha_0 = 0$$

$$H_a: \alpha_0 \neq 0$$

to determine if the constant term was significantly different from zero.

It was found (refer to Appendix A) that, in both cases,

$$V_{2g} = \alpha_1 V_2 \quad \text{and} \quad V_2 = \alpha_1 V_{2s}$$

were the better regression models since α_0's were small. This result is physically appealing since the wind should approach zero simultaneously at two closely located stations.

Once the better regression model is determined for each prediction method the next task is to determine which prediction method, if either, is better. This was done visually (see Figure 10) by plotting both prediction equations 2.5 and 2.6 on the scatter diagram of $\hat{V}_2$ vs. V_1. A more rigorous way of determining the better prediction method was to compare the residual sums of squares of the three regression models.

$$V_2 = \alpha_0 + \alpha_1 \hat{V}_{2s} + \alpha_2 \hat{V}_{2g}$$

$$V_2 = \alpha_0 + \alpha_1 \hat{V}_{2g}$$

$$V_2 = \alpha_0 + \alpha_1 \hat{V}_{2s}$$

This was done as in the Appendix and it was found that, in either case, adding the second variable to the regression model did not significantly increase its accuracy. The implication, then, is that neither prediction model is significantly better than the other.

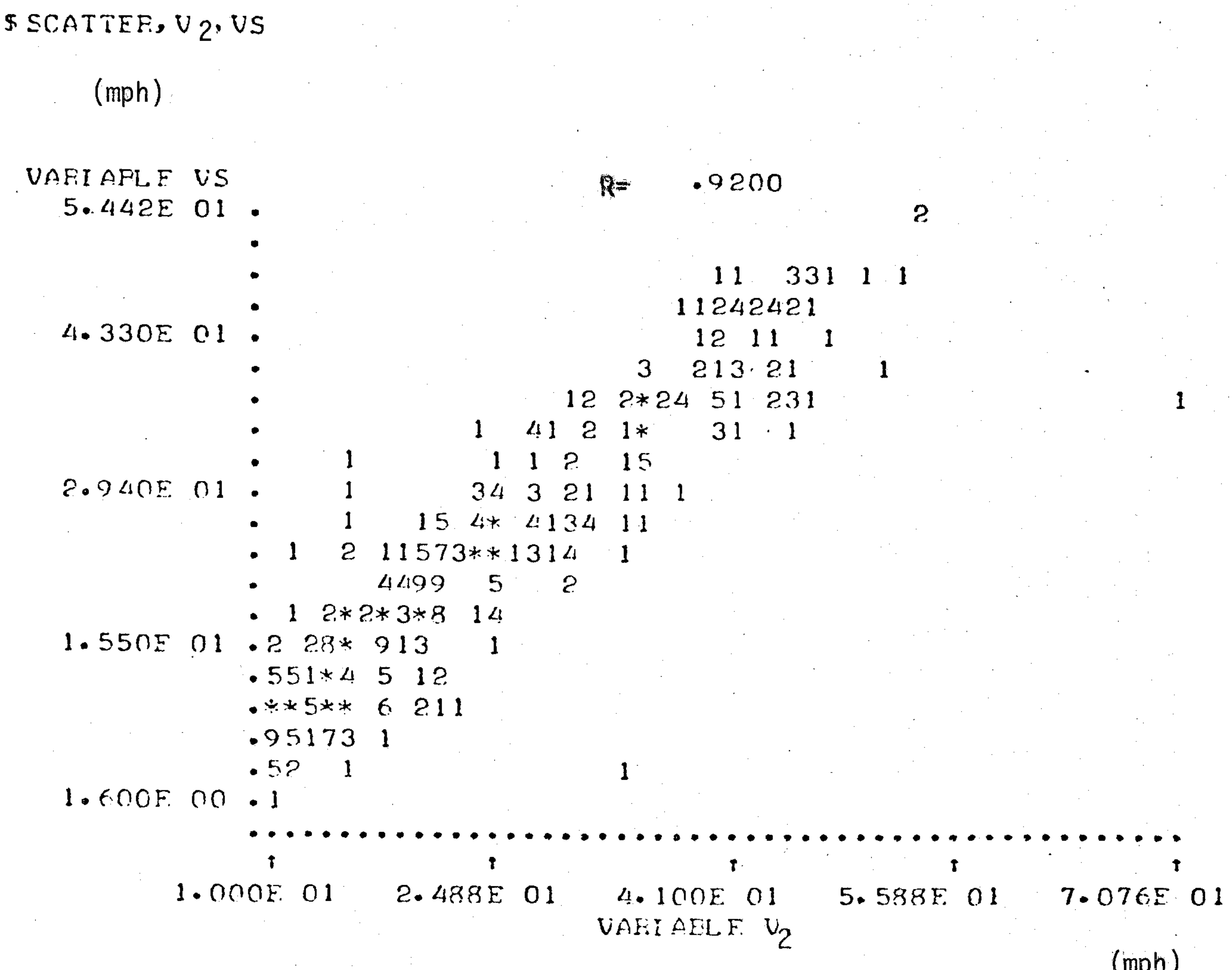


Figure 8

Statistically predicted wind, V_s, scattered on observed Yaquina Head wind, V_2.

Note: Asterisks indicated more than 10 observations at that coordinate value.
R = correlation coefficient

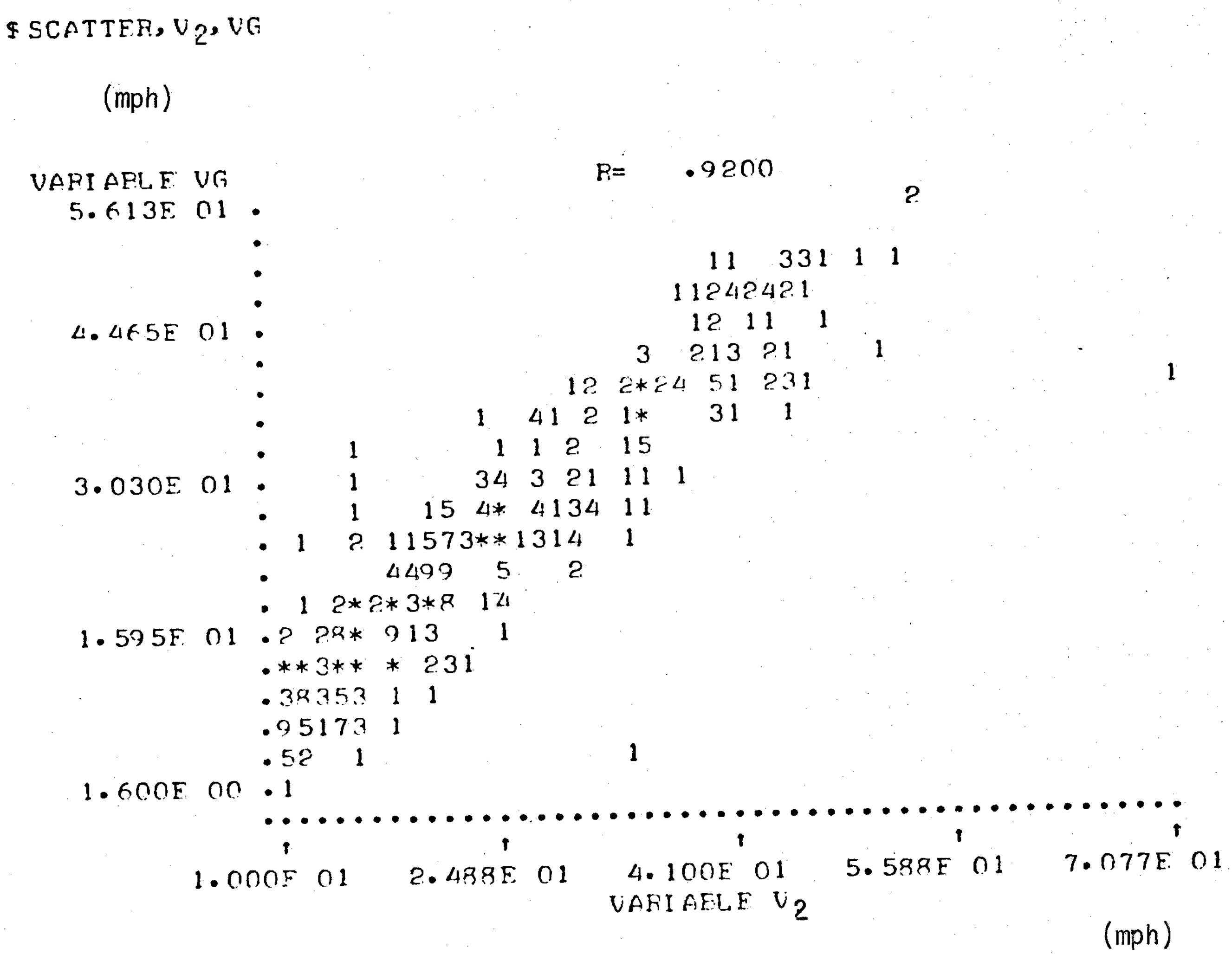


Figure 9

Geometrically predicted wind, V_g, scattered on observed Yaquina Head wind, V_2.

