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A Report of a Workshop Held

at Keystone, Colorado

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OFFICE OF RESEARCH AND DEVELOPMENT
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RESEARCH TRIANGLE PARK, NORTH CAROLINA 27711

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by

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NOTICE

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PREFACE

One of the most formidable challenges to the meteorological community is to satisfy the need for a capability to reliably describe, explain, and predict the behavior of the atmosphere in complex terrain. The infinite variations in the size, shape, slope and orientation of ridges and valleys, coupled with land and water interfaces, cause radical alterations in the characteristics of the atmosphere's boundary layer over short distances and time periods. Natural resources that are important to economic development and to recreational needs are often concentrated in such locales. Consequently, interests of those seeking to preserve certain amenities of life for themselves and future generations are often at variance with the interests of those seeking industrial growth. Equitable resolution of disputes over the use of resources and the degree of protection of the amenities frequently centers on the capability to assess the circulation and dispersion characteristics of the near surface portion of the atmosphere. The magnitude of the impact on air quality by human activity is a direct function of the atmosphere's behavior in complex terrain.

This report contains the thoughts and judgments of 32 atmospheric scientists who gathered to exchange recently acquired technical information and research results on atmospheric processes in complex terrain and to comment on matters relating to adjustments in current air quality modeling practices.

Since 1979, the American Meteorological Society (AMS) has collaborated with the Environmental Protection Agency (EPA) through a cooperative agreement to improve the scientific basis of air quality modeling. The organization of this Workshop on Dispersion in Complex Terrain has been carried out under this cooperative program.

I am indebted to the following people who participated in this workshop: S.P.S. Arya, North Carolina State University; S. Barr, Los Alamos Scientific Laboratory; W. Blumen, University of Colorado; N. Bowne, TRC Environmental Consultants, Inc.; L. Crow, Denver, CO; R. Fisher, EPA, Denver; D. Fox, USDA Forest Service; S. Hanna, Environmental Research & Technology, Inc.; D. Henderson, U.S. Park Service, Denver; T. Lavery, Environmental Research & Technology, Inc.; R. McNider, Department of Environmental Management, State of Alabama; R. Meroney, Colorado State University; W. Ohmstede, U.S. Army Atmospheric Sciences Laboratory; R. Petersen, NHC Wind Engineering; R. Pielke, Colorado State University; D. Randerson, NOAA Weather Service Nuclear Support Office; K. Rao, NOAA Atmospheric Turbulence & Diffusion Lab.; R. Rowe, University of Calgary; F. Schiermeier, EPA, Research Triangle Park; H. Slater, University of North Carolina; M. Smith, Meteorological Evaluation Services, Inc.; R. Smith, Yale University; W. Snyder, EPA, Research Triangle Park; G. Start, NOAA Air Resources Laboratories; R. Sykes, ARAP, Inc.; J. Tikvart, EPA, Durham; J. Weil, Martin Marietta Laboratories; F. White, National Research Council; D. Whiteman, Battelle Pacific Northwest Laboratories; G. Wooldridge, Utah State University; and J. Wyngaard, National Center for Atmospheric Research.

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Bruce A. Egan
Workshop Chairman

ABSTRACT

Since 1979, the American Meteorological Society has collaborated with the Environmental Protection Agency through a cooperative agreement to improve the scientific basis of air quality modeling. Under this continuing agreement, the American Meteorological Society conducted a workshop on dispersion in complex terrain in Keystone, CO, during May 17-20, 1983. The purpose of the workshop was to encourage atmospheric scientists working in the area of complex terrain dispersion modeling to exchange recently acquired information on atmospheric processes in mountainous terrain and to make recommendations regarding both the present application of air quality models to complex terrain settings and the research necessary to meet future needs.

This report contains the thoughts and judgments of 32 atmospheric scientists who gathered to exchange such technical information and research results on atmospheric processes in complex terrain and to comment on matters relating to adjustments in current air quality modeling practices.

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EXECUTIVE SUMMARY

The presence of mountainous terrain introduces significant complexities into the atmospheric transport and diffusion processes affecting ambient air quality concentrations in a given area. Terrain acts to distort otherwise organized flow patterns resulting in the creation of regions of converging and diverging flows, enhanced shear effects, and turbulent eddies. These alterations affect both flow trajectories and ambient turbulence levels to a large degree. Terrain also determines the development of local circulations in mountain-valley settings. The net effect on air pollution concentrations depends critically on the specific geometric and topographic relationships and on the characteristics of the flow fields. For similar source sizes and release heights, emissions from an air pollution source located in complex terrain may result in concentrations on nearby high terrain several times larger than the maximum concentration expected in the absence of the high terrain.

Similarly, stagnation effects in confined valleys can result in the build-up of concentrations much higher than those which would be observed under similar large scale meteorological conditions over flat terrain. For these reasons, the prediction of air quality concentrations in regions of complex terrain has remained a key area of concern for regulatory agencies and methods for quantifying atmospheric dispersion processes have received considerable attention over the past several years.

This workshop was convened by the American Meteorological Society via a cooperative agreement with the U.S. Environmental Protection Agency. Its purpose was to encourage atmospheric scientists working in this area to exchange recently acquired information on atmospheric processes in complex terrain and to make recommendations regarding both the present application of air quality models to complex terrain settings and the research necessary to meet future needs.

The following summarizes the major conclusions of the workshop about the present state-of-understanding of dispersion in complex terrain.

(1) Interaction of Elevated Plume with Windward Facing Terrain Features

The largest ground-level concentrations associated with elevated releases near terrain rising above plume height are often associated with stable atmospheric conditions. The dynamics of the air flow depends upon the Froude number of the upstream flow based on hill height. A related parameter, the dividing or critical streamline height appears to vertically separate a flow regime which can transport a plume up and over a terrain object from a flow regime which constrains plumes to stagnate or to pass around the sides of a terrain feature. Verification of the above concepts has emerged from physical modeling efforts for a variety of terrain shapes and the concepts are supported by field measurement results. Mathematical models are presently being refined for these situations. Further verification is needed, however, to understand the applicability of the concept to a broader variety and larger scales of terrain geometries.

(2) Turbulent Dispersion Rates in Regions of Complex Terrain

Atmospheric turbulent dispersion rates in complex terrain can often be expected to exceed those over flat terrain for otherwise similar conditions. This is especially true under stably stratified conditions and results from the presence of gravity-driven drainage flows, gravity waves, the production of shear from flow deformation, and the creation of eddies from upwind terrain features. The effect on ground-level concentrations depends upon the specific source-receptor geometry.

(3) Lee Side Effects

The flow on the lee side of terrain features can, under certain conditions, also cause high ground-level concentrations. During neutral conditions, flow "separation" can occur on leeward slopes, causing poor ventilation of emissions from lee side sources within the wake cavity region. Under stably stratified conditions, streamlines passing over the crest may pass closest to the surface on the leeward side. This could give rise to highest ground-level concentrations on the lee side from plumes originating upwind of a terrain feature. No widely accepted models exist for these situations.

(4) Valley Situations

A number of air pollution phenomena are associated with the constraints on ventilation that valleys impose or with the gravity-driven local flows created by valley side walls. The most severe effects are the occurrence of multi-day air pollution episodes within deep valleys during periods when high pressure systems stagnate over a region. Mathematical models for air pollution applications in deep valleys are largely in the development stage at the present time.

(5) Physical Modeling Capabilities

The use of physical modeling principles with wind tunnels and towing tanks has increased markedly over the past several years. These techniques allow systematic investigations of flow situations under controlled conditions not practically achievable with field studies. Properly interpreted, the results of these tests add substantially to our understanding of phenomena. Limitations remain for the study of two-dimensional terrain features under stable conditions and in the spectral range of turbulence which can be simulated.

(6) Mathematical Modeling Capabilities

As new information is emerging from theoretical efforts, physical modeling and field experiments, better and more refined mathematical models are being developed. Models have been developed or are under development to simulate many of the phenomena identified as important. No model exists which can simulate all of the phenomena for a given setting. The verification of models is difficult due to the general lack of extensive data bases. The trend of lower computer costs with time will encourage the development of more advanced models capable of using more extensive input data.

Recommendations emerging from the workshop were in several areas.

(1) Recommendations on the Use of the Science

- The workshop participants supported the approach taken by current major research efforts in gathering field and laboratory experimental data for ultimate use in developing better mathematical models.

- A need to quantify uncertainty in model predictions was identified together with the recognition that this involved obtaining more information about flow conditions than is generally needed to estimate mean values from deterministic models.

- A viewpoint was taken that the dispersion of pollutants in complex topography involved interactions of air flows and terrain structure leading to certain natural fluid dynamic time and space scales which would not necessarily be important for simpler (e.g., flat) terrain problems. If such time scales are larger than the averaging time of application interest, estimates of concentrations by deterministic models would contain larger uncertainties. This resulted in the suggestion that the stochastic nature of the phenomena be recognized and accepted by those developing or applying models for these circumstances.

- The meteorological input data needs for complex terrain models is greater than those required for level terrain models. Specific requirements for vertical profiles of temperature and velocity emerge from the need to estimate Froude numbers and dividing streamline height. On-site turbulence measures were also identified as being especially appropriate for complex terrain modeling efforts.

(2) Recommendations on Research and Development Needs

The workshop participants identified a number of specific technical areas needing further research to further advance our ability to predict ground level concentrations of pollutants in complex topography. Table 1 lists the topics in summary fashion and identifies the status of available observational data, physical conceptualizations, and modeling efforts. The order of topics in this list does not signify the order of priorities.

