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Forecasting local winds in a forest environment

David W. Goens
The University of Montana

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FORECASTING LOCAL WINDS IN A FOREST ENVIRONMENT

By

David W. Goens

B. S. (Meteorology), Oklahoma University, 1967

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ABSTRACT

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Director: Robert W. Steele RWS

Accurate forecasts of wind flow patterns are required to adequately predict the behavior of fires in mountainous forested areas. The purpose of this work was to investigate forecast techniques for predicting wind flow patterns in these complex topographical situations.

Basic wind flow patterns are investigated and summarized. Atmospheric modeling and forecast techniques are reviewed. A specific low level wind predictive model is examined in depth and applied in an actual fire situation. Results are compared with forecasts generated by more conventional techniques.

Wind flow patterns in the steep, narrow, forested valleys of the study area were found to behave in nearly classical manner. Forecasts generated by the predictive model were inconsistent and compared poorly with those prepared with standard methods. It is concluded that an experienced forecaster can consistently produce more accurate forecasts than the predictive model examined in most complex small scale situations.

ACKNOWLEDGMENTS

It is with a deep sense of gratitude that I acknowledge the assistance and guidance of my graduate committee:

Dr. Robert Steele, Chairman
Mr. Fred Gerlach
Dr. Darshan Kang
Mr. Robert Baughman

In addition, I wish to thank Dr. Rodney Norum of the U. S. Forest Service for keeping my perspectives in order and granting unlimited encouragement, and to Messers Ed Nelson, A. F. Burnham, and Lloyd Heavner, all of the National Weather Service. These gentlemen, my supervisors and co-workers, allowed me time to do this research by making the necessary adjustments in their work schedules. Mrs. Sandy Tribble deserves my special appreciation for her many hours work in typing and proofreading.

Last, but far from least, my loving thanks go to my wife, Donna. Without her encouragement and patience this work could not have been completed.

TABLE OF CONTENTS

APPENDIXES

LIST OF TABLES

LIST OF FIGURES

Chapter 1

INTRODUCTION

The air above and within the forest environment is constantly in motion. These motions can be defined as wind. Wind movements are a normal part of the natural environmental processes and can serve many useful functions. For example, winds aid in the pollination process by acting as a transporting agent, and seeds may be carried by the winds for great distances.

Just as pollination and regeneration are a part of the natural processes so is fire. It has been accepted that fire plays an important ecological role in the development and maintenance of the forest of the Northern Rocky Mountains (Barrows 1951, Beaufait 1971, et al.). One of the primary elements in the spread of fire is wind. Wind determines the rate and direction of fire spread and is one of the most difficult meteorological parameters to forecast.

When the forest is located in a variable topographic situation, such as found in any mountainous area, the behavior of wind flow patterns become even more complex. In the lower atmosphere above all terrain influences winds behave in a fairly consistent and predictable manner. The free air movements above the friction layer influence the winds near the surface, especially during a sunny, hot summer or fall afternoon when there is turbulent or convective mixing of the lower atmosphere.

In order to make a meaningful prediction of the behavior of a fire, the fire manager must have accurate data on fuels, topography and weather. Information on fuels and topography can be considered a nonvariable as they can be determined through direct observation or measurement. Information on weather, and winds specifically, present a more difficult problem. Direct measurements of temperature, humidity, precipitation, and winds can be made. The problem arises in the ability to reliably forecast what these meteorological parameters will be during a fire in the next and future burning periods.

Another growing concern requiring the ability to predict winds near the surface of the earth is the maintenance of air quality. Everyone wants a clean atmosphere, not only for purely aesthetical reasons, but in many cases for reasons of public health. The smoke generated by a wildland fire will disperse in a manner which is dependent upon atmospheric stability and winds. Smoke generated by a wildfire may be tolerated by the public, but smoke from a prescribed fire may draw severe criticism. If we are to continue to burn by prescription we must be able to forecast the behavior of the smoke and burn only under those atmospheric conditions which will provide adequate dispersal.

Many methods of forecasting winds have been developed and tried. Some of these methods are primarily objective while others are totally subjective. Since the advent of modern computer technology the modeling of many natural processes has taken great strides. The ability of these systems to handle large and complex volumes of data in short time periods has opened new avenues in applied research. In this area numerous mathematical models have been developed to forecast wind flow patterns. Some of these models do a reliable job in certain situations. However, the models developed up to this time show greatest reliability in fairly uniform terrain situations. It seems only logical to assume that given enough time, a consistently accurate model will be refined or developed for use in complex terrain. Based upon this assumption, this study was undertaken.

Dr. Michael A. Fosberg, et al. (1976) of the U. S. Forest Service Research Laboratory at Ft. Collins, Colorado has developed a mathematical model which predicts the low level winds in various terrain situations. Dr. Fosberg has tested this model in western Oregon and reports promising results. The model had not been tested in the steep and rugged terrain of the Northern Rockies, therefore its applicability in these situations was still somewhat unknown.

Dr. Fosberg's model, hereinafter referred to as the WINDS MODEL or MODEL, was selected for evaluation due to promising preliminary results. It was hoped that this particular model could be applied as a useful real time tool in complex terrain situations. However, the applicability of this study was not intended to be tied purely to Dr. Fosberg's model. It is hoped the techniques used in this evaluation could be applied in testing any of the present or future computer generated models.

Chapter 2

OBJECTIVES

The objectives of this study were as follows:

1. Review the flow patterns and forecasting techniques for local winds in the forest environment.

2. Assess the possibility of utilizing a computer generated wind forecasting model in a real time operational situation.

3. Assess the accuracy of the Fosberg WINDS MODEL:

    a. Determine whether inputs for the WINDS MODEL can be standardized for a specific locale.

    b. Assess the potential for using the WINDS MODEL to forecast smoke movement.

Chapter 3

LITERATURE REVIEW

Forecasting

The forecasting of winds in the lower atmosphere has always been a major problem for the operational forecaster. Efforts to describe the atmosphere and atmospheric processes have long been pursued. Early efforts were made by many of the great meteorologist and hydrodynamicist including von Helmhotz, Bjerknes, and Richardson (Hess 1959). Around 1910, Richardson began to explore the possibility of utilizing the complete set of five hydrodynamic equations to generate a forecast for the basic meteorological parameters. The data handling in itself was overwhelming by manual techniques and was one of the basic reasons that Richardson failed.

With the advent of modern computer technology modeling efforts have taken great strides. Since about 1948, the movement has pressed forward. Research in the late 1950's turned toward the utilization of the momentum equations, or as they are presently referred to, the "Primitive Equations (P.E.)" (Haltiner 1971). Only in the second half of the 1960's did computers become fast enough to permit the use of the Primitive Equation models in operational forecasting.

Wind forecasts generated by the Primitive Equation models are now being used operationally on a daily basis by the National Weather Service. Forecasts are generated twice daily based on the 0000 and

1200 Greenwich Mean Time (GMT) upper level observation data. The problem with these forecasts are that they are made for the atmosphere at and above the friction layer. The problem that is being addressed in this work are the winds within the friction layer. Therefore the Primitive Equation Forecasts have limited use, but may be used as one of the input parameters for another more specific model.

The Primitive Equation Model and derived products from operational runs are described by Hess (1959), Haltiner (1971), Badner (1972) and Ostby (1972).

More general descriptions of the character of the wind flow regime in the surface layer have been widely published. It is reasonably well understood and has been discussed in relationship to specific meteorological and physical variables. Petterssen (1956) outlines the behavior of winds in relationship to thunderstorms and squall lines as well as general characteristics of the wind field and frictional influences (also Byers, 1959). The dependence of winds and their relationship to temperature fields and ground cover has been discussed by Geiger (1950), Schroeder and Buck (1970), and Monteith (1976).

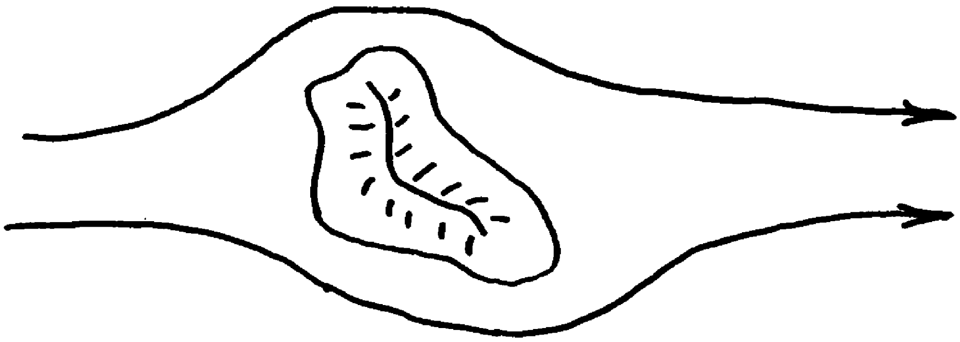
As can be seen, the physical and dynamical characteristics of wind fields have been adequately described in all types of terrain situations. In addition, recent developments in atmospheric research and computer technology have led to reasonably accurate short term forecasting of wind fields above the friction layer. The behavior of the wind fields within the friction layer are a major forecasting problem. Each case must be examined individually and all the physical and dynamic variables weighed to produce an accurate forecast. In recent years there has been a considerable amount of research in developing models to forecast these winds. Fosbergs' (1976) "Estimating Airflow Patterns Over Complex Terrain" is one of the more sophisticated models yet developed, and was the one chosen for evaluation in this study. Liu, Mundkur, and Yocke (1974) reviewed a variety of models with primary interest toward the spread of fire in California brush fields. Included in their review was the early (pre-publication) work of Fosberg along with five other diagnostic models.

Low Level Wind Flow Patterns

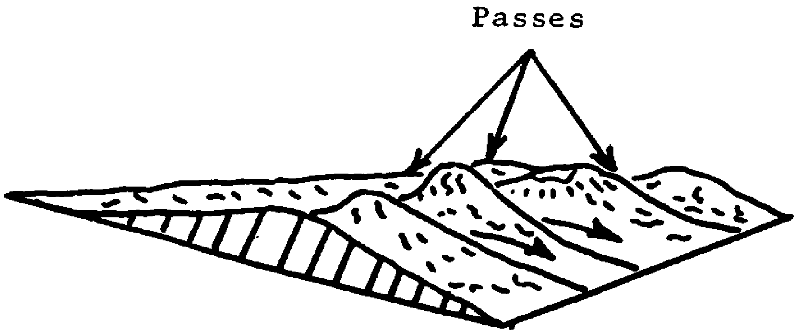
Mountainous topography presents a significant barrier to free air flow patterns. The topography represents a roughness factor that effects the wind pattern in various ways. When vegetation is imposed upon the topography, even more modification occurs. These two factors represent complex variables to modeling atmospheric processes in the lower levels as well as point forecasting of wind fields.

Topography.

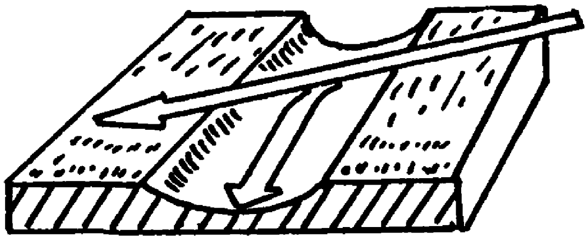
Winds are both modified and generated by topographic features. Topography is one of the primary factors controlling both the direction and speed of the wind in mountainous regions. Winds may be funneled through narrow canyons and passes, causing an increase in the speed of the flow and dictating its direction. Figure 1 illustrates some of the modification effects of mountainous terrain.



