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The Roles of Complex and Simple Terrain in the Estimation of Atmospheric Diffusion

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I. INTRODUCTION

Useful techniques for estimating transport and diffusion of airborne materials close to the ground under stationary and homogeneous meteorological conditions have been available for many years thanks to early theoretical guidance and well-executed field experiments. Over the years the practical applications have reached well beyond the original empirical basis to include complications arising from elevated and buoyant sources, travel over longer distances with the related interest in deeper layers of the atmosphere and temporal changes in wind and turbulence, and variations in the underlying surface. A variety of modeling approaches grew up to address the practical needs but experimental testing of the models has been limited. A revived interest in model validation has led to a series of detailed field measurement programs over the last five years emphasizing nonideal environments.

One of the major targets of emphasis has been complex terrain. Several agencies have identified practical needs for research into a wide spectrum of terrain-induced wind flow phenomena. The highly specialized yet integrated requirements for theory, numerical modelling and field experiments have led to the organization of teams that incorporate different specialties around a shared objective.

This paper attempts to establish a context for the dominant terrain effects including the role of vegetative cover. We explore some practical needs for a thorough understanding of terrain influence and review some of the phenomena that have been identified as complicating the transport and diffusion of pollutants. This paper also reviews a variety of methods that have been used to characterize the topography itself for atmospheric transport applications. The three papers to follow in this session will explore in greater detail the parameterization of phenomena driven primarily by thermal gradients, mechanical influences, and vegetative cover.

II. DIFFUSION IN SIMPLE TERRAIN

Turbulent diffusion over simple terrain is by no means a simple problem as witnessed by the fact that over 60 years of effort have been devoted to get us to our present state of knowledge. Although conceptually we are interested in the net transport wind to determine the position of the center of gravity of a plume or puff and the turbulence energy to determine the rate of spread about the center of gravity, the coupling of wind, temperature and turbulence profiles with height and time of day is complicated. In addition, elements of source geometry further complicate the problem. Theoretical guidance dating back to Taylor's (1921) work have offered an elegant framework for formulating the diffusion problem for conditions of homogeneous and stationary turbulence. Simple terrain gives us our best chance to satisfy the constraints of the theory, although natural large scale variability of the atmosphere still compromises the theoretical requirements.

The ground surface represents a boundary condition for methods of estimating wind, stability, and turbulence structure and the distribution of airborne material from a specified source. The ground is generally a momentum sink and moisture source and may be either a source or sink of heat (depending on time of day) and the type of contaminant. Profiles of virtually all important meteorological parameters depend strongly on height above ground as well as the properties of the ground surface itself (e.g., roughness, radiative properties, vegetative cover). Methods of turbulent diffusion in the atmospheric boundary layer that account for the spectral distribution of turbulence energy among components and the variation with height above ground hold promise for satisfying a large part of the estimation needs over simple terrain.

The most frequently used modelling concept for practical applications is the Gaussian plume, and it has served as a vehicle for many useful and innovative studies. The Gaussian model has been formulated in many ways, from methods simple enough to use arithmetic done in the implementer's head to complex computer algorithms.

A significant part of the research in atmospheric diffusion is directed at estimating lateral and vertical plume growth rates as a function of travel time or distance. Whether or not the computational scheme for concentration relies on a Gaussian distribution, the growth (or equivalently, the dilution) rates are second in importance only to the proper estimation of the mean plume axis. A great deal of our practical knowledge relies on an extensive set of empirical tracer data summarized, for example, by Draxler (1981). Many practical requirements stretch our empirical knowledge beyond its range of validity and current research trends are directed toward obtaining more reliable estimation methods for those problems not well covered in the conventional approach. These include extension to longer travel distances and meteorological domains such as the unstable boundary layer and the very low windspeed stable layer. Also, problems introduced by variations in the underlying boundary (complex terrain, urban complexes, vegetative canopy, shoreline) are receiving attention from both theorists and experimentalists. Finally source governed effects, such as positively and negatively buoyant sources, elevated and ground level sources, short and long release times are under continuing study. Each of the complications outlined here requires a careful diagnosis of the governing physical phenomena and then an appropriate computational mechanism for applying the physical knowledge. Some of the methods being applied are summarized below.