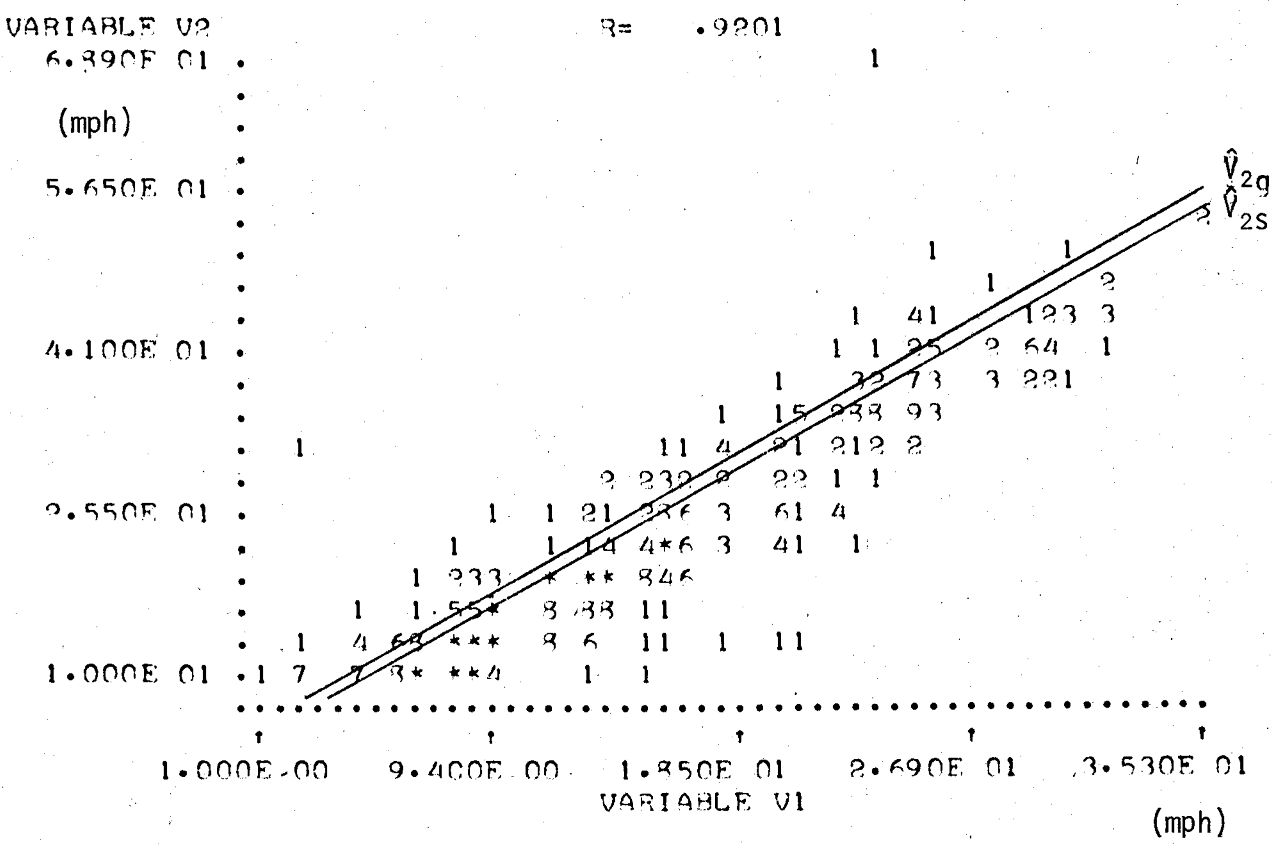


Figure 10

Yaquina Head wind, V_2, scattered on Yaquina Jetty wind.

VI SUMMARY AND DISCUSSION OF RESULTS

From the wind direction comparison analysis it was determined that winds from 185° to 205° would be used for the study. This analysis was necessary to determine if the two anemometers were measuring the same flow regime.

