A Comparison of Model Predicted to Observed Winds in the Coastal Zone

**Michael Garstang
Roger A. Pielke
Joseph W. Snow
Department of Environmental Sciences
University of Virginia**

July 1982

**Prepared for
Pacific Northwest Laboratory
under Agreement B-93492-A-Q of
Contract DE-AC06-76RLO 1830
U.S. Department of Energy**

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

NTIS Price Codes
Microfiche A01

Printed Copy

Pages	Price Codes
001-025	A02
026-050	A03
051-075	A04
076-100	A05
101-125	A06
126-150	A07
151-175	A08
176-200	A09
201-225	A010
226-250	A011
251-275	A012
276-300	A013

3 3679 00059 6421

A COMPARISON OF MODEL PREDICTED TO
OBSERVED WINDS IN THE COASTAL ZONE

Michael Garstang
Roger A. Pielke
Joseph W. Snow

University of Virginia
Department of Environmental Sciences
Charlottesville, Virginia 22903

June 1982

Prepared for
Pacific Northwest Laboratory
under Agreement B-93492-A-Q of
Contract DE-AC06-76RLO 1830
U.S. Department of Energy

Pacific Northwest Laboratory
Richland, Washington 99352

EXECUTIVE SUMMARY

Predictions of near-surface (10 to 100 m) wind velocities made by a mesoscale numerical model on a 10 km grid over and near the coastline are checked against observations. Two comparisons are made. The first is between observed and model-estimated mean annual wind power density at locations where surface observations exist in three coastal areas: the Chesapeake Bay, the Apalachee Bay and the South Texas coastal area. The second comparison is made between model predictions over the Delmarva Peninsula and adjacent ocean and observations made over a 120x30 km rectangle extending across the peninsula and out to sea.

In the first comparison, the surface observations are adjusted to 100 m using a climatologically derived α -value. Within the uncertainties of the adjusted observations a skill rating for the annual average 100 m layer-mean power density of 77% is obtained for the first two regions. The model, without diurnal variation of the large-scale pressure gradient, shows no skill for the South Texas coastal area. The presence of inland sloping topography in south Texas and northeast Mexico is suspected as being the reason why model predictions fail in this location.

In the second comparison, the skill of the model in predicting wind speeds over the coastal waters and in predicting the occurrence, location and magnitude of strong horizontal gradients in the wind field is of particular interest. Three tests of skill are carried out:

1. Measurement Error Analysis, where the percent of model predicted winds falling within the error limits of the measured values is used to evaluate skill.
2. Linear Correlation, where the closeness with which the predicted wind series duplicates the variations in the observed series is measured.
3. Unbiased Error Analysis, which deals with the square of the differences between predicted and observed values of wind and thus more directly assesses the skill of the model with respect to wind energy.

We conclude that the unbiased error analysis skill ratings of 81% and 76% are attained for two days of prediction-observation comparisons. In the meantime, the skill of the model in duplicating individual coastal wind fields is taken as 78%.

In addition, a qualitative comparison is made between the predicted fields of wind and the observed wind field. The predicted wind field unquestionably reproduces the observed field.

We conclude that for coastlines without inland sloping topography the mesoscale model usefully predicts the magnitude and location of the centers of maximum and minimum wind power. For coastal areas that border on inland sloping terrain a more complete initialization of the model is required.

TABLE OF CONTENTS

	Page
EXECUTIVE SUMMARY.....	i
TABLE OF CONTENTS.....	ii
LIST OF TABLES.....	iii
LIST OF FIGURES.....	v
1. INTRODUCTION.....	1
2. COMPARISON OF MODEL PREDICTED AND OBSERVED ANNUAL AVERAGE WIND POWER DISTRIBUTIONS.....	1
3. VERIFICATION OF MODEL PREDICTIONS FOR SPECIFIC METEOROLOG- ICAL CONDITIONS.....	3
3.1 30 January 1980.....	4
3.2 3 February 1980.....	5
3.3 Determination of the Model's Skill for Specific Coastal Zone Situations.....	6
3.3.1 Measurement Error Analysis.....	7
3.3.2 Coefficient of Linear Correlations.....	8
3.3.3 Average Squared Difference.....	10
3.4 Wind Power Density Prediction.....	11
4. CONCLUSIONS.....	12
5. REFERENCES.....	14
TABLES.....	15
FIGURES.....	34

LIST OF TABLES

	Page
Table 1: Verification of the annual average, 100 m layer-mean power density using data recorded within three mesoscale coastal areas.....	15
Table 2: Initialization and parameterization of the University of Virginia mesoscale model for the Chesapeake Bay Area on two operational days of the Wallops Island Verification Experiment.....	17
Table 3a: Observed and predicted wind speeds (m s^{-1}) for the morning flight on 30 Jan 80, initial and final 50 m tracks.....	18
Table 3b: Observed and predicted wind speeds (m s^{-1}) for the morning flight on 30 Jan, both 170 m rectangles.	19
Table 3c: Observed and predicted wind speeds (m s^{-1}) for the midday flight on 30 Jan 80, initial and final 50 m tracks.....	20
Table 3d: Observed and predicted wind speeds (m s^{-1}) for the midday flight on 30 Jan 80, large 170 m rectangle....	21
Table 3e: Observed and predicted wind speeds (m s^{-1}) for the afternoon flight on 30 Jan 80, initial and final 50 m tracks.....	22
Table 3f: Observed and predicted wind speeds (m s^{-1}) for the afternoon flight 30 Jan 80, both 170 m rectangles...	23
Table 4a: Observed and predicted wind speeds (m s^{-1}) for the morning flight on 3 Feb 80, initial and final 50 m tracks.....	24
Table 4b: Observed and predicted wind speeds (m s^{-1}) for the morning flight on 3 Feb 80, both 170 m rectangles...	25
Table 4c: Observed and predicted wind speeds (m s^{-1}) for the midday flight on 3 Feb 80, initial and final 50 m tracks.....	26
Table 4d: Observed and predicted wind speeds (m s^{-1}) for the midday flight on 3 Feb 80, large 170 m rectangle....	27

LIST OF TABLES (cont.)

	Page
Table 4e: Observed and predicted wind speeds (m s^{-1}) for the afternoon flight on 3 Feb 80, initial and final 50 m track.....	28
Table 4f: Observed and predicted wind speeds (m s^{-1}) for the afternoon flight on 3 Feb 80, both 170 m rectangles.....	29
Table 5: Absolute error limits ($\pm \text{m s}^{-1}$) for measured wind speeds from beginning to end of each flight component.....	30
Table 6: Numbers of "correct" wind speed predictions and percentages by flight and daily total for two WIVEX days.....	31
Table 7: Coefficient of linear correlation (r) and significance tests for all pairs of predicted and observed wind speeds on two WIVEX days.....	32
Table 8: Average of the square of the unbiased differences for all wind speeds on two WIVEX days.....	32
Table 9: Skill ratings (%) determined by various analyses...	33

LIST OF FIGURES

	Page
FIGURES 1-3: Annual average power density (W m^{-2}), layer-mean given for each 100 km^2 (10 km north-south x 10 km east-west) as determined from meteorological variables predicted by the numerical model of the atmosphere for the Chesapeake Bay, Apalachee Bay and South Texas Coast.....	34
FIGURE 4: Outlines of the 120x30 km aircraft flight track (solid rectangle) located within the 140x100 km Wallops Island verification experiment study area (broken rectangle).....	38
FIGURES 5A-7A: Observed wind speeds (m s^{-1}) and wind directions (meteorological deg.) at 170 m above the surface for aircraft flights made on 30 Jan 80.....	40
FIGURES 5B-7B: Predicted wind speeds (m s^{-1}) and wind directions (meteorological deg.) at 170 m above the surface for 30 Jan 80.....	40
FIGURES 8A-F: Space-time series of observed (solid dots) and predicted (open circles) wind speeds (m s^{-1}) at 50 and 170 m above the surface within the WIVEX study area on 30 Jan 80.....	47
FIGURES 9A-11A: Observed wind speeds (m s^{-1}) and wind directions (meteorological deg.) at 170 m above the surface for aircraft flights made on 3 Feb 80.....	54
FIGURES 9B-11B: Predicted wind speeds (m s^{-1}) and wind directions (meteorological deg.) at 170 m above the surface for 3 Feb 80.....	54
FIGURES 12A-F: Space-time series of observed (solid dots) and predicted (open circles) wind speeds (m s^{-1}) at 50 and 170 m above the surface within the WIVEX study area on 3 Feb 80.....	61
FIGURE 13A: Scatter diagram of wind speeds, 30 Jan 80.....	68
FIGURE 13B: Scatter diagram of wind speeds, 3 Feb 80.....	69

LIST OF FIGURES (cont.)

	Page
FIGURE 14A: Scatter diagram of the cube of measured wind speed, U_m^3 , versus predicted wind speed, U_p , for 30 Jan 80.....	70
FIGURE 14B: Scatter diagram of the cube of measured wind speed, U_m^3 , versus predicted wind speed, U_p , for 3 Feb 80.....	71
FIGURE 15: Areal distribution of measured wind power density (10^2 W m^{-2}) at 170 m above the surface, 0742-0859 EST, 30 Jan 80, within the WIVEX 120x30 km aircraft track.....	72
FIGURE 16: Areal distribution of predicted wind power density (10^2 W m^{-2}) at 170 m above the surface at 0828 EST, for the WIVEX study area. Predictions made by the University of Virginia mesoscale model initialized for 30 Jan 80.....	74

1. INTRODUCTION

A mesoscale numerical model has been used to generate estimates of the wind field centered on the coastline and extending approximately 150 km inland and 150 km seaward of the shore. Snow (1981) describes the model and the methods used in detail and Garstang et al. (1982) outline how these techniques might be applied to the selection of a wind energy conversion site on or near the coast.