Summation of the Keystone Workshop
May, 1983

1. Introduction

The need to estimate reliably the impact of emission sources in regions of complex terrain for regulatory decision-making purposes remains as a key challenge to the meteorological community. It has been identified as an area for further study and as a controversial area at all of the public hearings on the EPA Air Quality Modeling Guidelines, and at numerous professional society meetings and conferences. The report of the AMS/EPA Cooperative Agreement "Air Quality Modeling and the Clean Air Act" (AMS, 1981) identified dispersion in regions of mountainous terrain as one of the most important areas for further research and development activities.

The subject has in fact received considerable professional attention over the past several years as is evident from the large number of papers presented at AMS and APCA meetings as well as other specialty meetings and workshops. In July of 1979, the EPA sponsored a "Workshop on Atmospheric Dispersion Models in Complex Terrain" (Hovind et al., 1979) for purposes of developing specific recommendations to EPA with respect to the design of a multi-year program to address complex terrain modeling problems. On the basis of this, the EPA subsequently began a multi-phased program of field studies, physical modeling experiments and mathematical model development. Independently, the Electric Power Research Institute (EPRI), as part of their Plume Model Validation and Development (PMV&D) study (Bowne et al., 1983), has undertaken a field program which will include two experiments in complex terrain. The Department of Energy's Atmospheric Studies in Complex Terrain (ASCOT) program (Dickerson et al., 1980, 1983) has been investigating the problem from the perspective of energy development needs including geothermal power and oil shale. Although none of the above large research efforts is completed, they are at the stage where considerable field and laboratory experience has been gained. Also, a number of mathematical model development activities have been pursued and findings from these experiences are rapidly becoming available. For these reasons, the Steering Committee of the AMS/EPA Cooperative Agreement decided that it would be timely to review the progress made in this field and to encourage a discussion about what has been learned, what the implications are to present practice in dispersion modeling, and what these experiences might suggest with respect to possible augmentations to current research efforts.

To achieve these objectives, this Workshop on Dispersion in Complex Terrain was organized and conducted. The agenda for the workshop and a listing of the attendees are included in the Appendix. The specific purpose was to provide a forum for the exchange of technical information on atmospheric dispersion processes in mountainous terrain and the relationship of this information to the modeling of air quality concentrations in terrain settings. A specific focus for the workshop was to provide scientific information for use in the activities of EPA. The workshop's agenda emphasized measurements and observational data at the beginning. This focused attention on the new information obtained from field studies over the past few years and on the importance of understanding meteorological phenomena for model development in regions of complex terrain.

Following presentations on observed phenomena, the workshop proceeded to foster discussions focusing on modeling techniques - mathematical and physical. These topics were divided into three sections:

(1) Flow Field Modeling. Presentation and discussion on theory and practice of simulating the wind and temperature fields in complex terrain settings.

(2) Physical Modeling. Presentation and discussion on the use of and results from physical modeling experiments in wind tunnels and towing tanks.

(3) "Regulatory" Modeling. Presentation and discussion focusing on experiences and practice in predicting ambient concentrations for use in regulatory decision-making.

The final sessions of the workshop involved dividing the participants into two groups to address: (1) how recent findings should affect current practice in the application of models; and (2) future information and research needs. These included the development of recommendations or identification of consensus on modeling approaches, identification of areas needing further information, and recommendations to the technical and regulatory community at large regarding how to achieve future needs.

This document presents the conclusions made regarding the state-of-the-science of dispersion modeling in complex terrain, recommendations made on the use of the science for the application, and recommendations on future research needs.

2. State of the Science Review

A Phenomena of Importance

In this chapter, phenomena which are of special importance to the problem of estimating atmospheric dispersion processes in or near complex terrain are described. Where the phenomena are easily described by mathematical algorithms, these are presented.

(1) Interaction of Elevated Plumes with Windward Facing Terrain Features

Flow Parameters Affecting Flow Trajectories. If a source of emissions is located near a hill that is taller than its stack or release height, the possibility exists that the highest concentrations to be expected in the area will occur on the facing hillside when the airflow is from the stack toward the hill. These high concentrations would be expected either by direct plume impaction during strongly stable conditions, or by near misses as the streamlines pass close to the hill during less stable, neutral or unstable conditions. This section of the report addresses our knowledge of flow conditions on windward facing terrain features.

The presence of mountainous terrain has several effects on the flow upwind and above the terrain. It acts to distort the flow field causing accelerations/decelerations and associated turning, contractions and expansions of air parcels as they pass by terrain features. It also acts to alter the structure of turbulence within the region of flow near the surface. The dynamics of the ambient flow field upstream of a hill depend critically on the ambient density (or temperature) stratification.

In very stable conditions, vertical motion is opposed by restoring buoyancy forces. The stratification effect can be characterized by a Froude number Fr given by

$$Fr=U/Nh \quad (1)$$

where U is a characteristic wind speed for the upstream flow; N is the Brunt-Vaisala frequency given by

$$N = [-\frac{g}{\rho}\frac{\partial \rho}{\partial z}]^{1/2} \quad (2)$$

where g is the gravitational acceleration, ρ is the air density, and h is the hill height. The Froude number can be interpreted as a ratio of inertial to buoyancy forces in a fluid. Moderate to neutral stability (dominated by inertial effects) includes the range $1 < Fr < \infty$, whereas strongly stable conditions (dominated by buoyancy effects) encompass the range $0 < Fr < 1$.

One of the outstanding features of strongly stable flow about three-dimensional hills is the passage of fluid around the hill in essentially horizontal planes below some height H_c, which depends on the stratification. Above this height, fluid passes both over and around the hill; the height H_c is commonly called the "critical height" or "dividing streamline height." The idea of a region of horizontally layered flow was first predicted theoretically by Drazin (1961) for axisymmetric hills, and later confirmed in laboratory experiments for similar geometries by Riley et al., (1976), Brighton (1978), and perhaps most convincingly by Hunt et al., (1978). The last authors showed experimentally that for a uniform upstream velocity profile and a constant density gradient, H_c is given by

$$H_c = h(1-Fr) \quad (3)$$

This formula is consistent with a simple energy balance argument for an air parcel as first put forth by Sheppard (1956). Sheppard postulated that for a given environmental lapse rate, one could calculate the value of horizontal velocity far upwind which would enable air to just surmount a hill by equating the kinetic energy of a fluid parcel upwind to the potential energy change associated with lifting the parcel to the hillcrest. Snyder et al. (1985) have extended this argument to arbitrary velocity and density profiles and to a wide range of hill shapes with the result

$$1/2\ \rho U^2(H_c) = \int_{H_c}^{h} \rho N^2 (h-z)\,dz \qquad (4)$$

where H_c must in general be determined iteratively.

For two-dimensional ridges or very long finite ridges, the fluid can be blocked (i.e., effectively become stagnant) ahead of the obstacle. For these geometries, a well accepted formula for the dividing streamline height does not yet exist. In addition, there is ambiguity on the upstream extent of the blocked-fluid region and the variation in depth of the region with upstream distance. Thus, while solid evidence exists for flow field and H_c behavior for three-dimensional hills of not too large an aspect ratio, further experimental laboratory and field work is required to extend the dividing streamline concept to more general topography.

In addition to more experimental work, a more complete model is required for the dividing-streamline height. The simple energy argument of Sheppard assumes that the air parcel has a zero horizontal velocity at hilltop. However, this assumption is inconsistent with observed flow fields which show that fluid speeds up at the top of the hill. A more complete model is required to adequately explain the above speedup phenomena and to ensure reliable extension of the H_c concept to more complex geometries. For example, in less strongly stratified flows (Froude number greater than, but near unity), the hydrostatic solution of Smith (1980) is probably more applicable than potential flow. Whereas potential flow suggests symmetrical streamline patterns upwind and downwind of a symmetrical terrain feature, the hydrostatic solution does not.

In Smith's model, about halfway between h and H_c, stronger lateral streamline deflections will begin. These deflections are very sensitive to initial upstream elevation, so that a plume will spread into a dome shape covering the top of the mountain.

Near H_c the flow will be brought to rest and the flow will split. The plume will probably go to one side or the other and may oscilate back and forth, being very sensitive to upstream flow direction. Large concentrations are expected near this level as well as large apparent lateral diffusivity.

Dispersion in Strongly Stratified Flow. Strongly stratified flow below H_c has insufficient kinetic energy to pass over the hillcrest and, neglecting wind shear effects, such flows can be considered essentially horizontal as they pass around a hill. When the plume is flowing along the stagnation streamline, the plume will "impinge" on the hill resulting in surface concentrations nearly as large as those in the elevated plume's center (Snyder and Hunt, 1984).

Along the stagnation streamline, the flow diverges as it approaches the hill. Hunt et al., (1979) show that the large increase in the crosswind dispersion coefficient, σ_y, caused by diverging streamlines is almost compensated for by the decrease in wind speed, U, as the stagnation point is approached, and that at the stagnation point, $\sigma_y U$ is approximately the same as it would have been in the absence of the hill. These arguments suggest that the concentration at the stagnation point is approximately equal to that which would occur in the atmosphere without the hill. Full doubling of the concentration values due to surface "reflection" effects does not occur under these conditions.

