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TERRAIN EFFECTS ON ATMOSPHERIC TRANSPORT AND DISPERSION - A STATUS REPORT

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TERRAIN EFFECTS ON ATMOSPHERIC TRANSPORT AND DISPERSION - A STATUS REPORT

M. M. Orgill

SUMMARY

The future energy conversion activities in the western United States, such as oil shale production, fossil-fuel plants, geothermal development, and strip mining, may lead to significant deterioration in existing air quality in regions of complex terrain. Future air quality assessment methods need accurate information for describing atmospheric transport and dispersion in complex landforms.

A status report is given of the problem of transport and dispersion in complex terrain and evaluates the research methods and needs that are required for realistic solutions to the problem. A current multilaboratory complex terrain study at the Geysers geothermal resource area is developing methods and models to address the many aspects of dispersion in complex landforms. Initial results from this study will be presented and discussed.

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GLOSSARY OF TERMS

Symbol	Definition
$C(\vec{r})$, $C(x,y,z)$	Concentration of a gas or particulate material at a location downstream from a source
C_T	Chemical transformation mechanism
D_D	Dry deposition or impaction
D_W	Precipitation scavenging
d	Diameter of source
Fr	Froude number
H_m	Height of mixing layer
h_e	Effective stack height
h_s	Height of source or stack
K_{ii}	Coefficients of turbulent diffusivities for mass in x, y and z directions
N_s	Total number of sources
Pr	Prandtl number
Pe	Peclet number
Q_s	Source strength

GLOSSARY OF TERMS, Continued

Symbol	Definition
R	Resuspension mechanism
Re	Reynolds number
Ri	Richardson number
Ro	Rossby number
t	Sampling time
t_s	Dissemination time of pollutants by a source
T_s	Temperature of source effluent emission
U_a	Speed of wind at source height
V_g	Geostrophic or freestream wind velocity
$\vec{v}(z)$	Variation of wind velocity with height
$\frac{\partial v}{\partial z}$	Wind shear
w_s	Speed of source effluent emission
$Z(x,y,z)$	Three-dimensional terrain
z_o	Surface roughness
β	Stability parameter
σ_y,σ_z	Standard deviation of plume concentration distributions in the horizontal and vertical

INTRODUCTION

The energy conversion activities in the country, such as fossil-fuel plants, oil shale production, nuclear plants, geothermal development, uranium mining, strip mining of coal and other mining and smelter operations, may in many cases result in significant environmental impacts. Local, state and federal regulations are currently being written and implemented to control existing or proposed sources of pollution in order to achieve air quality standards and prevent significant deterioration of air quality in regions where excellent air quality has been the general rule. In the future, with increased energy conversion activities in regions of complex terrain, more stringent requirements may be required because of the possible identification of subtle environmental effects.

Current air quality assessment methods lack accurate techniques for describing atmospheric transport and dispersion for different land forms which are typical of the mountainous part of the country. Terrain-induced air flows, which are often simplified and neglected in theory and modeling, are not exceptional but represent a majority of environmental locations in the real world. The data base on terrain influences is not meager and has increased significantly during the past ten years, but is generally still inadequate for making quantitative assessments in many aspects of transport and dispersion in complex terrain.

An improved data base and understanding of complex terrain effects is necessary before accurate assessment techniques can be developed. Failure to obtain this greater understanding could lead to poor assessment

techniques with the result that preservation of environmental quality may be sacrificed or unnecessary economic penalties may be imposed on the developers of energy resources.

This paper gives a status report on the problem of transport and dispersion in complex landforms, reviews and evaluates the research methods and needs that are required to reach reasonable solutions to the problem and reports on some current research activities in respect to this problem.

TRANSPORT AND DISPERSION IN COMPLEX LAND FORMS

The problem of atmospheric transport and dispersion of fine particulate matter or gaseous material is most easily approached by considering the factors that influence the transport and spread of the pollutant from the source. The instantaneous or average concentration C of a particular pollutant at a location ($\vec{r}$) in a plume in mountainous terrain is a function of several variables, e.g.:

$$C(\vec{r}) = f(Q_s, N_s, h_e, t_s, \beta, \frac{\partial \vec{v}}{\partial z}, K_{ii}, H_m, \vec{v}(z), Z(x,y,z), z_o, D_D, D_W, R, C_T, t) \quad (1)$$

These variables can be generally categorized under five headings as follows:

<u>Source Characteristics</u>

$Q_s, N_s, h_e(w_s, T_s, h_s) t_s$

Atmospheric Motions

Transport Wind	Turbulence
$\vec{v}(z), \frac{\partial \vec{v}}{\partial z}$	$\beta, K_{ii}, \frac{\partial \vec{v}}{\partial z}$

Boundary Conditions

$Z(x,y,z), z_o, H_m$

Depletion Mechanisms

D_D, D_w, C_T

Resuspension

R

A schematic illustration of these various parameters and the role they play in transport and dispersion is shown in Figure 1.