In the work cited above the model is used to generate wind information at 10 km intervals over an area of up to 300x300 km. The horizontal wind vector is generated at 12 levels in the atmosphere starting at 4 m and extending upwards to 6 km. Winds are calculated every minute through twenty-four hours for weather conditions which are typical of the dominant meteorological regimes for a particular region of the coast. The regimes and regions are determined by analysis of the climatological record over a period of 10 years. The frequency of occurrence of the dominant meteorological regimes during the annual cycle is used to combine the model-predicted wind and wind power information into mean annual areal distributions of potential wind power.

The utility of the method outlined above depends in large part upon the validity of the model-predicted wind fields. The purpose of this report is to provide an estimate of the skill of the model in predicting the actual winds. We will present two comparisons:

- *A comparison between model-estimated mean annual power density at various meteorological station locations for the layer of the atmosphere from the surface to 100 m and the "observed" mean annual power density based upon the observed winds at each of these stations.

- *A comparison between winds observed by an aircraft over the coastal ocean and over land and model-predicted winds for the coastal zone on two selected days representing a dominant wintertime east coast wind energy regime.

2. COMPARISON OF MODEL PREDICTED AND OBSERVED ANNUAL AVERAGE WIND POWER DISTRIBUTIONS

Figures 1, 2 and 3 show the predicted annual average wind power distributions and the location of the surface stations to be used for the comparison. Table 1 provides details on each of these stations

including the exponent α used in the power law to derive winds at heights other than the level of measurements. Using the fact that $P \sim \bar{u}^3 \sim z^{3\alpha}$ (P being the height-dependent wind power density), the annual average power density was calculated at 10, 30, 50 and 100 m and a layer mean was obtained by weighting each level by 0.20, 0.20, 0.35 and 0.25 respectively. The resulting 100 m layer-mean, annual average power densities are plotted below the solid dots which locate the verification stations in Figures 1, 2 and 3 and are listed in Table 1 under "from data" column.

The corresponding model estimates are obtained by linear space interpolation of the 10x10 km grid-square centered values used to generate Figures 1, 2 and 3. These are entered above the station symbol and are also given in Table 1. The model-generated mean annual values shown in Figures 1, 2 and 3 are obtained by combining the distributions of the three dominant wind regimes for each region. The climatological frequency of occurrence of each regime over the entire year is used to properly weight each regime distribution and thereby produce the annual average distribution.

Each wind power density value, observed (from data) or predicted, is an inexact estimate of the true wind power; i.e., each contains error. The errors in the observed values result primarily from uncertainties in the mean wind speed and in the value of the exponent α . Allowing 1) the percent error in the annual average wind speed to be 1.0% for a period of data equal to 10 years plus an additional 0.5% for each year less than 10 years and 2) the uncertainty in the exponent to be 10.0% of α itself; then the percent error (+) in the 100 m layer-mean, annual average wind power computed from meteorological data is calculated. These errors are listed in the last column of Table 1. In order to determine the percent error in the predicted wind power, it is assumed that the observed value is the best estimate of the true wind power. For each station in Table 1, the prediction error is then computed as $((\text{predicted} - \text{observed}) / \text{observed}) \times 100$. These errors are given in the next-to-last column.

The predictive ability of the model is considered acceptable, and therefore useful, if the prediction error is within the limits of the observation error. Whenever the prediction error is greater than the observation error, then the excess error must be due to the deficiency of the prediction scheme. The skill of the prediction is determined as the ratio of the number of acceptable predictions to the total number of predictions. For the three mesoscale areas these skill ratings are 88% for the Chesapeake Bay area, 67% for the Apalachee Bay area and 0% for the South Texas coast area.

Good skill is demonstrated for the Chesapeake Bay area, acceptable skill for the Apalachee Bay area and no skill for the South Texas

coast. Separate analysis (Snow, 1981) shows that over the South Texas coast the model underestimates the observed wind primarily as a result of the influence of topography. The east-facing slopes of the southern Rocky Mountains and the Sierra Madre Oriental represent an elevated heat source by day and heat sink by night. The result is a diurnal oscillation in the pressure gradient force which was not dealt with in the model simulations.

We conclude that for the Chesapeake Bay and Apalachee Bay areas, the skill rating for annual average, 100 m layer-mean power density is near 77% and that for the meteorological and topographical conditions prevailing along the U.S. Atlantic and eastern Gulf coasts the model can provide reliable assessments of the average annual wind power density.

3. VERIFICATION OF MODEL PREDICTIONS FOR SPECIFIC METEOROLOGICAL CONDITIONS

Two important characteristics of coastal zone wind power are not directly addressed in the verification carried out in Section 2 which treated only land-based, average annual statistics. These are the numerical model's accuracy over the seaward portion of the coastal zone and the ability to duplicate strong spatial wind power gradients. There is no a priori evidence which suggests that a skill developed over land can be extended over the ocean. More importantly, in the annual average distributions, the gradients in wind power are not as strong as those found on some days because the summation over different distributions tends to eliminate strong, relatively short-lived gradients. Here the model's ability to reproduce strong gradients and to follow time changes in the wind field as dictated by the diurnal cycle of heating and cooling is tested.

A specific experiment, the Wallops Island Verification Experiment (WIVEX) was designed and carried out between 24 Jan and 5 Feb 1980 to provide an observational framework within which the model could be tested. In the analysis which follows, aircraft (National Center for Atmospheric Research's (NCAR) Queen Air) winds obtained at 50 m and 170 m over the rectangular flight-track shown in Figure 4 are used. The aircraft obtained winds out to approximately 60 km seaward of the shore line three times a day: early morning, near noon and late afternoon. The flight-track required 2 to 3 hours to complete. Winds, based on an inertial navigation system, were recorded once every second.

Two days, 30 Jan and 3 Feb 1980 both representative of the most dominant wintertime wind energy regime, are used for analysis.

3.1 30 January 1980

The general meteorological conditions in the vicinity of the Delmarva Peninsula on the 30th were as follows. It was essentially clear although some areas of rain middle-level clouds were found in late morning. These thickened and increased in amount during the afternoon. A small and fast-moving ridge was present in the middle atmosphere and high pressure centered on the south-central portion of Canada extended southeastward into the Carolinas. The initial geostrophic wind, determined primarily from the Wallops Island rawinsonde released at 1200 GMT (0700 EST) on the 30th, was 340° at 11.5 m s^{-1} . The final value, based upon the rawinsonde of 0000 GMT on the 31st (1900 EST on the 30th), was 320° at 10.5 m s^{-1} . The resulting low-level wind flow in the WIVEX study area was moderate northwesterly backing and diminishing in intensity with the passage of time after sunrise. Air temperature (shelter-height) was approximately -4°C and no precipitation occurred within the WIVEX study area during the daylight hours.

Between sunrise and sunset the standard three flights were made. Wind information obtained during these flights at levels 50 m (± 9 m) and 170 m (± 15 m) above the surface is used in subsequent comparisons as averages of 120 individual measurements, i.e., two-minute averages.

In general the wind field in the WIVEX study area close to sunrise is shown in Figure 5A. North-northwesterly flow was particularly strong, $\approx 12.0 \text{ m s}^{-1}$, 40 to 50 km offshore. The minimum speeds, $\approx 7.0 \text{ m s}^{-1}$, occurred over the land areas most removed from coastlines. Within two hours after sunrise the winds had increased both over land, $\approx 9.5 \text{ m s}^{-1}$, and over water, $\approx 13.0 \text{ m s}^{-1}$. A midday backing into the northwest and decrease in speeds, especially over water, is seen in Figure 6A. By late afternoon, Figure 7A, winds were still northwesterly and were nearly uniform in speed, $\approx 7.5 \text{ m s}^{-1}$, over both land and water.

Complete details of the initialization of the University of Virginia mesoscale model are given in Table 2. Two significant refinements are incorporated into the model for these WIVEX simulations. The first is the use of a time-varying geostrophic wind, discussed at the bottom of Table 2, and the second is the computation of the aerodynamic surface roughness according to the formulation of H. Lettau (1969).

Wind predictions were made by the model for the entire Chesapeake Bay area at one-minute intervals from one hour before sunrise until sunset. The fields of various meteorological variables for the WIVEX study area, at the 50 and 170 m levels, were printed out every 15 minutes throughout the integration. The fields of the horizontal wind components were used to produce Figures 5B-7B (and 9B-11B) which are the prediction analogues to the wind observations contained in Figures

5A-7A (and 9A-11A). All of these prediction fields are composed of information from more than one 15-minute printout. Even though the predictions are made at one-minute intervals throughout the integration it is not necessary to retain information at intervals closer than 15 minutes. Meteorological conditions at a particular grid point change relatively slowly, in terms of wind speed, rarely more than 0.2 m s^{-1} per 15 minutes.

Because the aircraft took between 2 and 3 hours to complete a given circuit, comparisons are made sequentially along the track, for each level, between model-predicted wind at 15-minute intervals and 2 minute averaged observed flight wind. The space and time series of wind speeds taken from Figures 5A-7A and 5B-7B are plotted in Figure 8. (The smoothness of the predicted series confirms the procedure of analyzing predictions at intervals no closer than 15 minutes.) The predicted values are obtained by isotach analysis of the wind speed fields in the vicinity of each solid square (aircraft location) in Figures 5B-7B.

The results on 30 Jan 1980 show a spatial and temporal correspondence between model-predicted and observed winds over the coast. Strong gradients near shore are observed and reproduced by the model during the early morning. As the day progresses these gradients weaken. General trends as well as some of the shorter time changes in the observed wind speed are followed by the model in the time series shown in Figure 8.

3.2 3 February 1980

The mid-tropospheric flow pattern over eastern North America on the 3rd was a narrow, nearly cut-off ridge centered over the province of Ontario and the upper Mississippi Valley, and a cyclone centered over the province of New Brunswick. In the lower atmosphere a shallow dome of cold, dry air, which had been centered in the Illinois-Indiana area during the previous day, weakened as it drifted southeastward into the Virginia-North Carolina area. Over the WIVEX study area these features resulted in clear skies throughout the daylight hours of the 3rd with an average shelter-height temperature of -5°C . The geostrophic wind near sunrise was 330° at 13.5 m s^{-1} and by sunset it had backed and slackened to 305° at 11.5 m s^{-1} .

