RESEARCH AND DEVELOPMENT TECHNIQUE FOR ESTIMATING AIRFLOW AND DIFFUSION PARAMETERS IN CONNECTION WITH THE ATMOSPHERIC WATER RESOURCES PROGRAM

Interim Report

April 1970

Prepared by

M. M. Orgill

J. E. Cermak

L. O. Grant

Period September 2, 1969 to February 28, 1970

Atmospheric Water Resources Research

Bureau of Reclamation

Contract No. 14-06-D-6842

Fluid Dynamics and Diffusion Laboratory

College of Engineering

Colorado State University

Fort Collins, Colorado

ABSTRACT

This report presents an outline of the research and tentative results concerning the problem of using scaled topographic models and laboratory techniques to study the transport and dispersion of cloud seeding material over mountainous terrain. Three mountainous areas along the continental divide have been selected by the Bureau of Reclamation for such studies. Each area has field cloud seeding programs in progress.

Keywords: Weather modification, cloud seeding, model studies, dispersion, boundary layers.

TABLE OF CONTENTS

TABLE OF CONTENTS - Continued

LIST OF FIGURES

I. INTRODUCTION

Statement of the Problem

Several field programs are now in progress concerning the problem of augmenting Water Resources in the Western states by artificially seeding wintertime orographic cloud systems. Artificial ice nuclei, in the form of silver iodide smoke from ground-based and air-borne generators, are released in the natural airstream where turbulence and convection currents are expected to carry the material into supercooled water clouds, and thus initiate precipitation by the Bergeron ice crystal process. Studies have indicated that orographic cloud systems in which systematic condensation is caused by geographical obstacles are most suitable for seeding. However, the realization of the delivery of the optimal distribution of seeding material to orographic cloud systems presents a complex theoretical and operational problem.

In order to help solve this complex problem several questions need to be answered in a quantitative manner. Such questions are:

1. Under given storm conditions will artificial freezing nuclei reach the target area?
2. How much of the target volume will be covered (i.e., horizontal and vertical dimensions of seeding plume) and in what concentrations? Or what is the vertical dispersion? Is the seeding material getting into the clouds and at what concentrations?
3. What role does stability, wind shear, orographic features and other natural factors play in distributing the seeding material?

The overall purpose of this research is to help provide some answers for the above questions by utilizing the wind tunnel as a tool to model the atmospheric planetary boundary layer over mountainous terrain and the transport-dispersion of a passive tracer material simulating the silver iodide seeding material. An adequate field sampling program for transport and dispersion measurements in mountainous terrain presents complex operational and logistical problems along with very expensive budgets. Mathematical and numerical models, although a logical approach, will need further development and possibly larger computers before they can adequately describe the three-dimensional airflow over complicated mountainous terrain such as found in Colorado. Therefore, the wind tunnel can serve a useful role in collecting information on this complicated problem.

The wind tunnel or laboratory method consists of making measurements of a dispersing tracer material over a scale model of selected terrain placed in a simulated atmospheric flow. Field measurements are to be used to confirm and/or correct the laboratory results. The general objectives for the proposed research are described below; more specific and intermediate objectives are described in the following sections:

1. Determine the full capability for laboratory simulation of flow over mountain barrers.
2. Investigate the feasibility of simulating dispersion characteristics and transport of particulate material such as silver iodide with a wind tunnel model.
3. Continue evaluation of the use of wind tunnel simulation for weather modicication operations in various types of orographic terrain.

4. Obtain field information on the relative dispersion and transport characteristics of tracers with particle sizes ranging from meter to molecular sizes.
5. Establish criteria for modeling operational programs for weather modification.

This report presents an outline of the research and results which have been accomplished on three selected topographic regions where operational cloud seeding is in progress or is being planned. The topographic areas are briefly discussed in the following section.

Topographic Areas under Investigation

1. Leadville-Climax region

The first region of interest is situated in the Central Colorado Rockies on the Continental Divide near Leadville. A Colorado State University weather modification experiment (Ref. 4) has been in progress for several years. Figure 1 shows the primary area of interest and the region which was modeled in the wind tunnel. Generally, the topography of this area consists of three types, blocking ridge (Red and White Mountain and Mosquito Range), valley (Eagle River Valley and others) and singular mountain (Chicago Ridge and Chalk Mountain).

The majority of the laboratory experiments have been completed for this site and tentative results appear in Ref.(1) and Ref. (2). Additional information on the laboratory and field program will be presented in section II.

2. Elk Mountain region

The second region of interest is situated near Elk Mountain in southern Wyoming between Laramie and Rawlins. Wintertime studies, conducted at the University of Wyoming's Elk Mountain research facility (Ref. 8), are investigating precipitation augmentation, tracking of seeding material and cloud physics of cap clouds. It is anticipated that the majority of the field data will be obtained by this group for the necessary simulation check between field and laboratory.

Elk Mountain is relatively isolated from other large terrain features and the geometry of its shape is relatively simple. It is classified as a singular mountain in contrast to the more complex terrain near Leadville and the Wolf Creek Pass area. Figure 2 shows the primary area of interest.

Laboratory experiments are in progress for this site and preliminary results will be discussed in section III.

3. Wolf Creek Pass region

The third region of interest is situated in the San Juan Mountains in southern Colorado. The area to be modeled is a 30 mile wide strip toward Wolf Creek Pass from Pagosa Springs. Initial field data are now being obtained by private contractors.

The Wolf Creek Pass area is typical of a blocking ridge type but complicated with river valleys and a concave topographic entrance when approach from the south-southwest. Figure 3 shows the topographic relief which will be modeled for the wind tunnel.

Laboratory experiments will probably begin in late April for this site. The topographic model is under construction at the present time, further details are presented in section IV.

II. LEADVILLE-CLIMAX STUDY

Topographic Model

The first topographic model of this study simulated the Eagle River Valley area and topography surrounding Climax, Colorado (Fig. 1). The direction of the free stream (or geostrophic) wind was approximately 320° or northwest. The horizontal and vertical scale of the model was 1:9,600. The dimensions of the overall model were approximately 25 ft. 6 in. x 5 ft 10 in. The lowest and reference elevation was 7,800 ft (2379m) and the highest was Mt. Lincoln at 14,284 ft (4350 m) msl. The maximum model height was 8 in. Further details on the topographic model are found in Refs. (1) and (2).

Laboratory Experiments

Six experimental periods utilizing the Colorado State University low-speed recirculating wind tunnel have been completed. Two atmospheric airflow types were simulated in the wind tunnel 1) a neutral stability airflow and 2) barostromatic or stably stratified airflow. Concentration measurements were made over the topographic model for both airflow types using radioactive Krypton as a passive tracer gas. Tentative problems and results have been presented earlier in Refs. (1) and (2). More detail results and comparisons with field data will be thoroughly explored in a technical report soon to be compiled and published.

Field Data

The primary objective of the field program is to collect sufficient information to check on the laboratory results. The program is not large-scale and therefore its objectives are quite limited. On occasion the program has benefited from other programs working in the same region. The principal objectives of the field program were:

1) Obtain sufficient radiosonde, pilot balloon and near surface data to define the vertical structure of the atmosphere in orographic terrain especially during conditions when cloud seeding would most likely be in operation.

2) Obtain data on the trajectory of air parcels by means of the superpressure balloon technique and also make estimates on the atmospheric dispersion from these same measurements.

3) Obtain surface samples of tracer material (e.g., silver iodide) downwind from generator sites in order to determine the dimensions of the tracer plume.

4) Obtain upper-level samples of the tracer material using a kite system and aircraft. Primary emphasis is on obtaining measurements on the vertical depth of the tracer plume by using an aircraft as a sampling platform.

To this date three field periods have attempted to complete the four objectives listed above. These have been:

December 16-20, 1968

December 8-16, 1969

January 13-16, 1970

The better data periods were December 8-12, 1969 and January 15-16, 1970. During these periods the following projects were at least partially successful:

1) Simultaneous radiosonde data taken at Minturn, Camp Hale and Fairplay.