- Statistical theory of diffusion: Fundamental concepts relating the properties of fluid particle ensembles to turbulence structure; rigorous but often limited to assumed homogeneous, stationary turbulence.
- Method of moments: Dynamical relationships derived from governing equations of fluid flow to selected moments of a concentration distribution of tracer.
- Monte Carlo and other stochastic methods: Numerical simulation of trajectories of an ensemble of fluid or real particles usually containing a random and deterministic component; very flexible method with research just beginning.
- Particle-in-Cell (PIC): used in conjunction with numerical grid methods trajectories of tracer fluid particles are calculated.
- K-Theory: relies on an assumed flux-gradient relationship; requires specification of diffusivity and calculates diffusion based on K and gradient; often used in numerical models; K should depend on travel time.
- Similarity theory: Universal functions are sought that describe plume growth dependence on turbulence structure; critical parameters are calculated that describe some features of plume growth useful in the surface layer.
- Higher order closure methods: Seek to avoid K-theory limitations by relating turbulent fluxes to higher order turbulent moments; mathematically complex but potentially very useful.

III. DIFFUSION IN COMPLEX TERRAIN

The problem of transport and diffusion in generalized terrain settings is a very difficult one involving interactions of different physical phenomenology on a variety of time and space scales. As such it doesn't readily lend itself to a systematic computational approach since the governing equations usually must be tailored to a particular scale and phenomenon. We must identify and solve pieces of the problem and rely on an extensive empirical basis to determine the scales and physical processes that dominate a given transport scenario. This approach is fundamentally different from a series of empirical site studies in that the separate studies are tied together through a framework of physical phenomenology. The approach is analogous to a jigsaw puzzle in which all the separate studies represent pieces that fit together to form an entire picture. Strictly pragmatic empirical site studies might be represented by an ensemble of pieces from different puzzles. Without the unifying element of the basic physics as expressed in the best available set of research models we will find it very difficult to deduce the generalized pattern of complex terrain transport.

Major complications to atmospheric transport and diffusion result from variations in the underlying boundary that may include everything from subtle changes in drag or heat flux to vigorous corrugations in the surface. Adopting the broadest definition of complex terrain as any underlying surface that is not flat and horizontally uniform we include not only mountains and valleys but shorelines, sloping flatland, cities and areas of nonuniform land use. Even the simplest nonhomogeneous configurations give rise to serious complications in diffusion estimation but good progress has been made in understanding boundary layer adjustments to a change in the underlying surface with no major terrain relief. There are many definitions of complex terrain depending on the particular application of interest. For atmospheric transport, one useful working definition might be that the terrain is complex when the trajectory of airborne material undergoes nonlinear variations caused by terrain-induced perturbations in the wind field (Fig. 1). This definition includes nonlocal topographic features, because the wind field perturbation may be a mesoscale eddy in the wake of a distant obstacle.

If one adopts airflow phenomena as a guideline to interpreting terrain influences, the next step is to identify and categorize the candidate phenomena. The first useful division separates mechanically and thermally driven circulations. Engill (1981) summarizes 11 descriptive airflow and diffusion phenomena in five general categories (dynamic and kinematic effects, local phenomena, boundary layer, radiation, and plume effects). The dynamic/kinematic category and eddies consist of primarily mechanical influences due to obstacle flows. Thermally-driven circulations are included in

Orgill's local phenomena category whereas features resulting from adjustment of vertical flux rates are categorized as boundary layer phenomena. The mechanical effects can be separated as primarily vertical or horizontal perturbations because buoyancy forces work largely on the vertically-displaced air. However, for a real three-dimensional geometry, the final trajectory fluctuations result from coupling of vertically and horizontally induced motions. For example, for flow over a ridge at an oblique angle to the mean wind direction, the confluence (and diffluence) in the vertical velocity accounts for acceleration (deceleration) of the horizontal velocity component normal to the ridge. The component parallel to the ridge is not similarly affected. Hence, when flow is accelerated it tends to turn toward normal to the ridge line and when it decelerates the direction approaches that of the ridge line as indicated in Fig. 2, traced from a laboratory simulation of wind over a simple ridge.

IV. SOURCES OF TURBULENT ENERGY

The presence of variable topography introduces several sources of momentum and turbulence energy that aren't present in boundary layers over plane surfaces. More highly parameterized models of the boundary layer may miss these additional energy sources although, if we apply truly fundamental principles, we should expect to see faithful relationships between turbulence quantities and the mean wind and temperature structure.

Slope winds, for example, are driven by pressure-density solenoids that arise when the main isotherms are quasi-parallel to the sloping ground as shown in Fig. 1. The more stable the lapse rate, the more vigorous will be the slope flow. The associated strong velocity shears may give rise to increased turbulence. If we rely solely on a temperature lapse rate to parameterize turbulent mixing we will face a dilemma that turbulence apparently increases with stability. On the other hand the local balance of turbulence between shear production and buoyant damping is characterized by the Richardson Number. This should continue to be a useful indicator even though there are topographic alterations to the mean wind structure.