The standard three aircraft flights were again completed on 3 Feb 1980 and examples of the morning, midday and afternoon observed and predicted values along the flight tracks are shown in Figures 9, 10, 11A&B. Table 2 provides the values used to initialize the model and Table 4 the comparison between the predicted and observed winds

along the flight track. Figure 12 shows the complete series of observed and predicted winds for 3 Feb 1980.

Time and space simulation by the model of the observed winds again appears reasonable although large individual departures of the predicted from the observed winds are more frequent on this day than on the 30th Jan. An analysis of the observed and predicted winds on these two days follows in the next section.

3.3 Determination of the Model's Skill for Specific Coastal Zone Situations

Determination of the skill of the model in duplicating individual meteorological situations is based upon the two days representative of the dominant wintertime wind energy regime. Because this is a dominant condition with high wind speeds relative to all other wind regimes occurring over the Chesapeake Bay and Eastern Shore, it is an important and somewhat difficult test of the model. Success or failure to simulate these conditions will not provide unequivocal evidence as to the model's usefulness but it will provide a very sound basis upon which at least a qualitative judgment can be made.

Three different determinations of skill are made. The first is similar to that applied to annual average wind power values. The second deals with the magnitude and significance of the coefficient of linear correlation and the last is based on the average squared departure between predicted and observed wind speeds.

The skill of the model is the primary topic of interest. However, in any numerical simulation both the integration and the initialization influence the results. The model's skill resides in the formulation and integration of the equations which comprise the physical principles on which the model is based. But the accuracy of the initialization is wholly dependent upon the skill of the numerical experimenter. The separation of these skills is never complete, but any verification scheme is preferable which emphasizes the model's contribution to the results. Initial conditions are reflected more in overall mean values than in variations; this is especially true for the winds. Initially, at any particular height, all grid-points in the model domain have the same wind vector. If the surface were uniform throughout the domain and if no diurnal heating-cooling cycle occurred, then all winds would remain invariant at their initial value. However, given surface contrasts and given a complete diurnal heat cycle, circulations develop in response to these forcings. These circulations, once initialization is complete, are solely the results of the model's operations; they are controlled entirely by the model's equations. Therefore, the spatial

and temporal variations are model-generated whereas the overall mean values reflect the experimenter's skill. The best specifications of the model's performance emphasize the variations.

Four variables are involved in the computation of wind power: three thermodynamic variables (pressure, temperature and water vapor content) and the wind speed. Of these the thermodynamic variables determine the air density. The percent variation of wind speed during any particular day in an area such as the coastal zone is at least 25 times, typically 50 times greater than that of air density. In addition, the cubic relationship between wind speed and wind power triples the impact of wind speed variations and therefore, for any particular day, the affect of changes in thermodynamic variables on wind power estimates is typically 10^2 smaller than that due to wind speed changes. The variations in wind power can therefore be determined from the analysis of the wind speed alone.

The following consideration allows wind direction to be ignored. The average discrepancy between predicted and observed wind directions for the two days is 10° to 11° (the maximum is 25°). Only the component of the wind normal to the plane defined by a rotating windmill blade is able to do useful work. That component varies as the cosine of the angle between the wind vector and the perpendicular to the plane of rotation. Therefore, the predicted wind directions are, for wind power purposes, at least 91% ($\cos(25)$) and on the average better than 98% ($\cos(11)$) accurate. This substantially exceeds wind speed accuracy and therefore wind directions need not be analyzed further.

3.3.1 Measurement Error Analysis

An analysis similar to that applied in Section 2 can be used to estimate the skill in predicting the WIVEX wind speeds. In particular, the percent of predicted values which fall within the measurement error limits of the observed values is a specification of the reliability of the prediction scheme. Both measurement and prediction are inexact estimates of the true wind speed, i.e., both contain error. The rationale applied is to allow the predicted wind an acceptable error limit equal to that of the observed wind. Thus, if the departure between observed and predicted values can be explained as due to error in measurement, then it is so explained and the prediction is characterized as "correct." But, if the departure is too large to be explained as measurement error, then the error in prediction must exceed that in measurement and the prediction is "wrong."

The error in the wind speed measured by the aircraft depends upon two onboard systems, the inertial navigation system (INS) and the air sensing probes system. During the WIVEX operations these systems per-

formed especially well and the time-independent absolute (2 standard deviations) wind speed error is $\pm 0.5 \text{ m s}^{-1}$. The INS is subject to a linear drift with the time elapsed since its alignment, a procedure carried out before each flight. Thus the wind speed error increases as the flight time increases. The net result is a total systematic error in the horizontal wind speed of $\pm 0.5 (1.0 + t) \text{ m s}^{-1}$, where t is the time elapsed (hrs) since the alignment of the INS. Any error in the measurements which is not accounted for by this expression is wholly random and, in the average of 120 individual values, is negligibly small. Therefore, the absolute measurement error for the two-minute average wind speed, viz. the total systematic plus the random error, is given by the above expression. For the six flights completed on the two days analyzed the values at the beginning and end of each flight are given in Table 5.

The percent of the total number of predictions which fall within the absolute measurement error limits, i.e., the percent which is "correct," is a specification of skill. In Table 6 the skill ratings for each flight and for all flights of each day and for both days combined are presented. Overall a 75% rating was attained. Prediction ability was most variable for the midday flight, 88% to 44%; and most consistent for the morning flight, 84%, on both days.

The skill determined by this simple error analysis applies to the whole prediction scheme, model operations and initialization combined, since it is influenced by the mean value of the wind speed. The magnitude of the geostrophic wind is the element in the initialization which most affects the mean wind speed at any height in the model. If the initial value of the geostrophic wind were changed somewhat, then the resulting skill, as determined by measurement error analysis, would also change. But the model's skill would be unaltered by such a change. Therefore this skill rating is sensitive to the initialization. The development of a method for determining skill which discriminates against the effect of initialization is needed in order to better assess the skill of the model itself.

3.3.2 Coefficient of Linear Correlation

The coefficient of linear correlation provides a measure of the closeness with which the predicted series of wind speeds duplicates the variations occurring in the observed series. Since the total-series mean values are not emphasized in the correlation analysis, it is a more unbiased test of the model's skill than the analysis based on the size of departures relative to measurement error, previously carried out. Testing the statistical significance of the correlation is an integral part of this skill specification.

In Table 7 are given the total number of prediction-observation pairs N and the value of the correlation coefficient r between predicted and observed wind speeds for all flight operations on the 30th and the 3rd. The meaning of these correlations is vague until they are tested for significance. Although the closer the value of the coefficient is to unity the better, unless the possibility of chance correlation or correlation by way of associations with a mutual third item is reasonably excluded, the value is not a measure of skill. The F-statistic is used for the test (Panofsky and Brier, 1968).

In general, the larger the value of F , the more significant the correlation is. More specifically, assuming that the correlation is really zero, the question is asked; How likely is it that a correlation coefficient of the magnitude found occurred due to random chance? If this likelihood turns out to be smaller than a pre-specified limit, then the correlation found is acceptable as real, i.e. is acceptable as significantly different from zero. The values of the F-statistic for which there is only a 0.5% likelihood that the correlation coefficient occurred by chance are listed in Table 7. Stated positively, if the calculated F-value exceeds the 0.5% test value, then the probability is at least 99.5% that the predicted series is really duplicating the observed series to some extent. The acceptance limits are set high because N is large but mainly because there is a third item to which both the observations and predictions are related, specifically the large-scale pressure gradient. Also, the number of degrees of freedom n needed in the computation of F is conservatively set at $\sqrt{N}$. If the computed F is larger than the test value, then the measure of the extent to which prediction duplicates observation is the value of the correlation coefficient.

The correlation coefficients for both days are significant and the overall skill rating is the average of the two values, specifically 77%. (Since the skill of the model is of primary interest, the determination of an overall r -value from the two daily values and not from the combined total of 409 pairs is appropriate. Inter-day differences are included in the model simulations by way of initialization and are in no way controlled by the model.)

Whereas the value of r is little influenced by differences in the full-day (total-series) means of the predicted and observed wind speeds, it is affected by the degree to which a trend in the observation series is reproduced in the predicted series. Due to the differential warming of the land, some slackening of the offshore flow is expected during the afternoon. This effect is controlled by the model in the simulation. However, on both days studied the strength of the large-scale pressure gradient decreased from sunrise to sunset; in terms of the geostrophic wind the changes were -1.0 m s^{-1} on the 30th; -2.0 m s^{-1} on

the 3rd. In the numerical simulations this large-scale effect was made a function of time, as detailed at the bottom of Table 2. Therefore the trend which the prediction series effected on each day is due partly to the model's integration and partly to the updating of the geostrophic wind, essentially an initialization function. The overall skill rating of 77% determined by the correlation coefficient analysis is not completely free of the influence of initialization.

Figures 13A&B are the scatter diagrams of predicted and observed wind speeds for the two comparison days. The regression lines (broken) and the perfect prediction line (solid) are shown. On the 30th, the tendency was to over-predict in the lower half of the speed range. The overall scatter on the 3rd was greater than on the 30th and the tendency was to under-predict the lower speeds. Although any bias is undesirable, the different sign on the two days suggests initialization and not a systematic flaw in the model as the error source.

3.3.3 Average Squared Difference

The third determination of skill is the least affected by initialization and is therefore the best estimate of model's skill. Given two comparable series (x_i, y_i) , the average of the squared difference between them which is not biased by any disparity in means is

$$E = \overline{(x_i - y_i - \delta)^2}$$

where $\delta = \bar{x} - \bar{y}$. Expansion of this expression gives

$$E = \sigma_x^2 + \sigma_y^2 - 2\sigma_{xy}$$

where σ^2 represents the variances or the covariance of the subscripted variables. If a maximum value of E can be determined, then the skill with which predictions, the y-series, duplicates the observations, the x-series, is

$$\epsilon = (E_{\max} - E)/E_{\max} .$$

The condition which results in a maximum E-value is that the x's and y's be totally uncorrelated, i.e. $\sigma_{xy}^2 = 0$. If, in addition, the greater of the two variances σ_x^2 or σ_y^2 is used then

$$E_{\max} = 2\sigma_{\max}^2 .$$

From Figures 8 and 12 it is evident that $\sigma_{\max}^2 = \sigma_x^2$, i.e. the variance of the observed series is greater than that of the predicted series. The skill rating ϵ minimizes the impact of differing means and therefore emphasizes the model's influence on the predictions.