2) Simultaneous pilot balloon data taken at four different locations from Minturn to Chalk Mountain. However, low cloud ceilings limited the vertical extent of the data.

3) Dual and single super pressure balloon runs taken in the Camp Hale, Leadville and Redcliff area. Six of the runs were tracked by a double theodolite technique and four runs were tracked by a M-33 radar and transponder system. The six runs tracked by double theodolite technique were done under general northwest wind conditions and tentative analysis of the runs appear to confirm some of the wind-tunnel transport results.

4) Some surface sampling of silver iodide tracer material was accomplished at Chalk Mountain, Tennessee Pass and Camp Hale.

Aircraft sampling of the tracer material has not been successful although two or more attempts were made to acquire such data. The primary objective for the remaining winter and late spring period is to achieve some aircraft sampling. These future results as well as the other field data will be discussed in the technical report now being compiled for publication.

III. ELK MOUNTAIN STUDY

Topographic Model

Construction methods, materials (expanded Polystyrene beadboard) and scale (1:9600) were essentially the same as for the Eagle River Valley-Climax model. However, discussion with the Wyoming research group revealed that the best operational direction of the freestream wind would be 250° or west-southwest. The dimensions of the model were

5 ft 9 in. x 12 ft. The lowest and reference elevation was 6,800 ft and the highest was Elk Mountain at 11,156 ft. The maximum height of the model was approximately 5½ in. The modeled area was shown in Fig. 2.

Generally, Elk Mountain is isolated but hills to the north and south complicate the topography. The windward side of the mountain rises gradually from a sagebrush plain while the leeward side descends abruptly from 11,156 ft to 8,000 ft within 3 km.

The only major obstruction upstream from Elk Mountain is an extension of the Park Range located some 65 km to the west-southwest. In the wind tunnel, this topographic relief was modeled by a gradual sloping triangular barrier approximately 5 cm in height. This additional fixture of the model assisted in the growth of a more realistic boundary layer.

Roughness features were approximated in the same manner as in the Eagle River Valley-Climax model. Small sand grains fixed with latex paint simulated roughness features, such as, forest growth, dryland brush growth, and rock outcroppings.

Flow Similarity

For these preliminary experiments, we have assumed neutral stability conditions in the wind tunnel or $\frac{\Delta\theta}{\Delta z}$ or $\frac{\Delta T}{\Delta z} = 0$. The lower boundary condition was provided by the topographic model. A triangular barrier 5 cm high and approximately 1.5 meter upstream from the principal model was placed in the wind tunnel to help simulate the upstream shear flow. This feature may be modified if the need arises. For dynamic or kinematic similarity the Reynolds number similarity was not required since the airflow was aerodynamically rough. In such cases the mean flow patterns are independent of the Reynolds number or viscosity (Ref. 9)

Since the stability was assumed neutral and the airflow occurred at a high Reynolds number the mean or ambient velocities in the tunnel and field were assumed the same. In these experiments the ambient velocity was 15 m/s.

Laboratory Experiments (measurements by K. Kitabayashi)

1. Experimental Procedure

a. Wind tunnel - The laboratory experiments for the Elk Mountain model were obtained during the period December 15-29, 1969 and were primarily for preliminary data on the flow characteristics and development of the boundary layer over the topographic model. All the experimental work was accomplished in the Colorado State University low-speed recirculating wind tunnel. A complete description of the wind tunnel is given in Ref. (3).

Figure 4 shows the model configuration and the principal positions where various measurements were obtained over the model.

b. Mean velocity profile measurements - The mean velocity distributions were measured using a 2 mm dia pitot tube, an electronic differential pressure transducer and a x-y plotter.

The airflow velocity was measured by moving the pitot tube remotely upwards from the surface of the model to outside of the boundary layer and then down again. The velocity of the pitot tube was 2 cm/min and was slow enough so as not to interfere with the airflow measurements.

Velocity profiles were obtained at 8 points on the model, 6 points on the upstream side and 2 points on the leeside of Elk Mountain.

c. Turbulence measurements - The fluctuating velocity component in the longitudinal direction $\overline{u'^2}$ was measured with a single wire probe. The sensor was a tungsten wire. The hot-wire probe was operated by a DISA constant temperature hot-wire anemometer.

The rms of the turbulent velocity fluctuations were measured from 0.5 cm above the model surface to outside of the boundary layer in intervals of approximately 1 cm. Measurements were made 5 points upstream and 1 point on the leeside of Elk Mountain.

d. Horizontal wind direction measurements near the surface Wind directions on the model were obtained by setting miniature bi-directional vanes of 2 cm length in intervals of 7 cm in the horizontal and 2 cm above the model. Photographs of the vanes were taken from top of the wind tunnel. These photographs were then enlarged to the same scale as a topographical map of the area and the wind direction vectors were then transferred to the map.

2. Experimental Results

a. Mean velocity profiles - As shown in Figs. 5 and 6, the mean velocity profiles, up to position 3, are similar to the usual turbulent boundary layer profile taken over a flat plate with no apparent effects from the topography. The boundary layer thickness is 14 cm or 1340 meters for the prototype scale. On the ascending slope of Elk Mountain the velocity at the lower portion of the boundary layer becomes slightly larger than the ambient velocity indicating that the model mountain is affecting the velocity field. At position 4' near the top of the mountain, the velocity still exceeds the ambient velocity $\overline{U}_\infty$ 2 cm from the surface. On the leeside of the mountain a separation region was observed at position 5 but begins to disappear by position 6.

b. Turbulence - The turbulent intensity of the streamwise component $\sqrt{\overline{u'^2}}/\overline{U}$ profiles resemble turbulence profiles over a rough wall boundary layer (Figs. 7 and 8). Values of turbulent intensity decrease from 10 - 15% near the model surface to 1% outside the boundary layer. In the separation region the turbulent intensities increase to 40 - 50% which is typical for such regions in high Reynolds number flow.

c. Spatial surface flow directions - Figure 9 shows the general flow direction pattern at approximately 2 cm (~200 meters prototype scale) above the surface. At the upstream slope, the airstream diverges due to the blocking effect of the mountain. On the lee side of the mountain, varying wind directions are typical of the separated region.

A tentative comparison has been made between the wind-tunnel wind directions and the vertical stream surfaces as computed by the University of Wyoming group using an adaptation of a computer model generated by LaVoie (Ref. 6). Generally, both results show the diverging flow around Elk Mountain but some differences are present. It is probably too early for any lengthy discussions on the differences but it will be advantageous to have these and other independent results as a check on future wind tunnel results.

Field Data

Radiosonde and pilot balloon data have been obtained from the University of Wyoming research group. The data were taken at a field site some 10 miles southwest of Elk Mountain. Vertical profiles of wind velocity, wind direction, temperature and humidity were observed up to 16,000 ft in most cases.

The present individual data are not abundant enough to attempt any classification of temperature or wind velocity profiles. For now only a mean of the wind and temperature data will be used for some preliminary calculations on estimating the planetary boundary-layer thickness. Figures 10 and 11 are the means of 10 soundings of temperature, wind velocity and direction.

As is well known, the planetary boundary layer is defined as the depth of the atmosphere which is significantly affected by the surface topography. This is an important parameter for diffusion studies and should be accurately modeled in the wind tunnel.

For mountainous regions the planetary boundary layer depth is not well known and few models or formulas exist for estimating it. However, many formulas and models exist for calculating this thickness over relatively flat surfaces.

Hanna (Ref. 5) has summarized the various methods for estimating the depth of planetary boundary layer

$$H = f(u_o^*,\ f,\ V_g,\ \alpha_o,\ \frac{\Delta\theta}{\Delta z}) \qquad (1)$$

where different combinations of the above parameters may give good results depending upon the stability conditions.