Diverting



Gapping



Channeling

Figure 1

Topographical Modifications
of the Wind Flow

Mountains not only act as barriers to the free air flow, but also have a direct effect on convective winds. Convective winds are formed on mountain slopes due to differential heating and cooling. Slopes that are oriented south and west receive more intense insolation during the middle and late portions of the day, but all aspects are effected. As the slope heats, air near the surface is warmed by conduction and rises by convection. Winds are generated as the warm air currents rise along the entire slope. After sundown, downslope winds are formed by similar dynamic processes and many times are a significant factor in transporting smoke or other pollutants.

The stability of the lower atmosphere is very important when considering any wind flow regime. Under unstable conditions, winds in the free air above the friction layer can be mixed downward to the surface. In mountainous areas this may cause a reinforcement of the normally occuring afternoon upslope winds, or it might possibly counteract the slope winds depending on slope orientation and the direction of the free air flow. The stability factor must be considered when constructing any type of wind model or wind forecasting technique.

Vegetation. All vegetation is a part of the friction layer which determine how the winds will blow near the surface. The effect of vegetation is controlled by its relative height and density. Since this study was conducted in a northern Rocky Mountain coniferous forest, comments will be restricted to effects relating to this type of vegetative cover.

As air flows over and through a canopy, both the velocity and direction of flow will be modified. The degree of velocity reduction will be a function of tree spacing, tree height, canopy density, and understory composition (Cooper 1965 and Bergen 1974). Gisborne (1941) developed wind profiles for different canopy densities and heights (see Figure 2). The general pattern observed by researchers has been, as one would expect, a reduction in the wind speed from the top of the canopy down. In fairly open stands, a definite sub-canopy maximum has been observed (note Figure 3, Bergen 1971). Trying to determine the amount of reduction within and below the canopy has been quite difficult. Baker (1950) stated that reductions of one third to one half of the free air wind, or winds in the open, could be expected. The amount of speed reduction is nearly impossible to quantify due to the tremendous point to point environmental variability. How much the wind speed is reduced on a specific forested site depends on the

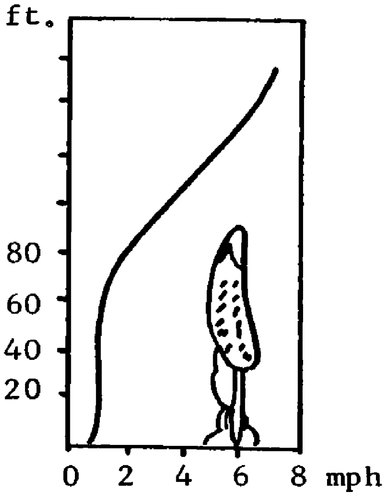


Figure 2

Dense Conifer Forest
with Understory
(Gisborne 1941)

detailed structure of the stand and the wind speed above the canopy. The relative drag of any frictional surface is much greater at high wind speeds than at low wind speeds (Schroeder 1970). At low wind speeds, the winds may be reduced by 30 percent to 40 percent, while with high wind speeds the reduction may be as great as 70 percent to 80 percent. This reduction again would vary with species, stocking level, height of canopy, etc.

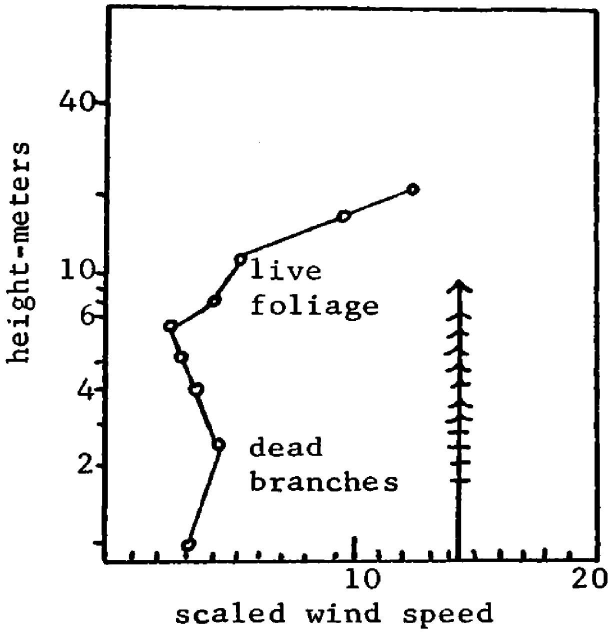


Figure 3

Wind Profile in a Conifer Stand
Without Understory (Bergen 1971)

Differences in microsite cause variabilities in the wind speed. Stand density and color will effect local heating and stability regimes, and therefore the local winds. Winds may be generated on slopes which are either timbered or open. On densely timbered slopes with closed canopies, the upslope wind will be strongest just above the canopy, while on open slopes the wind maximum will be felt three to four feet above the surface.

Local heating will cause instability, and this instability will allow free air winds above the surface to be mixed downward. The mixing within the tree canopy has been investigated (Bergen 1974), but no reliable results obtained. This is to be expected since the canopy is sufficiently porous to retard and dissipate sub-canopy heat, thereby preventing unstable lapse rates from developing from the surface through the canopy.

The problem of determining exact wind speeds through the canopy level has not been completely resolved. Standard instrumentation for official reporting sites demand that winds be measured at the 20-foot (6-meter) level (Fischer and Hardy 1972). This means that the winds will be measured (and forecast) at 20 feet above the surface effects in order to compensate for uneven ground cover. For example, in a mature, dense forest environment with a closed canopy and average tree height of 80 feet, the winds are supposed to be measured at the 100-foot level. This is obviously an unreasonable situation if a fire is burning in the understory with strong winds above.

A number of methods have been proposed to resolve the winds through the canopy. Cooper (1965) and later O'Dell (1975) suggested two separate and very different techniques, neither of which worked reliably or consistently. In 1978, Albini and Baughman proposed a technique for resolving this problem (see Appendix 2) which has been accepted at this time for use in national fire behavior predictions curriculums. This system was used to resolve the wind fields through the canopy for this study.

Chapter 4

STUDY AREA

The study was conducted on the 7,460-acre (3,019 ha) Coram Experimental Forest, on the Flathead National Forest, Flathead County, in northwestern Montana (Figure 4). This area was logged in 1974, under an intensive management plan with a variety of logging techniques. Six blocks, consisting of two clearcuts (14 and 17 acres; 5.7 and 6.9 ha), two shelterwoods (35 and 22 acres; 14.2 and 8.9 ha), and two sets of eight small clearcuts (average 0.8-acre; 0.3 ha) were logged with resulting residue treated under four different standards. In 1975, this study was conducted in conjunction with the prescribed burning of these logged areas. The burning prescriptions are outlined by Norum (1975) and related studies were conducted by Steele (1975), and Artley (1976).

The timber type in the study area is predominantly old growth larch (Larix occidentalis) and Douglas-fir (Pseudotsuga menziesii). Associated species include subalpine fir (Abies lasiocarpa) and Engelmann spruce (Picea englemannii).

The topography of the study area is quite steep with slopes ranging from 30 to 80 percent (17° to 39°). The ridges are mostly oriented north and south with the study area primarily on the east facing slope. Ridgetop elevations vary from approximately 5,500 feet (1,676 m) on the north to 4,600 feet (1,402 m) on the south. The

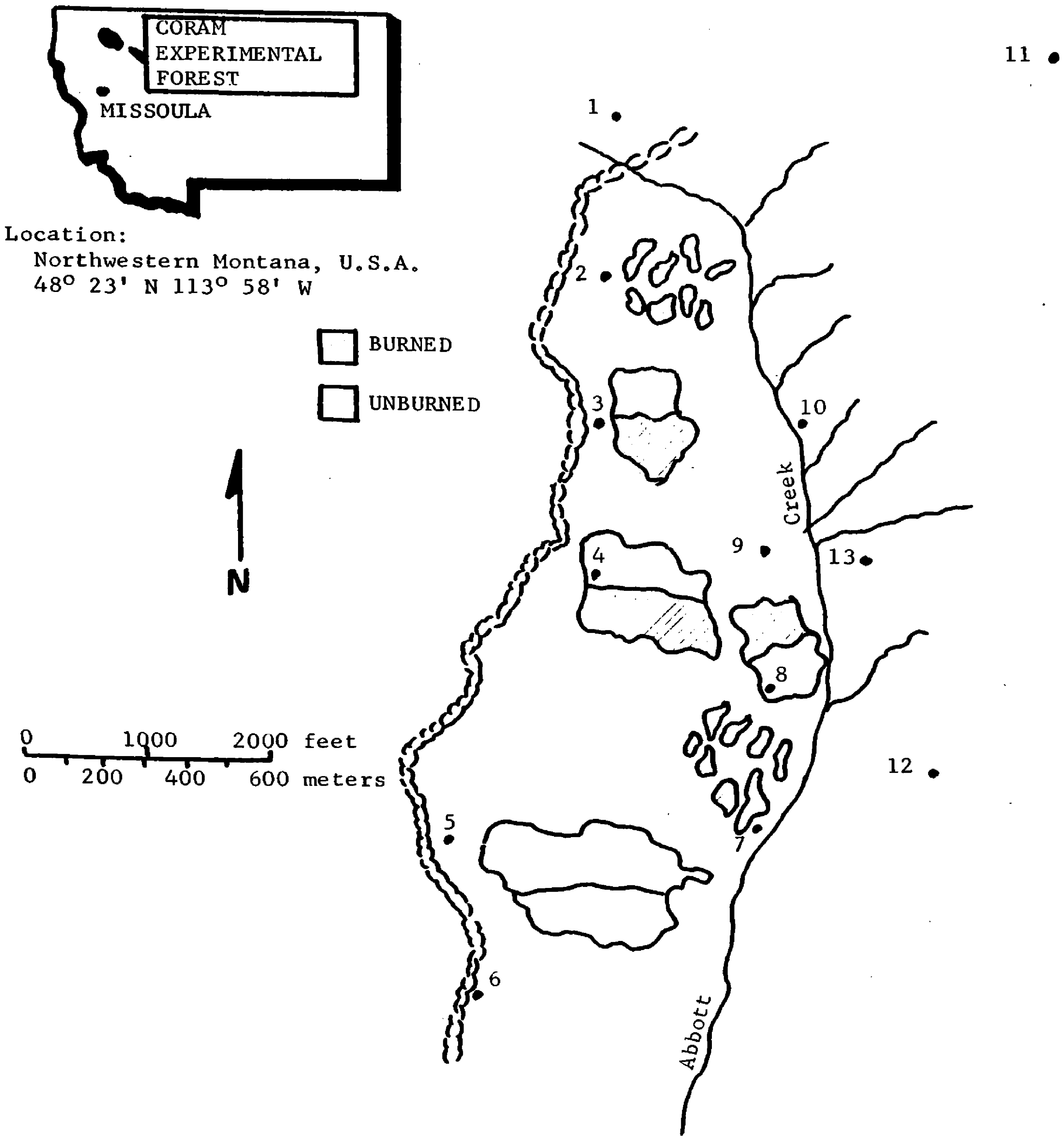


Figure 4

Study Area with Observation Sites Noted

bottom of the major drainage (Abbot Creek) varies from 4,700 feet (1,433 m) on the north to 3,900 feet (1,189 m) on the south. The highest point in the immediate area is Desert Mountain, elevation 6,436 feet (1,962 m), approximately 1½ miles (2½ km) north-northeast of the study site.