In Table 8 are listed E , its maximum value and ϵ for all wind information on the 30th and 3rd. Skill ratings for the two days are 81% and 76%, giving the estimate for the overall skill of the model by this method as the simple average, 78%.

The skill ratings determined by each analysis are listed in Table 9 for the 30th and 3rd. As has been pointed out, the analysis based upon the average of the square of the unbiased differences is probably the best estimate of the model's skill in predicting boundary layer winds. An overall rating of 78% for the two WIVEX days studied is respectable. As regards the ratings determined by the other methods, the measurement error analysis provides the best estimate of skill for the prediction scheme as a whole, i.e. the model's skill and the numerical experimenter's skill combined. Assuming that these two skills operate simultaneously, continuously and with approximately equal impact on the results, then any skill evaluation containing both is roughly the average of the two skills. From the overall ratings in Table 9, the implication is that the skill of the experimenter, specifically the skill involved in the initialization, is lower than that of the model's operation; $2(75) - 78 = 72\%$.

3.4 Wind Power Density Prediction

A skill rating of 78% implies a total percent error of 22%, i.e. percent error limits of $\pm 11\%$. Since wind power varies as the cube of wind speed, it is anticipated that the percent error in the wind power prediction $((\text{prediction} - \text{measurement})/100)/\text{measurement}$ will be 3 times that in the wind speed, approximate limits of $\pm 33\%$. In Figure 14 are plotted the various observed values of measured wind speed cubed for each predicted wind speed. (As discussed previously, uncertainty in density on any particular day are totally negligible in comparison to that associated with the wind speed cubed.) The perfect prediction line and the $\pm 25\%$ and $\pm 50\%$ error isopleths are also entered on the diagrams. If a tolerance of 1 standard deviation is allowed, i.e. 68% of all cubed wind speeds are included within these limits, then the percent error in wind predictions is $\pm 30\%$ on the 30th, $\pm 35\%$ on the 3rd, giving an average of $\pm 33\%$. The meaning is that (1) the distribution of errors is approximately normal and (2) the total percent error, 100% minus the skill rating, is close to the ± 1 standard deviation limits.

Although the percent error in wind power prediction is considerable, specifically $\pm 33\%$, it is not much larger than that inherent in wind power computations made from wind speed measurements. The wind speeds measured by the instrumented aircraft contain an average 2 standard-deviation measurement error of $\pm 1.4 \text{ m s}^{-1}$ (refer to Table 5).

The average measured wind speeds for the 30th and 3rd are 9.5 m s^{-1} and 10.4 m s^{-1} , respectively. The 2 standard deviation percent errors are therefore $\pm 15\%$ and $\pm 13\%$, or $\pm 14\%$ overall, resulting in an average 1 standard deviation error of $\pm 7\%$. Wind power computed from such data can be expected to contain a $\pm 21\%$ error.

Finally, a comparison of the measured and the predicted wind power density field in the WIVEX study area during the morning of 30 Jan is made. Figure 15 presents the areal distribution of wind power density within the large aircraft track for one circuit of the 120×30 km flight track. The values were computed from the aircraft measurements of wind speed and the requisite thermodynamic variables. The complete flight track required more than one hour to complete. The predicted distribution at a time approximately half way through the aircraft flight is given in Figure 16. Model-predicted values of wind speed and the thermodynamic variables were used to generate this field. The overall predicted pattern of power density is unmistakably that which was observed. The strong near-shore gradient and the phenomenon of a distinct maximum between 40 and 50 km offshore are quantitatively well reproduced. Over land, however, the predicted minimum values exceed those observed. In spite of some large individual discrepancies, the usefulness of numerically generated products such as Figure 16 in wind power assessment is evident.

4. CONCLUSIONS

Areal distributions of annual average, 100 m layer-mean wind power are produced for three areas of the U.S. Atlantic and Gulf coastal zone by numerical simulation of the most prevalent wind regimes. Long-term meteorological data for 14 locations within these areas are used to calculate similar layer-means. In two of the three areas, Chesapeake Bay and Apalachee Bay, the comparison of the wind power values calculated from the data with those generated by the numerical model indicates that in 77% of the cases, roughly in 3 out of 4 cases, the disparity between the values is smaller than the error inherent in the layer-mean wind power computed from the data. In the third area, the south Texas coastal zone, the complete physics of the low-level atmosphere was not included in the model simulations and therefore no predictive skill was demonstrated there.

A total of 409 prediction-observation pairs of wind speeds are analyzed to determine the skill of the numerical model in duplicating specific meteorological situations in the coastal zone. The measurements were made on two wintertime days by a low-flying instrumented aircraft making repeated transects of the Delmarva Peninsula coastal zone. The predictions were generated by the 3-dimensional version of the University of Virginia mesoscale model, initialized with pre-dawn

conditions for the two days. An overall skill rating of 78% was determined for the predicted wind speeds. The resulting total percent error 22% suggests percent error limits of $\pm 3\%(22/2)\%$ for predicted wind power. Analysis of the predictions confirms that the ± 1 standard deviation error limits in predicted wind power are $\pm 33\%$. The comparable limits in wind power computed from the wind speed measurements are $\pm 21\%$. In spite of errors which in individual cases may be large, the areal distributions of predicted wind power in the coastal zone contain a great deal of useful information.

5. REFERENCES

- Bethea, R. M., B. S. Duran and T. L. Boullion. 1975. Statistical Methods for Engineers and Scientists. Marcel Dekker, Inc., Publishers, New York, New York, 583 pp.
- Garstang, M., R. Pielke and J. W. Snow. 1980. Coastal Zone Wind Energy, Part III. A Procedure to Determine the Wind Power Potential of the Coastal Zone. Draft final report submitted to Battelle Pacific Northwest Laboratory, under contract B-93492-A-Q, 42 pp.
- Lettau, H. H. 1969. Note on Aerodynamic Roughness-Parameter Estimation on the Basis of Roughness-Element Description. J. Appl. Meteor., 8, 828-832.
- Panofsky, H. A. and G. W. Brier. 1968. Some Applications of Statistics to Meteorology. The Pennsylvania State University, University Park, Pennsylvania, 224 pp.
- Snow, J. W. 1981. Wind Power Assessment Along the Atlantic and Gulf Coasts of the United States. Ph.D. Dissertation, Department of Environmental Sciences, University of Virginia, Charlottesville, Virginia.

Table 1. Verification of the annual average, 100 m layer-mean power density using data recorded in the three mesoscale coastal areas.

Station Name	Anemometer Height (m)	Years of Data	Single-Level	Exponent (α)	100 m Layer-Mean Annual		Prediction Error (%)	Observed Error (%)
			Annual Average Power Density ($W\ m^{-2}$)		Average Power Density ($W\ m^{-2}$) From Data From Figs. 21, 25 or 29			
Chesapeake Bay Area:								
Dover, DE (AFB)	4.6	1957-64	85	0.124**	196	205	+ 4.6	+13.7
Andrews Field, DC (AFB)	20.7	1955-61	107	0.215**	181	197	+ 8.8	+13.6
Salisbury, MD (Wicomico Co. Airport)	15.2	1949-58	95	0.215**	196	192	- 2.0	+10.3
Patuxent River, MD (NAS)	29.0	1955-57	169	0.215	278	235	-15.5	+25.5
	4.0*	1960-64	57					
Wallops Island, VA (NASA, tower X-85)	10.0	1967-76	99	0.209**	259	245	- 5.4	+11.6
Hampton, VA (Langley AFB)	29.3*	1955-59	160	0.209	213	220	+ 3.3	+15.0
	4.0	1960-64	57					
Norfolk, VA (Regional Airport)	17.7	1955-58	142	0.209**	260	230	-11.5	+18.4
Virginia Beach, VA (Oceana NAS)	12.8*	1955-59	122	0.240	313	250	-20.1	+19.2
	4.0	1960-64	73					

Table 1 (cont.)

Station Name	Anemometer Height (m)	Years of Data	Single-Level Annual Average Power Density (W m^{-2})	Exponent (α)	100 m Layer-Mean Annual Average Power Density (W m^{-2})		Prediction Error (%)	Observed Error (%)
					From Data	From Figs. 21, 25 or 29		
Apalachee Bay Area:	.							
Tallahassee, FL (Dale Mabry Field, T-167)	16.5	1954-60	31	0.066**	37	72	+94.6	+ 9.7
Panama City, FL (Tyndall AFB)	10.3 3.0*	1955-57 1958-64	75 51	0.066	86	93	+ 0.1	+12.9
Tampa, FL (McDill AFB)	22.9 4.0*	1955-57 1958-64	66 47	0.061	72	67	- 6.9	+11.6
South Texas Coast Area:								
Corpus Christi, TX (NAS)	19.2* 6.7	1955-60 1961-64	259 160	0.213	456	142	-60.9	+15.1
Kingsville, TX (NAS)	17.4	1955-61	157	0.213**	294	131	-55.4	+14.0
Brownsville, TX (Int. Airport)	17.1	1955-60	191	0.213**	362	134	-63.0	+15.6

* Height used as basis for computing layer-mean power density. Criteria for selection; length of record or, if record lengths equal, greater height.

**Exponent not determinable for this station; value of nearest station used. (In the case of Dover, DE, Atlantic City, NJ was used.)