There are some nonlocal sources of enhanced turbulence in complex terrain settings including wakes from a wide variety of obstacles. Several authors (Hanna, 1969; Start et al., 1975) have observed turbulence intensities equivalent to near neutral stability classification during nighttime light wind conditions. The properties of this turbulence structure may be quite site dependent but efforts to document dependencies on height, stability and, to some extent, position for some classes of terrain setting. For instance, there may be a characteristic pattern as a function of distance from the head of a valley or distance downwind of a ridge line.

The confluence pattern of streamlines in flow over obstacles gives rise to local deformation zones that will, in turn, alter the turbulence structure. Frost et al. (1974), Jackson and Hunt (1974), and Taylor and Gent (1974) have obtained solutions for boundary layer flow including Reynolds stress over gentle obstacles (without flow separation). Taylor and Gent and Frost et al. (1975) include numerical calculations of turbulent energy that reach a maximum near the peak of the two-dimensional modeled hill. Bradley (1980) has made observations over a hill in Australia that are consistent with the available theory. Mean wind speed and the standard deviation of the turbulence components were approximately doubled over the values upwind of the hill and a windspeed maximum occurred at about 1/6 of the hill height above the ridge top. The concurrent increase of the mean wind and turbulence components suggests a constant value of the angular standard deviations (σ_θ, σ_ϕ) which, in turn, draws speculation that the turbulent spread of a diffusing plume should be unaltered. Conversely, Lee et al. (1981) observed about a 16% enhancement in lateral plume width parameters using tracer gas in a wind-tunnel simulation over a two-dimensional ridge with a similar aspect ratio to Bradley's hill.

A valuable theoretical tool, rapid distortion theory developed in the 1930's by Prandtl (1933) and Taylor (1935) to explain the behavior of grid produced turbulence in a wind tunnel, is being extended to atmospheric turbulence deformed by flow over hills (Hunt, 1973). The theory makes use of energy conservation principles to predict adjustments in the longitudinal, lateral, and vertical turbulence statistics when changes in the mean wind (elongation, shear) deform eddies on a time scale shorter than their lifetime. Sadeh and Brauer (1980) describe a similar analysis based on vorticity amplification by stretching and tilting in a distorting wind field. Given the characteristic scale of a particular terrain obstacle flow, rapid distortion effects will work selectively on the larger eddies present in the approach flow and hence alter the spectral distribution of energy (Panofsky et al. 1981).

Another feature of variable terrain is that the surface characteristics such as roughness, vegetative cover, ground moisture and temperature vary with location. In the west the trees tend to favor the higher terrain and canyons where there is available water. In the east a similar pattern is often the result of intentional land-use.

Considering the importance of temperature distributions on the meteorology of complex terrain settings, we have seen relatively little work on topographic effects on heat budgets. We need to address the roles of surface geometry and emissivity variations on the radiative component as well as coming to grips with some gritty problems of turbulent fluxes in complex terrain environments.

Once the critical elements of complex terrain meteorology are determined we who are interested in transport and diffusion still must address the fact that the main theoretical guidance we have is based on homogeneous turbulence. The setting of variable topography is fundamentally inhomogeneous. There are scales of transport and meteorological conditions for which terrain variation is minimized. We must identify these and document the errors involved in a simple parameterization. For a while, at least, we must rely on an empirical basis, perhaps extending our results from one site to "similar" sites. We may pursue the pragmatic expedient and in the interest of "first things first" attempt to establish the transport wind field and accept factors of several-fold in dilution estimate errors. In the long run, however, we must develop algorithms for turbulent diffusion under non-homogeneous conditions.

V. PARMATERIZING TERRAIN

An ultimate practical objective of research in complex terrain meteorology is to be able to use general weather information and topography (and perhaps a critical local observation) to estimate wind and turbulence fields. One important step towards achieving that goal is to adequately characterize those features of the terrain that are critical to the fields of interest. There probably is not one single method that is best for all applications because each application requires different space domains and averaging.

Orgill (1981) summarizes a series of land forms that are common elements of natural landscapes. Most settings can be described in some sense as a simple combination of slopes, ridges, hills, valleys, basins, shorelines, islands, bays or some other of the 20 land forms described by Orgill. Further abstraction of Orgill's landforms can result in four major classes as shown in Table I. Practical problems usually contain elements of two or more of the classes. For example, the Geysers area of California is for most cases studied a concave, thermally driven domain where slope winds are channeled into an axial valley flow. Quantitative efforts to describe the magnitude of the flow (Barr et al., 1980; Yamada, 1981) have required some consideration of enhanced surface drag due to the vegetative cover. Some cases were significantly affected by the free-stream wind forced over the (convex) ridge that bounded the experimental site. Hence all four major land form categories entered the interpretation of the Geysers field experiments.