Surface concentrations at an assumed point of impingement or stagnation can be estimated during plume meandering conditions by integration over the changes in wind direction. During any quasi-steady period, the concentration at the stagnation point is given by $C_i(\theta, \theta_d)$ where θ is the wind direction and θ_d is the stagnation wind direction. The hourly concentration is given by:

$$C_{max} = \int_\theta C_i(\theta,\theta_d)P(\theta)d\theta \tag{5}$$

where $P(\theta)$ is the frequency distribution of wind directions (Strimaitis et al., 1983). If the plume spread is due principally to plume meander, then

$$C_{max} = \bar{C}P(\theta_d)\alpha_s,$$

where

$$\bar{C} = Q/(\sqrt{2}\pi\sigma_z U\alpha_s x),$$

$$\theta = \theta_d \pm \alpha_s/2,$$

and x is the distance from the release to the stagnation point. If $P(\theta)$ is Gaussian, then

$$C_{max} = \frac{Q}{2\pi\sigma_z U\sigma_\theta x} \exp\left[-\frac{(\theta_o-\theta_d)^2}{2\sigma_\theta^2}\right] \tag{6}$$

where σ_θ is the standard deviation of the wind direction about the mean wind direction θ_o. $P(\theta)$ can also be specified explicitly by the observed distribution of winds during the hour.

Experimental Evidence. Snyder et al. (1982, 1985) have shown agreement of Eqn. 4 with laboratory simulations under stably stratified conditions. These tests were made at the EPA Fluid Modeling Facility and in the stratified wind tunnel at the Japanese National Institute for Environmental Studies. The concept of H_c was examined for a bell-shaped hill, a cone, a hemisphere, triangular ridges, a sinusoidal ridge, vertical fences and for a scale model of Cinder Cone Butte (CCB) near Boise, Idaho. Snyder and his co-workers have concluded that the integral equation for estimating H_c accurately predicted the separation of the flow regimes for a wide range of hill shapes and profiles.

The EPA-sponsored Small Hill Impaction Studies, conducted at Cinder Cone Butte (CCB), Idaho, and Hogback Ridge (HBR), New Mexico, (Lavery et al., 1983) have also shown that the integral formula for H_c discriminates between the flow regimes for both an isolated axisymmetric hill (CCB) and a very long ridge (HBR). Photos of oil-fog plumes and ground-level concentration patterns of two tracers released clearly distinguishes between the horizontal flow and the flow that goes over the hills. The H_c concept and its ability to predict whether plumes impinge upon a hill and pass around it or travel up and over a hill was also found by Ryan and Lamb (1984) and Ryan et al. (1984) to be valid at Steptoe Butte, a large (335 m), isolated hill in eastern Washington.

An analysis of the observed tracer gas concentrations and the meteorological data at CCB showed that the highest χ/Q occurred when the release height, H, was near or slightly higher than H_c. During this situation the plume was transported directly toward the hill and produced high ground-level concentrations. Lower releases tended to be transported around the hill sides and releases above H_c were transported up and over. The highest normalized concentration occurred when $H \sim H_c$.

The HBR experiment also showed that H_c discriminates between the flow regimes, although the nature of the flow below H_c is currently under investigation. A preliminary analysis of 34 tracer-hours showed that the highest χ/Q occurred when $H \leq H_c$.

Further field observations showing horizontal flow about larger-scale terrain features at low Fr have been reported by Williams and Cudney (1976). Field experiments by Rowe et al., 1982 also tended to validate the dividing-streamline concept for a ridge with a length about 50 times its height of 80 m.

Thus, there appears to be consistent agreement between field and laboratory observations on the flow structure over a three-dimensional hill, in particular the horizontal nature of the flow below H_c and the dependence of H_c on stratification. This is true for axisymmetric hills and for hills with small aspect ratios (with width/height ratios as large as 16) (Snyder et al., 1985).

Field experiment verification is still needed for the validity and applicability of the dividing-streamline concept for large terrain features (greater than several hundred meters).

Flow over Terrain during Neutral Conditions. It is generally accepted that the first-order effects of terrain on the flow on the windward face during neutral conditions can be estimated using modifications to potential flow theory (Hunt and Mulhearn, 1973; Hunt et al., 1979). For regulatory applications, a practical approach involves the superposition of a Gaussian plume model (steady state or "puff" type) onto trajectories determined by potential flow approximations (Isaacs et al., 1979; Hunt et al., 1979). Egan (1975) demonstrated that the "half-height" terrain correction factor followed from approximations of the effects of potential flow over a hemisphere but a "terrain-following" plume path assumption provided first order estimates for neutral flow over a two-dimensional (ridge-like) shape. Neutral conditions often are associated with high wind speeds and synoptically persistent meteorological conditions. Thus neutral conditions can be of importance to the maintenance of 24-hour average ambient air standards or Prevention of Significant Deterioration (PSD) increments, especially where "channeling" effects of terrain features on the wind fields are important.

Dispersion during Unstable Conditions. For most regulatory applications, "worst case" conditions for sources close to high terrain are expected to occur during stable or neutral conditions. For this reason, phenomena during unstable conditions have not been studied in depth. Because of the differential heating of mountain slopes during daylight hours, convection effects do result in sustained and significant updrafts and downdrafts. Also "fumigation" of pollutant material onto hilltops in mid to late mornings has been observed to result in short durations of high concentrations. Currently available models generally use the flow trajectories for neutral conditions also for unstable conditions.

Turbulence Levels in Regions of Complex Terrain. In general, turbulence levels over complex terrain are expected to be higher over complex terrain than over level terrain for the same atmospheric stability classification. These increased turbulence levels are most likely a result of the following phenomena.

(a) Nocturnal, radiational cooling which produces surface inversions is often coupled with very low wind speeds in level terrain and is likely to result in the generation of gravity-driven drainage flows in complex terrain. These flows result in the mechanical production of turbulence and time-dependent nonstationary secondary motions which periodically sweep the terrain.

(b) Topographic alteration of flow direction and speed will result in the production of shear in all directions which not only contributes to the production of turbulence but also results in large flow meandering.

(c) In complex terrain the presence of flow stratification is a key element in the production of regions of rapid flow acceleration and deceleration, waves, rotors, and "hydraulic" jumps which tend to produce shearing motions, and associated turbulence.

The effects of the above relative to flat terrain seem to be largest under stable conditions. During neutral and unstable atmospheric conditions, the effects of terrain on increasing turbulence levels generally appear to be smaller (Start et al., 1975; Egan, 1975).

Lateral turbulence levels in complex terrain are generally enhanced to a greater extent than vertical turbulence. Plume meandering and uplifting as a result of interactions with upwind terrain are reasons cited for an increase in horizontal dispersion rates. The extent to which such rates are larger at higher elevations above terrain is not well quantified. When the atmosphere is stably stratified, generalizations are difficult. Air parcels downwind of a ridge may be rapidly dispersed upward (or even upwind) by rotor zones or other eddy motions associated with lee side phenomena. Note, however, that terrain features, especially ridge-shaped features, can contribute to large scale stagnation of the air flow (blocking) at base locations and can result in very low winds with little net transport of pollutant material into or out of an area.

(2) Lee-Side Effects

Previous discussion has focused on the phenomena of importance in determining ambient air quality concentrations on upwind-facing slopes. Mathematical and physical modeling shows that high concentration can also be expected, for certain meteorological conditions, on the leeward slopes of mountains downwind of a source. Field measurements are uncommon for these situations as regulatory requirements have generally focused on obtaining information on the upwind facing slopes nearest to a pollution source.

This section provides a brief overview of the current understanding of flow in the lee of hills.

Neutral Flow. Simple flow field models, e.g., potential flow coupled with rapid distortion theory, work reasonably well for predicting surface concentrations on the upwind faces of hills, both two-dimensional and three-dimensional. However, these simple models are inadequate for predicting wake effects, even for hills of moderate slope (i.e., 15 degrees for two-dimensional hills and 25 degrees for three-dimensional hills), let alone for steep hills with separated wakes. Flows on the lee sides of hills are among phenomena expected to cause high ground-level concentrations in the vicinity of terrain and for which no routine model simulation techniques are available.

Snyder (1983) summarized a variety of idealized neutral-flow wind tunnel studies of plumes from stacks located both upwind and downwind of various terrain shapes. The results show that ground level concentrations on the lee side of the obstacle can be many times higher than would be expected if the terrain were not present. This increased concentration over the "no-obstacle" concentration when expressed in a ratio is termed the "terrain amplification factor" (taf). It is specifically defined as the ratio of the maximum concentration occurring in the presence of the hill to the maximum concentration that would occur from the same (elevated) source if it were located in flat terrain.

Physical modeling experiments using simulated atmospheric boundary layers show that plumes released downwind of variously shaped two-dimensional hills all resulted in taf's of 10 to 15, whereas plumes released upwind or on top of the hills produced taf's of 2-4. Two lee-side phenomena were observed to produce high taf's. One was the reverse flow within a cavity that recirculated plumes from stacks as high as the hill. The other was flow that had not separated but due to the low transport speeds and high turbulence levels, plumes dispersed rapidly to the ground farther downwind. High taf's were also observed from sources located on the lee-sides of three-dimensional hills. The highest taf's occurred when the source was placed approximately on the separation-reattachmert streamline. In the 3-D cases, higher crosswind aspect ratios (across wind length of hill divided by hill height) generally produced higher taf's for downwind sources and smaller taf's for upwind sources.