Table 2. Initialization and parameterization of the University of Virginia Mesoscale Model for the Chesapeake Bay Area on two operational days of the Wallops Island Verification Experiment

Element	30 Jan 80	1 Feb 80
Large-scale conditions:		
1) surface, 350 and 500 mb analyses	10/00 and 12Z, 11/00Z	1/00 and 12Z, 4/00Z
2) rawinsonde, Wallops Station	10/12Z and 11/00Z	1/12Z and 4/00Z
Mean latitude ($^{\circ}$ N)	38	38
Horizontal grid interval (km)	10	10
Horizontal grid size (X)x(Y)	10x16	10x16
Vertical levels	12***	12***
Time step(s)	60	60
Land surface:		
1) albedo	0.25	0.25
2) roughness length (cm)	13	13
Integration to steady state (hr)		
	1	1
Integration initiation	sunrise	sunrise
Initial planetary boundary layer (m)	1300	300
Initial shelter - height temperature (C)	-6.0	-7.0
Initial surface pressure (mb)	1026.0	1025.0
Sea surface temperature (C)	9.0**	9.0**
Free atmospheric lapse rate of potential temperature ($K\ km^{-1}$)	3.0	5.3
Geostrophic wind (msec, $deg/m\ s^{-1}$)	140/11.5 to 120/10.5*	110/13.5 to 105/11.5*
Wind shear to 6 km ($m\ s^{-1}\ km^{-1}$):		
1) u-component	-6.0	-4.5
2) v-component	-2.0	0.0
Soil characteristics:		
1) density ($g\ cm^{-3}$)	1.75	1.75
2) specific heat ($cal\ g^{-1}\ K^{-1}$)	0.50	0.50
3) diffusivity ($cm^2\ s^{-1}$)	0.0040	0.0040
4) wetness (%)	15.0	15.0

***Predictions made at twelve levels for wind (4, 10, 30, 50, 100, 170, 500 m, 1, 2, 3, 4, 6 km), at twelve levels for thermodynamic variables (surface, 7, 20, 40, 75, 115, 135, 750 m, 1.5, 2.5, 3.5, 5, 6 km) and at eleven depths in the soil (5 to 55 cm at 5 cm intervals).

**Sea surface temperature measurements were used, specifically shoreline and bay values of 4.0 C increasing to 11.5 C at 100 km offshore.

*Geostrophic wind was held at initial value for first two hours after sunrise and thereafter gradually changed to attain final value by 1400 local solar time.

Table 3a. Observed and predicted wind speeds (m s^{-1}) for the morning flight on 30 Jan 80, initial and final 50 m tracks. Observed values are two-minute averages centered at the time entered to the left; predicted values are at 15-minute intervals. These data are plotted in Figure 8. Letter entries refer to locations in Figures 5-7. * indicates a prediction outside the error limits in Table 5.

Observed Wind Speed			Predicted Wind Speed		
#	Time	m s^{-1}	Time	m s^{-1}	
a	0711	8.9	0713	9.5	
	0713	10.4	0713	10.4	
b	0715	11.4	0713	10.6	
	0717	10.9	0713	10.6	
c	0719	11.4	*0713	10.4	
	0721	11.8	*0728	10.7	
d	0725	10.7	0728	10.6	
	0727	10.7	0728	10.6	
e	0729	11.1	0728	10.6	
	0731	11.3	0728	10.6	
f	0735	11.6	0743	11.1	
	0737	10.9	0743	11.3	
g	0739	11.5	0743	11.4	
	0741	11.6	0743	11.5	

Mean
Values 11.01 10.71

Observed Wind Speed			Predicted Wind Speed		
#	Time	m s^{-1}	Time	m s^{-1}	
h	0941	12.6	0943	11.7	
	0943	13.0	0943	11.7	
i	0945	12.9	0943	11.5	
	0947	12.0	0943	11.1	
j	0949	11.3	0943	10.7	
	0951	10.1	0943	10.0	

Mean
Values 11.98 11.12

Table 3b. Observed and predicted wind speeds (m s^{-1}) for the morning flight on 30 Jan 80, both 170 m rectangles. (Otherwise the same as Table 3a).

Observed Wind Speed			Predicted Wind Speed		
#	Time	m s ⁻¹		Time	m s ⁻¹
A	0743	11.6		0743	11.5
	0745	10.5		0743	11.2
B	0747	9.6		0743	10.6
	0749	9.3		0743	10.2
C	0751	7.2		*0743	9.5
	0753	6.7		*0758	9.4
D	0755	7.4		*0758	9.3
	0757	6.5		*0758	9.2
E	0759	7.1		*0758	9.1
	0801	7.5		*0758	9.1
F	0803	7.9		*0758	9.2
	0807	10.6		0813	9.7
G	0809	11.3		0813	10.2
	0811	12.0		*0813	10.6
H	0815	11.4		0813	10.3
	0817	11.2		0813	10.0
I	0819	10.7		0813	9.8
	0821	8.6		0828	9.9
J	0823	7.8		*0828	9.9
	0825	9.3		0828	10.5
K	0827	10.4		0828	11.0
	0829	11.2		0828	11.6
L	0831	11.3		0828	12.0
	0833	11.9		0828	12.3
M	0835	11.8		0828	12.4
	0837	12.0		0843	12.6
N	0845	11.6		0843	12.7
	0847	11.6		0843	12.6
O	0849	11.4		0843	12.5
	0853	12.1		0858	12.7
P	0855	11.9		0858	12.7
	0857	12.0		0858	12.6
Q	0859	11.9		0858	12.3
	0901	11.7		0858	12.2
R	0903	12.9		0858	12.2
	0905	13.9		*0858	12.1
S	0907	12.8		0913	11.9
	0909	11.8		0913	11.6
T	0911	11.6		0913	11.0
	0913	10.2		0913	10.5
U	0915	9.0		0913	10.3
	0917	9.1		0913	10.2
V	0919	10.7		0913	10.5
	0921	9.6		0913	10.4
W	0923	8.9		0928	10.1
	0925	9.2		0928	9.9
X	0927	9.3		0928	9.7
	0929	10.1		0928	9.7
Y	0931	10.2		0928	9.9
	0933	10.5		0928	10.3
Z	0935	11.1		0928	11.0
	0937	12.5		0943	11.5
AA	0939	13.4		0943	12.0
Mean					
Values			10.46		
			10.37		

Table 3c. Observed and predicted wind speeds (m s^{-1}) for the midday flight on 30 Jan 80, initial and final 50 m tracks. (Otherwise the same as Table 3a).

#	Observed Wind Speed		Predicted Wind Speed	
	Time	m s^{-1}	Time	m s^{-1}
a	1144	9.0	1143	9.0
.	1146	8.6	1143	9.5
b	1148	9.5	1143	9.7
	1150	10.7	1143	10.0
c	1152	10.8	1158	10.0
	1154	11.8	*1158	10.3
Mean				
Values		10.07		9.75

#	Observed Wind Speed		Predicted Wind Speed	
	Time	m s^{-1}	Time	m s^{-1}
d	1312	9.5	1313	9.7
	1314	8.8	1313	9.5
e	1316	7.7	*1313	9.4
	1318	7.9	1313	9.3
f	1320	7.2	*1328	9.0
	1322	7.1	1328	8.8
g	1324	7.4	1328	8.6
	1326	7.0	1328	8.3
Mean				
Values		7.83		9.08

Table 3d. Observed and predicted wind speeds (m s^{-1}) for the midday flight on 30 Jan 80, large 170 m rectangle. (Otherwise the same as Table 3a).

#	Observed Wind Speed		Predicted Wind Speed	
	Time	m s^{-1}	Time	m s^{-1}
A	1158	11.7	1158	10.7
	1200	11.6	1158	10.6
B	1202	11.0	1158	10.4
	1204	10.5	1158	10.2
C	1206	9.5	1213	9.9
	1208	8.7	1213	9.7
D	1210	8.5	1213	9.5
	1212	8.0	*1213	9.3
E	1214	8.6	1213	9.2
	1216	8.5	1213	9.2
F	1218	9.4	1213	9.2
	1220	9.6	1213	9.3
G	1222	9.3	1228	9.2
	1224	9.3	1228	9.2
H	1226	10.0	1229	9.2
	1230	10.9	*1228	9.1
I	1232	9.9	1228	9.0
	1234	9.6	1228	8.9
J	1236	9.7	1228	8.7
	1240	8.5	1243	8.5
K	1242	8.3	1243	8.5
	1244	9.0	1243	8.4
L	1246	8.3	1243	8.4
	1248	9.2	1243	8.4
M	1250	9.2	1243	8.6
	1252	10.0	1243	8.8
N	1254	9.7	1258	9.1
	1256	10.2	1258	9.3
O	1258	11.2	*1258	9.5
	1300	11.0	1258	9.8
P	1302	11.2	1258	9.9
	1306	10.8	1258	10.0
Q	1308	10.3	1258	10.0
**	1310	10.3	1258	10.1
Mean				
Values		9.75		9.35

**Final observed wind speed not shown in Figure 6A due to superposition with first value.

Table 3e. Observed and predicted wind speeds (m s^{-1}) for the afternoon flight on 30 Jan 80, initial and final 50 m tracks. (Otherwise the same as Table 3a).

#	Observed Wind Speed		Predicted Wind Speed	
	Time	m s ⁻¹	Time	m s ⁻¹
a	1424	8.9	1428	8.1
	1426	8.5	1428	8.6
b	1428	8.4	1428	8.9
	1430	8.6	1428	9.0
c	1432	8.6	1428	9.2
	1434	8.6	1428	9.3
d	1436	9.0	1443	9.3
	1438	8.5	1443	9.4
e	1440	8.3	*1443	9.3
	1442	8.9	1443	9.2
f	1444	8.3	1443	9.1
	1448	8.6	1443	9.0
g	1450	8.8	1458	9.0
	1452	8.3	1458	8.8
h	1454	8.5	1458	8.7
Mean Values		8.59	8.99	

Observed Wind Speed			Predicted Wind Speed	
#	Time	m s ⁻¹	Time	m s ⁻¹
h	1650	9.9	1658	9.6
i	1652	9.3	1658	9.7
	1654	9.5	1658	9.8
j	1656	9.3	1658	9.8
	1658	9.1	1658	9.6
k	1700	9.5	1658	9.2
	1702	8.8	1658	8.6
Mean				
Values		9.34	9.47	

Table 3f. Observed and predicted wind speeds (m s^{-1}) for the afternoon flight on 30 Jan 80, both 170 m rectangles. (Otherwise the same as Table 3a).