One of the good methods recommended by Hanna was derived by Laikthtman (Ref. 7) given by

$$H = 1.3\ \overline{V}_g\ \frac{1}{(\frac{g}{\overline{T}}\ \frac{\Delta\theta}{\Delta z})^{\frac{1}{2}}} \qquad (2)$$

However, comparisons with the O'Neill field data by Hanna suggests that the constant should be 0.75. Using Eq. (2) with the constant 0.75, $\overline{V}_g = 15$ m/s , $\Delta\theta/\Delta z = 1.8 \times 10^{-3}$ °K/m and $\overline{T} = 270$°K the planetary boundary-layer depth was calculated as,

$$H \sim 1500 \text{ m}$$

for the mean conditions of the field. This value compares favorably with the "well mixed layer" defined by the Wyoming group for their modified La Voie numerical model.

In the wind tunnel the boundary layer for the neutral stability case is defined as the height where the local velocity approaches the free stream value. This is similar to Hanna's definition of the momentum boundary layer as the height where the local velocity approaches the geostrophic wind. For the field this depth is approximately 1-1.5 Km while for the wind tunnel it is approximately 1.4 Km (prototype scale).

Further experiments will be necessary in order to establish the boundary layer over the Elk Mountain model for the diffusion experiments but we anticipate that field information from the Wyoming group will help us in this problem.

IV. WOLF CREEK PASS STUDY

Topographic Model

The topographic model of the Wolf Creek Pass area is now in the construction stage. The geographical area to be modeled was shown in Fig. 3. The direction of the free stream (or geostrophic) wind will be 220° or south-southwest. The dimensions of the overall model is estimated to be 12 ft x 27 ft. The lowest and reference elevation will be 5,800 ft and the highest will be Summit Peak at 13,272 ft. The maximum model height is estimated to be approximately 9¼ in. The building material is styrofoam FR.

The horizontal scale will be 1:14,000 and the vertical 1:9,600. The effect of the exaggerated vertical scale on the experimental results will be considered in a later report.

Laboratory Experiments

None.

Field Data

None analyzed.

V. FUTURE WORK

Model Construction

The Wolf Creek Pass topographic model construction will continue through March until it is completed and readied for the wind tunnel.

Laboratory Experiments

1. Eagle River Valley and Climax model (northwest direction).

No further experiments are planned. All results are to be presented in a later technical report.

2. Elk Mountain model (southwest direction).

A second wind tunnel experimental period is scheduled for early April. The Colorado State University recirculating wind tunnel will be used during this experimental period. Experiments will be conducted on the development of the boundary layer and diffusion using radioactive Krypton as a tracer.

3. Wolf Creek Pass model (southwest direction).

Preliminary wind tunnel experiments will probably begin in April. The Colorado State University environmental wind tunnel will be used during this experimental period.

Field Work

1. Leadville-Climax area.

The possibility of utilizing an airplane for in-flight sampling of silver iodide and gaseous tracers has been extended into April. All field data will be analyzed and included in the technical report covering the wind tunnel results.

2. Elk Mountain area.

Closer communication with the University of Wyoming's Atmospheric Resources Research group will be established in order to acquire the necessary information and field data to supplement the laboratory study.

3. Wolf Creek Pass area.

Initial rawin or radiosonde and pilot balloon data will be acquired from Western Scientific Services, Inc.

VI. APPENDIX

The following personnel were associated with the research project during the period under review:

Professional Staff

Name	Project Responsibility
J. E. Cermak	Principal investigator
L. O. Grant	Co-principal investigator
M. M. Orgill	Supervisor of laboratory phase of program. Assists with the field program.
L. Hjermstad	Coordinator of field program
J. Garrison	Assisted with laboratory experiments
G. Woolridge	Assisted with field program

C. Chappell	Assisted with field program
M. Glasser	Assisted with field program
P. Lester	Assisted with field program.

Graduate research assistants and student help

K. Kitabayashi	Laboratory experiments and data analysis
P. Tao (temporary)	Data analysis
W. Tully	Data analysis and model construction
J. Dyer	Data analysis and model construction
H. Baker	Data analysis and model construction
S. Marsh	Model construction
F. Hein	Computer programming
D. McClure	Computer programming.

Several undergraduate students helped with the field program in December 1969.

Technical Assistance

Name	Project responsibility
B. Blinderman	Model construction.

Private Contractors

Western Scientific Service, Inc. assisted greatly in acquiring field data in December 1969 and January 1970.

Other Assistance

D. Dirks and others from the Atmospheric Resources Research group of the University of Wyoming assisted us by providing field data for the Elk Mountain site.

VII. REFERENCES

1. Cermak, J. E., Grant, L. O. and M. M. Orgill, 1969: Research and development technique for estimating airflow and diffusion parameters in connection with the atmospheric water resources program. Interim Report, CER68-69JEC-LOG-MMO-27, Fluid Dynamics and Diffusion Laboratory, Colorado State University.

2. Cermak, J. E., Grant, L. O. and M. M. Orgill, 1969: Research and development technique for estimating airflow and diffusion parameters in connection with the atmospheric water resources program. Final Report, CER69-70JEC-LOG-MMO-11, Fluid Dynamics and Diffusion Laboratory, Colorado State University.

3. College of Engineering, 1966: Fluid Mechanics Program. Fluid Dynamics and Diffusion Laboratory, Colorado State University, p. 36.

4. Grant, L. O., and P. W. Mielke, Jr., 1967: A randomized cloud seeding experiment at Climax, Colorado, 1960-65. Proceedings of the Fifth Berkeley Symposium on Mathematical Statistics and Probability, 5, pp. 115-131.

5. Hanna, S. R., 1969: The thickness of the planetary boundary layer, Atmospheric Environment, Vol. 3, pp. 519-536

6. Marwitz, J. O., Veal, D. L., Auer, Jr., A. H. and J. R. Middleton, 1969: Prediction and verification of the airflow over a three-dimensional mountain, Info. Circular No. 60, Natural Resources Research Institute, University of Wyoming.

7. Laikhtman, D. L., 1961: Physics of the boundary layer of the atmosphere. Translated by the Israel Program for Scientific Translations, Jerusalem, 1964.

8. Natural Resources Research Institute 1969: Atmospheric Resources Research. Final Report, Contract No. 14-06-D-6002. College of Engineering, University of Wyoming.

