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Project Summary

Contributions of the Fluid Modeling Facility to EPA's Complex Terrain Model Development Program

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The contributions of the EPA Fluid Modeling Facility (FMF) to the Complex Terrain Model Development Program (CTMDP) are described. These contributions included a wide range of laboratory studies and a limited amount of numerical modeling of flow and diffusion in neutral and stably stratified conditions in complex terrain. The goal of the CTMDP is the development of a dispersion model valid in complex terrain, with emphasis on plume impaction on nearby hills during nighttime stable conditions. Work at the FMF prior to the inception of the program divided the basic framework for the model—the dividing-streamline concept—and the focal point around which the field program was designed. Throughout the course of the CTMDP, the FMF interacted vigorously with the model developers by providing support in various ways. Early work provided direct support as an aid to planning the details and strategies of the field experiments and testing the limits of applicability of the dividing-streamline concept. Later work included exercises of "filling in the gaps" in the field data, furthering the understanding of the physical mechanisms important to plume impaction in complex terrain and in stably stratified flows in general, testing various modeling assumptions, providing data for "calibration" of various modeling parameters, and testing the ability of the laboratory models to simulate full-scale conditions. Simultaneously, the FMF responded to the needs of the regulatory arm of EPA, the Office of Air Quality Planning and Standards (OAQPS), by providing guidance concerning expected terrain effects and by conducting demonstration studies. Finally, several supplemental studies were conducted, broadening and expanding upon the specific requests of the model developers and the OAQPS.

This Project Summary was developed by EPA's Atmospheric Sciences Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

In the late 1970's the Office of Air Quality Planning and Standards (OAQPS) of the Environmental Protection Agency (EPA) identified a crucial need to develop an improved mathematical model that dealt with plume impaction from large sources located in mountainous terrain under stable flow conditions. A workshop was convened in 1979 to focus on complex terrain modeling problems and to develop recommendations to EPA with respect to the design of a program of experiments and model development efforts. Subsequently, the EPA outlined a plan to achieve the objective through an integrated program of model development, fluid modeling experiments and field studies of plume-terrain interactions on hills of progressively increasing size and complexity. This multi-year, multi-faceted program is known as the Complex Terrain Model Development Program (CTMDP).

The Fluid Modeling Facility (FMF) interacted vigorously with various groups participating in the CTMDP, and provided direct support and guidance in many different ways. The FMF research program has ranged from the development of broad guidelines and physical concepts to specific site studies and regulatory applications. The FMF has provided laboratory data to "fill in the gaps" in the field data and tested the validity of convenient modeling assumptions.

The complete report summarizes the contributions, both direct and indirect, of the FMF to the CTMDP. The discussion provides a historical perspective and a comprehensive list of FMF's accomplishments with respect to furthering the physical understanding of flow and diffusion in complex terrain. Over 65 publications have been generated from work conducted within the FMF on complex-terrain research. Only a few of the most important publications are highlighted herein.

Background

The major facilities of the FMF consist of a meteorological wind tunnel and a stratified water channel/towing tank. The wind tunnel has a test section 3.7m wide, 2.1m high, and 18.3m long, and a speed range of 0.5 to 10m/s. The towing tank is 2.4m wide, 1.2m deep, and 25m long. It is density-stratified using layered mixtures of salt water.

Research work conducted at the FMF prior to the inception of the CTMDP had a strong influence on the directions to be taken in the field work and on the type of model (i.e., physical concepts) to be developed. The stratified towing tank was commissioned in 1976 and rather fundamental studies were begun immediately on the structure of stably stratified flow over idealized three-dimensional hills and on diffusion from a point source within a stably stratified field of turbulence.

The first published reports on this work described the flow structure observed over a bell-shaped hill under neutral and stably stratified conditions. Earlier theoretical work, model experiments, and observations all indicated that, when the stratification is strong enough, the air flows in approximately horizontal planes around the topography. Up to that time, however, there had been little firm laboratory or field data as to how *strong* the stratification must be for any given streamline starting below the hill top to pass *round the side* rather than *over the top* of the hill.