The source characteristics consider the number, type, height, efflux velocity and temperature and dissemination time of the sources. These will vary depending on the type of energy production or dissipation operation. Atmospheric motions consist of mean motions and turbulence. Turbulence governs the diffusion of airborne material and is a function of atmospheric stability (β), directional and speed wind shear ($\frac{\partial \vec{v}}{\partial z}$), and surface roughness (z_o). The mean motions govern the direction and speed in which the diffusing plume will be transported. The geostrophic and ageostrophic components of the actual wind will determine the transport wind, which is also dependent on the orientation and height of land forms.

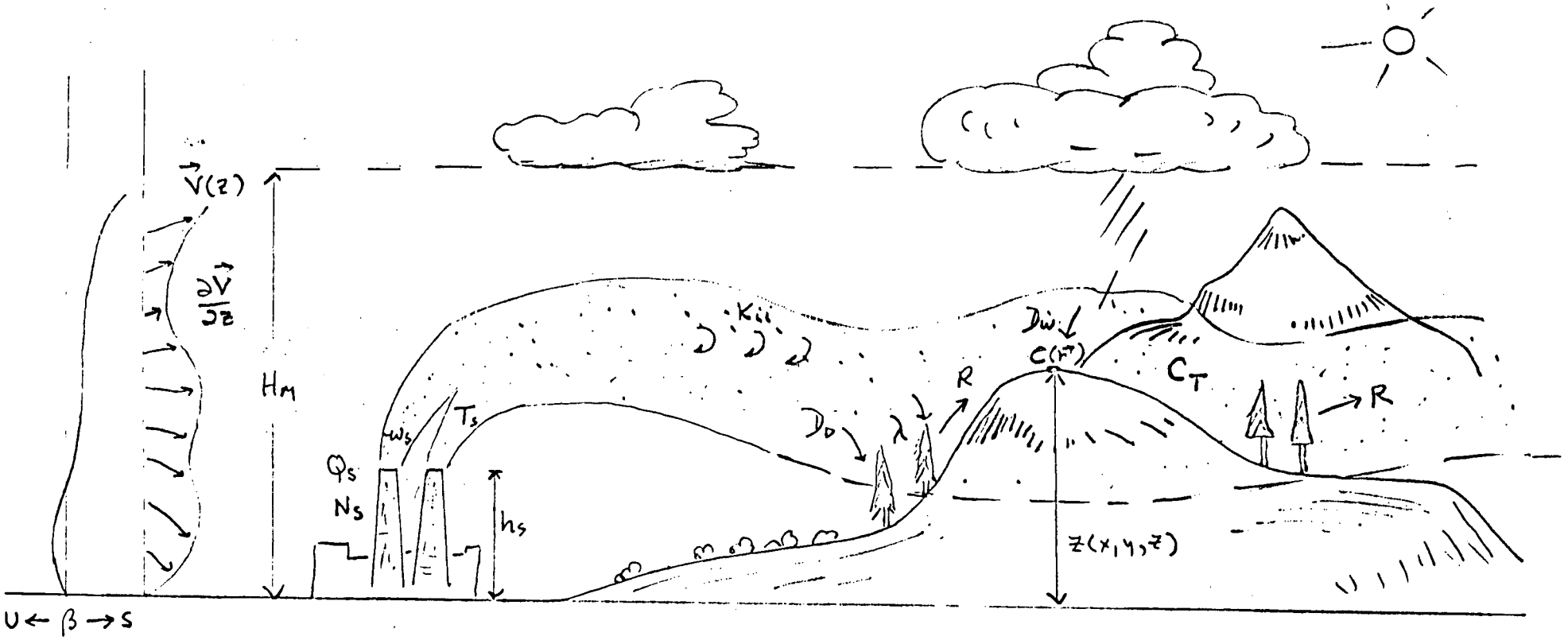

FIGURE 1. Schematic Illustration Depicting the Various Physical Mechanisms that Influence Transport and Dispersion in Complex Landforms

The lower boundary conditions, i.e. the terrain and roughness, may, depending on stability, enhance the effects of turbulence and mean motion and may also result in plume depletion. The mixing height (H_m) will determine the ultimate vertical extent of the pollutants and the trapping or ventilation of pollutants in confined terrain features, such as valleys and basins.