9. Sutton, O. G., 1953: Micrometeorology. McGraw-Hill Book Company, Inc., p. 78.

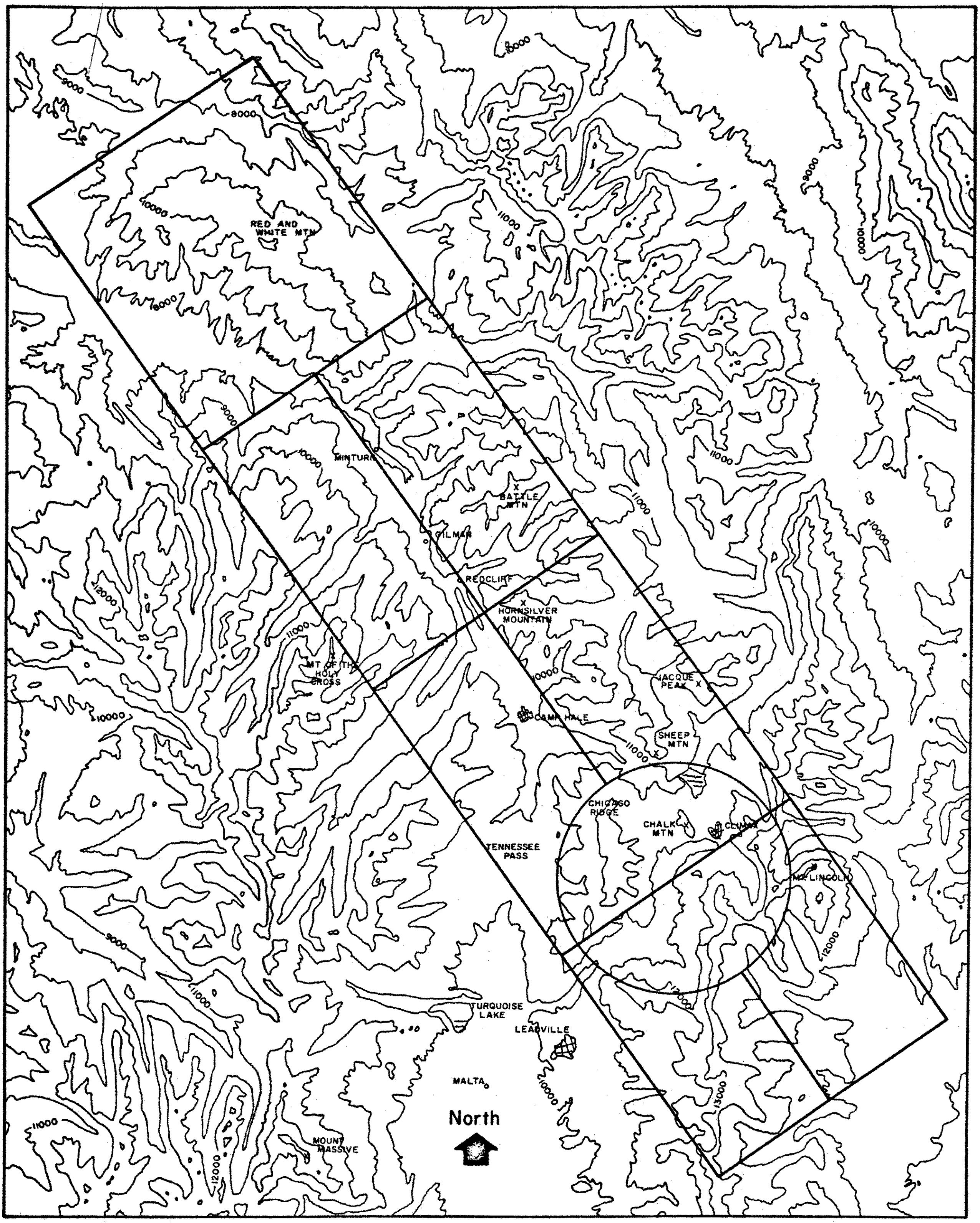

Fig. 1 Eagle River Valley and Climax topography modeled in wind tunnel

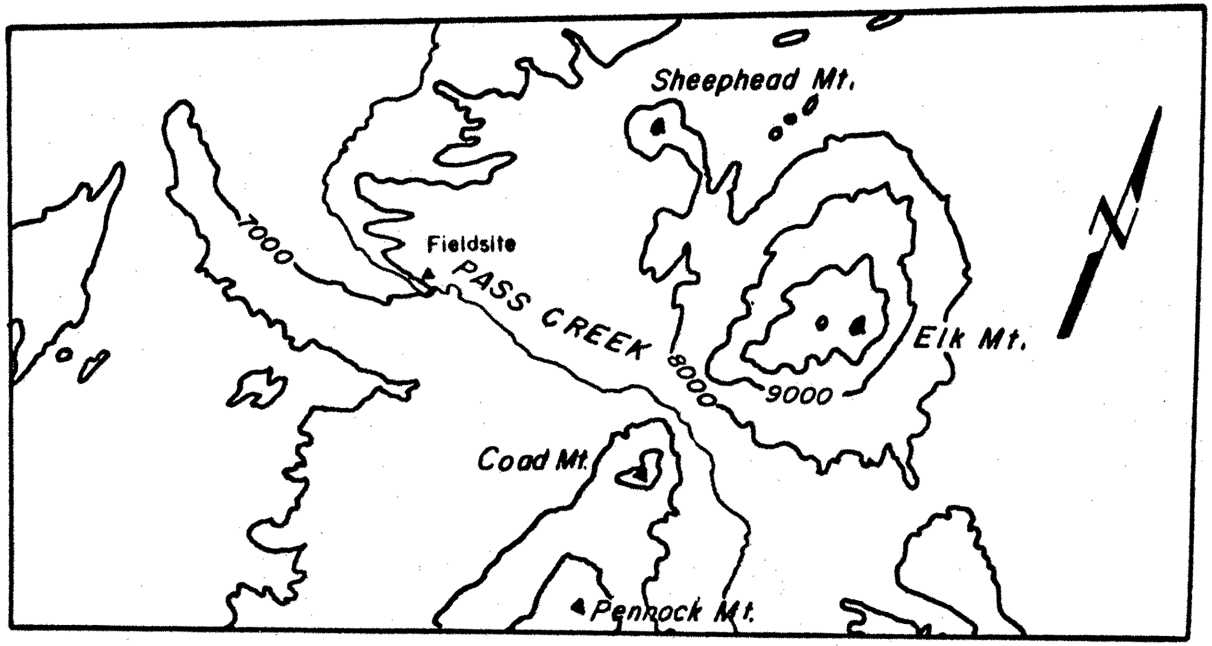

Fig. 2 Elk Mountain and vicinity modeled in wind tunnel

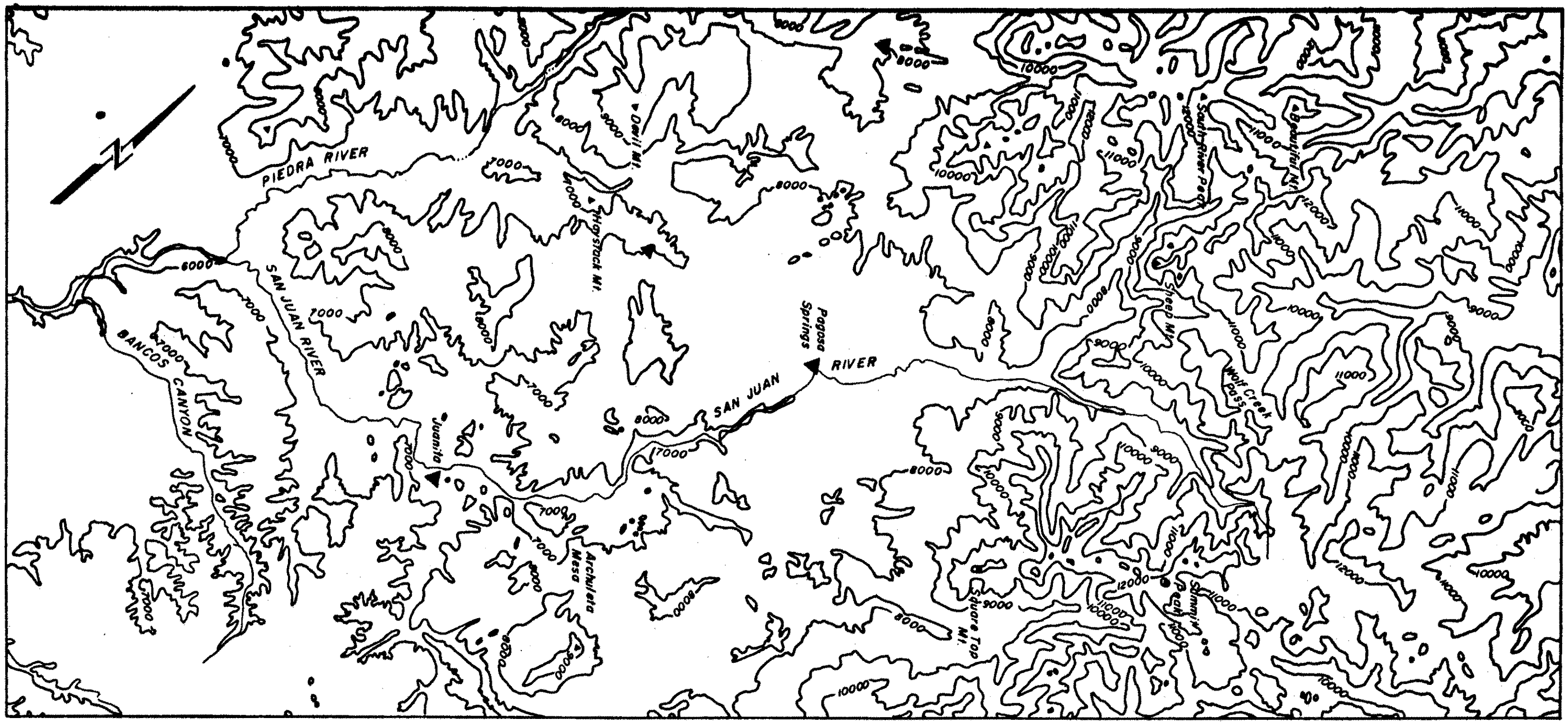

Fig. 3 Wolf Creek Pass and surrounding topography.
Full triangles represent proposed seeding generation sites