Chapter 5

METHODS

Verification Data

Data for verification and validation was collected at established observation sites during the period when prescribed burning took place. The study area was sectioned using a one quarter-mile (0.4 km) grid. Thirteen observation sites were selected at locations chosen to give a representative sample of data through a variety of exposures (see Figure 5), and to coincide as closely as possible with existing grid points. Considerations of accessibility were a major factor in site selection due to the limitations of manpower and equipment. However, care was taken so as not to knowingly create any bias in the verification data due to unique site characteristics. Appendix 3 gives a point-by-point description of the observation sites. Observation of meteorological elements were taken at least hourly from midday through the period of active burning each day. Temperature and humidity data were collected using sling psychrometers. Wind speed was taken with hand-held anemometers and wind direction determined with a compass.

Temperatures were observed to the nearest $\frac{1}{2}^{\circ}$F. Wind speeds were recorded as two-minute averages, and directions estimated to the nearest point on a 16-point compass, i.e., north, north-northeast, northeast, east-northeast, etc.

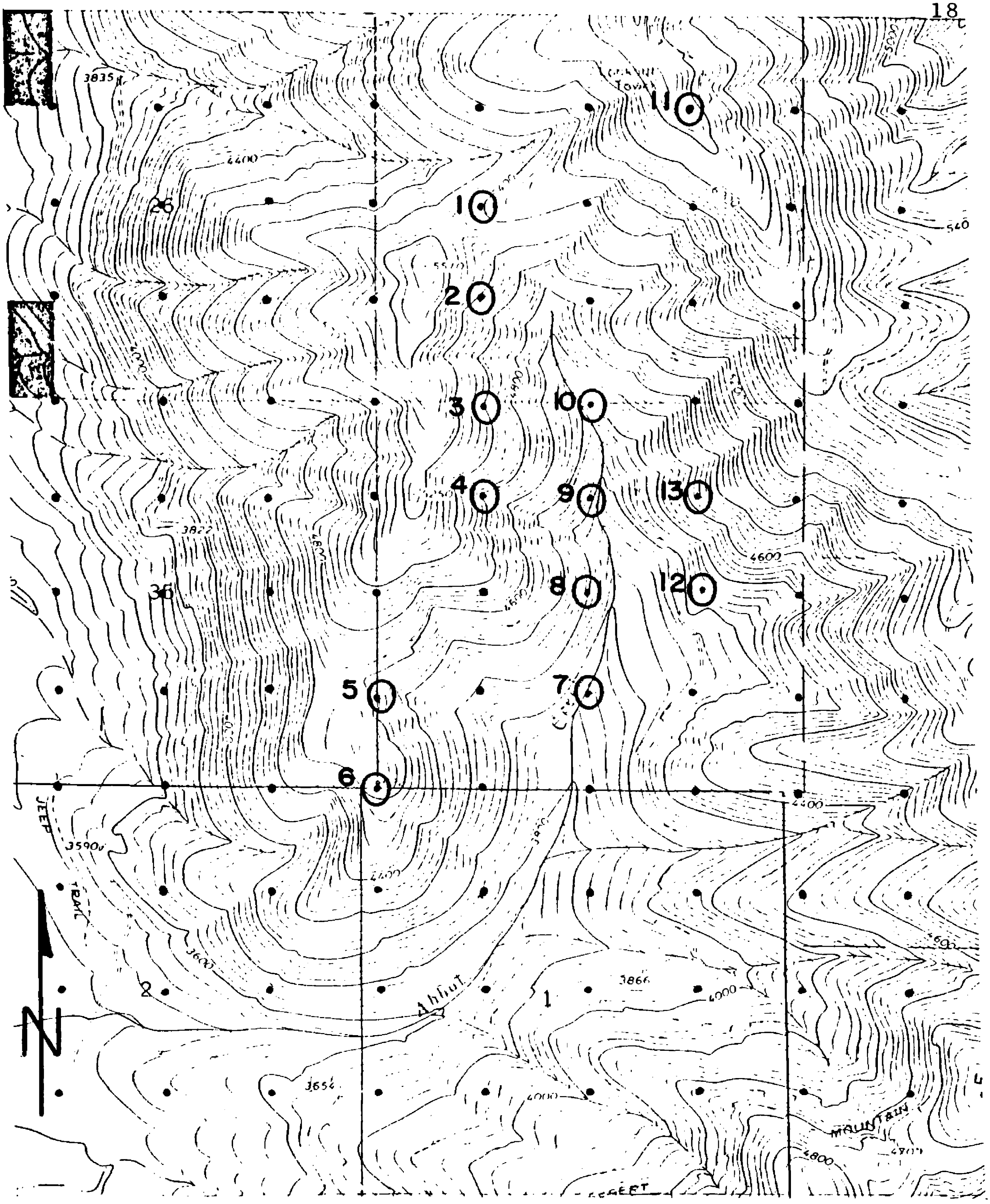


Figure 5

Observation Sites (Numbered) and Grid Points

Observations of the meteorological elements (wind speed and direction, temperature, and humidity) were collected for the thirteen observation sites by four separate observers. All of the observers received instructions on the proper techniques of observing and recording the data. There was an average of five observations taken at each site on every one of the six project days. In order to use the data for verification purposes, each of the elements had to be individually averaged for each site on each day. Wind speed was averaged over the period of observation, but emphasis was placed on those observations taken during the period of the afternoon when convective mixing was the greatest. Wind directions and temperatures were similarly recorded and weighted.

Since wind measurements were taken at eye level, or approximately 4.5 feet (1.4 m), it was necessary to adjust these readings to a standard exposure height. This was necessary to verify the WINDS MODEL forecast because this is the level of the MODEL forecasts. Since observations sites varied from nearly open to closed-dense timber stands, the height adjustments to reach the 20-foot (6-meter) standard level were necessarily variable. The technique used to adjust the wind readings is outlined in Appendix 2. A summary of the observed and the observed-adjusted data used for verification is found in Appendices 4 and 5.

A portable radiosonde unit was used to take atmospheric soundings of temperature, moisture, and winds during the early morning of each burning day. The runs were taken to a minimum of 400 millibars (about 24,000 feet, 7.3 km). This radiosonde unit was located at the

Coram Work Center approximately two miles (3.3 km) west of the study area, and the soundings were taken from this site (Figures 6 and 7).

Pilot balloon observations (PIBALS) were taken in conjunction with the daily radiosonde runs. This was done so that upper air wind data through the lower 12,000 feet (3.7 km) of the atmosphere would be available for planning, daily forecasting, and preliminary input data for WINDS MODEL calculations.

Data was also drawn from the National Weather Service regular network of surface and upper air observations. This network provided cross reference for observed surface data. Further, the upper air soundings from Great Falls, Montana and Spokane, Washington were used to make first estimates of potential temperature, stability, and upper level winds. These parameters were used for initial inputs during the operational feasibility portion of the study.

Time lapse cameras were located at preselected points to observe fire characteristics as well as smoke column development and behavior. Winds estimated from smoke column behavior were useful in evaluating actual free air winds during the burning periods.

Information and data for real time forecasts was secured through communications and neteorological monitoring equipment contained in a "Fire Weather Mobile Unit" (Figure 8). This unit was located at the Coram Work Center and included:

1. Surface winds equipment (speed and direction).
2. Hygrothermograph (temperature and humidity).
3. Single sideband radio (voice and data link).
4. Radio facsimile receiver (weather maps and charts).

Figure 6

Radiosonde Monitoring Unit

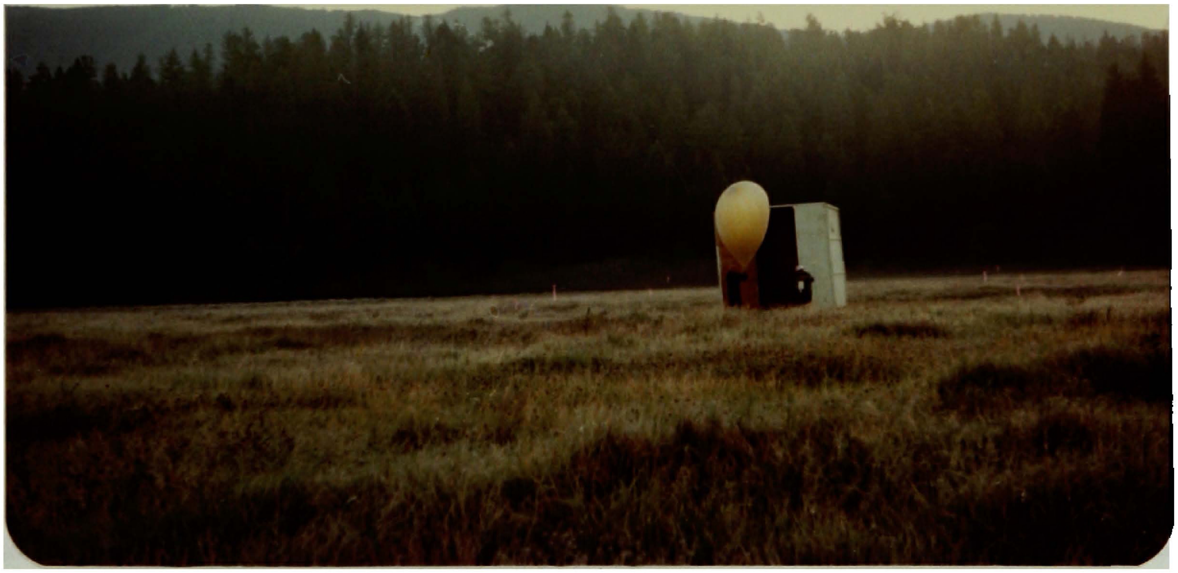


Figure 7

Radiosonde Release

Figure 8

Mobile Weather Unit

WINDS MODEL Forecasts

Data from the WINDS MODEL was collected in two separate sequences. The first set of data was not intended for MODEL validation, but rather to see if all of the necessary inputs could be collected and run in a real time situation. Figure 9 is a data flow chart depicting the sequence of data collection in the field, its relay to the computer hardware, and return to the field. Inputs for this run were preloaded as much as possible with all constant parameters (i.e., elevations of grid points, roughness lengths, latitude, etc.).

After returning from the field, reduction, refinement, and manipulation of input parameters was begun. The radiosonde runs taken at Coram were reduced utilizing a program on hand at the Northern Forest Fire Lab, Missoula.