Once the wind directions to be considered were specified, it was necessary to pick the appropriate speed catagories. It was found that the mean ratio ($\overline{V_2/V_1}$) for speeds less than 10 mph fluctuated unpredictably, so these low speeds were not used in the study. For speeds greater than 10 mph, ($\overline{V_2/V_1}$) was found to be 1.62, a value very close to the calculated value of 2 h/L + 1 = 1.64. This result by itself suggests the geometric model would be fairly accurate; at least for the particular data set September 1975 through March 1976.

The test, then, was to use the two model values to predict the next year's winds on Yaquina Head using the corresponding winds for the South Jetty. The predicted values $\hat{V}_{2s}$ and $\hat{V}_{2g}$ were calculated for each observation for September 1976 through March 1977. Regression analysis was then done for each prediction model and it was found that the appropriate regression models were:

$$\hat{V}_{2s} = 1.01\ V_2$$

and

$$\hat{V}_{2g} = 1.04\ V_2$$

Tests (see Appendix) were performed to see if the regression coefficients were significantly different from 1.00. It was found that they were not at the 99% confidence level. This result suggests that:

$$\hat{V}_{2s} \simeq V_2$$

and

$$\hat{V}_{2g} \simeq V_2$$

or, in other words, both the geometric and statistical prediction models reliably predicted the observed Yaquina Head winds.

The remaining analysis of interest was to see if one prediction method was better than the other. The appropriate test was performed, (again, see Appendix), and the results showed that combining the models in a multiple variable regression equation showed no significant improvement over either of the single variable regression equations. The implication is that both prediction methods do extremely well and that a combination of the two does not significantly improve the prediction ability.

VII CONCLUSIONS

The objective of this study has been to examine and evaluate two different methods of predicting wind speeds at a remote location. One method is based on an approximate analytical solution to the governing fluid equations; the other method relies on a statistical analysis of available data.

The geometric prediction method employs the best available physical approximation of topographical effects on the flow field. Yaquina Head was chosen for this study because, among other things, its three-dimensional geometry might not be a bad approximation to the theoretical, two-dimensional, hill. If the geometric model could closely predict winds on Yaquina Head, then possibly it could become a useful tool for determining wind speeds on other hills. The results show a remarkably good comparison between model predictions and observation; thus, hope is generated for using this model in more general applications.

The other prediction method examined here was based on an observed statistical relationship between winds at Yaquina Head and the South Jetty. There are no physical relationships assumed for this method. The test here was to see if the observed relationship, for one year, between wind speeds at two locations would be a good predictor of that relationship for the next year. It was found at least for these two locations and the two years considered that the relationship holds.

The conclusions from this study can be summarized as follows:

1. At least for one particular hill, the hilltop winds can accurately be predicted by knowing the upstream winds and the height and length of the hill.

2. Statistical models can be used to predict winds, future and past, at a remote location if that location has some data to compare with a long-term measurement station.

The success of the two prediction methods in this study suggests both methods should be incorporated, where applicable, into wind flow assessment programs before expensive, intensive instrumentation is initiated.

VIII REFERENCES

Draper, N. and H. Smith, 1966: Applied Regression Analysis, John Wiley and Sons, Inc., New York.

Frost, W., J.R. Maus, and G.H. Fichtl, 1974: 'A Boundary Layer Analysis of Atmospheric Motion Over a Semi-Elliptical Surface Obstruction.' Boundary Layer Meteorology, Vol. 7, pgs. 165-184.

Guthrie, D., C. Avery, and K. Avery, 1974: Statistical Interactive Programming System (SIPS), Technical Report No. 36, Department of Statistics, Oregon State University, May 1973, corrected edition March 1974.

Jackson, P.S., and J.C.R. Hunt, 1975: 'Turbulent Wind Flow Over a Low Hill.' Quarterly Journal of the Royal Meteorological Society, Vol. 101, pgs. 929-955.

Taylor, P.A.and P.R. Gent, 1974: 'A Model of Atmospheric Boundary Layer Flow Above an Isolated Two-Dimensional "Hill"; An Example of Flow Above "Gentle Topography".' Boundary Layer Meteorology, Vol. 7, pgs. 349-362.

APPENDIX

This section contains the various regression models and their respective analysis of variance tables, as well as the appropriate statistical tests necessary for an appropriate model selection.

The statistical testing consists of using values from the analysis of variance for each regression model in either a t or f-test to determine the significance of the regression coefficients. The f-test is:

If $\frac{A - B}{C} > F(\nu_1, \nu_2, 1-\gamma\%)$,

then reject $H_0: \alpha_0 = 0$.