The depletion mechanisms are several and include gravitational settling, precipitation scavenging, surface impaction, electrostatic attraction, adsorption (coagulation), chemical transformation and photochemical processes. Resuspension by winds and thermal activity may re-entrain particulate pollutants into the lower boundary layer to be dispersed and redeposited downstream.

Existing research studies have considered many of these mechanisms that influence plume transport and dispersion. However, information gaps still exist in the development of quantitative formulations that can adequately describe the mechanisms for these terrain-induced phenomena.

TERRAIN-INDUCED AIR-FLOW PHENOMENA

Geomorphology, or the study of land forms, provides a general classification of terrain types that is a useful preliminary start when considering the terrain effects of solitary land forms on transport and dispersion. Some of the land form types that one encounters are:

- plateau
- peneplain
- cliffs
- canyons
- passes or saddles
- slopes
- basins
- islands
- terraces

- ridges
- hills
- mountains
- bays (shoreline)
- gaps
- gorges
- valleys
- mesas

In many modeling studies a particular solitary landform, such as a hill, mountain ridge or valley, is utilized. However, in the real world, many areas in mountainous terrain will be composed of a number of different landforms which add to the complexity of the problem. This is definitely the case for long-range transport.

Complex terrain exerts a definite influence on atmospheric motion, turbulence, temperature, pressure, and moisture distribution. Land forms can influence atmospheric motions on all scales from the long-wave ridge and trough through lee and wake phenomena to small turbulent eddies.

Terrain features affect atmospheric motion in four ways:

(1) through boundary-layer effects as the result of surface friction (roughness) and local pressure gradients;

(2) by the barrier or orographic - dynamic effect caused by blocking of air flow, spatial pressure differences, and the excitation of gravity oscillations;

(3) through thermal effects (heating and cooling) due to vertical and spatial temperature gradients; and

(4) channeling of air flow due to the presence of topographic valleys and canyons.

At a site in complex terrain, all four of these effects (roughness, dynamic, thermal, channeling) may operate in unison. The importance of a given effect will change from day to night, day to day, etc., depending on the larger scale air-flow patterns and type of land forms.

These four terrain effects produce a number of physical phenomena that are unique to these domains. A major problem with present dispersion and transport models is their failure to completely incorporate many of these phenomena. A few of these phenomena are listed below:

- deformation of air flow;
- diurnal air flows (slope-valley winds);
- separation of air flow;
- high-level convective heat sources;
- gravity oscillation (lee waves, etc.);
- mechanical and thermal turbulences;
- plume impaction;
- valley and basin stagnation;
- orographic cloud systems; and
- vegetation canopy effects.

The present data base has examined many of these phenomena but a better quantitative understanding of these terrain effects and their role in transport and dispersion in complex terrain is still lacking.

A preliminary survey(1) of 124 studies (∿1950 to present) concerning transport, dispersion and air pollution in complex terrain is shown in

(1) Survey in progress and information in Table I will be updated before formal paper.

Table I and gives a breakdown according to type of study and general landform that was under investigation. Table I shows graphically the relative importance of different landforms in transport and dispersion studies. Obviously, valleys have attracted the most attention because of their favorable location for polluting sources, and the effects of valley's topography and meteorology on dispersion. Table I also shows that many landforms have not been investigated very extensively and should be considered in future studies.

THE RESEARCH METHODS

There are essentially four methods that have been used in the past to study transport and dispersion in complex terrain. These methods are: (1) theoretical, (2) field experimental, (3) physical modeling, and (4) numerical simulation.

The theoretical method has used four principal approaches to represent dispersion in a turbulent atmosphere:

(1) gradient-transport or eddy-diffusivity theory;

(2) statistical theory and methods;

(3) similarity theory or dimensional analysis; and

(4) the practical scheme, the Pasquill-Gifford dispersion coefficients versus distance.