Physical modeling results indicate that typical lengths of reversed flow regions are of order 10 hill heights for two-dimensional hills and 2 to 10 hill heights for three-dimensional hills. In addition, strong trailing vortices downwind of three-dimensional hills have been observed in laboratory studies. The strong downwash caused by these vortices can result in large surface concentrations.

While no specific mathematical models can be suggested at this time, it is recommended that sources located 10 hill heights or closer downwind of a terrain feature be investigated for possible high impacts due to the obstacle. While physical modeling provides a cost-effective means for examining such a system systematically, field studies based upon detailed tracer releases can serve to identify maximum ground level concentrations. Snyder (1981) and references in Snyder (1983) provide information on the proper use of physical models to account for lee side influences.

Stratified Flow. Under strongly stratified flows, pollutants released below the dividing-streamline height on the lee side of hills have been observed to be recirculated to the hill surface and to cover a narrow vertical band spread over roughly a 180 degree sector of the hill surface. Whereas instantaneous concentrations are observed to be considerably lower than those associated with impaction (from upwind sources), long-term-average concentrations may be larger than impaction concentrations because the wind meander will significantly reduce the time-averaged impaction concentrations, but not the lee-side concentrations. Even simple models for predicting lee-surface concentrations from downwind sources are not available.

(3) Valley Situations

Many air pollution sources such as cities, roads, industrial operations and energy production facilities are located in mountain valleys. It has been recognized for at least 40 years (Hewson and Gill, 1944) that air pollution problems can arise from these sources due to the special meteorological processes that occur in valleys.

The workshop attendees separated the discussion of the dynamics of individual plumes interacting with high terrain from discussions of the special flow conditions associated with valley settings. The processes identified to be of special importance to the valley situations include nocturnal drainage flows, fumigation, flow channeling by valley sidewalls, and persistent low wind speed stable flows. For purposes of presentation, it is convenient to distinguish between relatively shallow valleys, deep, draining valleys, and closed valleys.

Shallow Valleys. Shallow valleys were defined by comparison of valley sidewall height to the effective height of a plume from a source affecting air quality in the valley. A valley is "shallow" if the plume is significantly higher than the terrain features. Under these conditions, the plume is cut off from the valley boundary layer during stable conditions and reacts in a manner analogous to a plume over flat terrain. Although the trajectory of the plume may be steered somewhat by the valley orientation, the centerline of the plume is higher than the valley sides or ridges forming the valley.

Preliminary results reported at the workshop and described by Reynolds et al., (1984) from the EPRI Plume Model Validation and Development project tracer studies at Bull Run, Tennessee (a shallow valley), indicated that terrain influences on lifting of the plume paths were not observed as the plumes from the facility usually followed trajectories that were parallel to the valley axes. Other analyses (e.g., Turner and Irwin, 1982) indicate that flat terrain models overestimate the ground level concentrations on terrain if the plume centerline is not deflected upward.

Deep, Draining Valleys

Scientific investigations of valley flows have, so far, focused primarily on improving our understanding of the physics of valley meteorology, and only a few important research studies have focused directly on air pollution investigations (e.g., Start et al, 1975; Hewson and Gill, 1944). An improved understanding of valley nocturnal drainage flows is now becoming available from the U.S. Department of Energy's Atmospheric Studies in Complex Terrain (ASCOT) program (Dickerson, 1980, 1983). Other work has focused on the breakup of nocturnal valley temperature inversions in deep valleys (Whiteman, 1982). This work has led to a thermodynamic model of temperature inversion breakup (Whiteman and McKee, 1982) and, more recently, to an initial model of air pollution concentrations produced on the valley floor and sidewalls due to post-sunrise fumigations of elevated nocturnal plumes (Whiteman and Allwine, 1983). In these studies the effects of convective boundary layers which grow over heated valley surfaces after sunrise, the effect of upslope flows produced over the sidewalls, and the effect of compensating subsiding motions over the valley floor have been simulated but need field evaluations.

In actual valleys, topographic complications can be expected to greatly influence the development of local circulations and the dispersion of pollutants emitted within the valley. The diversity of valley shapes, orientations, presence of tributory valleys, and presence of terrain constrictions along the valley axes can be expected to influence the development of the along-valley circulations, turbulence levels, and other important aspects of valley meteorology.

Closed Valleys. Certain valleys with weak or obstructed outflow have been characterized as trapping valleys in contrast with draining valleys with vigorous outflow. The accumulation of cool air draining from the sides of the trapping valleys will build up a deep, stable layer during nighttime hours that is capped by a stronger inversion at the interface with the above-valley air near the top of the cold pool. Pollution plumes emitted into this domain are likely to be confined below the inversion and between the valley sidewalls.

In addition to diurnal trapping regimes, certain synoptic conditions produce stagnation episodes. High pressure systems characterized by low wind speeds, clear or foggy skies, subsidence inversions and nocturnally-produced ground level inversions, may exist for 4-5 day periods. During these episodes, additional emissions are not compensated by flushing so that air quality can continually degrade to the point of threatening human health. The pollution conditions are not stationary, as there may be sloshing of air masses within the valley. The DOE ASCOT program characterized diurnal pooling and stagnation within one California valley in 1979 and 1980. Murphy et al., (1984) studied the accumulation of smoke from space heating in a trapping valley in Colorado and Marlatt et al. (1981) studied the structures of a trapping valley inversion.

The shape of a closed valley creates unique flow regimes. Limited field data show that nighttime radiational cooling of the surrounding mountain slopes can create a downslope drainage flow that appears to reach maximum strength just prior to local sunrise. The drainage flow tends to move toward the lowest point in the valley. Available data are inadequate to determine if a gyre usually develops over the valley low point prior to sunrise. Some observations from the Nevada test site (Randerson, 1984) indicate that material released at ground level within a closed valley at night can be transported out of the valley. The implications of this situation for air quality modeling are clear. An effluent released into a stratified environment can be transported out of the valley, and this is difficult to explain physically. No data are available to permit a quantitative description of the behavior of effluents released into a thermally-stratified valley.

Dispersion over Complex Terrain with Superimposed Convective Circulation. In flat terrain, convective flows frequently lead to the fumigation of pollutants trapped aloft or the early downwash of a looping plume resulting in high ground level concentrations. Convective flows developing over hills, ridges, or more complex terrain may significantly alter streamline patterns, separation and stagnation locations, and hill wake turbulence. It is possible that non-homogeneous radiative heating caused by slope orientation could result in different convective scales than commonly associated with horizontal terrain. These perturbed spatial or time scales could result in worst-case ground-level concentrations from lee impaction, sudden subsidence or downdrafts.

Orgill (1981) cites the pioneering studies by Hewson and Gill (1944) and describes two types of fumigation phenomena within valleys. Type I, a simple diurnal fumigation, occurs during the early morning hours when surface heating develops convection up to an elevated plume. Pollution reaches the valley bottom nearly simultaneously throughout the valley in this case. Type II, a dynamical fumigation (Tyson, 1968), may also be related to the morning transition when an up-valley wind undercuts the well developed, down valley, mountain wind. A marked discontinuity in the wind and turbulence fields is produced, leading to severe dynamic fumigations. In this case the fumigation event propagates up-valley with time. Whiteman and McKee (1979) have identified wind and temperature structures associated with the conditions for dynamic fumigation. Associated with the 1982 ASCOT field program, Whiteman et al., (1984) performed tracer experiments to further document the time and space character of the fumigation.

One of the major aims of the DOE ASCOT program is to contribute to a better understanding of the relationship of the details of these fumigation phenomena to the structure of the winds, temperature, turbulence and valley topography.

B Physical Modeling Capabilities

The report of the 1979 Workshop on Complex Terrain (Hovind et al., 1979) has a fairly detailed discussion on the background and similarity criteria for physical modeling in mountainous terrain. In addition, the workshop document discusses the relative merits of the wind tunnel and towing tank. Since the workshop, the EPA has published a document (Snyder, 1981) that describes in detail the fundamental principles, practical applications and the hardware associated with physically modeling atmospheric dispersion. EPA also has published a guideline document (Huber, 1981) that specifies the necessary elements of a physical modeling study for assessing the stack height required so that a plume is not adversely affected by wakes and eddies of nearby terrain (or buildings).

(1) Comparisons of Field Data with Laboratory Results

Since the 1979 workshop, several comparisons of physical model simulations with actual field observations have been made. Weil et al., (1981) described field and wind tunnel experiments conducted for the Westvaco Pulp Mill situated in the hilly terrain of Western Maryland. The wind profiles measured at similar locations under unstable stratification in the wind tunnel and in the field showed good agreement as did the ground-level concentrations on the windward side of a nearby hill. The observed concentrations in the wind tunnel were consistently lower than those in the field on the leeward side of the hill but only by a factor of about 1.6.

Snyder and Lawson (1981) reported on a series of experiments attempting to simulate, in a towing tank, field results from the Cinder Cone Butte, Idaho experiment. In particular, one hour from the field experiment that represented very stable atmospheric conditions was simulated. The results of the tests showed that the crosswind concentration distributions in the towing tank were exceedingly narrow and that maximum concentrations were 5 to 10 times larger than those observed in the field. This was attributed to the fact that low frequency fluctuations in wind speed and wind direction are not present in the towing tank. An ad hoc attempt was made to simulate the low frequency wind fluctuations by superimposing concentration patterns from tows done at a series of discrete wind speeds and wind directions. This attempt was moderately successful in that 80% of the model concentrations were within a factor of 2.5 of the field concentrations. Snyder and Lawson felt agreement would have been better had wind data at plume altitude been available.