Hunt and Snyder (1980) showed evidence for a dividing streamline of height H_s such that streamlines below H_s would impinge on the hill surface and follow the surface around the sides, whereas streamlines above H_s would go over the top. They suggested the simple forumula

$$H_s = h\,(1 - F) \qquad (1)$$

as the criterion to determine whether a plume embedded in the flow approaching the hill would impact on the surface or surmount the top, for $0<F<1$ ($F=U_\infty/Nh$ is the Froude number where U_∞ is the approach-flow wind speed, N is the buoyancy frequency, and h is the hill height). This forumla was demonstrated through towing-tank experiments to be valid for a linearly stratified environment and a uniform approach-flow velocity profile.

This formula provided the basis for a simple conceptual model (Hunt et al, 1979) that was used as the framework for the CTDM and, indeed, as the framework for the design of the CTMDP. This conceptual model divides the flow-field into two regimes, a lower layer below the dividing-streamline height which flows in essentially horizontal planes around the hill—this flow may thus be described in terms of two-dimensional flow around a cylinder—and an upper layer above the dividing-streamline height which may be described in terms of a modified potential flow over a cut-off hill.

Snyder et al (1980) presented further evidence from towing-tank experiments in support of the simple formula, they showed it was applicable to other shapes of axisymmetric hills, namely a cone and a hemisphere. Furthermore, they presented another simple formula and supporting experimental data for determining whether an elevated (step) inversion would surmount a hill. This second formula, which predicts the point at which the interface just reaches the hilltop, is

$$\frac{U_\infty^2}{(g h_0 \Delta\rho/\rho_1)} = 2\left[\frac{h}{h_0} - 1\right] \qquad (2)$$

where g is the acceleration due to gravity, h_0 is the height of the interface (far upwind), $\Delta\rho$ is the density difference across the interface, and ρ_1 is the density of the fluid between the interface and the surface.

The "state of the science" immediately prior to the contract award was as follows. The dividing-streamline concept had been shown to be a useful conceptual framework to use in describing the structure of strongly stratified flow around three-dimensional hills. It had only been shown to be valid, however, for quite a limited range of hill shapes, all of which were axisymmetric. It had only been verified under uniform stratification (linear density gradient) or under a step inversion (sharp density interface), under a uniform approach-flow velocity profile, and, of course, only under steady-state, small-scale laboratory conditions.

Results and Conclusions

The major CTMDP contract was awarded in June 1980, and the work plan called for the small hill impaction study to begin at Cinder Cone Butte (CCB), Idaho, in September. Almost immediately, the FMF conducted towing-tank experiments to aid in the detailed planning and design of the field experiments. The first study provided guidance with regard to the location of the main meteorological tower. A second study provided guidance for smoke- and tracer-release strategies, for preselecting locations for samplers and cameras, and for choosing in advance several different sampler strategies to account for variations in flow regimes and wind fields. A third study tested the validity of an integral formula for predicting the dividing-streamline height.

In anticipation of the field study at CCB, the question arose as to how to predict the dividing-streamline height when the wind profile was not uniform and the density gradient was not linear. This was of paramount importance in planning the release scenarios, as the release locations and heights were to be chosen in real time during the field study based upon the incoming real-time meteorological data. J. C. R. Hunt immediately sketched the now well-known integral formula as

$$\frac{1}{2}\rho U_\infty^2(H_s) = g\int_{H_s}^{h}(h-z)\left[-\frac{\partial\omega}{\partial z}\right]dz. \qquad (3)$$