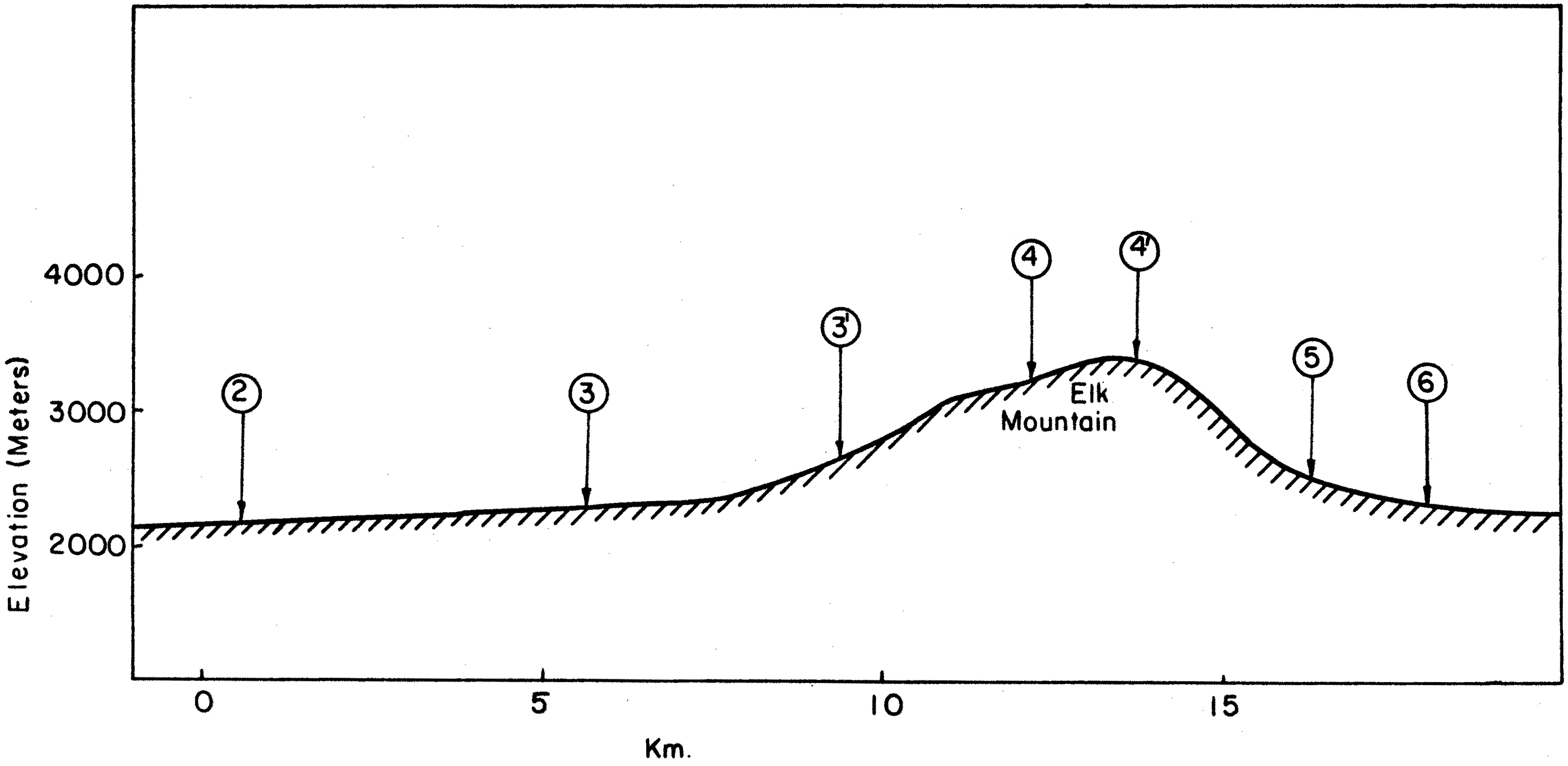

Fig. 4   Cross section of Elk Mountain and measurement locations for laboratory experiments