Other field/laboratory comparisons for complex terrain settings include studies by Meroney (1980) and Meroney et al. (1980), which simulated wind speed and direction measurements at sites in New Zealand and Hawaii. The measurements in the laboratory correlated well with those in the field.

(2) Complex Terrain Applications of Physical Modeling

Since the promulgation of the stack height regulation in 1979, numerous physical modeling studies have been conducted to evaluate the effect of terrain wakes and eddies on dispersion (Greenway et al., 1981; Petersen and Cermak, 1979; Petersen, 1981; to list a few). These assessments have demonstrated that physical modeling can be used in a regulatory environment to define good-engineering-practice stack heights.

Mountain-valley and drainage wind simulations were conducted (Petersen et al., 1980; Cermak and Petersen, 1981) to provide qualitative information about flow in deep valleys and quantitative information for use in refining and calibrating a numerical model. The physical simulation was also used to assist in the design of a field experiment.

Petersen and Twombly (1982) conducted a wind tunnel experiment to evaluate maximum concentrations on elevated terrain under stable stratification. They compared the EPA Valley model and a new model that included potential flow theory and the dividing streamline concept with the wind tunnel simulation. The average ratio of Valley model prediction to wind tunnel observation was 2.6 whereas the ratio for the new model was 1.2.

Snyder (1983) conducted neutral flow wind tunnel experiments with a stack situated upwind, on-top and downwind of three different shaped hills. Ground-level concentrations were then measured with and without the hill present. An amplification factor was defined to be the ratio of maximum concentration with and without the hill. Snyder summarized these amplification factors as a function of hill shape, stack location and stack height.

These studies by no means represent all the applications of physical modeling since 1979. It is apparent, however, that physical modeling has been used to assess concentrations in complex terrain for the following situations: 1) plumes impacting elevated terrain under neutral, unstable and stable stratification, 2) plumes affected by the wakes and eddies of upwind terrain, 3) plumes released in deep valleys under stable nighttime conditions.

C Mathematical Modeling Capabilities

One of the more important effects of complex terrain on the plume transport and diffusion problem is the modification of the ambient flow field. Flow field assumptions in existing diffusion models for regulatory applications are quite crude. For example, diffusion models for computing concentrations on the windward slope of isolated hills assume that the same horizontal velocity exists everywhere, upstream as well as over the crest of the hill, in contrast to the streamline deformation and flow speedup which actually occurs. Some of these models attempt to account for the closer passage of streamlines to elevated terrain and deformation of plumes by using a "terrain correction" factor as discussed earlier, but as noted, even these models ignore many details of the corresponding velocity changes and deformation effects on plume spread.

In this section of the report a brief description of models currently recommended by EPA as screening techniques is followed by a discussion of mathematical modeling techniques for simulating various flows in more detail.

1. Current EPA Recommended Models

EPA has not yet established a guideline model for use in complex terrain settings where plume heights are expected to be below the height of nearby terrain. EPA does recommend the Valley, COMPLEX I and sometimes COMPLEX II models for use as conservative screening techniques for these situations. Research on the development of a refined model is currently underway (Lavery et al., 1983). The following provides a brief description of present screening models.

The Valley model (Burt, 1977) uses a Gaussian plume dispersion equation modified to include 22.5^{o} "sector averaging" of the crosswind distribution. Vertical dispersion is calculated using Pasquill-Gifford dispersion curves. The model can be run to calculate 24-hour average concentrations or annual averages. Under stable conditions, the model assumes that a plume travels toward terrain with no vertical deflection until the plume centerline approaches to within 10 m of a terrain surface. Thereafter a minimum stand-off distance of 10 m is assumed. Full doubling of concentrations due to reflection occurs. At surface elevations above the plume height, concentrations are assumed to decrease linearly with height, reaching a value of zero at 400 m above the initial plume height. Under neutral or unstable conditions, the plume trajectory assumed is "terrain-following" - producing concentration values equivalent to those which would be obtained in the absence of terrain. For screening analyses, the Valley model is commonly used with assumed worst-case meteorological inputs of a stack-top wind speed of 2.5 m/sec. and Pasquill-Gifford stability class F vertical dispersion coefficients. A 24-hour average concentration is obtained by assuming that these conditions could occur for 6 hours within a 24-hour period.

The COMPLEX I (EPA, 1981a) and COMPLEX II (EPA, 1981b) models are multiple point source models capable of using sequential meteorological input data. Under stable conditions, the algorithms for plume impaction within COMPLEX I are the same as those within Valley. COMPLEX II differs from COMPLEX I by using crosswind dispersion coefficients instead of 22.5° sector averaging. For neutral and unstable conditions the models use a 0.5 terrain correction factor to lift the plume centerline height above terrain height.

2. Windward Flow about Isolated Hills

The flow models discussed in this section, while highly simplified, address some of the major effects of hills on perturbing an airstream, i.e., streamline convergence and divergence and the associated fluid acceleration and deceleration. The models are considered for two stratification regimes, neutral/unstable and stable; all are based on inviscid flow.

For neutral/unstable conditions, potential flow can be applied following the work of Hunt and Mulhearn (1973), Jackson and Hunt (1975), and Britter et al., (1981). These authors showed that for two-dimensional hills and outside a thin "inner region," the flow behaves like an inviscid shear flow. Furthermore, they find that potential flow is a useful concept for flow speedup, as confirmed with field and wind tunnel measurements. The Jackson and Hunt theory has been extended to three-dimensional hills by Mason and Sykes (1979a, b) and found to be in good agreement with wind observations about a small hill.

Potential flow has been applied in a number of nonregulatory diffusion models for a variety of terrain shapes: three-dimensional hills (Hunt et al., 1979), simple combinations of hemispherical and cylindrical shapes (Isaacs et al., 1979), and arbitrarily-shaped three-dimensional hills (Weil et al., 1981). The last application employs a potential flow code developed by the McDonnell-Douglas Company (Hess and Smith, 1962) and is based on the surface source method. Further work is required to adapt these methods to actual terrain sites for use in regulatory applications. Of particular concern here is how much terrain detail must be included to get an adequate prediction of the flow field and the associated concentration distribution.

For stably stratified flow about three-dimensional hills, we consider two stratification regimes: moderately to weakly stable ($Fr > 1$) and strongly stable ($Fr < 1$). For moderate to weak stratification, Smith (1980) showed that linear theory, i.e., linearized momentum equations for low hills, can predict qualitatively reasonable flow patterns. The theory correctly predicts the tendency of the flow to be diverted around a mountain for both round hills and also near the end of a long finite ridge. For general finite amplitude hills (not necessarily low) and $Fr \gg 1$, the momentum equations can also be linearized in density stratifications, i.e., by considering a small perturbation in stratification about the neutral, potential state. In contrast to the more commonly used small-height linearization, it has the great advantage of being applicable to any terrain slope or height. The most general outline of this approach is given in Drazin (1961). However, its only application so far has been to two-dimensional hills (Baines and Grimshaw, 1979). A central question with regard to the latter approach, i.e., stratification perturbation to potential flow, is to how small a Froude number it can be applied. This question, as well as how well the above approach predicts flow patterns about terrain obstacles, must be assessed experimentally. Physical modeling would be of value in this assessment.

In strongly stable stratification ($Fr < 1$), the flow about large three-dimensional hills is confined to horizontal planes below a certain height H_c, which depends upon the stratification. Such horizontal layering has been predicted theoretically by Drazin (1961) and demonstrated in stratified towing tank experiments by Riley et al., (1976), Hunt et al., (1978), and Weil et al., (1981) for various terrain geometries. It has also been observed in the atmosphere (Williams and Cudney, 1976; Rowe et al., 1982; and Wooldridge and Furman, 1984). Drazin suggested that the two-dimensional potential flow could serve as a useful ambient wind model for the horizontally layered regime. It should be emphasized that potential flow is applicable only on the windward side of the hill; it cannot describe flow within the separated wake in the lee of the hill. A key problem in applying the model to real terrain sites is the choice of appropriate lateral boundary conditions, a problem also discussed below in the context of mesoscale modeling.

Above the horizontally layered regime, fluid passes mostly over the hill, as predicted by Drazin and as demonstrated in the aforementioned laboratory experiments. Hunt et al. (1984) suggest a useful ambient flow model for the fluid passing over the hill. It is the linear stratified flow theory (for $Fr \gg 1$) applied to a "cut-off" hill, i.e., that portion of the hill above the horizontally layered regime defined by H_c. Thus, one could use Smith's (1980) theory (for the limit $Fr \gg 1$) and "push" it to $Fr \approx 1$. We note that in stable stratification, theory predicts that fluid flowing over the hill does so asymmetrically, i.e., streamlines pass closer to the surface on the leeward than on the windward side of the hill. Thus, in some instances, for a plume passing over a hill we should expect higher surface concentrations on the leeward side as observed in the physical modeling experiments (Snyder and Hunt, 1984).

Models for stratified conditions, when implemented for regulatory applications, will require more detailed meteorological data inputs than are generally available. Specifically, knowledge of the temperature and velocity structure as a function of height from the surface to heights above the terrain features will be required.

3. Mesoscale Flow Models

This discussion of mesoscale models considers flow models which may be applied in complex terrain for distance scales of the order of 50 kilometers. Major breakthroughs have been achieved in recent years in the development of flow models because of improved high speed computer systems. Concurrently, there has been development of improved flow models, thus making it feasible to use these models for applications in a variety of complex situations.