#	Observed Wind Speed		Predicted Wind Speed	
	Time	m s^{-1}	Time	m s^{-1}
A	1456	8.7	1458	8.9
	1458	8.3	1458	8.6
B	1500	8.0	1458	8.5
	1502	7.4	1458	8.3
C	1504	7.3	1458	8.2
	1506	6.7	*1513	8.2
D	1508	7.0	1513	8.1
	1510	6.9	1513	8.1
E	1512	7.2	1513	8.0
	1514	8.2	1513	8.0
F	1516	7.5	1513	7.9
	1520	8.0	1528	8.1
G	1522	8.3	1528	8.3
	1524	8.3	1528	8.4
H	1528	7.5	1528	8.4
	1530	8.3	1528	8.4
I	1532	8.0	1528	8.5
	1534	7.5	1528	8.6
J	1536	7.6	1543	8.7
	1538	7.8	1543	8.9
K	1540	7.9	1543	9.2
	1542	7.9	1543	9.4
L	1544	7.8	*1543	9.6
	1546	7.5	*1543	9.7
M	1548	7.5	*1543	9.3
	1550	8.1	*1543	9.9
N	1554	7.5	*1558	9.8
	1556	7.2	*1558	9.7
O	1558	7.0	*1558	9.6
	1602	7.6	*1558	9.6
P	1604	7.6	*1558	9.5
	1606	7.5	*1613	9.6
Q	1608	7.5	*1613	9.5
	1610	7.6	*1613	9.4
R	1612	7.3	*1613	9.6
	1614	7.9	*1613	9.7
S	1616	8.3	1613	9.7
	1618	8.0	1613	9.6
T	1620	8.0	1613	9.4
	1622	9.2	1628	9.2
U	1624	9.5	1628	9.0
	1626	9.5	1628	8.8
V	1628	9.2	1628	8.7
	1630	9.8	1628	8.8
W	1632	8.4	1628	8.6
	1634	8.9	1628	8.4
X	1636	8.1	1643	8.4
	1638	8.6	1643	8.3
Y	1640	8.7	1643	8.5
	1642	8.9	1643	8.6
Z	1644	9.7	1643	8.9
	1646	9.5	1643	9.3
AA	1648	9.7	1643	9.6
Mean				
Values		8.07	8.91	

Table 4a. Observed and predicted wind speed (m s^{-1}) for the morning flight on 3 Feb 80, initial and final 50 m tracks. Observed values are two-minute averages centered at the time entered to the left; predicted values are at 15-minute intervals. These data are plotted in Figure 12. Letter entries refer to locations in Figures 9-11. * indicates a prediction outside the error limits in Table 5.

#	Observed Wind Speed		Predicted Wind Speed	
	Time	m s^{-1}	Time	m s^{-1}
a	0704	9.3	0708	8.8
	0706	11.8	*0708	9.8
b	0708	13.6	*0708	10.5
	0710	13.4	*0708	10.9
c	0712	12.9	*0708	11.0
	0714	12.8	*0708	11.0
d	0716	12.5	*0708	11.0
	0720	12.0	0723	11.5
e	0722	12.5	0723	11.5
	0724	12.7	*0723	11.4
f	0726	13.3	*0723	11.4
	0730	13.2	*0723	11.4
g	0732	12.5	0738	11.9
	0734	12.4	0738	12.0
h	0736	12.3	0738	11.9
	0738	13.0	0738	11.8

Mean
Values 12.5 11.1

#	Observed Wind Speed		Predicted Wind Speed	
	Time	m s^{-1}	Time	m s^{-1}
i	0946	14.3	0953	13.0
	0948	13.9	0953	13.0
j	0950	12.7	0953	12.9
	0952	11.5	0953	12.8
k	0954	11.1	0953	12.4
	0956	10.9	0953	12.0
l	0958	11.1	0953	11.4
	1000	9.8	0953	10.7

Mean
Values 11.9 12.3

Table 4b. Observed and predicted wind speeds (m s^{-1}) for the morning flight on 3 Feb 80, both 170 m rectangles. (Otherwise the same as Table 4a).

#	Observed Wind Speed		Predicted Wind Speed	
	Time	m s^{-1}	Time	m s^{-1}
A	0740	12.7	0738	11.9
	0742	12.8	0738	11.5
B	0744	12.1	0738	11.2
	0746	12.1	*0738	10.8
C	0748	12.4	*0753	10.6
	0750	10.3	0753	10.3
D	0752	9.7	0753	10.2
	0754	10.2	0753	10.1
E	0756	9.0	0753	10.1
	0758	9.3	0753	10.2
F	0800	9.4	0753	10.1
	0804	9.4	0808	10.7
G	0806	11.6	0808	11.1
	0808	13.0	0808	11.4
H	0810	13.5	*0808	11.6
	0816	13.3	0808	11.7
I	0818	13.0	0823	11.7
	0820	12.4	0823	11.5
J	0822	11.7	0823	11.3
	0824	10.9	0823	11.1
K	0826	11.1	0823	11.1
	0828	12.8	0823	11.3
L	0830	12.9	0823	11.8
	0832	13.0	0838	12.5
M	0834	13.1	0838	13.0
	0836	13.5	0838	13.3
N	0838	13.2	0838	13.6
	0840	12.7	0838	13.9
O	0844	12.1	0838	13.8
	0846	12.6	0838	13.8
P	0848	12.8	0853	14.0
	0850	12.8	0853	13.9
Q	0854	12.9	0853	13.9
	0856	13.0	0853	13.8
R	0858	13.3	0853	13.6
	0900	12.3	0853	13.5
S	0902	13.5	0908	13.3
	0904	13.5	0908	13.4
T	0906	13.7	0908	13.4
	0908	13.2	0908	13.3
U	0910	13.5	0908	12.9
	0912	12.7	0908	12.5
V	0914	13.0	0908	12.2
	0916	11.9	0908	12.8
W	0918	13.2	0923	12.6
	0920	14.3	*0923	11.5
X	0922	13.6	0923	11.7
	0924	13.6	0923	12.9
Y	0926	12.6	0923	11.7
	0928	11.0	0923	12.4
Z	0930	10.1	0923	12.1
	0932	10.9	0938	11.0
AA	0934	11.0	0938	10.9
	0936	11.5	0938	11.0
BB	0938	12.1	0938	11.4
	0940	12.9	0938	11.8
CC	0942	11.1	0938	12.6
	0944	12.4	0938	12.2
Mean				
Values		12.1		12.0

Table 4c. Observed and predicted wind speeds (m s^{-1}) for the midday flight on 3 Feb 80, initial and final 50 m tracks. (Otherwise the same as Table 4a).

#	Observed Wind Speed		Predicted Wind Speed	
	Time	m s^{-1}	Time	m s^{-1}
a	1114	9.2	1108	9.7
	1116	9.0	*1123	10.1
b	1118	9.7	*1123	10.5
	1120	9.1	*1123	11.0
c	1122	9.7	*1123	11.4
	1124	10.7	*1123	11.9
d	1126	10.4	*1123	12.2
	1128	10.5	*1123	12.4
Mean				
Values		9.8		11.1

#	Observed Wind Speed		Predicted Wind Speed	
	Time	m s^{-1}	Time	m s^{-1}
e	1248	8.1	*1253	10.5
	1250	7.9	*1253	10.3
f	1252	7.5	*1253	10.1
	1254	6.8	*1253	9.7
g	1256	6.9	*1253	9.5
	1258	6.9	*1253	9.2
h	1300	7.2	1253	8.9
	1302	7.8	1308	8.4
i	1304	9.0	1308	7.9
	1306	8.7	1308	7.6
Mean				
Values		7.7		9.2

Table 4d. Observed and predicted wind speeds (m s^{-1}) for the midday flight on 3 Feb 80, large 170 m rectangle. (Otherwise the same as Table 4a).

#	Observed Wind Speed		Predicted Wind Speed	
	Time	m s^{-1}	Time	m s^{-1}
A	1130	10.2	*1123	12.5
	1132	10.4	*1138	11.9
B	1134	10.3	*1138	11.6
	1136	9.9	*1138	11.2
C	1138	9.3	*1138	10.9
	1140	9.1	*1138	10.6
D	1142	7.7	*1138	10.3
	1144	7.3	*1138	9.9
E	1146	8.1	*1138	9.7
	1148	8.6	1153	9.2
F	1150	9.6	1153	9.2
	1152	10.4	1153	9.4
G	1154	10.5	1153	9.5
	1156	11.3	*1153	9.5
H	1158	11.6	*1153	9.6
	1200	11.2	*1153	9.6
I	1204	10.9	*1208	9.3
	1206	11.1	*1208	9.2
J	1208	9.8	1208	9.0
	1210	10.4	*1208	8.9
K	1212	9.3	1208	8.8
	1214	9.3	1208	8.7
L	1216	9.1	1208	8.6
	1218	9.1	1223	8.4
M	1220	9.3	1223	8.3
	1222	9.0	1223	8.3
N	1224	9.2	1223	8.4
	1226	8.4	1223	8.6
O	1228	9.1	1223	9.0
	1230	9.8	1223	9.5
P	1232	9.7	1238	9.8
	1234	10.3	1238	10.3
Q	1236	9.8	1238	10.6
	1240	9.3	1238	10.9
R	1242	9.3	*1238	11.0
	1244	8.5	*1238	11.0
S	1246	8.1	*1238	11.1
Mean				
Values		9.6		9.8

Table 4e. Observed and predicted wind speeds (m s^{-1}) for the afternoon flight on 3 Feb 80, initial and final 50 m track. (Otherwise the same as Table 4a).