This integral formula is based upon simple energy arguments. It answers the question: "in a strongly stratified flow approaching a hill, does a particular fluid parcel at some height upstream possess sufficient kinetic energy to overcome the potential energy required to lift itself through the density gradient from its upstream elevation to the hill top?" The left-hand side may be interpreted as the kinetic energy of the parcel far upstream at elevation H_s, and the right-hand side as the potential energy gained by the parcel in being lifted from the dividing-streamline height H_s to the hill top h through the density gradient dp/dz. This integral formula was persumably applicable to a fluid with any shape of stable density profile and, presumably, with any shape of approach-flow velocity profile. In practice, it must be solved iteratively, because the unknown H_s is the lower limit of integration; the formula can easily be reduced to the simpler formulae (1) and (2) by using the boundary conditions applicable to those special cases. The third study thus attempted to verify this integral formula under density profiles similar to those expected at CCB. A typical nighttime temperature profile in the Snake River Basin (site of CCB) was found to consist of a strong, surface-based inversion of depth 50 to 100m and a weaker inversion above extending to several hill heights. Hence, the stratified towing tank was filled with a strong density gradient near the surface and a weaker gradient above. A vertical rake of 3 tubes was positioned well upwind of the hill (a model of CCB), and neutrally buoyant dye was emitted from each tube. For each tow, a particular stack height (center tube) was chosen and the general formula was integrated numerically using the measured density profile to predict the towing speed required such that the center streamer would rise to the elevation of the saddle point of CCB, i.e., the minimum height of the draw between the two peaks. If the formula were correct, then, the lower streamer should go around the side of the hill, the upper streamer should go over the top, and the center one should split. The height of the break-point between the two gradients was then reduced and the process repeated. In all, 12 tows were made, varying the height of the break-point or the dividing-streamline height (release height) each time.

Figure 1 shows a side view of the impinging streamers during a typical tow, i.e., the upper streamer going through the draw, the lower streamer going round the side, and the middle one splitting. The density profiles were integrated in accordance with Equation (3) to find the dividing-streamline heights as functions of the towing speed. The agreement between the predictions and observations was excellent. The results of this set of experiments provided confidence in the validity of the general integral formula for predicting the height of the dividing streamline for a wide range of shapes of stable density profiles.

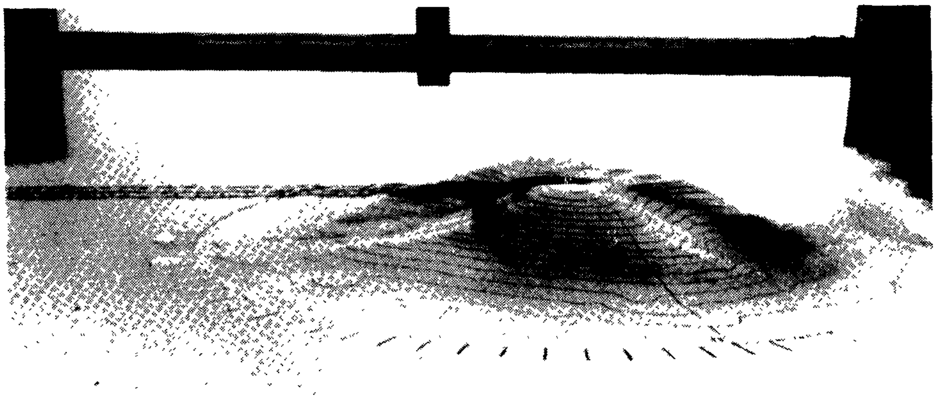

Figure 1. *Oblique view of impinging streamers on CCB. Middle dye streamer is released on the dividing-streamline height; others at ±1 cm (±6 m full scale).*

Subsequent to the field study, one particular hour of the field data at CCB was selected for simulation in the towing tank. That hour was 0500 to 0600, 24 October 1980 (Case 206), which may be characterized as very stable, i.e., light winds and strong stable temperature gradients. Measurements made during the towing-tank experiments included ground-level concentrations under various stabilities and wind directions, vertical distributions of concentration at selected points, plume distributions in the absence of the hill, and visual observations of plume characteristics and trajectories.

This series of tows showed that the surface-concentration distributions were extremely sensitive to changes in wind direction. For example, Figure 2 shows that the distribution shifted from the north side of the hill to the south side with a shift of only 5° in wind direction. Comparisons of individual distributions with field results showed much larger maximum surface concentrations and much narrower distributions in the model results. To account for the large variability in the winds measured during the hour, a matrix of 18 tows (three wind directions x six wind speeds) was conducted, and the concentration patterns were superimposed. The resultant superimposed model concentrations compared very favorably with field measurements. The largest model concentrations were within a factor of two of the highest field values, and 70% of the model concentrations were within a factor of two of the observed field values.