One of the most common approaches for estimating concentrations of airborne pollutants downwind from emitting sources is using the

TABLE I. A Survey of Research Studies on Transport, Dispersion, and Air Pollution According to Type of Study and Different General Land Forms

Type of Land Form/Study	Theoretical	Field	Numerical	Laboratory	Field Combination	Lab Combination	Totals
Plateau		1					1
Peneplain (Rolling Terrain)	1	3			1		5
Cliffs	1	2	1				4
Hills	5		1	4			10
Mountains	1	7	1				9
Valleys	12	19	7	2	5	2	47
Canyons		3					3
Passes		1					1
Slopes		1					1
Shoreline (Bays, etc.)	2	6	4	3	1		16
Gaps							0
Gorges							0
Basins	2	3	2		2		9
Terraces							0
Mesas							0
Combination Land Forms	2	10	3	2	1		18
TOTALS	26	56	19	11	10	2	124

Gaussian plume model and the Pasquill-Gifford dispersion coefficients (σ_y, σ_z) i.e.:

$$C(x,y,z) = \frac{Q}{\Pi\sigma_y,\sigma_z\bar{v}} \exp - \left\{ (h_e^2/2\sigma_z^2) + (y^2/2\sigma_y^2) \right\}$$

Over the past 15-20 years, a number of efforts have been directed toward developing new dispersion coefficients that account for the dispersive effects of terrain-induced thermal and mechanical turbulence. To date, a number of site-specific studies for rural, rolling terrain, shoreline environment and deep-valley or canyon terrain have developed terrain dispersion coefficients for use with the Gaussian plume model. These site-specific models have reported accuracies as good as a factor of 2.[1,2]

Generally, none of the theoretical methods are completely adequate for describing the many complex aspects of dispersion in complex terrain, although a number of site-specific models have provided useful information in defining some limits of dispersion over selected complex landforms. The theoretical approach will continue to illuminate and provide comparative information for certain aspects of complex terrain problems, but will probably never be able to provide the total solution because of the complexities and mathematical constraints.

Field measurements on transport and dispersion have been taken for over 20 years. The techniques utilized are chemical or particulate tracers, sampling equipment, radar, superpressure balloons, remote sensing, aircraft and networks of wind sensors. The resultant data

provide the basic information concerning transport and dispersion phenomenology. Unfortunately, the experiments are usually of short duration and during selected or random weather conditions due to the high cost of maintaining lengthy field operations.

Field experiments are necessary because they provide data on complex terrain air-flow phenomena, data for model input and testing of theoretical concepts. The existing data base is still inadequate to satisfy these needs for many of the common landforms associated with energy and pollutant sources.

The laboratory approach, either by wind tunnel or water channel - towing tank, has proven to be a viable technique for assessing the dispersion of pollutant sources located in complex terrain. During the past 15 years, the application of the laboratory technique has ranged from planning orographic cloud seeding strategies to urban air pollution assessment and depicting dispersion over hilly terrain by visualization techniques. In all these studies, the model results were in approximate agreement with corresponding available field observations.

The principal advantage of laboratory studies is that air-flow and dispersion data can be obtained over simulated three-dimensional terrain by visualization or by quantitative measurements. Usually the model study is relatively inexpensive compared to field studies. The major difficulty with the laboratory technique is the restrictions imposed by a laboratory environment. Modeling a turbulent Ekman boundary layer over complex terrain in an exact sense is not possible in a laboratory setting.

Similarity between field and model requires identical spatial distribution of concentration. This requires complete similarity between two air-flow systems of different length scales, e.g. the spatial distribution of a pollutant concentration would depend to a large extent on the following dimensionless parameters:

(1) Geometric similarity

$$\frac{z_o}{z}, \frac{z}{H_m}$$

(2) Kinematic similarity

$$Ro, \frac{\vec{v}(z)}{V_g}$$

(3) Thermal similarity

Ri,Fr

(4) Dynamic similarity

Re,Pr,Pe

(5) Source similarity

$$Fr, \frac{U_a}{w_s}, \frac{d}{h_s}$$

It is well known that all these dimensionless parameters cannot be satisfied exactly, hence, partial similarity is evoked. Partial similarity, the relaxation in strict similarity between field and model air-flow and physical processes has generally been successful when one considers the less-detailed aspects of dispersion and transport over complex terrain features.[3,4]

Numerical simulation of transport and dispersion in complex terrain has seen considerable development since the initial attempts by Hino using a two-layer numerical model.[5] This initial study showed that a workable numerical model must be able to calculate a physical and reasonable three-dimensional wind field over simulated terrain. Generally, there are presently three classes of numerical wind field models: (1) primitive equation models, (2) simplified physics models, and (3) objective wind analysis models.

The primitive equation or simplified physics models show the greatest promise for providing the necessary calculated wind fields, although they may require a lot of computer storage and time. The air-flow models provide the input data to advection and diffusion models. Some typical diffusion models are: (a) Eulerian models with a closed-form solution to the steady-state advection-diffusion equation (bivariate Gaussian plume model), (b) Lagrangian models, (c) combined Eulerian-Lagrangian methods for solving the advection-diffusion equation wherein Lagrangian markers trace the movement of the pollutant through fixed cells, (d) box models based on a concentration-of-mass equation for pollutants, and (e) Monte Carlo methods.