#	Observed Wind Speed			Predicted Wind Speed	
	Time	m s^{-1}		Time	m s^{-1}
a	1427	9.4		*1423	7.1
	1429	9.6		*1423	7.6
b	1431	9.0		*1438	8.2
	1433	8.7		1438	8.4
c	1435	8.8		1438	8.7
	1437	8.8		1438	8.9
d	1439	8.6		1438	9.1
	1443	8.4		1438	9.2
e	1445	8.0		1438	9.1
	1447	8.5		1453	9.0
f	1449	8.6		1453	8.9
	1453	8.9		1453	8.8
g	1455	8.6		1453	8.6
	1457	8.2		1453	8.4
h	1459	8.5		1453	8.1

Mean					
Values		8.7			8.5

#	Observed Wind Speed			Predicted Wind Speed	
	Time	m s^{-1}		Time	m s^{-1}
h	1653	10.2		1653	9.1
i	1655	9.8		1653	9.2
	1657	10.0		1653	9.3
j	1659	10.0		1653	9.4
	1701	9.0		1708	9.3
k	1703	8.8		1708	8.9
	1705	8.3		1708	8.3
l	1707	7.8		1708	7.6

Mean					
Values		9.2			8.9

Table 4f. Observed and predicted wind speeds (m s^{-1}) for the afternoon flight on 3 Feb 80, both 170 m rectangles. (Otherwise the same as Table 4a).

#	Observed Wind Speed		Predicted Wind Speed	
	Time	m s^{-1}	Time	m s^{-1}
A	1501	8.8	1508	8.2
	1503	8.7	1508	8.0
B	1505	7.9	1508	7.8
	1507	8.9	*1508	7.5
C	1509	9.4	*1508	7.4
	1511	9.2	*1508	7.4
D	1513	10.5	*1508	7.4
	1515	9.1	*1508	7.4
E	1517	8.7	*1523	7.4
	1519	8.9	*1523	7.3
F	1521	9.4	*1523	7.3
	1525	9.3	*1523	7.3
G	1527	9.4	*1523	7.5
	1529	9.4	*1523	7.5
H	1531	8.7	1538	7.6
	1533	8.0	1538	7.6
I	1535	8.2	1538	7.6
	1537	9.2	*1538	7.6
J	1539	9.5	*1538	7.7
	1541	9.6	*1538	7.3
K	1543	9.9	*1538	8.0
	1545	9.9	*1538	8.4
L	1547	9.8	1553	8.9
	1549	10.0	1553	9.2
M	1551	9.6	1553	9.4
	1553	9.2	1553	9.7
N	1555	9.3	1553	9.8
	1559	8.7	1553	9.7
O	1601	8.1	1608	9.6
	1603	7.9	*1608	9.5
P	1607	8.4	1608	9.4
	1609	7.7	1608	9.3
Q	1611	9.0	1608	9.1
	1613	7.8	1608	8.9
R	1615	8.2	1608	8.9
	1617	8.7	1623	9.2
S	1619	10.0	1623	9.3
	1621	10.1	1623	9.3
T	1623	10.0	1623	9.1
	1625	9.8	1623	8.8
U	1627	9.1	1623	8.4
	1629	9.3	1623	8.1
V	1631	9.1	1638	8.1
	1633	9.6	1638	8.0
W	1635	8.8	1638	8.0
	1637	8.5	1638	7.8
X	1639	9.4	1638	7.7
	1641	8.5	1638	7.6
Y	1643	9.9	*1638	7.6
	1645	10.3	*1638	7.8
Z	1647	10.8	*1653	8.2
	1649	10.6	1653	8.7
AA	1651	10.1	1653	9.1
Mean Values		9.1	8.3	

Table 5. Absolute* error limits ($\pm$ m s⁻¹) for measured wind speeds from beginning to end of each flight component. Time (hh mm, EST) at which inertial navigation system aligned is given in parentheses for each flight.

Day	FLIGHT		
	Morning	Midday	Afternoon
30 Jan 80	(0639)	(1102)	(1348)
	$\pm$ 0.8 to 2.1	$\pm$ 0.9 to 1.7	$\pm$ 0.8 to 2.1
3 Feb 80	(0606)	(1032)	(1402)
	$\pm$ 1.0 to 2.4	$\pm$ 0.9 to 1.8	$\pm$ 0.7 to 2.0

*The absolute error is equivalent to $\pm$ 2 standard deviations, i.e. the probability is less than 1 in 20 that the true value of the horizontal wind speed, in any instance, is outside these limits.

Table 6. Numbers of "correct" wind speed predictions and percentages by flight and daily total for two WIVEX days. "Correct" means predicted value departs from observed value by not more than the absolute measurement error.

Day	Morning	Midday	Afternoon	Total
30 Jan 80	61 of 73 84%	42 of 48 88%	59 of 75 79%	162 of 196 83%
3 Feb 80	69 of 82 84%	24 of 55 44%	53 of 76 70%	146 of 213 69%
				308 of 409 75%

Table 7. Coefficient of linear correlation (r) and significance tests for all pairs of predicted and observed wind speeds on two WIVEX days. N is the number of pairs, n is the number of degrees of freedom ($\sqrt{N}$). $F = r^2(n-1)/(1-r^2)$. The 0.5% test values of F are taken from Bethea et al. (1975), Table VI.

Day	N	r	n	F	F(0.5%)
30 Jan 80	196	0.793	14	22.03	11.10
3 Feb 80	213	0.749	15	17.89	10.80

Table 8. Average of the square of the unbiased differences for all wind speeds on two WIVEX days. Refer to text for explanation of elements.

Day	E	$E_{\max}$	ϵ
30 Jan 80	1.024	5.399	0.810
3 Feb 80	1.702	6.975	0.756

Table 9. Skill ratings (%) determined by various analyses.

Day	Measurement Error	Correlation Coefficient	Unbiased Differences
30 Jan 80	83	79	81
3 Feb 80	69	75	76
Overall	75	77	78

FIGURES 1-3. Annual average power density (W m^{-2}), layer-mean given for each 100 km^2 (10 km north-south x 10 km east-west) as determined from meteorological variables predicted by the numerical model of the atmosphere. Centers of relative maximum (X) and minimum (N) are indicated along with solid isolines at 50 W m^{-2} intervals. Land areas are shaded. The land-water boundary is depicted in detail for ease of orientation and location whereas in the computer integrations the character of the surface for each grid-square is represented by its percent of land area. The locations of meteorological stations used to verify predictions are shown as heavy solid dots.

FIGURE 1.

Chesapeake Bay Area.

Annual average, 100 m layer-mean power density ($W m^{-2}$).

X - maximum, N - minimum, $\oplus$ - latitude/longitude intersection,

ppp

● - verification station, ppp - model prediction, ddd - from data.

ddd

FIGURE 2.

FIGURE 3.

FIGURE 4. Outlines of the 120x30 km aircraft flight-track (solid rectangle) located within the 140x100 km Wallops Island verification experiment study area (broken rectangle). The outlines are superimposed upon a model-produced daily average, layer-mean (surface to 100 m) power density distribution for typical wintertime conditions in the Chesapeake Bay area. Isolines are in $W\ m^{-2}$, 'X' marks center of maximum, 'N' minimum power density. Circled numbers are way-points along the flight-track.

FIGURE 4.

FIGURES 5A-7A. Observed wind speeds (m s^{-1}) and wind directions (meteorological deg.) at 170 m above the surface for aircraft flights made on 30 Jan 80. Each value is a two-minute average of one-second data. The +'s are the aircraft positions halfway through each averaging interval. The coastline is shown as a light solid line with the rectangular flight track overlaid. The letters identify every other location for orientation with respect to Figures 5B-7B and correspond to entries in Table 3 and Figure 8. All flight tracks proceed alphabetically with small letters signifying 50 m and capital letters 170 m measurements.

FIGURES 5B-7B. Predicted wind speeds (m s^{-1}) and wind directions (meteorological deg.) at 170 m above the surface for 30 Jan 80. Predictions, made by the University of Virginia mesoscale model, are available at 15-minute intervals and are given for each 10×10 km grid-square of the WIVEX study area. The local solar time (hhmm) of the entries appears in the margin and the spacial extent of each time is shown as a light broken line. The coastline and the overlaid rectangular flight track are shown as light solid lines. The center point of any grid-square is located midway between the decimal point of the speed entry and the top of the center digit of the direction entry. Solid squares and letters correspond to observational locations shown in Figures 5A-7A.

FIGURE 5A. Morning flight, large 170 m rectangle.

FIGURE 5B. Morning flight, 30 Jan 80, large 170 m rectangle.

FIGURE 6A. Midday flight, large 170 m rectangle.

FIGURE 6B. Midday flight, 30 Jan 80, large 170 m rectangle.

FIGURE 7A. Afternoon flight, large
170 m rectangle.

FIGURE 7B. Afternoon flight, 30 Jan 80, large 170 m rectangle.

FIGURES 8A-F. Space-time series of observed (solid dots) and predicted (open circles) wind speeds (m s^{-1}) at 50 and 170 m above the surface within the WIVEX study area on 30 Jan 80. Abscissa letters refer to locations in Figures 5-7.

FIGURE 8A. Morning flight, 30 Jan 80, initial and final 50 m tracks.

FIGURE 8B. Morning flight, 30 Jan 80, both 170 m rectangular tracks.

FIGURE 8C. Midday flight, 30 Jan 80, initial and final 50 m tracks.

FIGURE 8D. Midday flight, 30 Jan 80, large 170 m rectangular track.

FIGURE 8E. Afternoon flight, 30 Jan 80, initial and final 50 m tracks.

FIGURE 8F. Afternoon flight, 30 Jan 80, both
170 m rectangular tracks.

FIGURES 9A-11A. Observed wind speeds (m s^{-1}) and wind directions (meteorological deg.) at 170 m above the surface for aircraft flights made on 3 Feb 80. Each value is a two-minute average of one-second data. The +'s are the aircraft positions halfway through each averaging interval. The coastline is shown as a light solid line with the rectangular flight track overlaid. The letters identify every other location for orientation with respect to Figures 9B-11B and correspond to entries in Table 4 and Figure 12. All flight tracks proceed alphabetically with small letters signifying 50 m and capital letters 170 m measurements.