Numerous other studies were conducted to test the validity and limits of applicability of the dividing-streamline concept for example, examining the effects of shear in the approach-flow velocity profile, of the crosswind aspect ratio of the hill, of the hill slope, and the effect of the wind angle on a long ridge. These results were published separately as parts of papers on studies done for a variety of different purposes, but the specific aspects dealing with the validity and applicability of the dividing-streamline concept were extracted and published collectively by Snyder et al (1985).

In response to a request from the model developers, a series of measurements was made of plume characteristics in flat terrain and over a three-dimensional hill immersed in the simulated neutral atmosphere boundary layer of the meteorological wind tunnel. Effluent was released at a number of elevations, upwind distances, and positions laterally offset from the centerplane determined by the wind direction and the center of the hill. Sufficient concentration measurements were made to enable the construction of plume cross sections at the downwind position of the hill center and, in a few cases, at the upwind base of the hill. These data were analyzed to provide the desired information on horizontal and vertical plume deflections and deformations effected by the hill. One of the more dramatic examples is shown in Figure 3. In this case, the source was on the centerplane at ground level, 6 hill heights upwind of the hill center (the skirt of the hill extended to

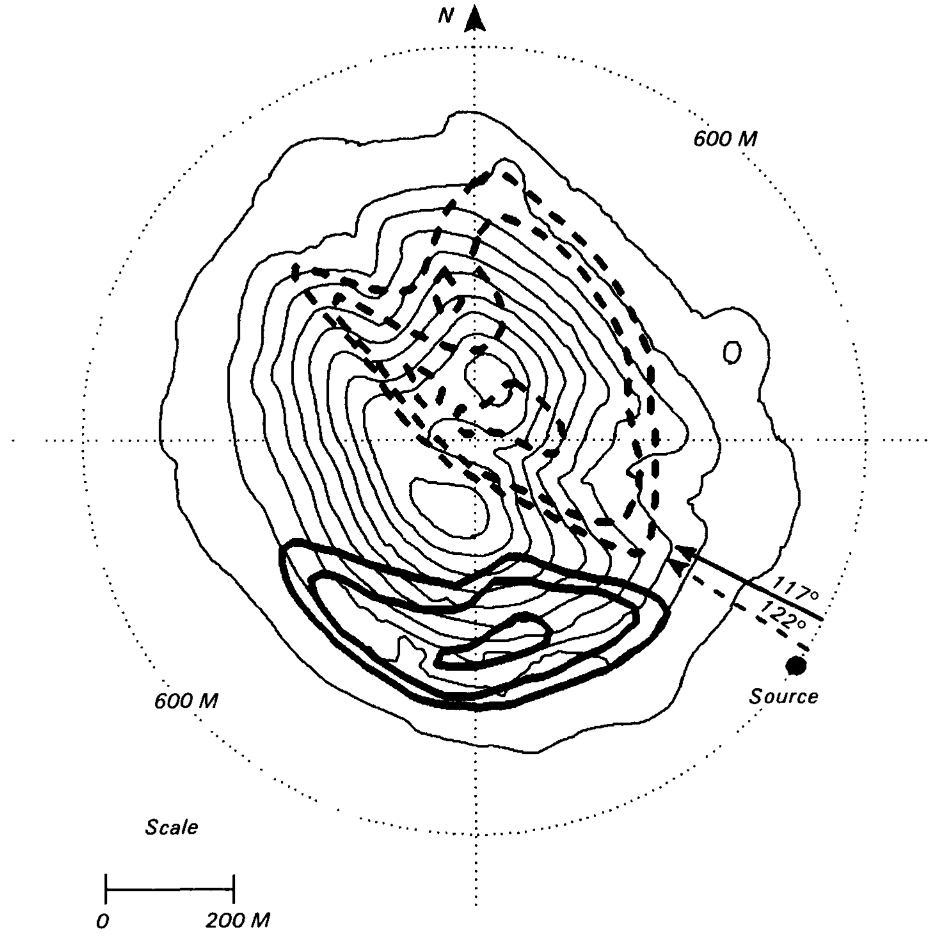

Figure 2. *Concentration distributions measured during individual tows of CCB with $H_s/h = 0.31$ and $H_D/h = 0.38$; wind direction: ——— 117°, – – – 122°.*