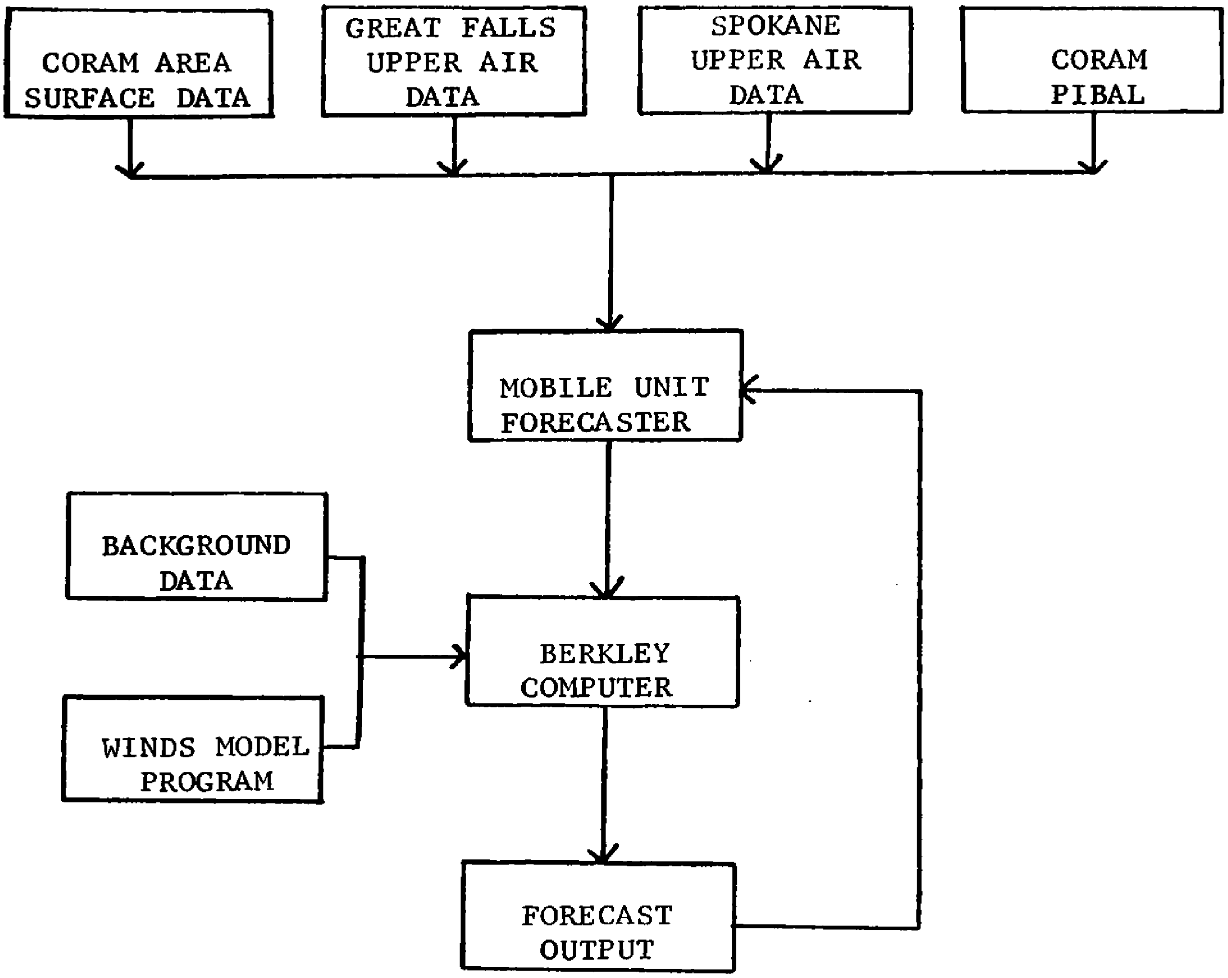


Figure 9

Data Flow Chart for WINDS MODEL
Field Evaluation

The input parameters for the initial WINDS MODEL calculations were derived by examining the upper air soundings from Spokane, Washington and Great Falls, Montana. By airmass comparisons and existing weather conditions, estimates for the local environmental lapse rates, winds, and the temperature field could be made. After the Coram soundings were reduced, the following were noted:

1. The wind fields in the levels from 7,000-10,000 feet MSL were very consistent between Coram Radiosonde, Coram PIBAL and the two soundings from Spokane and Great Falls. The 6,000-foot and below winds

were not consistent, as expected, due to terrain influence.

2. The temperature fields above 850 mb in the three soundings were reasonably consistent.

3. The stability parameters computed were somewhat variable. This can be explained through examination of the calculation process. The height and temperature of the 850 mb surface is one of the prime inputs. This level is very near the surface at Coram and reasonably close at Great Falls. There was a fairly wide variance in the values for this level, which explains the difference in the calculated stability parameter. For the final MODEL calculation the stability data determined from the CORAM soundings was used.

Grid Spacings

In order to use the WINDS MODEL at any location, the underlying terrain must be described. This is done by superimposing a grid over the terrain and reading off elevations at each grid point. Fosberg recommends grid spacing of one Km (0.6-mile) or greater, tied of course to the complexity and relief variations in the terrain. Fosberg suggests that 500 m (0.3-mile) is probably the minimum grid spacing the MODEL will handle properly. Upon examination of the terrain of the Coram Experiemental Forest it was found that the one Km (0.6-mile) grid spacing would not adequately describe the topography of this area. Since one of the prime objectives was to describe wind fields in this complex terrain, it was determined that smaller grid intervals would be used even though it would be forcing the MODEL. Consequently, a grid interval of one quarter-mile (402 m) was established. No evaluations were made at any greater grid intervals since it would not meet with the overall objectives.

Level Selections

The selection of the MODEL input levels was guided by recommendations from Fosberg, and by trial and error. Fosberg suggests that the top of the "rigid lid" should normally be expected to be 1,500-2,000 m (5,000-6,500 feet) above the smoothed terrain. This was accepted and used. The "shallow layer" was suggested as 1.25 times the difference between the smoothed and actual terrain. This was also accepted. The reference wind levels were picked through trial and error. Any winds from the 8,000-foot (2,438 m) MSL level and above gave wind fields that were consistently too strong. Winds below 6,000 feet (1,828 m) were too close to the actual terrain influences and gave inconsistent results. The 6,000 and 7,000 feet (1,828 and 2,133 m) MSL levels gave the most consistently accurate results so further investigations were limited to those levels.

In order to gain more experience with the WINDS MODEL two other areas were selected and MODEL forecasts run. One of these areas was McCauley Butte on the southwest edge of Missoula, and the other was along the east slopes of the Continental Divide near Helena, Montana. Results from these runs were consistent with those found with the Coram data.

Data output from MODEL calculations came in the form of a computer printout with wind speeds in meters per second. In order to more fully utilize the outputs, selected points were plotted on a topographic map and wind fields analyzed with streamline techniques

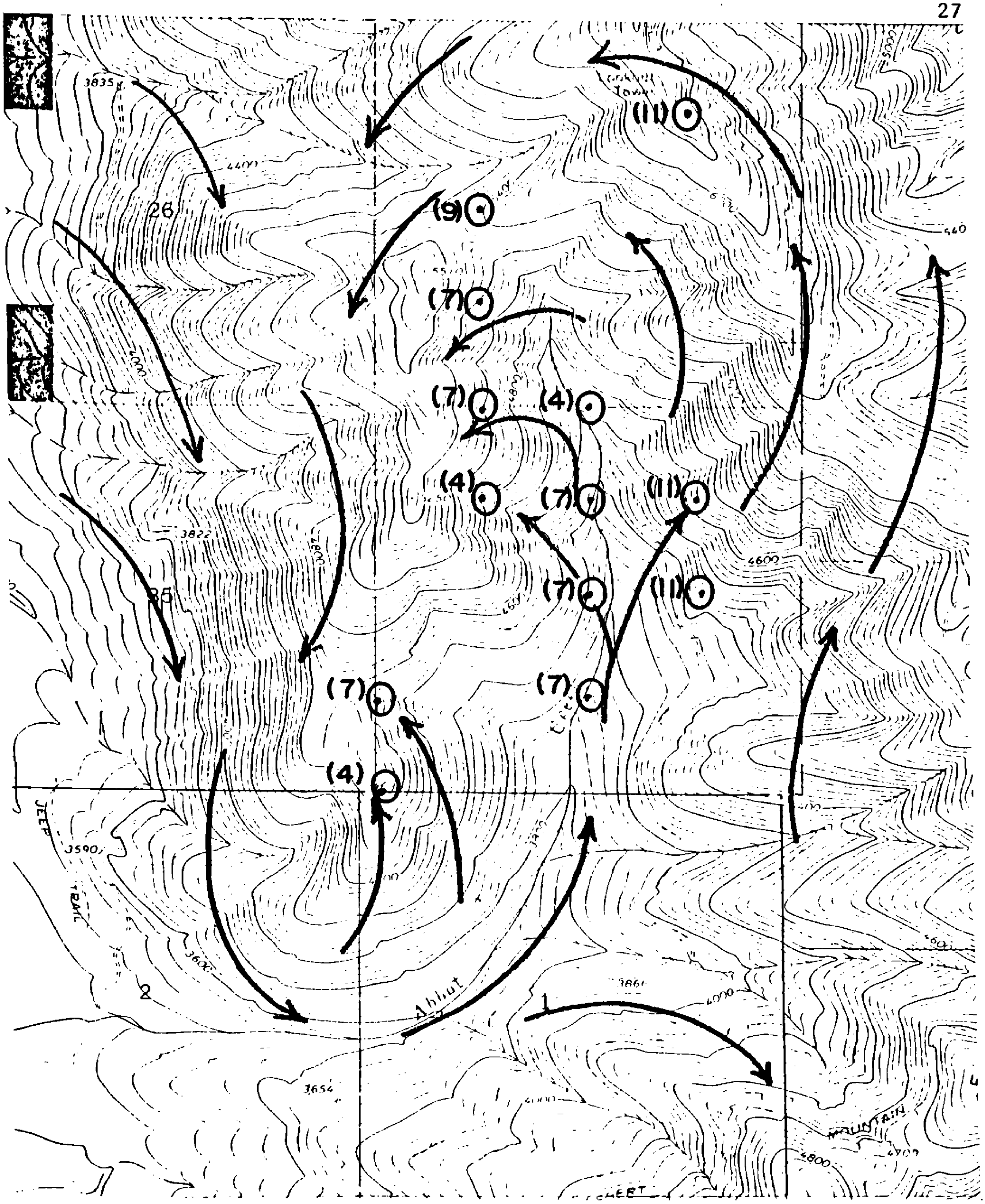
(Figure 10). Wind speed values were converted to miles per hour since these are the units used in the standard fire behavior predictions system.

Standard Forecasts

The National Weather Service Fire Weather Forecast Branch has the responsibility for providing specialized forecasts to all land management agencies in the United States. To provide this service, specially trained meteorologists are stationed throughout the country. These meteorologists are specialists in mountain meteorology and microscale forecasting. Although forecasting is considered a science, wide variations in forecasts and forecasters can be attributed to experience primarily, however forecasting is recognized as being nearly as much an art as it is a science. The author is one of these National Weather Service Fire Weather Forecasters and was responsible for the forecasts generated for the Coram project. The forecasts were prepared as objectively and scientifically as possible with no emphasis or thought given to trying to "beat" the MODEL.

The forecasts prepared followed the standard format for specialized fire weather products. Forecasts for prescribed fire situations normally show a shift in emphasis toward the critical burning parameters and special emphasis is placed on temperature and winds at planned time of ignition.