Mesoscale flow models may be classified into three major categories: 1) fluid dynamic models, 2) diagnostic models, and 3) objective analysis models. There are many existing models in each of these three categories.

Improved computer systems, and more efficient numerical schemes which solve the complex equations, have made practical applications of the mesoscale models more feasible. For example, applications can be simplified by allowing topographic data, models and graphical output to be integrated with "user friendly," menu-driven codes (Fox et al., 1983). These mesoscale flow models may be used in various ways to assist with air quality analyses. However, there is a need for additional model evaluation studies to compare the flow fields generated by the models with wind flow observations. Flow models may be used to calculate wind fields in complex terrain situations where there are few meteorological data measurements (Pielke et al., 1983). The models can be coupled with various advection/diffusion schemes to simulate dispersion of pollutants. Insight into air stagnation in basins and valleys with resultant air pollution buildup, and flushing of pollutants from basins and valleys may be analyzed. The characteristics of mountain and valley flows can be better understood by simulating cases where local terrain drives the drainage or the upslope flows. Diagnostic or mass consistent models (e.g., Sherman, 1978; Davis, et al., 1984; King and Bunker, 1984) have been applied to produce flow fields for three-dimensional complex terrain settings. These models to not, however, include thermal effects directly. The diagnostic models can be used to obtain a better understanding of the controlling influences of strong synoptic flow patterns on the local flow fields.

4. Land and Sea Breeze Interaction with Complex Topography. There has been considerable investigation of sea- and land breezes over flat terrain; however, the interaction of these circulations with complex terrain along and inland from the coast has been investigated relatively less. Recent studies have documented the movement of pollution offshore in the land breeze, its fumigation down to the surface layers, and its subsequent movement back onshore (McRae et al., 1982). This recirculation of pollution, which can occur for several days or more at a time in the Los Angeles basin, can result in aged pollutant plumes with high concentrations of secondary pollutants. In other investigations, numerical studies have demonstrated that sea and land breezes in complex terrain are not simply a superposition of sea and land breezes over flat terrain, with mountain-valley circulations in complex terrain. One reason for this is that mountain-valley circulations near a coastline can result in subsidence over the shoreline which will, in turn, diminish the interaction of the sea breeze. Thus, such mesoscale systems must be treated in their entirety.

5. Modeling of Slope and Mountain/Valley Flows

a. Existing Models. Defant's (1951) descriptive model of slope and mountain/valley flows, while rudimentary, provides practical guidance for understanding thermally driven circulations in well defined valleys. According to Defant, at night shallow-downslope flows on the valley sidewalls (directly driven by temperature deficits near the surface) produce a deep pooling of cool air in the valley. If there are variations in the valley depth or width, an along-the-valley axis flow will develop. The along-the-valley axis flow can be quite deep depending on the depth of the pool of cool air. Defant's descriptive model, while addressing the three-dimensionality of the problems, cannot of course provide details of the flow, handle interaction with synoptic winds, or address turbulent structure.

Because the full problem is so complex, recent models have separated the problem into components. Rao and Snodgrass (1981), and Smith and Garrett (1983), and others have concentrated on the slope drainage flows. These slope flow models appear to reproduce quite well the observed temperature and velocity structure.

Recently, full three-dimensional primitive equation models have been developed and applied to slope and valley flows, e.g., Egger (1981), McNider (1981), and Yamada (1981). Despite continuing initialization and boundary problems, these models offer the promise of including the slope-valley flow dependence, and of dynamically simulating the evolving thermal and turbulent structure.

b. Applications. While full treatment of the flow with primitive equation models is possible, actual application of the models has been limited primarily to idealized terrain, neglecting synoptic interactions. Egger (1981), McNider and Pielke (1981) and Bader and McKee (1983) addressed a simple three-dimensional valley opening onto a plain. The results from these idealized applications appear to agree qualitatively with recent observations, (e.g., Whiteman (1982)), and the descriptive ideas of Defant.

c. Input Data. For mass-consistent models the data requirements can be quite voluminous, especially if the flows are primarily thermally driven, since thermal effects can only be included through wind observations. For dynamic primitive equation models the input data are fairly simple if the synoptic flow is assumed spatially uniform and steady. The basic input information required is the topography, initial temperature distribution, and gradient wind speed and direction.

As mentioned, definite problems for dynamic models still exist in the areas of flow initialization and boundary conditions. Computation speed is also a major drawback, with computer memory and speed requirements outside the reach of most applications.

d. Treatment of Dispersion Processes. Because of spatial variations in both wind direction and turbulent structure, it is unlikely that simple Gaussian-dispersion models can be utilized with such numerical flow models. Small-grid, finite-difference, advection-diffusion calculations might be applicable. Lagrangian particle models for point source transport and dispersion are also promising.

3. Recommendations

A number of recommendations evolved from the workshop. These included statements regarding current research efforts and the use of current technology, suggestions of specific research needs focused on near-term needs (and which presumably could be accomplished in the near-term) and suggestions regarding the longer term research needs. As will be seen, some of these latter suggestions may equally well relate to other applications of geophysical fluid dynamics. The recommendations are organized into two categories relating to recommendations on the Use of the Science and recommendations on Future Research Needs.

A Use of the Science

(1) Comments on Current Research Efforts. First of all, it should be noted that there seemed to be a consensus among the workshop participants that the approach taken over the past several years with a focus on gathering more field data on transport and diffusion processes in complex terrain settings was appropriate. The need for large efforts to gather field data was strongly recommended at previous workshops on this topic (e.g., EPA Workshop on Atmospheric Dispersion Models in Complex Terrain (Hovind et al., 1979), DOE Workshop on Research Needs for Atmospheric Transport and Diffusion in Complex Terrain (Barr et al., 1977)), and the research programs of EPA, DOE and EPRI have been very responsive to these needs. The increased use of wind tunnels and water channels in applying physical modeling techniques to study flow phenomena was also supported by the participants. The notion of performing scale model tests in parallel with full scale field experiments performed in complex

terrain was viewed as providing an excellent methodology to understand the effects of physical scale on the phenomena of concern and to investigate systematically the effects of changes of dispersion patterns with flow conditions. Such systematic investigations are difficult and expensive to accomplish in field experiments. Emerging mathematical modeling techniques for predicting concentration values in complex terrain account for the physical phenomena of importance better than earlier models. A number of these developments have been made hand-in-hand with the increased data bases emerging from the field and physical modeling programs.

(2) Need to Quantify Uncertainties in Model Predictions. One of the recurring issues surfacing at this workshop was the need for modelers to incorporate uncertainty of predictions into the process of using models. The group recognized the regulatory application needs of having decisions made on the basis of certainty and on the basis of computations made for both short and long averaging times and for infrequent events. An admonition to include uncertainty into the modeling evolves from the fact that the flow over complex terrain, like any other atmospheric flow, is turbulent in most regions at most times. This turbulence thus has both temporal and spatial scales. These scales are not determined simply by the universal flow physics; they are also strongly influenced by the structure of the topography, by the interactions of this topography with the ambient, larger-scale atmospheric circulation, and, in dispersion applications, by the nature and geometry of the pollution sources.

The stochastic nature of the atmosphere coupled with its nonstationarity and spatial complexity leads to significant uncertainty in any prediction of its behavior. It is virtually impossible to measure initial conditions in a manner which represents this complex flow. The measurement problem is magnified in complex topography where small scale boundary forcing is related to small scale variability of the surface. In idealized conditions (flat terrain) a recent AMS/EPA workshop (Fox, 1984) recognized that inherent uncertainty would remain even if the measurement problem could be removed due simply to the difference between individual realizations of seemingly identical flows. In practice, physical models offer an opportunity to investigate components of this source of variance. It is possible that the physical constraints of topography might tend to reduce this variance because of the more frequent occurrence of locally organized secondary flows (slope flows, etc.). To the extent this may occur, such inherent variability may be less over complex terrain. This notion, however, is hypothetical at this time - it has not been demonstrated.

The recommendation to include uncertainty into the modeling process has several implications. Firstly, it will not be a simple task. Deterministic models have evolved from development techniques attempting to achieve "best fits" of predictions with observations without (until rather recently) attempting to match uncertainties of predictions with uncertainties in the observations. Further, the amount of information required to quantify uncertainty is greater than that needed to estimate "mean" values since uncertainty of all the various input values and parameters needs to be assessed. For example, theoretical and observational work on uncertainty indicates a strong dependence of concentration fluctuations on the source exit conditions even at large downwind distances (Sawford, 1983; Fackrell and Robins, 1982). Secondly, there follows a suggestion that the effects of uncertainty in input data and parameters should be studied with physical models where a degree of control of variables with time can be maintained. Thirdly, the recommendation is supportive of pursuits of higher-order closure modeling which includes consideration of higher statistical moments of distributions and of large-eddy simulation modeling wherein uncertainty can be quantified by interpretation of output results of multiple simulations. Finally, the recommendation is consistent with the charge to rely on field data (with appropriate consideration of stochastic variability) to evaluate the statistical performance of models.

(3) Meteorological Input Requirements for Complex-Terrain Models. An underlying concept in the field of dispersion modeling is that one cannot expect a dispersion model to perform well without appropriate input data. Generally, "appropriate" is interpreted as being of good quality, being representative of the flow field of interest and providing reliable information on the flow parameters of importance. Some specific recommendations appropriate for dispersion models as applied to regulatory applications are provided below.