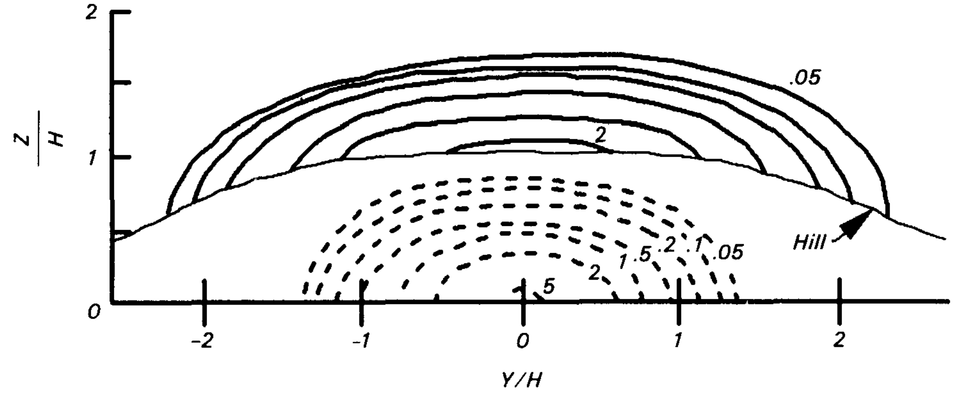

Figure 3. *Plume cross sections measured in presence (———) and in absence (– – –) of axisymmetric CCB model at x = 0 (hill center). $H_s/h = 0$, $x_s/h = -6$, $y_s/h = 0$.*

5h). Plume cross sections measured at the position of the center of the hill, both in the presence and in the absence of the hill are shown. The hill effected a 91% increase in the lateral plume width. In this case, the maximum surface concentration (at the same downwind distance) was decreased by a factor of 2 but, of course, the area of coverage by large concentrations was greatly increased. Detailed data reports were provided to the model developers immediately, and the results were published by Snyder and Lawson (1986).

As a result of these and similar measurements, refinements were made to CTDM. Specifically, the calculation procedures were modified to utilize the strain inferred or measured over the crests of two- and three-dimensional hills in the wind tunnel, i.e., the T-factors in the model were adjusted in accordance with wind-tunnel data. Substantial improvements in the CTDM predictions of terrain amplification factors were obtained, as described by Strimaitis and Snyder (1986).

One of the important overall goals in this effort was to ascertain what circumstances lead to the largest ground-level concentrations (glc's), i.e., are larger glc's expected when the plume from an upwind source impinges on the hill or when the source is downwind of that hill such that the plume is caught in a recirculation region and downwashed to the surface? Which are likely to lead to larger glc's, two-dimensional or three-dimensional hills? Stable conditions or neutral conditions? In each of these circumstances, what orders of magnitude of surface concentrations may be expected?

A simple method used to intercompare effects of terrain on the maximum glc and to determine worst-case conditions is through the the terrain amplification factor, *A*, which is defined as the ratio of the maximum ground-level concentration occurring in the presence of the terrain feature, χ_{mx}, to the maximum that would occur from the same source located in flat terrain, χ^o_{mx}, i.e., $A = \chi_{mx}/\chi^o_{mx}$. This definition is useful only for elevated sources, of course, because for ground-level sources, the maximum surface concentration occurs at the source itself.