During the past five years, a number of different numerical techniques has been developed and tested for estimating dispersion and transport in complex landforms. Generally, many of these past studies have emphasized the importance of calculating the expected three-dimensional wind flow in order to make reasonable predictions of ground-level concentrations for complex terrain situations. The physical realism provided by a three-dimensional wind-flow calculation has the benefits of correct plume path

calculation, correct prediction of the position of the maximum concentration, and correct pattern of ground level and elevated concentrations including lateral dispersion over terrain obstacles. Present developed numerical models claim that their predicted values are within a factor of 2 of the measured field data and are generally better than predicted values from Gaussian plume models.[1,2]

It is evident that such research techniques have their advantages and disadvantages when considering the complexities of transport and dispersion in complex land forms. Each technique can contribute information to solving this difficult physical problem. Researchers should continue to use the advantages of each technique to help solve the remaining poorly defined aspects associated with this problem.

SOME RESEARCH NEEDS

Some of the problems that the above research methods need to investigate in greater detail are:

(1) the development of better physical and numerical models for simulating wind fields and turbulence (dispersion coefficients) over different types of complex land forms;

(2) medium- and long-range (up to 100 km) transport and dispersion of plumes;

(3) physical and chemical transformation in plumes; and

(4) removal or scavenging of pollutants from plumes.

The data base for wind and turbulence measurements for different types of complex landforms is very incomplete, and this aspect is very important for understanding the dispersion mechanism in rough terrain. Wind and turbulence measurements near the surface and aloft are needed for assisting the development of better physical and numerical models.

The medium- and long-range transport of plumes by the ambient- and terrain-induced winds is becoming an important and timely problem for air quality studies. Current models generally calculate spatial concentration fields over distances of 5 to 10 km and sometimes more, but with less confidence in the accuracy of the results. Studies over uniform terrain have shown that pollutants from sources in one or more states may gradually be transported to other surrounding states by large-scale wind patterns. As more energy development activities take place in states of rugged terrain, the medium- and long-range transport of pollutants will become more of a problem for maintaining air quality standards in pristine areas of good air quality.

An area of research that is becoming more important in complex terrain situations is the plume chemical transformation and scavenging mechanisms. The depletion and deposition of pollutants in the ecosystems and budgets of pollutants remaining in the air are increasing important problems that will need answers in the future.

MULTIAGENCY RESEARCH PROJECT

The complexities of air flow and dispersion in complex terrain can only be adequately described and understood by a concentrated research

program utilizing the four research methods discussed previously. A multiagency effort towards funding and technical and administrative supervision of the programs may be desirable, since many of the goals and results of such a proposed program would be of interest to several agencies.

A number of different Federal and private agencies, such as DOE, EPA, U.S. Forest Service, Bureau of Reclamation, EPRI, NSF, USGS, NASA, etc. have interests that require quantitative information concerning transport and dispersion in complex terrain. The Wind Energy Program under the Department of Energy is synthesizing certain meteorological data and developing numerical wind models that may have potential application to transport and dispersion problem. NCAR has numerical and field capabilities which, if incorporated in such a project, would lend much assistance in obtaining relevant data. A number of universities also would have capabilities that could be utilized in such a project.

The details of a multiagency project have been outlined by a workshop in Albuquerque, New Mexico,[6] and parallels many ideas made in this status report concerning research methods and needs. Essentially, the workshop suggested a broad-range program using: (1) data reviews and analyses, (2) field experimental studies in local and regional scales, (3) selection of field sites, (4) theoretical and physical modeling, (5) numerical simulation, and (6) studies on chemical transformation and removal processes.

The initial development of a multilaboratory program under DOE/OER and Lawrence Livermore Laboratories started during fiscal year 1979.

The goal of this program is to develop methods, through the use of models, improved physical understanding through field programs, to help assess the impact of developing energy sources in areas of complex terrain. The Geysers Known Geothermal Resource Area (KGRA) has been selected as the initial location for this program although other locations will probably be defined in the future. Some initial results from this program will be presented at the meeting.

CONCLUSIONS

A multiagency or multilaboratory research program and the funding of new programs may be expected to produce a more adequate data base on complex terrain problems, a greater understanding of atmospheric transport and dispersion in complex terrain, and greater reliability in air quality prediction. This forthcoming information will be very important in the development of various energy resources, particularly in the western states, as well as improving prediction ability for environmental problems throughout the United States.

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