Sometimes the land form categories of Table I depend on orientation to the mean wind as in the case of a slope or cliff. Also some sites involve combinations of basic forms that may lead to different interpretations. For example, ensembles of convex features lead to concave areas in between. Orgill points out that generic land forms are useful for deducing fundamental meteorological behavior, if properly defined including supporting information on:

- orientation
- slope magnitude
- elevation and relief
- roughness.

Computer methods (Fig. 4) hold a great potential for characterizing topography if they are incorporated into good physics-based systems. Geomorphologists have developed some excellent approaches. We need to adapt the methods to our specific meteorological needs and perhaps introduce some new methods based on statistics (MacCready et al., 1974) or other mathematical basis and using computer-based schemes seems most appropriate.

Table I. Land form Classification

Class of Land form	Flow Phenomenon
Convex	Deformation, waves, wakes
Concave	Channeling, stagnation
Frictional	Boundary layer
Thermal	Slope flows, land-sea breeze

VI. An INTEGRATED APPROACH

Among the reasons that the meteorology of complex terrain settings has retarded analytical progress are:

1. Many physical processes are involved.
2. Nonlinear interactions are prevalent, not only nonlinear hydrodynamics but feedback processes between different phenomena.
3. Many different scales of phenomena interact.
4. Fully three-dimensional processes are very important to the ultimate behavior.

This combination of complexities puts an emphasis on a team approach in which specialists in theory, modeling and experiments interact with shared objectives on specific tasks. The important steps involve:

1. Problem perception in which the practical need is assessed in terms of the most likely complications of terrain-induced meteorology, source and receptor distributions.

2. Identification of likely governing phenomena; a task that depends on the whole team but must include observations.

3. Modeling with relevant computational codes and laboratory facilities leading to predictions of concentration/deposition patterns and identification of additional data or interpretation needs.

4. Field tests designed to address specific hypotheses and involving adequate data to test the models.

5. Feedback loops leading to upgrading of models and experiments.

The Department of Energy's ASCOT program is one example of an integrated team in which participants from national laboratories, federal agencies and universities maintain a continuing dialogue with three topical points of intersection: physical concepts, modeling, and measurements. Efforts are made to see that the models address the phenomena that are observed. Several classes of models are used in the design and analysis of field experiments. The models currently in use in ASCOT include data driven analysis such as mass-consistent wind field algorithms, and one, two and three dimensional models based on fundamental concepts. Parallel developments proceed with research and operational models. The former stress as much as possible the relevant physics without worrying too much about computer costs. Their objective is to assist the scientists in understanding the governing processes and to demonstrate that these processes can be calculated. The goals of the operational modeling effort is to seek a broader parameterization so that computing efforts will be modest and costs reasonable to a user agency for frequent application in assessments.

In another integrated approach, the Environmental Protection Agency and its contractors are investigating the perturbed transport wind field and diffusion pattern associated with a Gaussian-shaped hill. The program seeks a balance between field measurements, modeling and laboratory simulation.

A more extensive coordination between EPA, DOE and the Electric Power Research Institute is currently in the planning stages. Each organization will contribute effort and facilities to a joint project of mutual interest.

VII. SOME SUGGESTIONS FOR WHITTLING THE PROBLEM INTO BITE SIZES

To address a complicated practical problem, particularly one with the added confusion of terrain influences, in a single step is a mind-boggling challenge. It is vital that we partition the problem into components that can be solved and the solutions verified. Also, the scientific community must agree on a context so that the partial solutions can all contribute toward a common goal without too much redundancy. Of course, there is a wide variety of practical objectives that get us involved in the first place. We must meet these objectives while contributing our little piece to the overall context. In the following paragraphs are some thoughts on narrowing the problem down to workable pieces.

First we must start from what we know. Just because a site contains a topographic complication, it does not rule out the utility of conventional transport and diffusion methods. Under some meteorological conditions the terrain effect may be minimized or some practical problems may not be sensitive to the complications. A careful assessment must be made of the errors involved in simplifying the analysis.

Several authors have attempted to combine effects of several contributing phenomena in a simple linear combination. This allows us to calculate something that we can handle such as a single phenomenon, component or scale one at a time, then combine them in a straightforward way to yield a potentially complex field of wind, temperature or turbulence. This type of analysis should contain an estimate of the errors involved in neglecting feedback.

Another simplification in the analysis phase is to determine the scale of the governing phenomenon and concentrate the effort on that scale. Numerical approaches are greatly simplified by this step.