A wide range of neutral-flow wind-tunnel studies was conducted at the FMF on diffusion from sources located in the vicinities of two- and three-dimensional hills. Table 1 lists approximate values of

Table 1. *Summary of Terrain Amplification Factors for Sources in the Vicinity of Hills in Neutral Flow*

Source Location	*Hill Type*	*A*
Downwind	*Two-Dimensional*	*10-15*
Downwind	*Three-Dimensional*	*5-6*
Upwind	*Three-Dimensional*	*2-4*
Upwind	*Two-Dimensional*	*1-3*
Top	*Two-Dimensional*	*0.5-1*

maximum terrain amplification factors that were found in the various situations. From the standpoint of a fixed stack height, the worst location for a source appears to be just downwind of a two-dimensional ridge. Downwind sources generally result in larger glc's because of the excess turbulence generated by the hills and because the effluent is generally emitted into a low speed region where the streamlines are descending toward the surface. Maximum A's are considerably larger than those downwind of three-dimensional hills. Also, the sizes of the recirculating cavity regions downwind of three-dimensional hills are generally much smaller than those downwind of two-dimensional ridges. With regard to upwind sources, terrain amplification factors are larger for three-dimensional hills because, in such flows, streamlines can impinge on the surface and/or approach the surface more closely than in two-dimensional flows.

The maximum terrain amplification factors as listed in Table 1 are useful only for scoping a particular problem or for finding the worst possible situation. They do not provide practical estimates for use by, say, an air pollution meteorologist in determining the maximum glc resulting from a particular power plant or for determining the best location for that plant. For that purpose, the concept of a "window" of excess concentrations is more useful. For any given plant location (say, upwind of a hill), there is a *limited* range of stack heights H_s for which a *significant* amplification of the glc will occur. (For sake of argument, we will here define significant as a factor of 2.) This amplification can occur only if the position of the maximum glc lies on or near the hill surface. For small H_s, χ_{mx} will occur upwind of the hill and thus be little influenced by the hill, so that A ($\equiv\chi_{mx}/\chi^{o}_{mx}$) will approach unity. If H_s is too large (for example, $H_s \gg h$, the hill height), χ_{mx} will lie well beyond the hill and A will again approach unity. In either case, there is little amplification. A "window" of intermediate stack heights and locations exists, however, where A's will significantly exceed unity. These "windows" of critical H_s values have been measured by Lawson and Snyder (1985) for two typical hill shapes that might be found in the real world, one axisymmetric, the other two-dimensional. The results are shown in Figure 4. The 1.4-window, for example, extends to about 14h upstream, 10h downstream, and as high as 1.8h in the vertical for the axisymmetric hill. For the two-dimensional hill, this 1.4-window extends about 8h upstream, 15h downstream, and as high as 2.2h in the vertical.

Such contour maps as provided in Figure 4 can be very useful for the practioner. Once an acceptable terrain amplification factor (or "excess concentration") is decided upon, it is a simple matter to trace the window on the contour map to determine the area (plant location and/or stack height) to be avoided. Conversely, from such maps, the likely maximum glc for a potential site and stack height can be estimated. The use of terrain amplification factors simplifies the application of these data to full-scale situations. The expected maximum glc in flat terrain is calculated (from mathematical models or standard curves), then the concentration in the presence of the hill is simply the product of this quantity and the TAF.

Summary

The EPA Fluid Modeling Facility has conducted a wide range of laboratory studies and a limited amount of numerical modeling of flow and diffusion in association with the CTMDP. The goal of the CTMDP is the development of a dispersion model valid in complex terrain, with emphasis on plume impaction on nearby hills during nighttime stable conditions. Work at the FMF prior to the inception of the program provided the basic framework for the model—the dividing-streamline concept—and the focal point around which to design the field program.