FIGURES 9B-11B. Predicted wind speeds (m s^{-1}) and wind directions (meteorological deg.) at 170 m above the surface for 3 Feb 80. Predictions, made by the University of Virginia mesoscale model, are available at 15-minute intervals and are given for each 10×10 km grid-square of the WIVEX study area. The local solar time (hhmm) of the entries appears in the margin and the spacial extent of each time is shown as a light broken line. The coastline and the overlaid rectangular flight track are shown as light solid lines. The center point of any grid-square is located midway between the decimal point of the speed entry and the top of the center digit of the direction entry. Solid squares and letters correspond to observational locations shown in Figures 9A-11A.

FIGURE 9A. Morning flight, large 170 m rectangle.

FIGURE 9B. Morning flight, 3 Feb 80, large 170 m rectangle.

FIGURE 10A. Midday flight, large 170 m rectangle.

FIGURE 10B. Midday flight, 3 Feb 80, large 170 m rectangle.

FIGURE 11B. Afternoon flight, 3 Feb 80, large 170 m rectangle.

FIGURES 12A-F. Space-time series of observed (solid dots) and predicted (open circles) wind speeds (m s^{-1}) at 50 and 170 m above the surface within the WIVEX study area on 3 Feb 80. Abscissa letters refer to locations in Figures 9-11.

FIGURE 12A. Morning flight, 3 Feb 80, initial and final 50 m tracks.

FIGURE 12B. Morning flight, 3 Feb 80, both 170 m rectangular tracks.

FIGURE 12C. Midday flight, 3 Feb 80, initial and final 50 m tracks.

FIGURE 12D. Midday flight, 3 Feb 80, large 170 m rectangular track.

FIGURE 12E. Afternoon flight, 3 Feb 80, initial and final 50 m tracks.

FIGURE 12F. Afternoon flight, 3 Feb 80, both
170 m rectangular tracks.

FIGURE 13A. Scatter diagram of wind speeds, 30 Jan 80. Broken line is regression, $U_m = 1.13 U_p - 1.58$. Perfect prediction is solid line, $U_m = U_p$. Over-predictions are below, under-predictions above the solid line.

FIGURE 13B. Scatter diagram of wind speeds, 3 Feb 80. Broken line is regression, $U_m = 0.77 U_p + 2.55$. Perfect prediction is solid line, $U_m = U_p$. Over-predictions are below, under-predictions above the solid line.

FIGURE 14A. Scatter diagrams of the cube of measured wind speed, U_m^3 , versus predicted wind speed, U_p , for 30 Jan 80. Isolines of percent error in predicted wind power, $(U_p^3 - U_m^3)/U_m^3 = \ell\ell$, where $\ell\ell = -50, -25, \pm 0, +25$ and $+50\%$, are plotted. (U^3 is wind power density divided by the atmospheric density. However, since the percent error in atmospheric density contributes little to the percent error in power, the $\ell\ell$ values are essentially the percent errors in power.) Over-predictions are below, under-predictions above the $\pm 0\%$ error, the solid line.

FIGURE 14B. Scatter diagrams of the cube of measured wind speed, U_m^3 , versus predicted wind speed, U_p , for 3 Feb 80. Isolines of percent error in predicted wind power, $(U_p^3 - U_m^3)/U_m^3 = \ell\ell$, where $\ell\ell = -50, -25, +0, +25$ and $+50\%$, are plotted. (U^3 is wind power density divided by the atmospheric density. However, since the percent error in atmospheric density contributes little to the percent error in power, the $\ell\ell$ values are essentially the percent errors in power.) Over-predictions are below, under-predictions above the $+0\%$ error, the solid line.

FIGURE 15. Areal distribution of measured wind power density (10^2 W m^{-2}) at 170 m above the surface, 0742-0859 EST, 30 Jan 80, within the WIVEX 120x30 km aircraft track. 'X' specifies area of maximum power density ($> 1260 \text{ W m}^{-2}$), 'N' the area of minimum (approximately 150 W m^{-2}). Dashed line is the Maryland-Virginia border. Aircraft position at 0828 is shown.

FIGURE 15.

FIGURE 16. Areal distribution of predicted wind power density (10^2 W m^{-2}) at 170 m above the surface at 0828 EST, for the WIVEX study area. Predictions made by the University of Virginia mesoscale model initialized for 30 Jan 80. 'X' specifies areas of maximum power density (offshore 1210 W m^{-2}), 'N' the area of minimum (490 W m^{-2}). Aircraft position at 0828 is shown.

DISTRIBUTION

No. of
Copies

No. of
Copies

OFFSITE

A. A. Churm DOE Chicago Patent Group 9800 S. Cass Avenue Argonne, IL 60439	Richard Katzenberg 3100 Highland Place Washington, DC 20008
D. Ancona Department of Energy Wind Energy Technology Division 1000 Independence Avenue Forrestal Building, Room 5F059 Washington, DC 20585	E. J. Warchol Bonneville Power Administration P.O. Box 3621 Portland, OR 97208
C. I. Aspliden Battelle Memorial Institute Washington Operations Office 2030 M Street, N.W. Washington, DC 20036	S. J. Hightower Bureau of Reclamation Denver Federal Center Building 67, Code 254 Denver, CO 80225
S. D. Berwager Department of Energy Wind Energy Technology Division 1000 Independence Avenue Forrestal Building, Room 5F059 Washington, DC 20585	Joe Hennessy Wind Energy Program California Energy Commission 1111 Howe Avenue, Mail Stop 66 Sacramento, CA 95825
G. P. Tennyson Department of Energy Albuquerque Operations Office P.O. Box 5400 Albuquerque, NM 87110	R. Nolan Clark Department of Agriculture S.W. Great Plains Research Center Bushland, TX 79012
27 DOE Technical Information Center	Jay Tappan Department of Energy State of Oregon Labor and Industries Building Room 111 Salem, OR 98310
Dr. K. C. Spengler American Meteorological Society 45 Beacon Street Boston, MA 02108	Dr. Edgar DeMeo Electric Power Research Institute 3412 Hillview Avenue Palo Alto, CA 94303
Tom Gray American Wind Energy Association 1621 Connecticut Avenue, N.W. Washington, DC 20009	Thomas R. Hiester Flow Research 21414 68th Avenue, South Kent, WA 98031

No. of
Copies

Dr. Walter Frost
FWG Associates, Inc.
Route 2, Box 271-A
Tullahoma, TN 37388

James D. West
HQ MAC/DEEE
Scott AFB, IL 62225

Gary G. Worley, Maj. USAF
HQ AF-ESC/RDVA
Tyndall AFB, FL 32403

Gary L. Johnson
Electrical Engineering Department
Kansas State University
Manhattan, KN 66506

Marlatt and Associates
3611 Richmond Drive
Fort Collins, CO 80521

V. F. Garrett
Montana Energy and MHD Research
and Development Institute, Inc.
P.O. Box 3809
Butte, MT 59701

J. Konigsberg
Montana Energy Office
Capital Station
Helena, MT 59601

Phillip French
NASA Scientific and Technical
Information Facility
P.O. Box 8757
Baltimore/Washington International
Airport
Baltimore, MD 21240

R. A. Wolf
NASA/Lewis Research Center
Mail Stop 500-201
Cleveland, OH 44135

No. of
Copies

M. J. Changery
National Oceanic and Atmospheric
Administration
National Climatic Center
Federal Building
Asheville, NC 28801

C. F. Chappell
Office of Weather Research
and Modification
National Oceanic and Atmospheric
Administration
Boulder, CO 80303

E. W. Hewson/J. E. Wade
Atmospheric Sciences Department
Oregon State University
Corvallis, OR 97331

Terry J. Healy/C. Hansen
Rockwell International
Rocky Flats Plant
P.O. Box 464
Golden, CO 80401

E. Kadlec
Sandia Laboratories
Division 5443
P.O. Box 5800
Albuquerque, NM 87115

W. A. Tolbert, Capt. USAF
SERI Site Office/RTL0
1617 Cole Boulevard
Golden, CO 80401

Solar Energy Research Institute
1617 Cole Boulevard
Golden, CO 80401

Bruce Bailey
Atmospheric Sciences Research
Center
State University of New York
at Albany
Albany, NY 12222

No. of
Copies

No. of
Copies

N. E. Suhs
Tennessee Valley Authority
1360 Commerce Union Bank Building
Chattanooga, TN 37401

Dr. Tom Schroeder
University of Hawaii at Manoa
Department of Meteorology
2525 Correa Road
Honolulu, HI 96822

Dr. N. K. Wagner
Department of Civil Engineering
University of Texas
Austin, TX 78712

Dr. Michael Garstang
Department of Environmental Sciences
University of Virginia
Charlottesville, VA 22903

G. D. Thomann
Wichita State University
P.O. Box 44
Wichita, KS 67208

Farrell Smith Seiler
Wind Energy Report
Box 14 - 104 S. Village Avenue
Rockville Centre, NY 11571

W. Van Dyke
Wind Farms, Ltd.
639 Front Street
San Francisco, CA 94111

Richard L. Berry
Atmospheric Environment
4905 Dufferin Street
Downsview, Ontario
M3H 5T4
CANADA

Dr. Neil Cherry
Lincoln College
Canterbury
NEW ZEALAND

ONSITE

DOE Richland Operations Office
P.O. Box 550
Richland, WA 99352

H. E. Ransom

43 Pacific Northwest Laboratory
Battelle Boulevard
Richland, WA 99352

W. R. Barchet
J. W. Buck
J. R. Connell
J. C. Doran

C. E. Elderkin
D. L. Elliott
W. J. Formica
R. L. George
D. L. Hadley

S. K. Heflick
V. K. Hopkins (15)
A. H. Miller

E. L. Owczarski
W. T. Pennell

D. C. Powell
J. J. Praino
J. V. Ramsdell
D. S. Renné

W. F. Sandusky
H. L. Wegley
L. L. Wendell
R. K. Woodruff

Technical Information - Library (5)
Publishing Coordination (2)