In field experiments it is very valuable to screen the measurement requirements so that each series of measurements is designed to address a particular hypothesis. It is terribly tempting to make observations to "see what it looks like" but the risk of suffocating under ponderous and irrelevant data sets is greater than the benefits of serendipitous discovery. We have found a multi-phase field expedition to be quite useful. Based on a general governing hypothesis (e.g. an expected valley wind domain) we set up a minimal network of fixed stations and conduct a brief series of soundings. With a crude "climatology" of surface observations and a few cases of vertical profiles we are usually able to guess at the representativeness of the domain we have observed. This helps to reduce the risk of major surprises in the next phase when greater investments of manpower and equipment are involved.

The second phase is an expedition of several weeks duration in which some detail is sought in the atmospheric structure and its effect on tracer plumes. Usually, there are enough unexpected phenomena that it is advisable to follow up with another measurement series.

If it is necessary or desirable to move into a monitoring phase where routine observations of meteorology and air quality are collected and processed for an extended period of time, the information gained from the expeditions can make the final phase much more effective.

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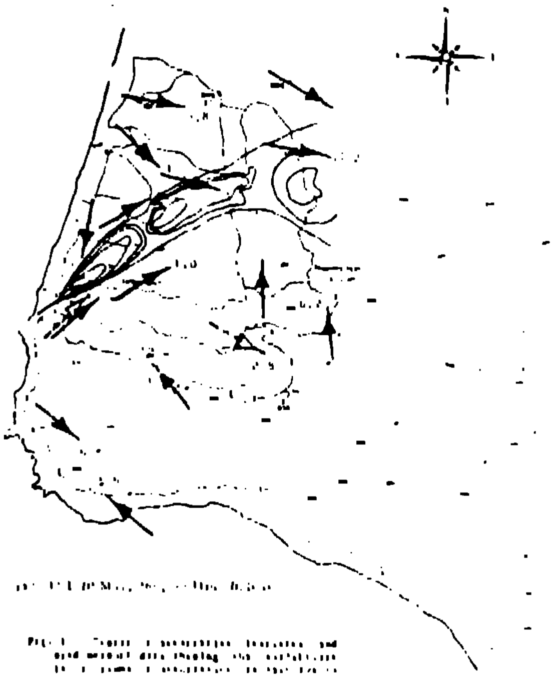
Figure Legends

Fig. 1. Tracer concentration isopleths and wind network data showing the variability in a plume concentration pattern due to terrain (taken from Hinds and Nickola, 1967).

Fig. 2. Streamline deflections in vertical and horizontal directions due to flow over a simple ridge at 60° orientation to the mean flow.

Fig. 3. Cross section of potential temperature along the axis of Anderson Creek Valley, CA, July 24, 1979.

Fig. 4. An example of a computer-generated perspective view of the topography in the Cobb Mountain Anderson Creek Valley Area of northern California.



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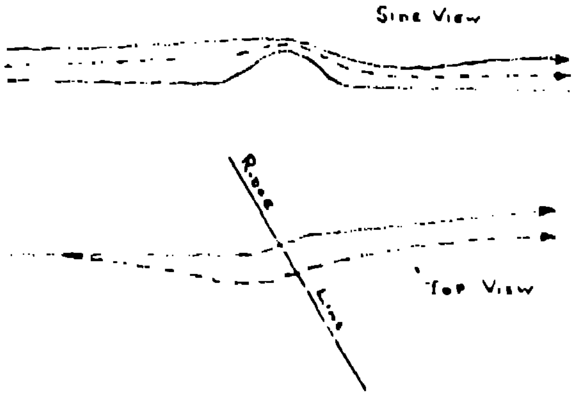


Fig. 2. Streamline deflections in vertical and horizontal (line form) due to flow over a simple ridge at 60° orientation to the mean flow.

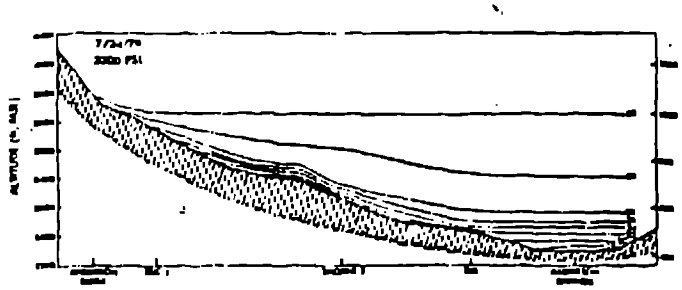


Fig. 3. Cross section of potential temperature along the axis of Anderson Creek Valley, July 24, 1979.