A = Residual sum of squares for the regression model when $\alpha_0 = 0$.

B = Residual sum of squares for the regression model when $\alpha_0 \neq 0$.

C = Residual mean square error for the regression model when $\alpha_0 = 0$.

α_0 = Constant term in the regression equation

ν_1 = degrees of freedom of the regression

ν_2 = degrees of freedom of the residual

γ = the percent error accepted for the test.

The t-test is:

$$\text{If} \quad \frac{\alpha_0 - \alpha_{10}}{\sqrt{\frac{\text{Resid. M.S.}}{\text{Sum squares}, X}}} > t(\nu, \gamma/2)$$

then reject $H_0: \alpha_1 = \alpha_{10}$

where α_1 = regression coefficient

α_{10} = the hypothesized regression coefficient

Resid M.S. = the residual mean square for the regression model tested.

Sumsquares, $X = \Sigma(X_i - \bar{X})^2$ where X is the independent variable in the regression model.

ν = degrees of freedom, n-1 (number of observations)

γ = the percent error acceptable for the test

STAT = C_s

GEO = C_g

To examine the statistical model STAT = $\alpha_0 + \alpha_1$ HEAD we test the following hypotheses:

1. Is α_0 significantly different from zero?

H_0: $\alpha_0 = 0$

H_a: $\alpha_0 \neq 0$

The test:

$$\frac{A - B}{C} = \frac{10104.8 - 10089.1}{20.5}$$

$$= .77 < F\ (1{,}506,\ 99\%)$$

$$= .77 < 6.70$$

therefore H_0 can not be rejected or in other words α_0 is not significantly different than zero so choose STAT = α_1 HEAD as the preferred regression model (See Table 3).

2. Is α_1 significantly different from 1.00?

H_0: $\alpha_1 = \alpha_{10} = 1$

H_a: $\alpha_1 = \alpha_{10} \neq 1$

The test:

$$\frac{\alpha_1 - \alpha_{10}}{\sqrt{\frac{S}{(X_i - \bar{X})^2}}} = \frac{\alpha_1 - \alpha_{10}}{\sqrt{\frac{\text{Resid M.S.}}{\text{Sumsquares, HEAD}}}}$$

Table 3

Statistical Analysis of $V_S = \alpha_0 + \alpha_1 V_2$ Regression Model

$REGRESS,$V_S$,$V_2$

V_S = 2.4183E+01

:ADD,V

V_S = 4.3813E-01 +9.9340E-01 V_2

:AVTABLE

ANALYSIS OF VARIANCE TABLE

Source	DF	SUM OF SQUARES	MEAN SQUARE
TOTAL	493	6.57167706E 04	1.33299737E 02
REGRESSION	1	5.56277065E 04	5.56277065E 04
RESIDUAL	492	1.00890640E 04	2.05062277E 01

R SQUARED = .84647657

:DROP,0

V_S =+1.0087E+00 V_2

:AVTABLE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE
TOTAL	494	3.54621350E 05	7.17856984E 02
REGRESSION	1	3.44516500E 05	3.44516500E 05
RESIDUAL	493	1.01048497E 04	2.04966524E 01

R SQUARED = .97150524

:END

$$= \frac{1.009 - 1.000}{\sqrt{\frac{20.50}{56369.34}}}$$

$$= .472 < t\ (507,\ 99\%) = 2.576$$

therefore H_0: $\alpha_1 = 1.00$ can not be rejected so accept the model STAT $= \alpha_1$ HEAD where $\alpha_1 = 1$ or STAT = HEAD is the better regression model.

To examine the geometric model GEO $= \alpha_0 + \alpha_1$ HEAD we test the following hypotheses:

1. Is α_0 significantly different from zero?

H_0: $\alpha_0 = 0$

H_a: $\alpha_0 \neq 0$

The test: $\frac{A - B}{C}$

$$= \frac{10741.1 - 10722.9}{24.79}$$

$$= .84 < F(1,506,\ 99\%)$$

$$= .84 < 6.70$$

therefore H_0 can not be rejected or in other words, α_0 is not significantly different than zero, so choose GEO $= \alpha_1$ HEAD as the preferred regression model (See Table 4).