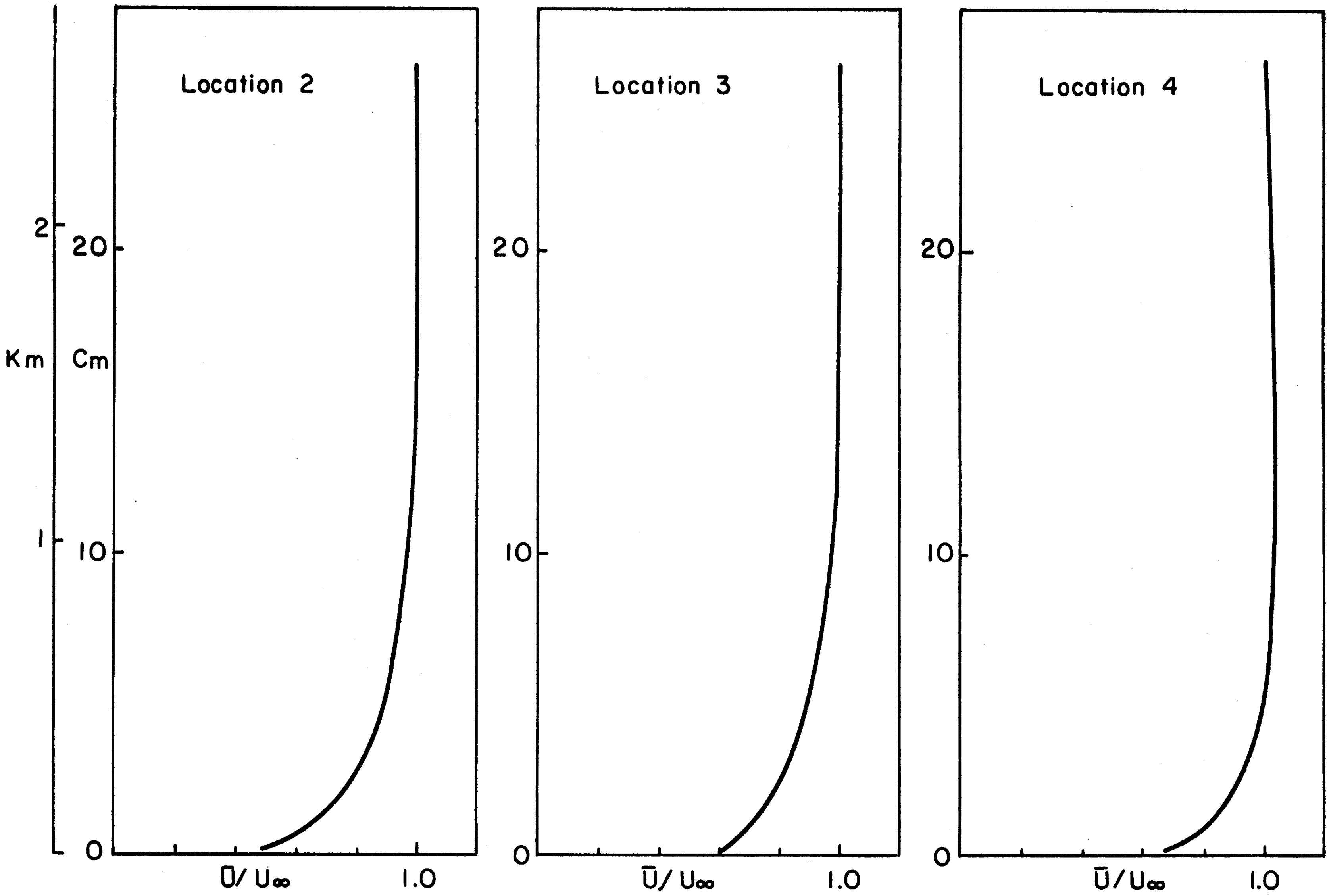

Fig. 5 Mean velocity profiles over the Elk Mountain model

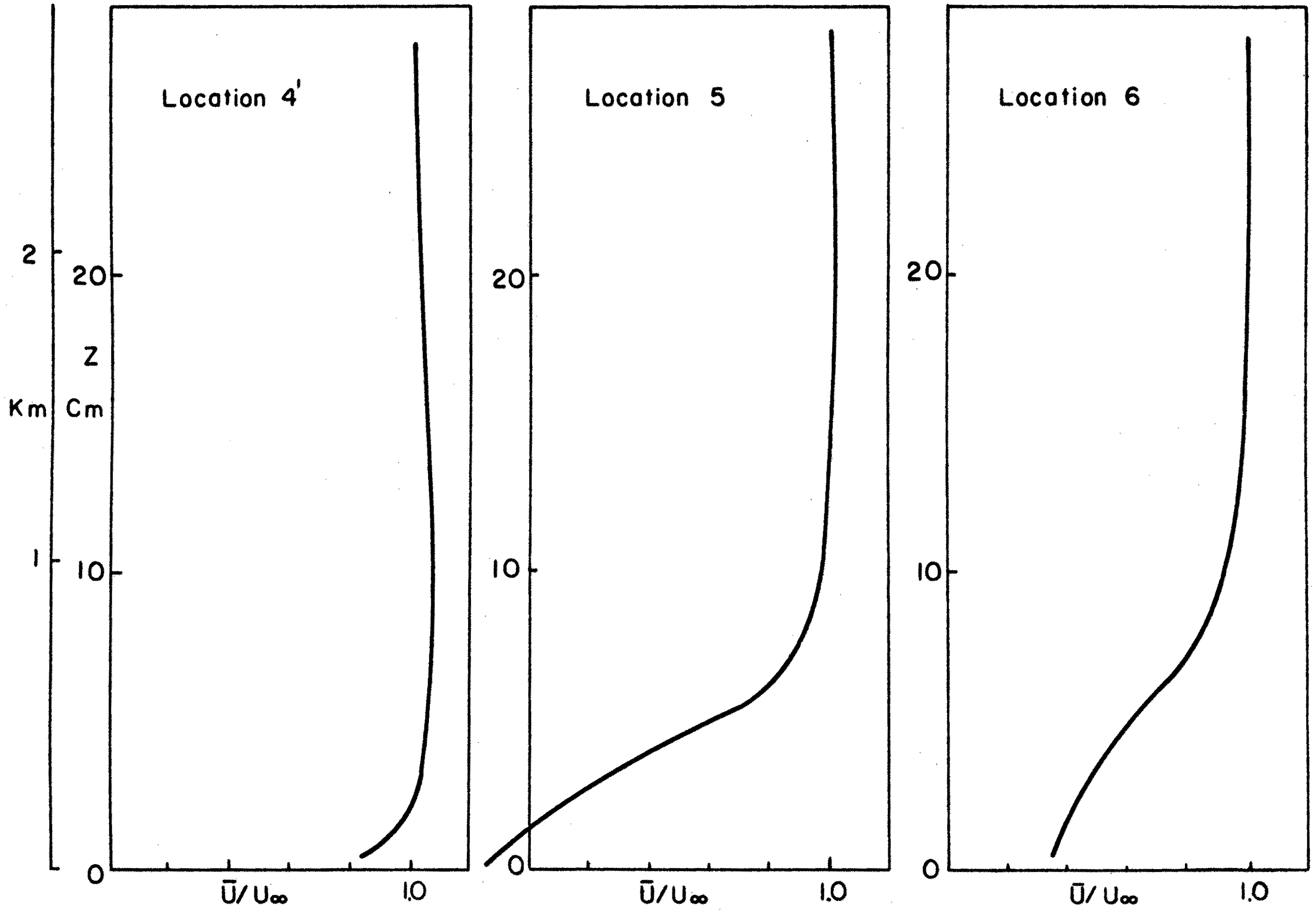

Fig. 6 Mean velocity profiles over the Elk Mountain model

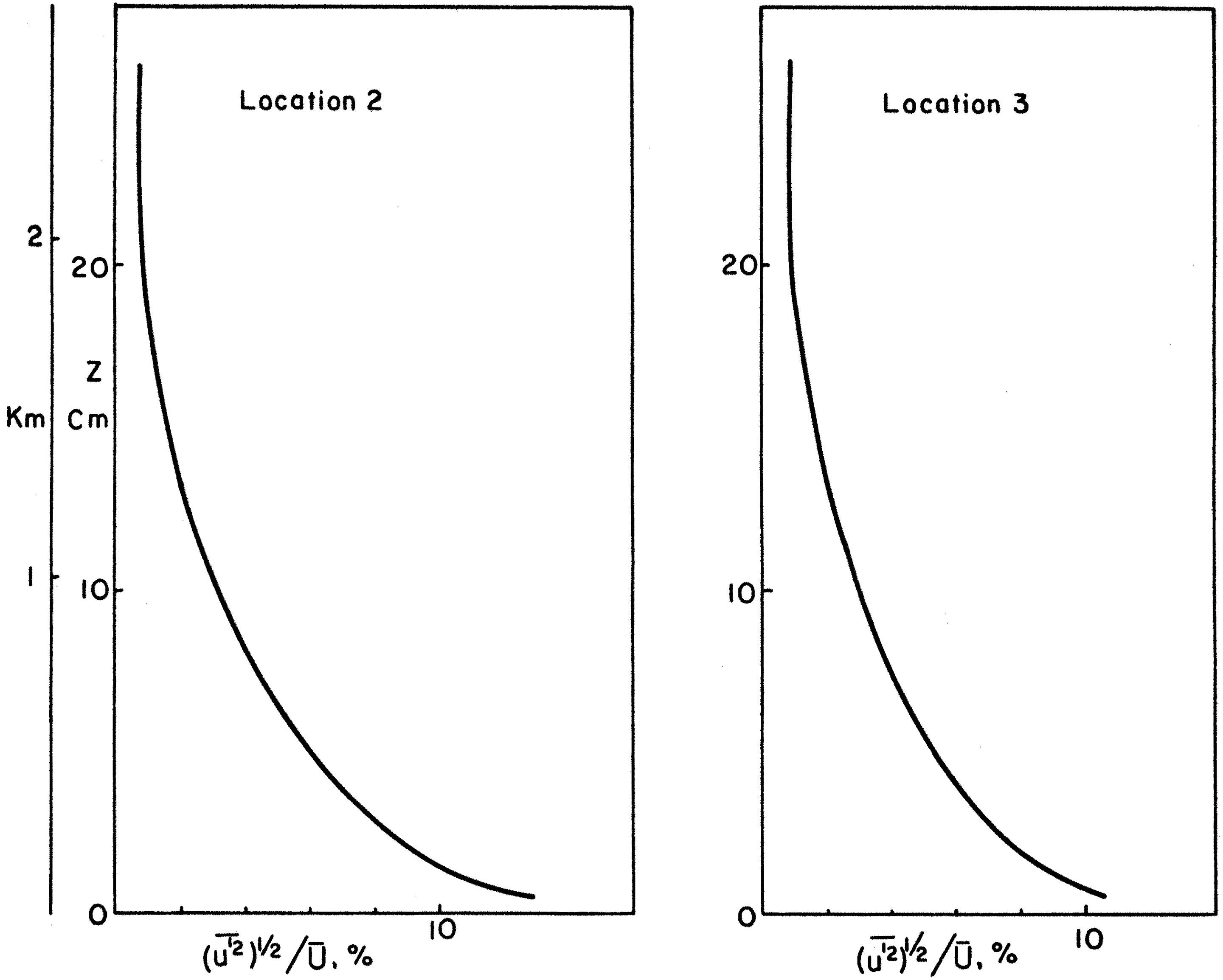