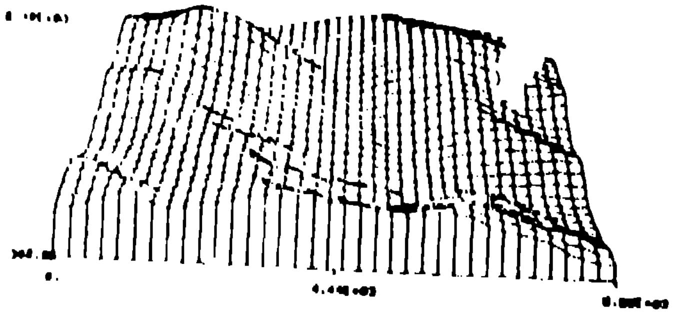
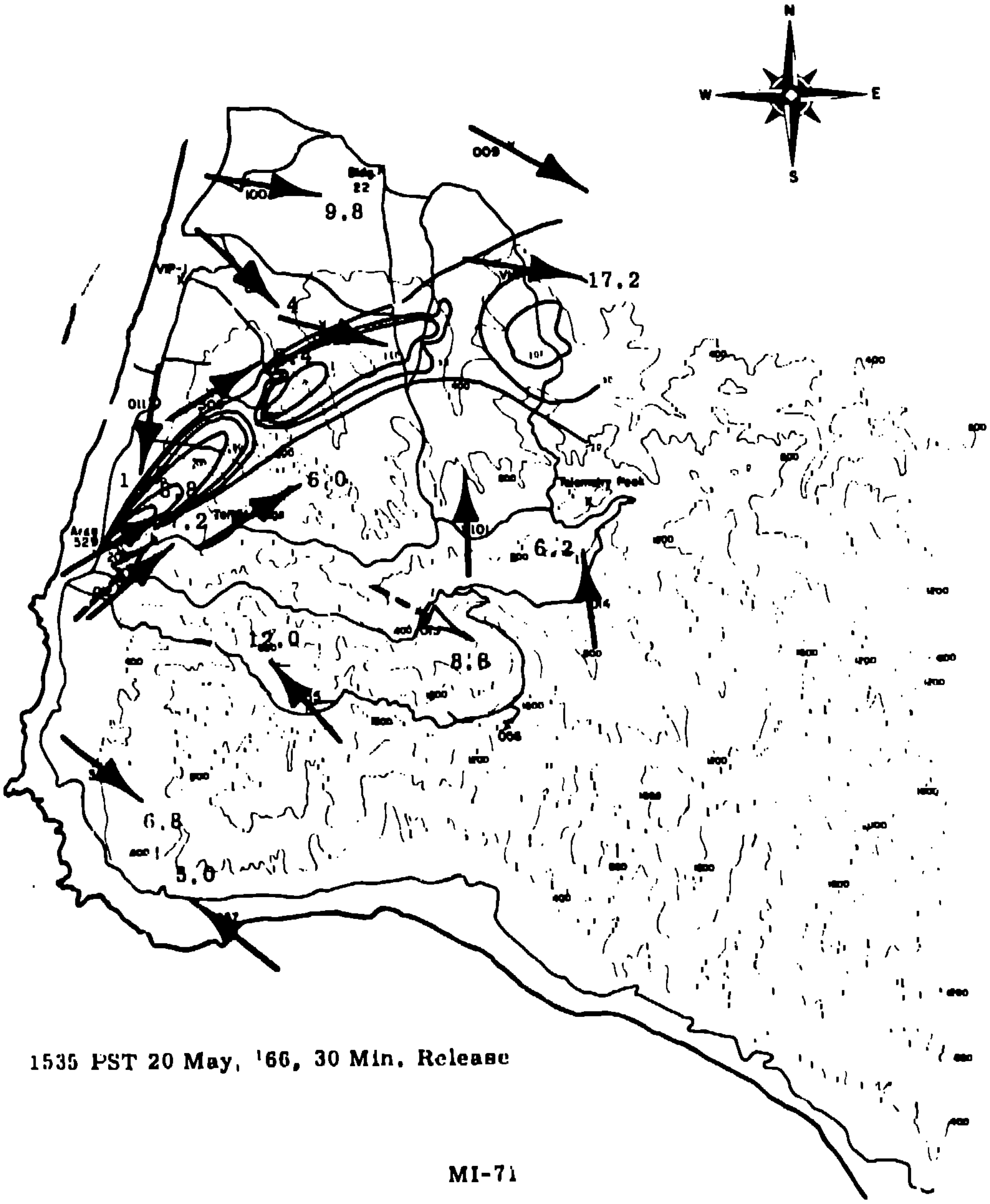


Fig. 4. An example of a computer-generated perspective view of the topography in the [illegible] Anderson Creek Valley Area of northern California.