2. Is α_1 significantly different from 1.00?

H_0: $\alpha_1 = \alpha_{10} = 1.00$

H_a: $\alpha_1 = \alpha_{10} \neq 1.00$

The test: $\frac{\alpha_1 - \alpha_{10}}{\sqrt{\frac{\text{Resid M.S.}}{\text{Sumsquares, HEAD}}}}$

$$= \frac{1.0402 - 1.0000}{\sqrt{\frac{21.79}{56369.34}}}$$

$$= 2.045 < T\ (507,\ 99\%)$$

$$= 2.045 < 2.576$$

therefore H_0 can not be rejected so we accept the model GEO $= \alpha_1$ HEAD where $\alpha_1 = 1$ or GEO = HEAD is the better regression model.

TABLE 4

Statistical Analysis of $V_g = \alpha_0 + \alpha_1 V_2$ Regression Model

REGRESS, V_g,V_2

V_g =2.4942E+01

:ADD,V

V_g =4.7020E-01 +1.0238E+00 V_2

:AVTABLE

ANALYSIS OF VARIANCE TABLE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE
TOTAL	493	6.98062810E 04	1.41594890E 02
REGRESSION	1	5.90833721E 04	5.90833721E 04
RESIDUAL	492	1.07229089E 04	2.17945303E 01

R SQUARED = .84639049

:DROP, 0

V_g =+1.0402E+00 V_2

:AVTABLE

ANALYSIS OF VARIANCE TABLE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE
TOTAL	494	3.77117960E 05	7.63396680E 02
REGRESSION	1	3.66376870E 05	3.66376870E 05
RESIDUAL	493	1.07410905E 04	2.17872019E 01

R SQUARED = .97151796

:END

Which, if either, of the prediction methods - GEO or STAT - is better? We accept the models:

HEAD = STAT

HEAD = GEO

But, is one better than the other or would

$$HEAD = \alpha_0 + \alpha_1 \; GEO + \alpha_2 \; STAT$$

be better yet (See Tables 5 and 6)? To determine this, a multiple regression is done by adding a second independent variable to see if it improves the model.

H_0: $\alpha_2 = 0$

H_a: $\alpha_2 \neq 0$

The test: $\frac{A - B}{C} = \frac{8658.87 - 8639.75}{17.60}$

$= 1.09 < F(1,506, 99\%) = 6.70$

$= 1.09 < 6.70$

therefore H_0 can not be rejected in the presence of α_1.

Similarly,

H_0: $\alpha_1 = 0$

H_a: $\alpha_1 \neq 0$

The test: $\frac{A - B}{C} = \frac{8654.01 - 8639.75}{17.60}$

$= .81 < F(1,506, 99\%)$

$= .81 < 6.70$

therefore H_0 can not be rejected in the presence of α_2.

The conclusion is that observations at the "HEAD" are not predicted any better by adding the second variable to the regression model for

TABLE 5

Statistical Analysis of $V_2 = \alpha_0 + \alpha_1 V_g + \alpha_2 V_s$

$REGRESS,$V_2$,$V_g$,$V_s$

V_2 = 2.3903E+01

:ADD,V_g,V_s

V_2 = 3.3881E+00 +6.2571E+00 V_s
-5.2443E+00 V_g

:AVTABLE

ANALYSIS OF VARIANCE TABLE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE
TOTAL	493	5.63693360E 04	1.14339424E 02
REGRESSION	2	4.77295883E 04	2.38647941E 04
RESIDUAL	491	8.63974773E 03	1.75962276E 01

R SQUARED = .84672965

:DROP,V_g

V_2 = 3.2963E+00 +8.5210E-01 V_s

:AVTABLE

ANALYSIS OF VARIANCE TABLE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE
TOTAL	493	5.63693360E 04	1.14339424E 02
REGRESSION	1	4.77153222E 04	4.77153222E 04
RESIDUAL	492	8.65401383E 03	1.75894590E 01

R SQUARED = .84647657

:END

TABLE 5 (Continued)

\$REGRESS,V_2,V_g

V_2 = 2.3903E+01

:ADD,V_g

V_2 = 3.2830E+00 +8.2672E-01 V_g

:AVTABLE

ANALYSIS OF VARIANCE TABLE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE
TOTAL	493	5.63693360E 04	1.14339424E 02
REGRESSION	1	4.77104697E 04	4.77104697E 04
RESIDUAL	492	8.65886633E 03	1.75993218E 01

R SQUARED = .84639049

:END

\$SUMSQRS, V_2

V_2 = 56369.33604

either STAT or GEO. Since neither model significantly improves the other, then we can conclude, from a statistical point of view, that neither model is significantly better than the other.