Fig. 7 Turbulent intensity profiles over the Elk Mountain model

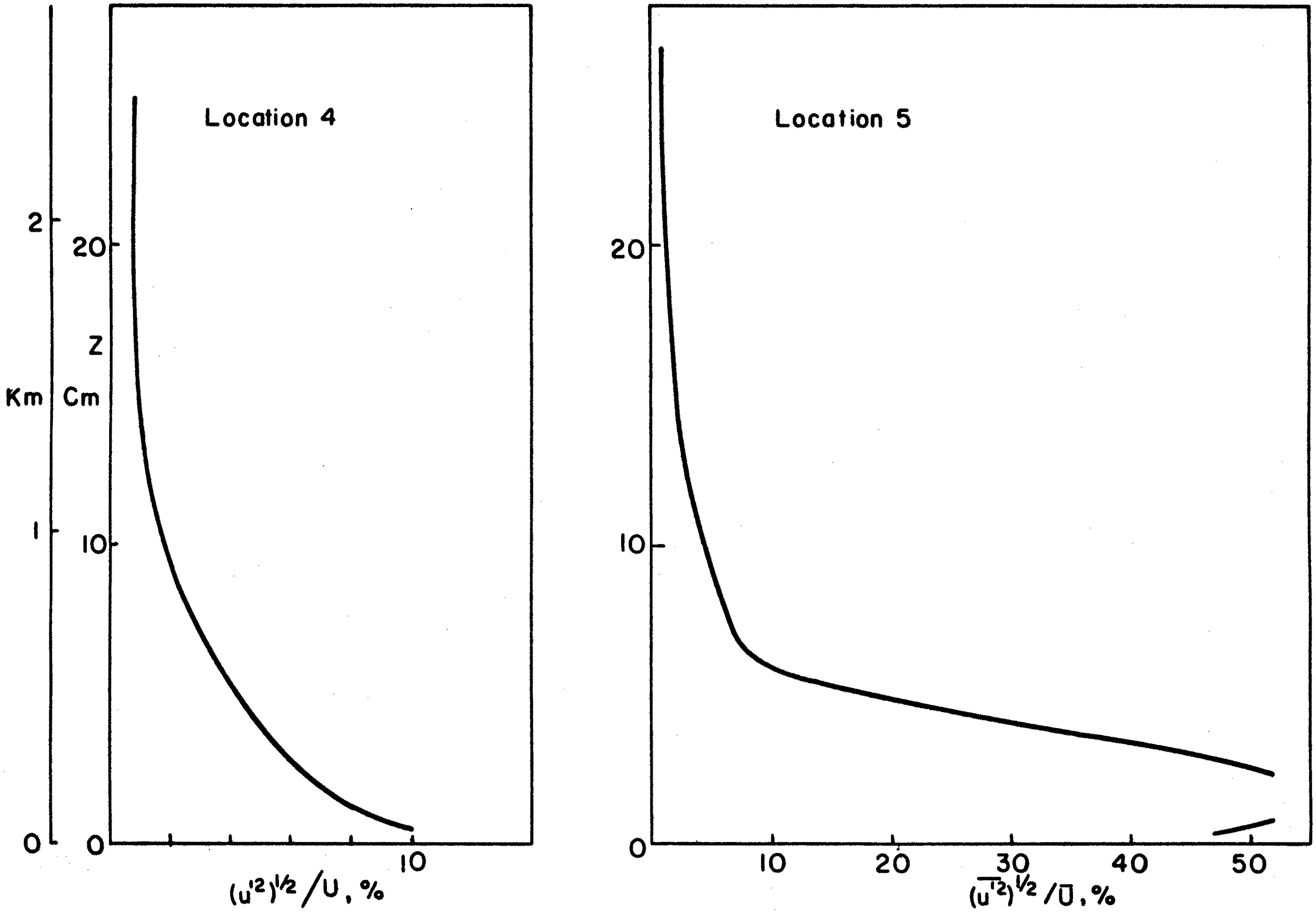

Fig. 8 Turbulent intensity profiles over the Elk Mountain model

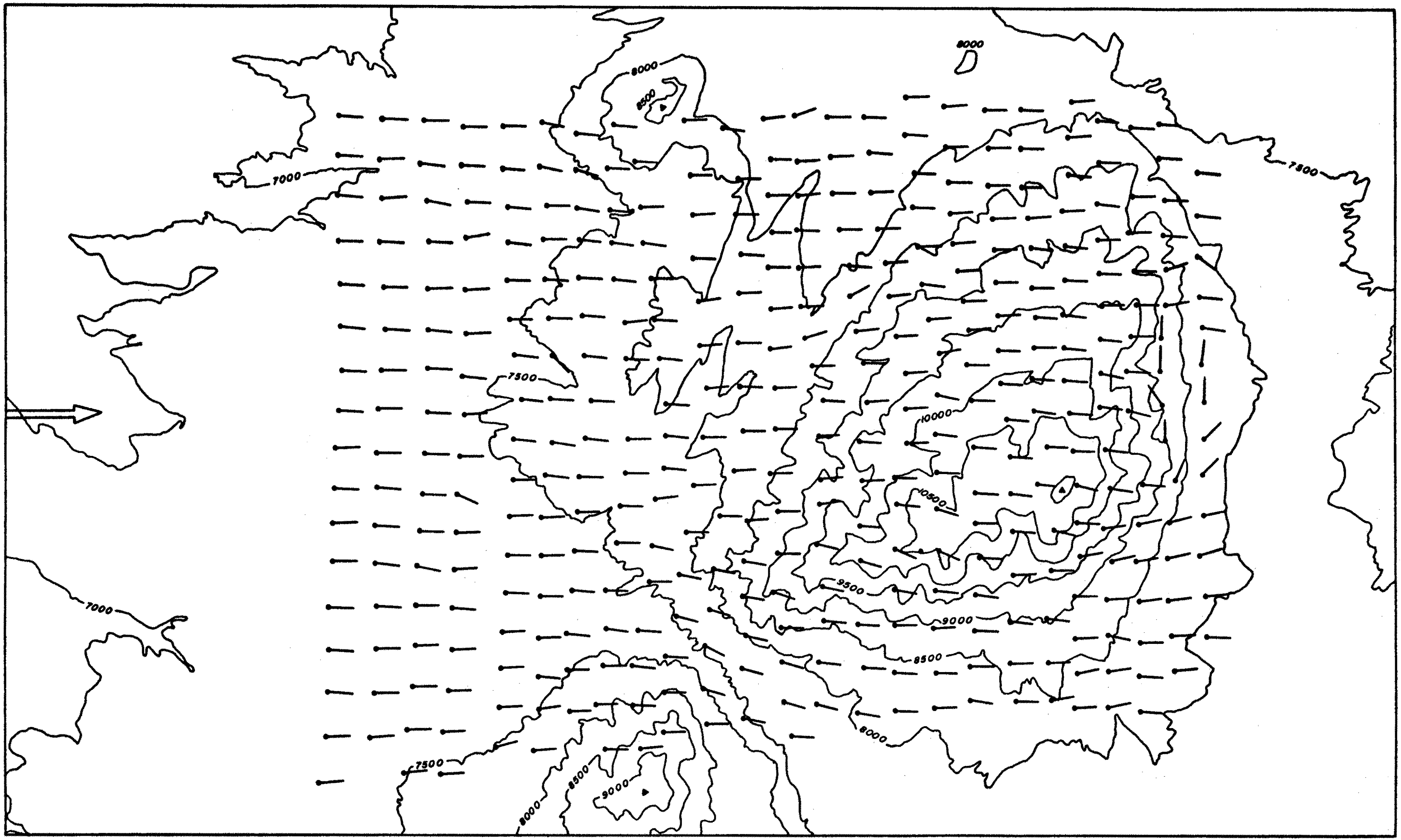

Fig. 9 Mean surface flow directions over the Elk Mountain model