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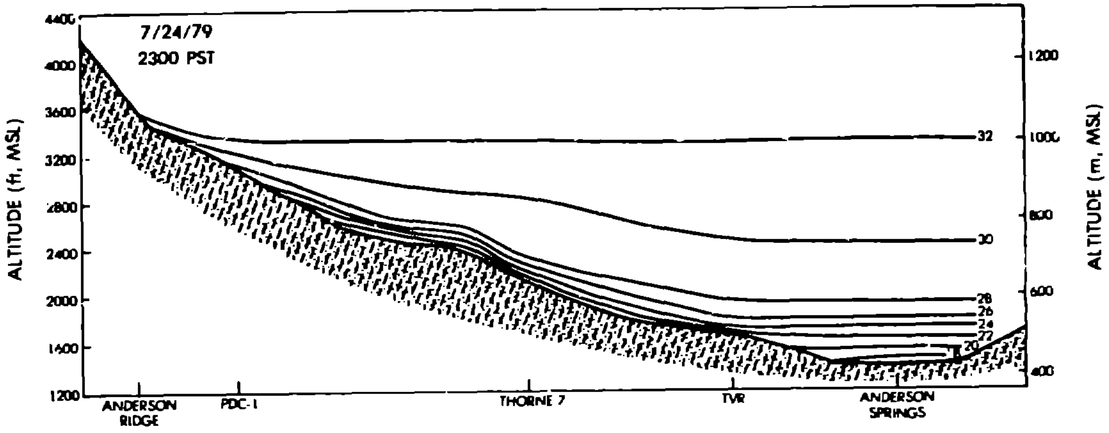
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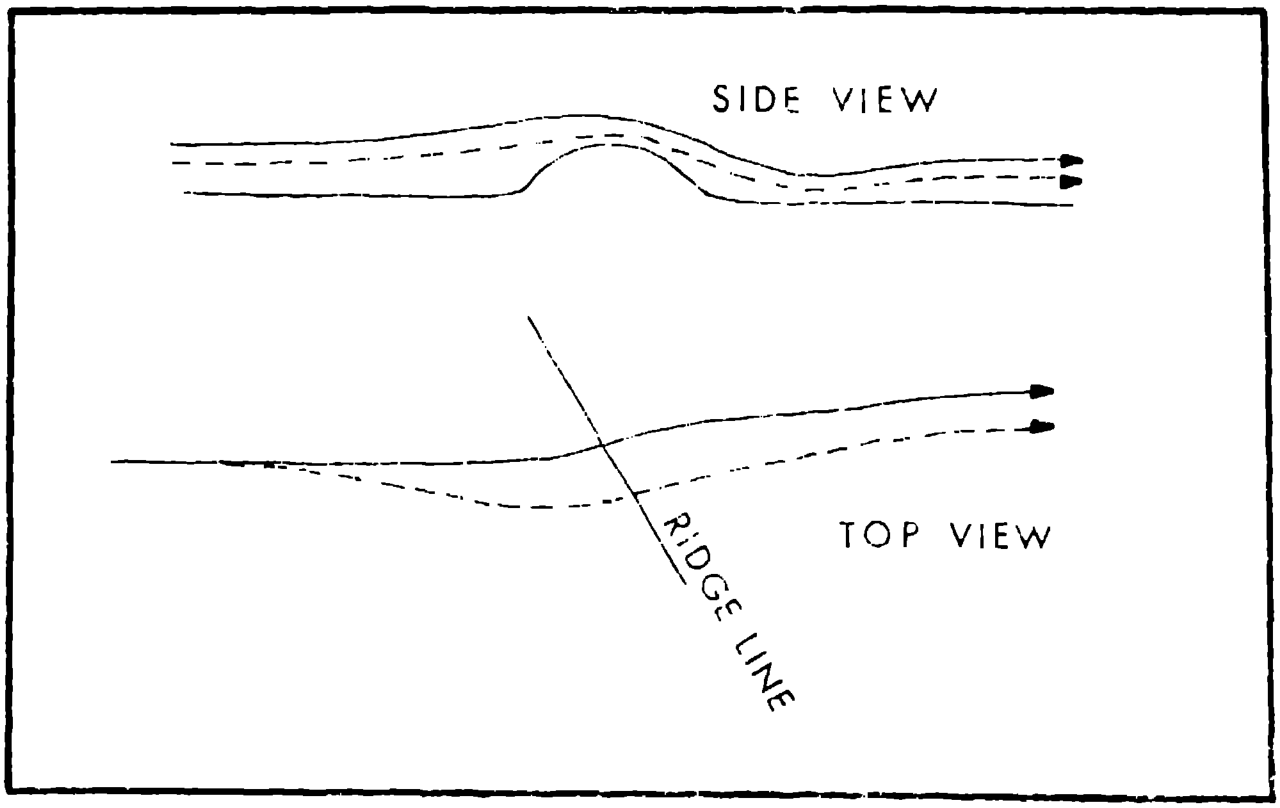
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RIDGE LINE