The set of meteorological data collected must be representative for the site of the source and the probable paths of pollution diffusion, including those paths which are highly repeatable and those that are expected to produce the highest levels of ground level impact for the time periods that have regulated pollution standards. The data sets must be adequate to be used for the modeling of the annual, 24-hour, and 3-hour averaging times of pollution impacts.

All sites in complex terrain will have unique characteristics and will deserve careful examination of the surrounding topography. The initial plan for collection of meteorological data should be discussed with the meteorological staffs of applicable regulatory bodies before data collection begins, so that any special modeling input needs can be met.

For an elevated source, an adequate data set would probably include, but would not be limited to, the following:

- At least one instrumented tower with the data feeding to a data logger and strip chart backup for wind and temperature. The instruments should include wind direction and speed at two or more levels, turbulence measurements at the top of tower (as near to plume height as practical), temperature measurements and delta T measurements.

- Solar radiation measurements near the base of tower.

- Collection of additional wind data on a continuous basis at other locations at or near the suspected points of high impact on air quality.

- Radar or theodolite-tracked tetroons carrying minisondes. They will describe three-dimensional trajectories at specific sites over ranges of a few to some tens of kilometers. The temperature sensor will provide information on the energetics of flow along slopes and in mountain valleys.

- To apply the integral form of calculating H_c, vertical profiles of wind U(Z) and temperature T(Z) measured upwind of the terrain to heights at least as high as the terrain height are desired. It is impractical to construct towers to heights of 200 or 300 m or higher, so remote sensing devices are needed. Doppler acoustic sounders can provide information on wind profiles. Alternatively, tethersondes or minisondes could be used with a shorter tower to measure temperature profiles.

Possibilities for special studies to augment the basic data described above might include tracer studies over limited time periods during the season(s) of primary concern. Such a study would involve release of a tracer gas from the effluent point of interest along with samplings at sites in the region of anticipated impact. By identifying "worst-case" atmospheric conditions, tracer releases would be necessary on only a limited number of days. Wind tunnel studies allow systematic investigation of cause and effect and provide a means of extrapolation from field information (see Section 2B).

While the above suggestions relate rather specifically to a single category of sources, there appeared to be a consensus among workshop participants that detailed meteorological data including direct measures of turbulence intensity should be required for use in complex terrain dispersion models. The need for such data is greater for mountainous settings than for flat terrain settings because of the importance of site specific phenomena on turbulent dispersion processes.

Another recommendation relating to the use of meteorological input data in models evolved from the recognition that more advanced models will probably require more detailed inputs. Current regulatory practice requires that one or more years of hour-by-hour values of wind speed and direction, stability class, and mixing depth be input sequentially, so that all sets of three-hour and daily averages are computed. The purpose of this procedure is to allow evaluation of the highest and "highest, second-highest" concentration averages. Concern is expressed that the associated volume of computations may be excessive unless simplifications are made in the simulation algorithms to reduce total computation costs. An alternative approach which should be considered would be to be selective in identifying worst-case meteorological scenarios to be used and thereby encourage the use of more computation time-intensive algorithms if they were deemed to be superior.

(4) <u>Suggestions on Improving Present Screening Models</u>

(a) For impingement on high terrain, the group recognized the importance of screening models, as applied by regulatory agencies, to eliminate the need for detailed assessments for facilities having minor ambient air impacts. A screening model was defined in this context as a conservative model which can be used without any meteorological data, e.g., worst-case meteorological assumptions are made. Worst-case Valley is the present EPA screening model for terrain higher than a source height and assumes a specific wind speed, a specific duration of wind direction, specified temperature profiles and dispersion rates, and arbitrary "miss" distances for plume paths. The group felt that because of concerns over the arbitrariness and elementary nature of the assumptions already in Valley, that it would not provide a good basis for improvement. Adding more complexity would not necessarily make this model any more reliable, because further arbitrary meteorological assumptions would be required. Use of the critical streamline height concept, which was raised specifically in discussion (Rowe, 1982), requires assumptions about the vertical variations of temperature and velocity. Members of the group thought it unwise to add complexity requiring more detailed meteorological data inputs to a model which would be used in the absence of such data.

It was felt that better screening models could be developed by a two-fold effort:

1. Examine existing data available from ambient air quality or tracer measurements for a variety of sources in terrain settings to see if uniformly-conservative screening algorithms could be developed on the basis of comparing peak observed and predicted concentrations.

2. Develop screening techniques which were consistently conservative. That is, develop methods which would not result in biases in the decision-making depending upon differences of source-topographic situations (i.e., biased against sources located close to terrain vs. further from terrain, etc.). The degree of overprediction expected from such models should be quantified.

(b) At present, no screening model is available or can be recommended for predicting maximum air pollution concentrations due to diurnal fumigations or light wind high-stability dispersion conditions in deep valleys. Further research and evaluation of actual concentration data are necessary before such models can be developed and used with confidence.

(5) Suggestions on the Use of Physical Modeling Techniques

The advances made in developing laboratory techniques and in the understanding of the limits of applicability of physical modeling techniques suggest that increased reliance be placed on their use. Application of these techniques should be considered for those situations where they are appropriate.

(a) Consideration for Screening Models. Physical modeling can provide a source of useful information regarding the expected maximum concentrations at a proposed site. In particular, fluid modeling could be used to estimate the maximum short term average (e.g., 1-hour or less) concentrations under plume impaction conditions as a function of hill Froude number, stack height, and stack location. The optimum stack location and height could then be selected so that concentrations are mimimized. In addition, fluid modeling could be used to estimate the short term concentrations due to terrain wake or cavity effects. For screening purposes, it would have to be assumed that the conditions modeled would actually occur. If on-site or representative off-site data are available, more realistic estimates can be made. For mountain-valley or drainage-type flows, the wind tunnel may not be able to simulate the worst-case condition which appears to occur during transition. Another technique would have to be employed for these situations.

(b) Detailed Evaluations. If the screening evaluation suggests that plume impact or terrain wake or cavity effects will cause standards to be exceeded, a more refined modeling analysis could be undertaken.

Physical modeling could be used during this evaluation to help refine and validate a site-specific model (if the length scales are not too large). The basic components of the model, such as plume trajectory and dispersion parameters, could be evaluated as a function of stability, wind direction and wind speed. The model's ground-level concentration estimates could then also be compared with the wind tunnel results. Once the validated model (for hourly concentration estimates) is fully tested, it can be applied using on-site meteorological data to estimate concentrations for the prescribed averaging times (3-hour, 24-hour, annual). Post-concentration monitoring is suggested at the location predicted to give the highest concentrations. This information could be used to assess the performance of the technique. Physical models can also be used to assist in the design of field programs for complex terrain settings.

B Future Research and Development Needs

The workshop attendees elected to identify research needs, and establish some priority associated with them, for the problems of predicting ground-level concentration of air pollutants in complex topography. These problems are focused on concerns with the highest concentration values which can result, and of course with understanding the physics that contribute to these high values.

After considerable deliberations a set of problems were established, which in the opinion of participants, bracketed the physical situations which can lead to maximal ground-level concentrations in complex terrain. Of the seven problems finally selected, four involved stable stratification, two involved the unstable planetary boundary layer, and three involved detailed flow field considerations. The problems were further recognized to be composed of subcomponents of a more fundamental nature. They were qualified by, in addition to their subcomponents: (a) whether some observational data had been collected on the problems; (b) whether a physical conceptualization of the problem had been developed; (c) whether physical or numerical modeling efforts had been called for or already conducted; and (d) whether a further major field effort was deemed necessary. Table 1 lists the topics and summarizes these considerations. The ordering of tasks does not necessarily imply priority. A brief synopsis of the issues for each of the tasks is provided below.

(1) Stable Plume Impaction. Physical modeling and field studies have established that in stable flows a critical elevation exists which differentiates the flow which goes around a hill from the flow which goes up and over a hill. In combination with information on plume height and dimensions, better estimates of the location and magnitude of ground-level concentrations can be made. Field studies should now be directed toward establishing the validity of this concept in larger scale and more complex (less idealized) terrain situations. It is likely that mathematical modeling of this phenomenon would yield additional insights not otherwise obtainable.

(2) Lee-Side Effects Laboratory modeling of both neutral and stable flows over 2-D and 3-D topography has shown that elevated concentrations may be associated with a source located downwind of the terrain. A sounder, physically based understanding of these phenomena is needed. A combination of theoretical and laboratory modeling is called for in an attempt to provide such an understanding. Some field research will be important, especially as the theoretical understanding develops. Numerical models capable of predicting separation and reattachment points for neutral conditions and two-dimensional hills are presently feasible and should be extended and evaluated with data.

(3) Fumigation. The upset of a stable layer in a valley has been identified for many years as contributing to high ground level concentrations. Although the physical concepts of this process are reasonably well understood, it was suggested that laboratory modeling might help to refine the understanding. Equally important is the conduct of a field experiment focused on these events. Numerical models and fluid modeling (e.g., Bell and Thompson, 1980) can be used to understand the diffusion processes near the valley top where strong wind shears occur. More generally, mathematical models need to be developed to describe dispersion processes in the transition region just above and below hill crests.