The forecasts for the local winds were prepared by considering a variety of data. Winds in the lower levels of the atmosphere as recorded on the morning PIBAL run and stability as calculated from mountain-valley wind regime all were prime inputs to the forecasts. A



Key

Figure 10

↗ Wind Direction
⊙ Observation Site   WINDS MODEL Output - 9/10/75
( ) Wind Speed (mph)

sample forecast is shown on the following two pages.

On the ground examination of the microsite conditions helped familiarize the meteorologist with physical characteristics that could have an effect on the wind regime. The daily record of observations from each site was examined as persistence had been found to be an extremely good guide in many cases.

Equipment in the Weather Mobile Unit provided complete forecast guidance information in the form of prognostic weather charts and interpretive discussions from the state and national forecast offices. All of this data was compiled and integrated with the forecasters personal experience to produce the daily forecasts. It is recognized that the information provided by these techniques is somewhat individualized. However, basic dynamical and physical processes were considered in producing every forecast. These forecasts were later checked by other qualified forecasters and no significant or unreasonable bias was discovered. Therefore, it was felt that these forecasts were justified as "Standard Forecasts," logically prepared and on par with what could normally be expected.

NOAA Weather Service
FCSTR: Dave Goens
Mont. State Mobile Unit
At Coram Work Center

Sep. 10, 1975
Forecast #3
Coram Exp. Burns
Released at 0930MDT

Discussion...

Cold air is plunging southward into eastern Montana today. This is in response to the upper ridge pushing north into the Gulf of Alaska, allowing the colder Canadian air to move southward with the northerly flow aloft. The airmass continues quite dry, so precipitation risk remains negligible. As the cold air drives the pressures up today in Eastern Montana, there will be some spilling of the cooler air into Western Montana tonight and Thursday. Cooler temperatures and an increase in winds are in the offing...Our problem is, how much wind...

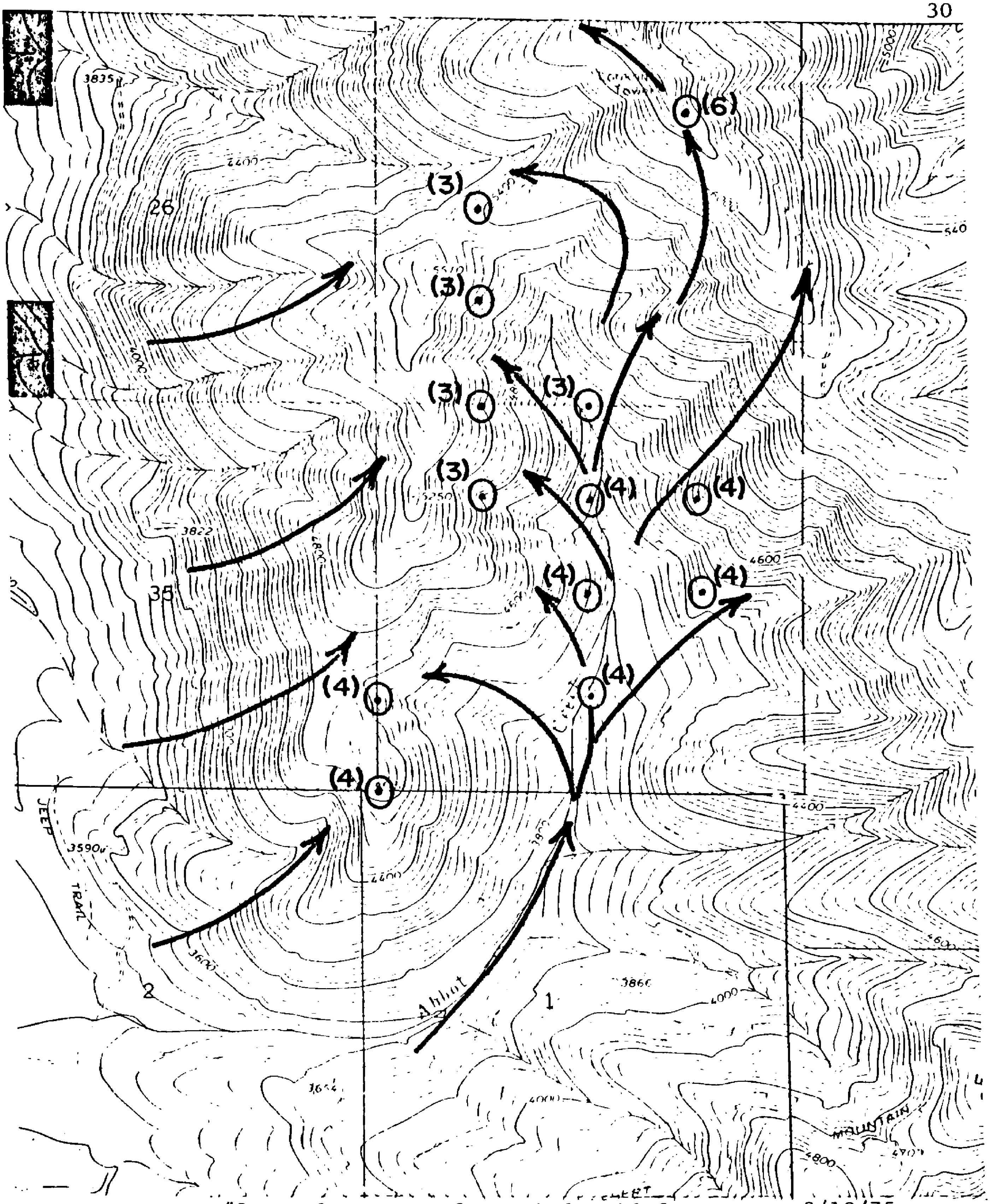
Today... Sunny and warm. Max temp at burn site 73, Min humidity 35%...Winds light upslope 3-6MPH till 1600, then light downslope. See Forecast supplement for more detailed wind forecast.

Tonight... Fair and cool. Good humidity recovery. Winds generally light, except chance of increasing ridgetop winds by sunrise ...These winds will be northerly to northeasterly 5-15MPH.

Thursday...Cooler with max temp near 62, humidities a little higher. Winds in the free air above the ridgetops north to northeasterly 10-15MPH. On the surface at the head of the Abbot Creek drainage the wind will be variable in direction with max speed 10-15MPH. Lower in the drainage they will be lighter...8-12MPH mostly upslope during the afternoon.

Ventilation will be good today, poor again this evening.

Outlook for Friday and Saturday...Cool and dry with decreasing winds.



Forecast #3 Supplement Surface Winds Midafternoon - 9/10/75

Key
↗ Wind Direction
⊙ Observation Site
() Wind Speed (mph)

Chapter 6

DATA EVALUATION

Limits of Accuracy

In this section the accuracy of the forecasts generated both by the model and standard techniques will be discussed. Before proceeding it appears necessary to define limits of accuracy by which outputs will be evaluated.

Since the concentration of concern in this work is the prediction of winds for use in fire control and management then the limits of error in forecasting should be governed by consideration of wind generated fire behavior characteristics. Specifically, how does the speed and direction of wind influence the character of fire spread? How much error is too much? First of all the impact of directional error will be discussed.

Since fire will normally spread in the direction the wind is blowing it is imperative that this direction be known. An error in direction as little as 90 degrees can be critical regarding safety of line personnel and placement of resources. In prescribed fire, an error of as little as 30 degrees can mean that the fire has escaped prescription. Personnel on the ground can normally check the forecast based on what is observed, but in the pre-planning process this modification can not always be anticipated. Therefore in this study the error in the direction parameter is considered critical when it exceeds three compass points (16-point compass). This value represents an error of 67.5 degrees. This is more than is usually permissable in "real world" situations, but allows for some on site adjustments.

Wind speed is extremely critical in the behavior of fire, especially as far as fire intensity and rate of spread are concerned. This can be seen quite readily by looking at the effects of winds of different velocity in a given fire situation. Albini (1976) outlines a technique for predicting fire spread and intensity. Using this technique it can be illustrated that a change in the wind speed of three to six mph in a constant fuel/topography situation can result in a change in rate of spread on the order of 250 percent and burning intensity of over 300 percent. Based on a series of calculations of this nature, it was decided that an error of three to six mph would be critical for wind speed predictions.

Accuracy of WINDS MODEL

Daily WIND MODEL forecasts for both Run #1 and Run #2 show a high degree of variability. Results of both runs were tabulated and a summary can be found in Table 1. A more complete listing of WINDS MODEL forecast for all observation sites can be found in Appendix 4. To more completely understand the MODEL forecasts it is necessary to look not only at averaged error but also at some of the specific daily point forecasts. This first section will deal with numerical verification, and in a later section some interpretative verification of specific daily forecasts will be discussed.

Run #1. Primary input wind for Run #1 was taken from the 6,000-foot (1,829 m) level. Other input data were held constant as noted previously.

Adjusted observed winds show a wide range from calm upwards to nearly 20 mph (9 mps). For all 13 sites on all six days only 18 percent of the WINDS MODEL forecasts fell into the three mph or less "Hit" category, and 32 percent fell into the six mph or less category.

The MODEL results show a positive bias on five of the six days. In other words, the MODEL forecast winds that were too strong those five days - on the other day, there was a negative bias.

Wind direction MODEL forecasts were accurate to within three compass points or less nearly 63 percent of the time. Three of the six days show very good accuracy (82 percent) while the other three are relatively poor.

Run #2. Primary input wind for Run #2 was taken from the 7,000-foot (2,134 m) level with other input values held constant as before.

The accuracy of Run #2 was again compared with the control data, that is the adjusted observed wind data. For all sites on all days MODEL speed outputs fell into the three mph or less category only 22 percent of the time; into the six mph or less category 39 percent of the time.

The MODEL again consistently over forecast wind speeds. On five of the six days a positive bias was observed, while on the other day the bias was negative. On one of the days that the MODEL grossly over forecast the wind, a weather pattern produced some erratic burning

Table 1

MODEL Forecasts

Run #1

Day	Wind H	Speed M	Error* B	Wind H	Direction Error* B
1	1	3	9	10	3
2	4	1	8	6	7
3	7	4	2	5	8
4	0	0	11	6	5
5	0	1	10	9	0
6	1	1	9	8	3
	13	10	49	44	26

% H = 18%
% H+M = 32%
% M = 68%

%H = 63%

Run #2

Day	Wind H	Speed M	Error* B	Wind H	Direction Error* B
1	0	0	13	8	3
2	4	4	5	7	5
3	3	0	10	9	5
4	0	0	11	7	4
5	4	4	3	9	3
6	5	4	2	9	2
	16	12	44	49	22

% H = 22%
% H+M = 39%
% B = 61%

% H = 69%

* H = Hit, wind speed error zero to three mph, direction error less than or equal to three compass points.

M = Marginal hit, wind speed error four to six mph.

B = Bust, wind speed error greater than six mph, direction error greater than three compass points.

conditions which will be discussed in more detail in the last section of this chapter.

Wind direction MODEL forecasts were accurate to within three compass points 69 percent of the time. Once again, on three of the days direction forecasts were reasonably good.