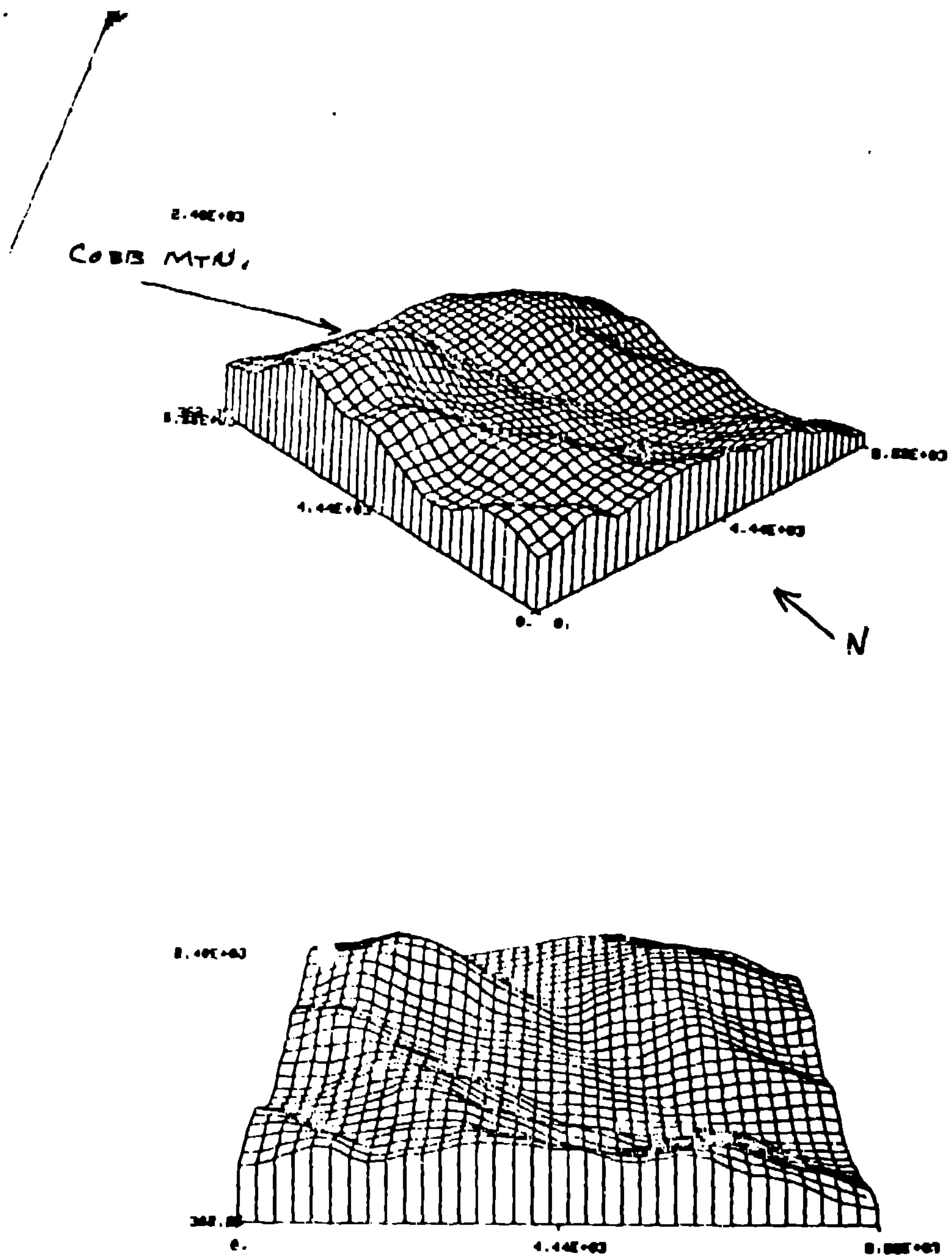

Fig. 4. An example of a computer-generated perspective view of the topography in the Cobb Mountain Anderson Creek Valley Area of northern California.

Fig 4