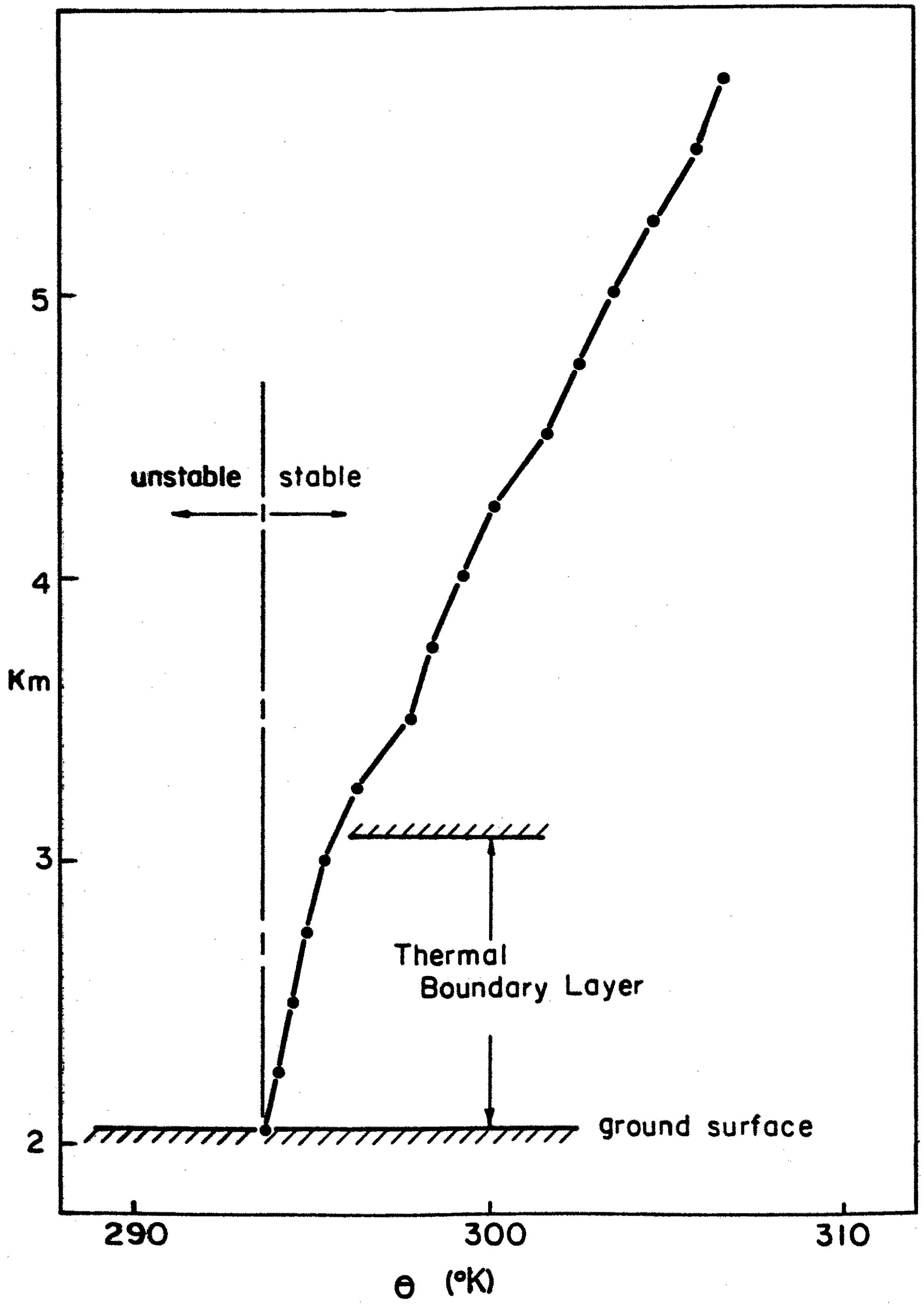

Fig. 10 Mean potential temperature profile for 10 soundings at the Elk Mountain field site

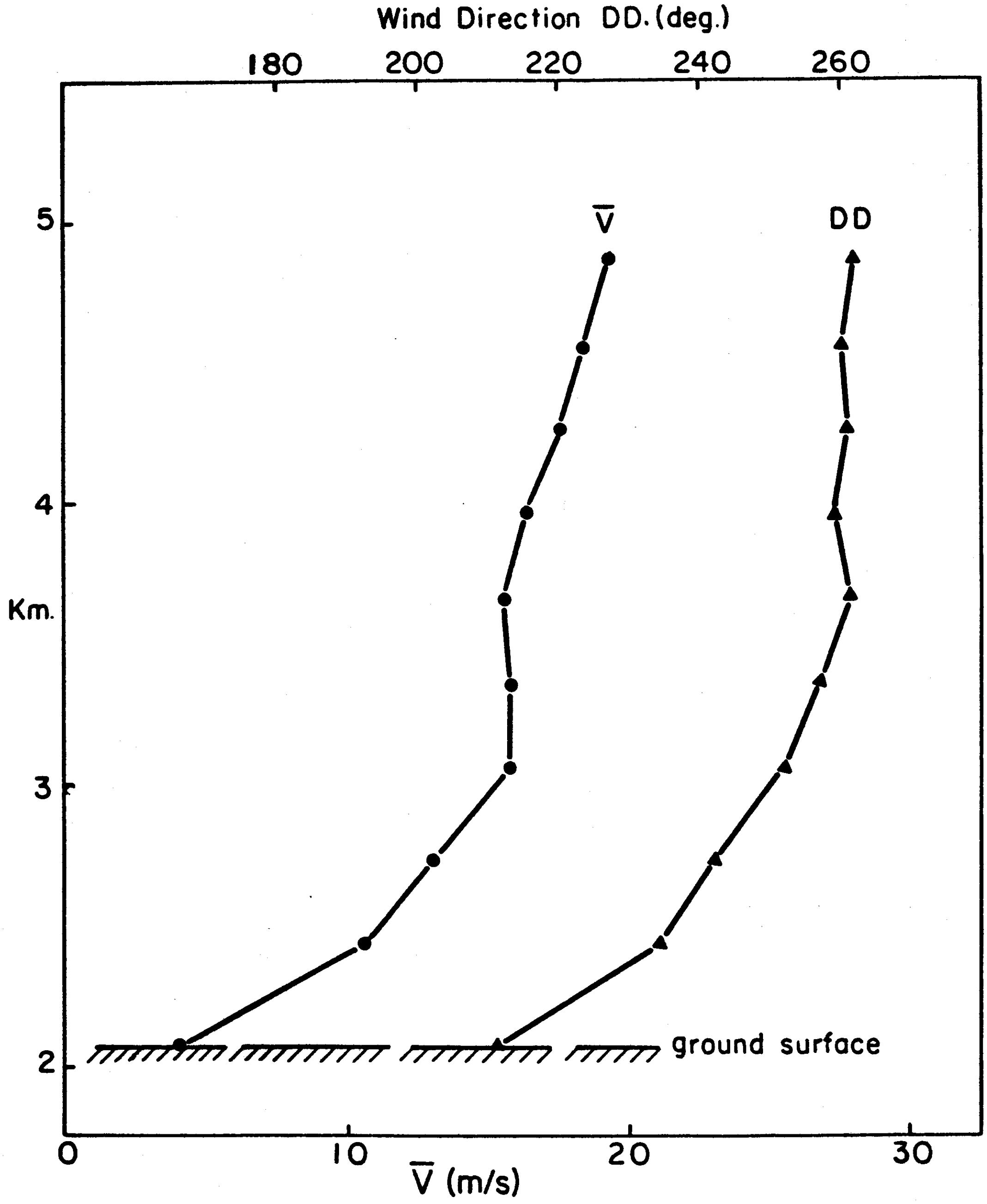

Fig. 11 Mean wind speed and direction profiles for 10 soundings at the Elk Mountain field site