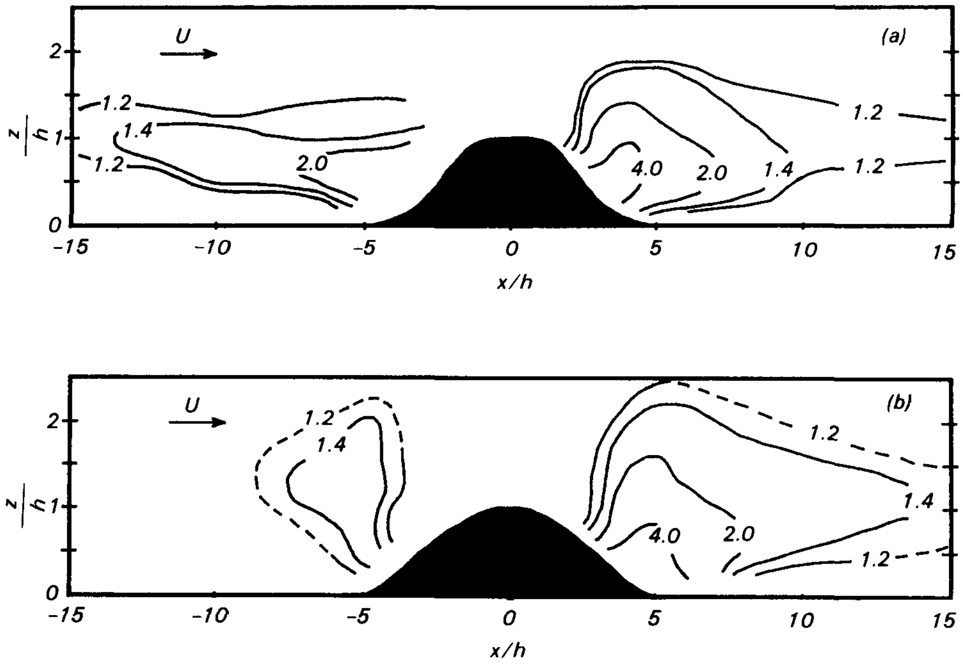

Figure 4. *Contours of constant terrain amplification factors over (a) axisymmetric hill and (b) two-dimensional ridge. Note that vertical scale is exaggerated by a factor of 3.*

Throughout the course of the CTMDP, the FMF interacted vigorously with the model developers by providing support in various ways. Early work provided direct support in planning the details and strategies of the field experiments and solidifying and testing the limits of applicability of the dividing-streamline concept. Later work included excerises of "filling in the gaps" in the field data, furthering the understanding of the typical mechanisms important to plume impaction in complex terrain and in stably stratified flows in general, and testing the ability of the laboratory models to simulate full-scale field conditions. And, as the needs arose, the FMF tested various modeling assumptions, concepts, and hypotheses and provided data for "calibration" of various parameters within the CTDM model.

Simultaneously, the FMF responded to the needs of the regulatory arm of EPA, OAQPS, by providing guidance concerning expected terrain effects and by providing a demonstration study—an example for industries to follow in conducting good-engineering-practice stack height determinations in complex terrain. Also, a broad range of supplemental studies was conducted, expanding and enlarging upon the specific requests of the OAQPS and the CTDM model developers to provide information of general use to the scientific and air pollution modeling communities. Many of the data sets generated in the course of this program have been provided to and used by various groups (nationally and internationally) in the development, testing and evaluation of complex terrain dispersion models.

The most significant contributions included (1) the conceptual framework for the mathematical model (i.e., the division of the flow-field into two regimes, a lower layer below the dividing-streamline height which flows in essentially horizontal planes around the hill, and an upper layer above the dividing-streamline height which is treated as modified potential flow over a cut-off hill) and the detailed experimental validation and establishment of limits of applicability of these concepts, (2) verification of the integral formula for the height of the dividing-streamline—this allowed computations of the dividing-streamline height under arbitrary approach-flow conditions, including shear in the approaching wind-speed profile and nonlinear temperature gradients, (3) demonstration of the extreme sensitivity of surface concentration patterns to wind direction under strongly stratified conditions, (4) measurements of plume deflections and deformations over hills in neutral flow—these permitted adjustment of the T-factors in CTDM and resulted in substantial improvements in the CTDM predictions, and (5) the introduction of the concept of "windows of excess concentration" and measurements of terrain amplification factors—these provided simple and practical methods for estimation and intercomparison of effects of terrain and source locations on maximum ground-level concentrations that may result from sources placed in the vicinities of hills.

Only the highlights of the FMF contributions to the CTMDP are contained in the present summary. The complete report provides much more detail and a comprehensive list of over 65 publications generated from the work conducted at the FMF on complex-terrain research.

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The complete report, entitled "Contributions of the Fluid Modeling Facility to EPA's Complex Terrain Model Development Program," (Order No. PB 87-227 682/AS; Cost: $13.95, subject to change) will be available only from:

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