Accuracy of Standard Forecasts

Standard technique forecasts were issued twice daily. The primary forecast was issued in the morning between 0900 MDT and 0930 MDT. An example of this forecast is found in the previous chapter (pages 29 and 30). In general the standard forecast shows more consistancy. Forecasts were made for a midflame height, or approximately four feet (1.2 m). This was done because the wind observations were being taken at that height. In addition, the fire prescription called for low intensity burns, confined beneath the canopy in the shelterwoods, and to flame lengths less than eight feet in the clearcuts. This allowed midflame height winds to be around the four-foot level. Verification was thereby simplified since the winds did not have to be resolved through the canopy.

Standard forecasts were accurate to within three mph 81 percent of the time and were accurate to within six mph 99 percent of the time. The overall bias was positive as forecast wind speeds were consistently slightly higher than the actual wind speeds observed.

Wind direction forecasts were also quite good. Wind directions were forecast to within three compass points 93 percent of the time. The last three days verification show that wind directions were forecast correct to within three compass points 100 percent of the time and this is a trend that should normally be expected. As a forecaster becomes familiar with a given area and the behavior of the local wind regime, wind direction forecasts should become better.

A summary of verification results for standard forecasts is shown in Table 2, and complete verification results are shown in Appendix 5.

Table 2

Standard Forecasts

Day	Wind H	Speed M	Error B	Direction H	Error M
1	10	3	0	9	2
2	11	2	0	10	2
3	13	0	0	12	1
4	7	3	1	11	0
5	8	3	0	9	0
6	9	2	0	11	0

% H = 81% % H = 93%

% (H+M) - 99%

% B = 1%

Discussion of WINDS MODEL Versus Standard Forecasts

In the prediction of fire behavior it becomes necessary for someone to interpret the elements of the forecast. If the forecast comes in the form of a computer printout, that data must be transferred to a more usable format. In the case of the WINDS MODEL output, the data was plotted on a topographic background map.

In plotting the WINDS MODEL data some very interesting results were noted. In cases where upper level winds were light, less than seven mph (3 mps), forecast speeds and directions were quite reasonable. The resultant wind fields conformed well with expected upslope/downslope regimes and speeds were within acceptable limits. A plotted MODEL forecast wind field with a streamline analysis is shown in Figure 10.

Whenever upper level winds became stronger and exceeded nine mph (4 mps) the results from the WINDS MODEL became suspect and verification was poor. In a majority of cases, the surface level winds were forecast to be much stronger than observed, but just as seriously, the direction component was predominately the same as that of the upper flow. Since this was contrary to what was observed, the implications for fire management and/or control are potentially grave. Had this been an active "going" fire situation and this forecast used to position manpower and resources, the potential for serious loss would be great.

The handling of the worst case situation by the model led to further questioning of the reliability of the system. On that day, September 11th, the weather pattern changed. A frontal system moved through the project area from the northeast, upper level winds shifted from the northwest to easterly, and the lower levels of the atmosphere became quite unstable. In this situation, the model magnified the upper level winds and forced them downward into the narrow drainages and totally overpowered the slope wind effect. This was totally contrary to what was actually observed and forecast speeds at all elevations were unrealistically strong.

Inherent in this model is the assumption that advection terms are ignored. This means that all elements considered in calculations are confined within the model boundaries, and anything outside those finite boundaries is ignored. This implies that the MODEL should handle steady state conditions best, and that outputs near the upstream boundary are necessarily questionable. A serious deficiency in this situation is that any movement of weather systems (fronts, squall lines, etc.) outside the model boundaries are not considered. In the Northern Rocky Mountains, fast moving systems are common during the normal fire season, and many times are responsible for major conflagrations. It would seem reasonable to expect a dependable forecast scheme to have the capability to predict at least some potential for longer range effects. However, it appears this particular model is deficient in this regard.

Forecasts generated by the on-site meteorologist were significantly more useful than the model forecasts. The winds were forecast not only in the general sense but were tailored for specific sites and times. A forecast wind flow chart was prepared daily to give fire management officials a more specific picture of expected micro-scale winds. This chart proved quite useful in preparing detailed fire behavior predictions and helped later during the verification process. On the worst case day (September 11th), the standard forecast also had its worst day for verification purposes. The wind speeds were over-forecast, although not nearly as badly as the MODEL (64 percent hit versus 0 percent), but direction forecasts verified 100 percent (versus

60 percent for the MODEL).

In summary, it seems that the WINDS MODEL predictions were most accurate in noncritical, light winds situations that required a minimum of interpretation. Standard forecast had greater flexibility and tended to handle the full spectrum of situations with greater reliability.

Chapter 7

CONCLUSIONS

In summarizing the results of this study, the objectives will be reviewed and specific conclusions drawn.

Objective 1

Wind flow patterns in complex, forested terrain environments are controlled by many variables. Wind patterns can be generalized into slope and valley winds and effects of terrain such as channeling and blocking can be identified. Microsite influences are sometimes difficult to predict and can best be determined by on-site observations. Specific flow patterns in most situations are adequately described in the literature.

Forecast schemes for predicting wind patterns in these areas are limited. Generalized forecasts for the free air above the frictional influence of the terrain are available regularly by computer generated products. Wind flow patterns within the friction layer are dependent on data availability and individual forecaster experience.

Objective 2

This study demonstrated that it is possible to use a computer generated forecast model in a real time operational situation. It became apparent that for a MODEL as complicated as the one evaluated to be useful the inputs would have to be preloaded and ready before the operational situation occurred. The input data is very detailed and describes some very complex atmospheric interactions. The user must have a broad scientific background with some specific working knowledge of forestry, mathematics, and meteorology to adequately handle all input variables. People with this type of knowledge are not normally found in the field as working resource managers. This means that the usefulness of the MODEL is probably limited, and its applicability in the average fire situation is not realistic at this time.

Objective 3

Although the WINDS MODEL appears to have promise in certain terrain situations, its usefulness in complex terrain situations is in doubt.

Through trial and error and judicious selection of input data, the WINDS MODEL can produce forecasts, but of only marginally acceptable accuracy. It was found that it could not consistantly produce accurate forecasts in all situations (variable meteorological conditions). It was found that the inputs could be standardized if meteorological elements were stagnant. In changing weather conditions the MODEL performed poorly. It was felt that this was probably due to boundary conditions and the grid spacing. The MODEL was asked to perform in a resolution mode that was near its limit. However, this resolution (¼-mile grid) is required to adequately describe many complex terrain situations.

Smoke generated by the Coram fires dispersed well. Most fires burned actively with a well developed convective column which carried the smoke upward into the free air flow. Residual smoke was minimal and behaved as expected, flowing downslope/downcanyon in the late afternoon and into the night. The WINDS MODEL forecast for the afternoon was unusable for smoke movement since most smoke was carried aloft above surface wind influence. The late afternoon WINDS MODEL forecast indicated normal downslope/downcanyon flow and the smoke moved accordingly. Although the MODEL was accurate in this sense, it was of limited usefulness since this movement was easily predicted by standard techniques and/or local experience.

Chapter 8

SUMMARY

The forecasting of wind flow patterns in forest environments remains a difficult problem. Great strides in computer modeling of wind fields have been made in the past few years. These models do a good job in certain terrain situations, and poorly in others. It is necessary to recognize the limitations of these systems and not expect a specific model to perform beyond its capabilities.

It appears as if the on-site meteorologist can consistently produce a better site specific forecast at this time. His value is further enhanced when his interpretive capabilities are considered.

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APPENDIX 1

The Fosberg WINDS MODEL

Structure

The Fosberg WINDS MODEL was derived through a simplification of the fundamental Navier-Stokes flow equation. The simplification resulted in a one-layer model of atmospheric boundary layer flow, and its development was directed for use in complex terrain. In general, the model is based on terrain induced flow, thermally induced flow, and frictionally induced flow.

In the development of the model, advection terms were neglected. This greatly simplifies the mathematics, but a complete description of the dynamical processes is lost. The terrain, thermally and frictionally induced flow were superimposed on a background flow across the computational boundaries. Each of these disturbances were assumed to take place only within the computational area and were allowed to act only over a small finite time interval. Flow following the ground surface was obtained by a coordinate transform. A rigid upper surface above the terrain was assumed in order to define the top of the atmospheric slab.

Procedures for solution of the equations involve serial approximations which superimpose a new physical effect on the previous solution. The first step in the solution was to transfer the large scale background wind into a terrain-induced modification of the throughflow. This step provided a local throughflow wind. Next, thermal and frictional modifications of the vorticity and divergence were introduced. These changes were superimposed on the terrain induced flow. Finally, stream functions and velocity potentials were calculated so that wind speed and direction could be defined at all interior points.

Data Required

The study area must be described by a grid point system. The grid scale may be varied with minimum desirable grid spacing of 500 meters. For each computational or grid point, the model requires temperature, pressure, elevation, and roughness length. Several single valued coefficients are required to complete the model. Most important are the static stability and the large scale wind speed and direction. Less important coefficients are the eddy viscosity, the latitude, and the large scale vorticity if strong curvature exists in the large scale flow pattern.

Output from the model is simply a vector wind (speed and direction) at the six-meter height above the roughness length parameter for each computational grid point.

APPENDIX 2

Albini and Baughman Wind Reduction Procedure

Midflame Wind

Midflame wind speed is estimated from the 20-foot wind, the nature of the canopy or lack of one, and the topography. The accompanying wind reduction table (20' wind speed to midflame wind speed) is provided for this purpose.

Wind flowing near the ground is slowed by friction caused by roughness of the surface. The nature of the wind reduction has been studied for many years. Frank Albini and Bob Baughman at the Northern Forest Fire Laboratory have developed a method of estimating the midflame wind speed based on the depth of the fuel bed and whether or not there is a canopy sheltering the fuel. In general, fuels without an overstory canopy can be considered exposed. Fuels beneath a canopy may still be considered exposed if the force of the wind can penetrate the canopy from an edge rather than as a result of wind shear from above the canopy. If the needles of the canopy have been burned away by a crown fire, this can change a sheltered situation into an exposed one. Hardwood standard with fallen leaves should be considered to have exposed surface fuels.

Exposed fuels. Use the upper portion of wind reduction table to determine the midflame wind.

Sheltered fuels:

1. Daytime or heating conditions use the lower portion of the wind reduction table to determine the midflame wind speed.

2. Nighttime or cooling conditions for fuels sheltered from the wind.

a. Use the lower portion of the wind reduction table to determine the midflame wind speed expected from the 20-foot general wind component.

b. Combine this midflame value with the downslope midflame value. If they are both in the same direction, add them together. If the general wind component is upslope, take the difference between them.

Thunderstorms

If thunderstorms are forecast with an expected wind speed, different procedures will have to be used for estimating midflame wind speed. The direction of thunderstorm winds is very unpredictable. An estimate of their effect upon rate of spread and intensity can be made, but reliable predictions of fire growth is probably not possible. Strong winds are caused by downdrafts that strike the earth, turn and travel sideways.

Estimate the midflame wind speed as the average value between the forecast speed and the midflame value from the upper portion of the wind reduction table.

Example. If winds of 25 to 30 mph are forecast, the upper table for fuel Model 2 gives 10 mph. The average between 10 and 25 to 30 is about 18 mph. The expected time that these winds will last is generally short. Use local experience to make that estimate.