(4) Trapping Valley. There exists a class of valleys which because of their orientation cause drainage winds to pool at their base forming a thick stable air mass. When circumstances are such that diurnal heating and momentum transport from above are insufficient to break this inversion, very high concentrations

may occur. A combination of laboratory and field experiments was recommended to quantify the existing understanding of this situation. Studies of how to develop adequate meteorological inputs for these conditions are also needed. Further guidance on the development of parameterizations of physical processes could be provided by numerical simulation models. The interactions between the evolving circulations which develop on different length scales are thought to be one of the key scientific problems in dealing with valley meteorology.

Another important need is data to document the depth of the stable boundary layer over the valley. The relationship between the depth of this stratification and the strength and persistence of drainage winds should be determined.

Future studies should address both diurnal and synoptic stagnation conditions in trapping valleys -- especially those with populations and pollutant sources. Field and modeling studies should address the critical topographic and meteorological conditions for occurrence, as well as the resulting air quality degradation.

(5) Convective Boundary Layer over Complex Terrain. As a result of intensive theoretical, numerical and physical modeling studies, as well as definitive field experiments, we have achieved a fairly complete understanding of the evolution of the convective planetary boundary layer (PBL) over homogeneous terrain. Similar systematic studies of the convective PBL over complex topography are generally lacking. There are also no studies of the interaction between the topographically induced motions (such as in the separated cavity and wake regions) and the buoyancy-driven convective motions and their combined effects on the dispersion of pollutants in complex terrain.

In order to understand the above problem, the following types of studies should be conducted in a sequential manner:

a. Construct simple slab models for the convective PBL over a uniformly but significantly sloping terrain and over 2-D hills or ridges.

b. Conduct physical modeling studies of boundary layers over isolated 2-D and 3-D hills of different slopes and shapes in both neutral and unstable conditions.

c. Conduct numerical modeling (large eddy simulation) studies of the convective PBL over 2-D and 3-D isolated hills.

The studies proposed here should be very useful in improving the understanding of the spatially inhomogeneous convective PBL in complex terrain and its parameterization in mesoscale numerical models of flow and dispersion. These will also indicate to what extent and under what types of topographical situations our current knowledge of the homogeneous flat-terrain convective PBL can be transferred or applied for modeling purposes.

(6) Mesoscale and Longer Range Transport and Diffusion. Although not contributing to the highest ground-level concentrations, the transport of pollutants over scales upward of 15 km to as far as 200 km is important because of Class I PSD increments. The research necessary here is twofold. First, a more fundamental understanding of the physics is probably necessary before much significant progress can be made. Second, although a great many models exist, they are all unverified. It is recognized that chemical transformation and removal processes become

important aspects of models applied to longer distance transport issues. The problem of longer range transport and diffusion in complex terrain requires the combination of a wind field model with an appropriate diffusion scheme. Evaluation of such a combined approach is not easily accomplished. Both the wind field and the diffusion components require attention. As was discussed earlier, various procedures are available to simulate winds, all of which involve some compromise. The best that can be expected is that ranges of appropriate performance can be defined for each class of model. These can be developed by combinations of theoretical and field studies which are recommended. Evaluation of the diffusion component can rely on work done near the source but will ultimately require a tracer study conducted over complex terrain. The CAPTEX experiment (CAPTEX, 1984) may provide this requirement for eastern rolling terrain; however, there remains a need for western complex terrain tracer studies.

(7) Sea/Complex Terrain Interface. Analysis of dispersion in coastal terrain involves further meteorological complications associated with the coupling of land-sea breezes with mountain-valley flows, discontinuities of surface temperature, etc. It was felt that although it is common for pollution sources to be located in such regions, relatively little research has been done in this area.

A number of more general concerns were expressed by the group during discussions of the above research needs. There was concern that we ought to better recognize that dispersion of pollutants in complex topography is a special subset of the geophysical fluid dynamics of stratified flows. As such, under stable stratification, influences of topography can be felt well above, up and downwind of the topography.

As a result a caution was raised regarding the extrapolation of conceptualizations which are valid and useful for simple (flat) terrain problems to problems in complex topography. Interactions between the physics of stratified flow and the topographic structure lead to certain natural time and space scales in the flow. In cases where such time scales are larger than the averaging time of application interest, estimates of concentration by deterministic models will contain larger uncertainties. There were repeated references to the difficulty of developing any deterministic and generalized solution. Hence it was suggested that the basic stochastic nature of the phenomena should be accepted, and that statistical approaches be used to characterize the uncertainty.

Consideration of the more fundamental aspects suggested that the seven problems in Table 1 depended upon an understanding of the following, more basic items:

a. The space and time scales of the flow as a function of topography and other types of forcing or boundary conditions.

b. The depth of the planetary boundary layer in complex terrain.

c. The interaction of the planetary boundary layer with the free air above it.

d. The space and time variation of turbulence as a function of stability and topography.

e. The generalization of the dividing-streamline concept to arbitrary shapes and scales of hills.

f. The effects of radiation on the flow field in complex terrain.

g. Effects of wakes in the flow over complex topography.

h. The identification and measurement of meteorological and other data which are representative of the flows.

This list represents a very comprehensive set of basic issues stemming from the fundamental complexity of stratified fluid dynamics, when coupled with nongeneral specific topographic environments (real topography). The associated uncertainty in the ability of simple models to simulate these processes needs to be a key concept kept very much in the forefront of any applications in complex topography.

TABLE 1

RECOMMENDED FUTURE RESEARCH TOPICS

TOPIC	HYPOTHESES OR SUBCOMPONENTS TO BE TESTED	DATA GATHERING STATUS/NEEDS	PHYSICAL MODEL STATUS/NEEDS	PHYSICAL MODELING
Stable Plume Impaction	Dividing Streamline Height; Scales of Applicability	Data Available or Scheduled to be Gathered	Some Accomplished	Some Accomplished
Effects on Lee Side Sources	Downwash; Dividing Streamline Height	Field Data Needed	Some Accomplished	Development Needed
Fumigation in Complex Terrain	Boundary Layer Depth; Turbulence Character-istics	More Field Data Needed	Modeling Needed	Some Accomplished
Stagnant Air Masses Within Valleys	Interaction of Boundary Layer with Free Atmo-phere; Sloshing and Net Ventilation Rates	Field Data not yet Needed	More Modeling Needed	More Development Needed
Convective Flows in Complex Terrain	Interaction of Boundary Layer with Slopes	Field Data not yet Needed	Exploratory Modeling Needed	Some Accomplished
Mesoscale Transport	Flow Field Models; Boundary Layer Depth	More Data Needed	Not Applicable	Some Accomplished
Coastal/Complex Terrain Interface	Boundary Layer Depths; Data Representativeness	Field Data not yet Needed	Modeling Needed	Modeling Needed

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WORKSHOP ON DISPERSION IN COMPLEX TERRAIN
Keystone, Colorado

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APPENDIX 2

WORKSHOP ON DISPERSION IN COMPLEX TERRAIN

Keystone, Colorado
May 17-20, 1983

Preliminary Schedule

Tuesday, May 17, 1983 "Review of Phenomena"

8:00	Introduction, Objectives of Workshop	B. Egan	
8:30-10:00	EPA-CTMD Study Experiences	T. Lavery	(1 hour Presentation, ½ hour Discussion)
10:30-12:00	DOE-ASCOT Program Field Experience	S. Barr	(1 hour Presentation, ½ hour Discussion)
1:30-3:00	EPRI Bull Run Study Field Experience	N. Bowne	(1 hour Presentation, ½ hour Discussion)
3:15-5:30	Group Discussion on Phenomena of Importance	M.E. Smith, Moderator	

Participants will be encouraged to present short Contributions on this Topic to be followed by more general Discussion

Wednesday, May 18, 1983 "Review of Modeling" D. Randerson, Moderator

8:30-10:00	Flow Field Modeling	R. Pielke	(1 hour Presentation, ½ hour Discussion)
10:30-12:00	Physical Modeling	W. Snyder	(1 hour Presentation, ½ hour Discussion)
1:30-3:00	Regulatory Modeling	S.R. Hanna	(1 hour Presentation, ½ hour Discussion)
3:15-5:30	Group Discussion on Modeling Approaches	D. Randerson, Moderator	

Participants will be encouraged to present short Contributions on this Topic to be followed by more general Discussion

5:30	Subgroup Assignments

Thursday, May 1983 "Develop and Document Findings"

8:30-12:00	Meet as two working Subgroups to define Areas of Agreement and Disagreement
	Group 1: Suggestions for Model Applications, B. Egan, Moderator
	Group 2: Suggestions for Future Information Needs, D. Fox, Moderator
1:30-2:30	Reconvene entire Workshop to review Progress
3:00-5:30	Return to separate working Groups, Report Writing

Friday, May 20, 1983 "Wrap up Discussion"

8:30-10:00	Continue with Report Writing
10:30-12:00	Discussion of Workshop Findings in Draft Form
12:00	Departure

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15. SUPPLEMENTARY NOTES

16. ABSTRACT

A workshop was convened by the American Meteorological Society under a cooperative agreement with the U.S. Environmental Protection Agency. The purpose of the workshop was to encourage atmospheric scientists working in this area to exchange recently acquired information on atmospheric processes in complex terrain and to make recommendations regarding both the present application of air quality models to complex terrain settings and the research necessary to meet future needs.

This report contains the thoughts and judgments of 32 atmospheric scientists who gathered to exchange such technical information and research results on atmospheric processes in complex terrain and to comment on matters relating to adjustments in current air quality modeling practices.

17. KEY WORDS AND DOCUMENT ANALYSIS

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