WIND REDUCTION TABLE

(20' Wind Speed to Midflame Wind Speed)

<table>
<tr><td colspan="10">Fuels under sparse trees or timber fuels directly exposed to wind; include thermal winds in 20 ft. estimate.</td></tr>
<tr><td colspan="2">20-ft. wind =</td><td>0-3</td><td>4-7</td><td>8-12</td><td>13-18</td><td>19-24</td><td>25-31</td><td>32-38</td><td>40 up</td></tr>
<tr><td colspan="2">Fuel Model</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">1</td><td>1</td><td>2</td><td>4</td><td>6</td><td>8</td><td>10</td><td>13</td><td>16</td></tr>
<tr><td colspan="2">*2</td><td>1</td><td>2</td><td>4</td><td>6</td><td>8</td><td>10</td><td>13</td><td>16</td></tr>
<tr><td colspan="2">3</td><td>1</td><td>2</td><td>4</td><td>7</td><td>10</td><td>12</td><td>15</td><td>19</td></tr>
<tr><td colspan="2">4</td><td>1</td><td>3</td><td>6</td><td>8</td><td>12</td><td>15</td><td>19</td><td>24</td></tr>
<tr><td colspan="2">5</td><td>1</td><td>2</td><td>4</td><td>6</td><td>9</td><td>12</td><td>15</td><td>18</td></tr>
<tr><td colspan="2">6</td><td>1</td><td>2</td><td>4</td><td>7</td><td>10</td><td>12</td><td>15</td><td>19</td></tr>
<tr><td colspan="2">*7</td><td>1</td><td>2</td><td>4</td><td>7</td><td>10</td><td>12</td><td>15</td><td>19</td></tr>
<tr><td colspan="2">*8</td><td>1</td><td>2</td><td>4</td><td>6</td><td>8</td><td>10</td><td>13</td><td>16</td></tr>
<tr><td colspan="2">*9</td><td>1</td><td>2</td><td>4</td><td>6</td><td>8</td><td>10</td><td>13</td><td>16</td></tr>
<tr><td colspan="2">*10</td><td>1</td><td>2</td><td>4</td><td>6</td><td>8</td><td>10</td><td>13</td><td>16</td></tr>
<tr><td colspan="2">11</td><td>1</td><td>2</td><td>4</td><td>6</td><td>8</td><td>10</td><td>13</td><td>16</td></tr>
<tr><td colspan="2">12</td><td>1</td><td>2</td><td>4</td><td>7</td><td>9</td><td>12</td><td>15</td><td>18</td></tr>
<tr><td colspan="2">13</td><td>1</td><td>2</td><td>5</td><td>7</td><td>10</td><td>13</td><td>16</td><td>20</td></tr>
<tr><td colspan="10">*Fuels often sheltered from wind by canopy cover. Downslope winds beneath canopy must be superimposed upon midflame wind speeds given below.</td></tr>
<tr><td rowspan="2">Shade Intolerant</td><td>Open</td><td>.5</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td></tr>
<tr><td>Dense</td><td>.5</td><td>1</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td></tr>
<tr><td rowspan="2">Shade Tolerant</td><td>Open</td><td>.5</td><td>1</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td></tr>
<tr><td>Dense</td><td>0</td><td>0</td><td>1</td><td>1</td><td>2</td><td>2</td><td>3</td><td>3</td></tr>
</table>

<u>Note</u>: Fuel models 8 and 10 were used for wind reductions when necessary for this study.

APPENDIX 3

Observation Site Descriptions

Site 1. Northwest exposure - in a NW-SE saddle - dense timber - closed canopy.

Site 2. East to southeast exposure - upper one third of slope - semi-open - small clearcuts below - dense timber above.

Site 3. East exposure - upper one third of slope semi-open - clearcut below - dense timber above.

Site 4. East to southeast exposure - upper one third of slope - in the timber - shelterwood cut below - dense timber above.

Site 5. East to northeast exposure - near top of ridge in a saddle - in the timber - shelterwood cut below - dense timber above.

Site 6. Southwest to southeast exposure - moderately dense timber - canopy semi-open.

Site 7. South to southeast exposure - lower one third of slope - semi-open on the edge of a small clearcut with dense timber all sides.

Site 8. East exposure - lower one third of slope - semi-open - clearcut below - dense timber above.

Site 9. Southeast exposure - lower one third of slope - small opening in dense timber.

Site 10. South to southwest exposure - drainage bottom - dense timber - closed canopy.

Site 11. Southwest exposure - top of ridge - semi-open - scattered timber and brush.

Site 12. Southwest exposure - lower one third of slope - semi-open - old brushy clearcut above - dense timber below.

Site 13. Southwest exposure - lower one third of slope - small opening along road in dense timber.

APPENDIX 4

WINDS MODEL Verification

This appendix gives the specific verification date for the WINDS MODEL calculations. The heading blocks are defined as follows:

1. Model Wind/mph. This is the model output wind for the nearest grid point to each specific observation site. The units are miles per hour.

2. Observed Wind/mph. This is the average daily wind observed at each of the observation sites at the 4½-foot (1.5 m) level. The units are miles per hour.

3. Adjusted Observed Wind/mph. This is the observed wind, resolved through the canopy to standard height.

4. Difference. This is the difference between Model Wind and Adjusted Observed Wind.

5. Model Direction. This is the wind direction forecast for each observation site.

6. Observed Direction. This is the observed wind direction at each observation site.

7. Difference. This is the difference between the Model Direction and Observed Direction. It is determined by assigning each direction a number based on a 16-point compass, i.e., NNE=1, NE=2, ...S=8,...S=12,...N=16.

Run # 1

Date Site #	Model Wind/mph	Observed Wind/mph	Adjusted Observed Wind/mph	Difference (M-AO)	Model Direction	Observed Direction	Difference
Sept. 8							
1	13	0	3	10	ENE	--	--
2	9	1	8	1	E	SSE	3
3	9	0	2	7	ESE	SE	1
4	7	0	2	5	SE	--	--
5	13	1	3	10	SSE	SW	3
6	13	2	8	10	SSE	SW	3
7	9	2	8	7	SSE	SSE	0
8	11	3	15	7	SSE	SE	1
9	7	3	13	6	SE	ENE	3
10	7	2	13	6	E	ESE	1
11	33	4	10	23	NE	SSW	7
12	11	6	15	-4	SE	SSE	1
13	13	3	13	0	ESE	SSE	2

D ≤ 3 = 1
3 < D ≤ 6 = 3
D > 6 = 9
BIAS POS

Avg D = 2.3
D ≤ 3 = 10

Date Site #	Model Wind/mph	Observed Wind/mph	Adjusted Observed Wind/mph	Difference (M-AO)	Model Direction	Observed Direction	Difference
Sept. 9							
1	29	0	3	26	NNE	--	--
2	18	2	8	10	NNE	SSE	6
3	13	2	8	5	NE	E	2
4	9	2	8	1	ENE	ENE	0
5	13	1	5	8	SE	NE	4
6	15	1	6	9	SE	NE	4
7	15	2	8	7	ESE	SE	1
8	15	2	13	2	ESE	SE	1
9	11	2	8	3	E	SSE	3
10	18	2	15	3	NE	SSE	5
11	57	2	10	47	NE	SW	8
12	20	2	8	12	ESE	SW	5
13	26	3	13	13	E	SSE	3

D ≤ 3 = 4
3 < D ≤ 6 = 1
D > 6 = 8
BIAS POS

Avg D = 3.5
D ≤ 3 = 6

Run # 1

Date Site #	Model Wind/mph	Observed Wind/mph	Adjusted Observed Wind/mph	Difference (M-AO)	Model Direction	Observed Direction	Difference
Sept. 10							
1	9	1	6	3	ENE	N	3
2	7	2	10	-3	ENE	SSE	4
3	7	3	13	-6	ENE	SE	3
4	4	4	10	-6	NE	SE	4
5	7	4	13	-6	ESE	ENE	2
6	4	2	10	-6	SE	WSW	5
7	7	3	10	-3	SW	SE	4
8	7	4	19	-12	SSW	ESE	4
9	7	2	8	-1	SW	SE	4
10	4	1	13	-9	SW	NW	4
11	11	4	10	1	E	WNW	7
12	11	4	13	-2	SSW	SW	1
13	11	3	13	-2	SSW	S	1

$D \leq 3 = 7$
$3 < D \leq 6 = 4$
$D > 6 = 12$
BIAS NEG

Avg $D = 3.5$
$D \leq 3 = 5$

Date Site #	Model Wind/mph	Observed Wind/mph	Adjusted Observed Wind/mph	Difference (M-AO)	Model Direction	Observed Direction	Difference
Sept. 11							
1	127	1	3	104	NE	N	2
2	86	2	8	76	ENE	SSE	4
3	59	3	8	55	ENE	SSE	4
4	46	1	3	39	E	SE	2
5	51	M	-	-	ESE	M	-
6	48	M	-	-	SE	M	-
7	51	3	10	41	ESE	SE	1
8	55	4	15	40	E	ESE	1
9	64	3	13	51	ENE	SE	3
10	95	2	13	82	ENE	SSE	4
11	198	2	6	192	NE	ENE	1
12	90	3	10	80	E	SW	6
13	116	2	10	106	ENE	SSW	6

$D \leq 3 = 0$
$3 < D \leq 6 = 0$
$D > 6 = 11$
BIAS POS

Avg $D = 3.1$
$D \leq 3 = 6$

Run # 1

Date Site #	Model Wind/mph	Observed Wind/mph	Adjusted Observed Wind/mph	Difference (M-AO)	Model Direction	Observed Direction	Difference
Sept. 12							
1	62	0	3	59	E	--	--
2	46	3	8	38	E	E	0
3	37	1	5	32	E	SE	2
4	29	0	2	27	E	--	--
5	33	M	--	--	ESE	M	--
6	24	M	--	--	ESE	M	--
7	13	3	8	5	SSE	SE	1
8	17	3	10	7	SE	ESE	1
9	20	2	8	12	ESE	SE	1
10	26	2	15	11	ESE	SE	1
11	53	3	6	47	E	SE	2
12	24	2	10	14	SE	SSW	3
13	31	2	10	21	SE	SSE	1

D ≤ 3 = 0
3 < D ≤ 6 = 1
D > 6 = 10
BIAS POS

Avg D = 1.5
D ≤ 3 = 9

Date Site #	Model Wind/mph	Observed Wind/mph	Adjusted Observed Wind/mph	Difference (M-AO)	Model Direction	Observed Direction	Difference
Sept. 13							
1	48	1	6	42	E	S	4
2	37	3	10	27	E	SE	2
3	31	2	10	21	E	SE	2
4	24	1	2	22	E	SSE	3
5	29	M	--	--	ESE	M	--
6	22	M	--	--	SE	M	--
7	15	4	13	2	S	SE	2
8	19	4	15	4	SSE	ESE	2
9	15	2	8	7	SE	SE	0
10	20	2	13	7	ESE	SE	1
11	37	2	6	31	E	SW	6
12	20	3	10	10	SSE	WSW	4
13	22	3	8	14	SE	S	2

D ≤ 3 = 1
3 < D ≤ 6 = 1
D > 6 = 9
BIAS POS

Avg D = 2.5
D ≤ 3 = 8

Run # 2

Date Site #	Model Wind/mph	Observed Wind/mph	Adjusted Observed Wind/mph	Difference (M-AO)	Model Direction	Observed Direction	Difference
Sept. 8							
1	48	0	3	41	NE	--	--
2	28	1	8	20	ENE	SSE	4
3	20	0	2	18	E	SE	2
4	15	0	2	13	ESE	--	--
5	26	1	3	23	SSE	SW	3
6	29	2	8	21	SSE	SW	3
7	24	2	8	16	SE	SSE	1
8	24	3	15	9	SE	SE	0
9	22	3	13	9	E	ENE	1
10	33	2	13	20	ENE	ESE	2
11	83	4	10	73	NE	SSW	7
12	35	6	19	16	ESE	SSE	2
13	44	3	13	31	E	SSE	3

D ≤ 3 = 0
3 < D ≤ 6 = 0
D > 6 =13
BIAS POS

Avg D = 2.5
D ≤ 3 = 8

Date Site #	Model Wind/mph	Observed Wind/mph	Adjusted Observed Wind/mph	Difference (M-AO)	Model Direction	Observed Direction	Difference
Sept. 9							
1	24	0	3	21	NNE	--	--
2	17	2	8	9	NE	SSE	5
3	13	2	8	5	NE	E	2
4	9	2	8	1	ENE	ENE	0
5	11	1	5	6	SE	NE	4
6	11	1	6	5	SSE	NE	5
7	13	2	8	5	SSE	SE	1
8	11	2	13	2	SSW	SE	3
9	7	2	8	-1	SW	SSE	3
10	4	2	15	-11	WNW	SSE	6
11	17	2	10	7	NNE	SW	7
12	15	2	8	7	SSW	SW	1
13	10	3	13	-3	SW	SSE	3

D ≤ 3 = 4
3 < D ≤ 6 = 4
D > 6 = 5
BIAS POS

Avg D = 3.3
D ≤ 3 = 7

Run # 2

Date Site #	Model Wind/mph	Observed Wind/mph	Adjusted Observed Wind/mph	Difference (M-AO)	Model Direction	Observed Direction	Difference
Sept. 10							
1	68	1	6	62	ENE	N	3
2	55	2	10	45	NE	SSE	5
3	42	3	13	29	ENE	SE	3
4	24	4	10	14	ENE	SE	3
5	26	4	13	13	ESE	ENE	2
6	22	2	10	12	SSE	WSW	4
7	29	3	10	19	SSW	SE	3
8	22	4	19	3	S	ESE	3
9	9	2	8	1	SSE	SE	1
10	13	1	13	0	E	NW	6
11	37	4	10	27	E	WNW	7
12	31	4	13	18	S	SW	2
13	26	3	13	13	S	S	0

D≤ 3 = 3
3< D≤ 6 = 0
D > 6 =10
BIAS POS

Avg D = 3.2
D≤ 3 = 9

Date Site #	Model Wind/mph	Observed Wind/mph	Adjusted Observed Wind/mph	Difference (M-AO)	Model Direction	Observed Direction	Difference
Sept. 11							
1	244	1	3	241	E	N	4
2	185	2	8	178	E	SSE	3
3	136	3	8	128	ENE	SSE	4
4	97	1	3	94	ENE	SE	3
5	101	M	--	--	E	M	--
6	66	M	--	--	E	M	--
7	35	3	10	25	SE	SE	0
8	48	4	15	33	ESE	ESE	0
9	79	3	13	66	ESE	SE	1
10	132	2	13	119	E	SSE	3
11	238	2	6	232	ESE	ENE	2
12	99	3	10	89	ESE	SW	5
13	141	2	10	131	ESE	SSW	4

D≤ 3 = 0
3< D≤ 6 = 0
D > 6 =11
BIAS POS

Avg D = 2.6
D≤ 3 = 7

Run # 2

Date Site #	Model Wind/mph	Observed Wind/mph	Adjusted Observed Wind/mph	Difference (M-AO)	Model Direction	Observed Direction	Difference
Sept. 12							
1	9	0	3	6	ESE	--	--
2	9	3	8	1	SE	E	2
3	9	0	5	3	ESE	SE	1
4	7	M	2	5	ESE	--	--
5	11	M	--	--	ESE	M	--
6	9	3	--	--	ESE	M	--
7	2	3	8	-6	SE	SE	0
8	4	2	10	-6	SSE	ESE	2
9	4	2	8	-4	S	SE	2
10	7	3	15	-8	S	SE	2
11	15	2	6	9	E	SE	2
12	7	2	10	-3	S	SSW	1
13	9	2	10	-1	SSE	SSE	0

$D \leq 3 = 4$
$3 < D \leq 6 = 4$
$D > 6 = 3$
BIAS NEG

Avg D = $\frac{12}{8}$ = 1.5
$D \leq 3 = 9$

Date Site #	Model Wind/mph	Observed Wind/mph	Adjusted Observed Wind/mph	Difference (M-AO)	Model Direction	Observed Direction	Difference
Sept. 13							
1	13	1	6	7	E	S	4
2	11	3	10	1	ESE	SE	1
3	13	2	10	3	ESE	SE	1
4	11	1	2	9	ESE	SSE	2
5	15	M	--	--	SE	M	--
6	15	M	--	--	SE	M	--
7	11	4	13	-2	SSW	SE	3
8	11	4	15	-4	S	ESE	3
9	9	2	8	-1	S	SE	2
10	7	2	13	-6	SSW	SE	3
11	7	2	6	1	ENE	SW	7
12	15	3	10	5	SSW	WSW	2
13	13	3	8	-5	SSW	S	1

$D \leq 3 = 5$
$3 < D \leq 6 = 4$
$D > 6 = 2$
BIAS POS

Avg D = 2.6
$D \leq 3 = 9$

APPENDIX 5

Standard Forecast Verification

This appendix gives the specific verification data for the Standard Forecast Verification. The heading blocks are defined as follows:

1. Forecast Wind/mph. This is the wind speed derived by standard forecast techniques. The units are miles per hour.

2. Observed Wind/mph. This is the average daily wind observed at each of the observation sites at the 4½-foot (1.5 m) level. The units are miles per hour.

3. Difference. This is the difference between Forecast Wind and Observed Wind.

4. Forecast Direction. This is the wind direction forecast by standard techniques for each observation site.

5. Observed Direction. This is the observed wind direction at each observation site.

6. Difference. This is the difference between the Forecast Direction and Observed Direction. It is determined by assigning each direction a number based on a 16-point compass.

Date Site #	Forecast Wind/mph	Observed Wind/mph	Difference (F-O)	Forecast Direction	Observed Direction	Difference
Sept. 8						
1	4	0	4	SE	--	--
2	4	1	3	SE	SSE	1
3	4	0	4	ESE	SE	1
4	4	0	4	ESE	--	--
5	4	1	3	SE	SW	4
6	4	2	2	SSE	SW	3
7	4	2	2	S	SSE	1
8	4	3	1	SSE	SE	1
9	4	3	1	SSE	ENE	4
10	4	2	2	SSE	ESE	2
11	6	4	2	SW	SSW	1
12	4	6	-2	SSW	SSE	2
13	4	3	1	SSW	SSE	2

$D \leq 3 = 10$
$3 < D \leq 6 = 3$
$D > 6 = 0$
BIAS POS

Avg D = 2
$D \leq 3 = 9$

Date Site #	Forecast Wind/mph	Observed Wind/mph	Difference (F-O)	Forecast Direction	Observed Direction	Difference
Sept. 9						
1	4	0	4	SE	--	--
2	4	2	2	SE	SSE	1
3	4	2	2	ESE	E	1
4	4	2	2	ESE	ENE	2
5	4	1	3	SE	NE	4
6	4	1	3	SSE	NE	5
7	4	2	2	S	SE	2
8	4	2	2	SSE	SE	1
9	4	2	2	SSE	SSE	0
10	4	2	2	SSE	SSE	0
11	6	2	4	SW	SW	0
12	4	2	2	SSW	SW	1
13	4	3	1	SSW	SSE	2

$D \leq 3 = 11$
$3 < D \leq 6 = 2$
$D > 6 = 0$
BIAS POS

Avg D = 1.6
$D \leq 3 = 11$

Date Site #	Forecast Wind/mph	Observed Wind/mph	Difference (F-O)	Forecast Direction	Observed Direction	Difference
Sept. 10						
1	3	1	2	NE	N	2
2	3	2	1	SE	SSE	1
3	3	3	0	SE	SE	0
4	3	4	-1	SE	SE	0
5	4	4	0	E	ENE	1
6	4	2	2	SW	WSW	1
7	4	3	1	S	SE	2
8	4	4	0	SE	ESE	1
9	4	2	2	SE	SE	0
10	3	1	2	SSW	NW	5
11	6	4	2	NW	WNW	1
12	4	4	0	SW	SW	0
13	4	3	1	SSW	S	1

$D \leq 3 = 13$
$3 < D \leq 6 = 0$
$D > 6 = 0$
BIAS POS

Avg D = 1.1
$D \leq 3 = 12$

Date Site #	Forecast Wind/mph	Observed Wind/mph	Difference (F-O)	Forecast Direction	Observed Direction	Difference
Sept. 11						
1	6	1	5	NE	N	2
2	6	2	4	SE	SSE	1
3	6	3	3	SE	SSE	1
4	6	1	5	SE	SE	0
5	10	M	--	NE	M	--
6	10	M	--	NE	M	--
7	5	3	2	SE	SE	0
8	5	4	1	SE	ESE	1
9	5	3	2	SE	SE	0
10	5	2	3	SSW	SSE	2
11	15	2	13	E	ENE	1
12	5	3	2	SW	SW	0
13	5	2	3	SSW	SSW	0

$D \leq 3 = 7$
$3 < D \leq 6 = 3$
$D > 6 = 1$
BIAS POS

Avg D = .7
$D \leq 3 = 11$

Date Site #	Forecast Wind/mph	Observed Wind/mph	Difference (F-O)	Forecast Direction	Observed Direction	Difference
Sept. 12						
1	2	0	2	E	--	--
2	5	3	2	SE	E	2
3	5	1	4	SE	SE	0
4	5	0	5	SE	--	--
5	7	M	--	NE	--	--
6	7	M	--	SW	--	--
7	5	3	2	SE	SE	0
8	5	3	2	SE	ESE	1
9	5	2	3	SE	SE	0
10	2	2	0	SSW	SE	3
11	8	3	5	SE	SE	0
12	5	2	3	SW	SSW	1
13	5	2	3	SSW	SSE	2

$D \leq 3 = 8$
$3 < D \leq 6 = 3$
$D > 6 = 0$
BIAS POS

Avg D = 1
$D \leq 3 = 9$

Date Site #	Forecast Wind/mph	Observed Wind/mph	Difference (F-O)	Forecast Direction	Observed Direction	Difference
Sept. 13						
1	2	1	1	SSE	S	1
2	5	3	2	SE	SE	0
3	5	2	3	SE	SE	0
4	5	1	4	SE	SSE	1
5	7	M	--	NE	M	--
6	7	M	--	SW	M	--
7	5	4	1	SE	SE	0
8	5	4	1	SE	ESE	1
9	5	2	3	SE	SE	0
10	2	2	0	SSW	SE	3
11	7	2	5	SW	SW	0
12	5	3	2	SW	WSW	1
13	5	3	2	SSW	S	1

$D \leq 3 = 9$
$3 < D \leq 6 = 2$
$D > 6 = 0$
BIAS POS

Avg D = 0.7
$D \leq 3 = 11$