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Project Summary

EPA Complex Terrain Model Development: Final Report

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The Complex Terrain Model Development (CTMD) project has met its original objectives of producing an atmospheric dispersion model appropriate for regulatory application to elevated sources of air pollutants located in complex terrain. The model development effort has focused on predicting concentrations during stable atmospheric conditions.

The program, initiated in June 1980, has involved the performance of 4 major field experiments which produced a wealth of data for model development and verification purposes. The first experiment, held at Cinder Cone Butte (CCB) in Idaho, involved the extensive use of a mobile release system to provide a high capture rate of ground-level concentrations resulting from elevated plumes flowing toward the butte. The second experiment, at Hogback Ridge (HBR) near Farmington, New Mexico, featured a very long ridge that provided a site for testing the importance of terrain aspect ratio on the flow dynamics. The final field experiments were held at the Tracy Power Plant (TTP) near Reno, Nevada. This Full Scale Plume Study (FSPS) provided a large-scale test of the modeling concepts developed. Data were also obtained from a series of fluid modeling studies performed at EPA's Fluid Modeling Facility. These tests provided confirmation of some of the basic theoretical principles adopted in the modeling effort and provided information on plume behavior as a function of systematic changes in terrain shapes, release heights and distances to terrain objects.

The Complex Terrain Dispersion Model (CTDM) is an advanced Gaussian model that uses a flow algorithm to provide terrain-induced plume trajectory and deformation information. CTDM is suitable for regulatory use, but it requires substantially more information on terrain and local meteorology than complex terrain screening models. With simpler data bases, it demonstrates degraded performance.

The model evaluation effort concentrated first on the use of field data collected within this program. Subsequent tests were made with two other data sets obtained from SO_2 monitoring networks near a large paper mill and a large power plant, both located in complex terrain. Statistical performance results of CTDM were compared with those of other complex terrain models of current regulatory interest or use. The model evaluation demonstrates that CTDM has superior performance in the majority of tests and has consistently good performance among all the sites. The statistical performance of CTDM in complex terrain settings is shown to be comparable to the performance of EPA's current refined flat terrain models in simple terrain settings.

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

The CTMD program was initiated by EPA in response to long-standing controversies in the technical and regulatory communities over the lack of reliable methods for predicting air quality concentrations in regions of mountainous or complex terrain. Of particular concern was the absence of a verified dispersion model for predicting ambient air concentrations during stable atmospheric conditions, the conditions expected to give rise to the highest short-term concentrations.

The components of the CTMD program and the progress made are well-detailed and documented in a number of reports. In particular, five Milestone Reports were written during the course of the program which describe in detail the model development efforts, the field experiments, the data gathering and interpretation efforts, and the model evaluation efforts performed during the course of this program.

This report describes a refined model, the Complex Terrain Dispersion Model (CTDM) that was developed during the CTMD program. Comparisons of model.predictions with observations at five complex terrain sites are presented for CTDM and complex terrain screening models. Results of a sensitivity analysis of CTDM are discussed. Finally, the limitations of CTDM, project conclusion remarks, and recommendations for further research are presented.

Field and Fluid Modeling Program Results

Data collected at each of the field experiments were archived for use in the model development and evaluation phases of this program and for future use. To alleviate the difficulty others have had trying to utilize raw data from large field experiments, EPA has developed Modelers' Data Archives (MDA's) for each experiment. The MDA's are subsets of the complete data sets which are thought to be of most use to those involved in dispersion model development. The raw data have been collected in a series of computer files which are available on magnetic tape from the Terrain Effects Branch of EPA.

A progression of understanding emerged from these experiments. Observations from CCB demonstrated the validity of the dividing streamline concept or critical height, H_C, in simulating the flow fields during stable atmospheric conditions. Tracers and smoke released directly upwind of the butte and above H_C were generally observed to flow up and over the butte, in accordance with theory, while plumes released below this height were generally observed to pass around to the side of the butte. At HBR, the dividing streamline concept also was shown to be applicable, although the flow behavior below this height was different from that observed at CCB. In particular, at HBR, the lower portion of the flow was "blocked" behaving as a relatively stagnant flow with correspondingly low wind speeds. The largest concentrations observed at HBR occurred for releases below H_C and the magnitude of the concentrations (normalized by release rate) were much larger than those observed at CCB,or subsequently at the FSPS. Observations from the FSPS at the Tracy site showed both kinds of behavior for releases below H_C. There were portions of the flow which, when they encountered high terrain away from the valley walls, became relatively stagnant as observed at HBR. Plumes embedded in flows having a primary down-valley component and encountering terrain obstacles protruding from the valley side walls, on the other hand, exhibited an ability to lift up and over the terrain or readily pass around the sides as seen at CCB.

An integral part of the CTMD program from the beginning was .the efforts undertaken at EPA's Fluid Modeling Facility (FMF) at Research Triangle Park, NC. Theoretical aspects of the phenomena associated with interactions of stable atmospheric flows with terrain obstacles suggested that scaled-down, fluid modeling experiments could be used to investigate many of the fluid mechanical issues. Experiments at the FMF included simulations with models of CCB and HBR and for conditions corresponding to some of the field experiments. Verification of the dividing streamline concept was a central focus for experiments that included testing of the effects of changes in release height and terrain shape. Another series of experiments addressed the effects on maximum surface concentrations of sources of different heights being placed upwind and downwind of simply-shaped terrain obstacles.

Overview of CTDM

CTDM is a point-source Gaussian plume dispersion model designed to estimate hourly-averaged concentrations of plume material at receptors near an isolated hill or near a well-defined segment of an array of hills. When a hill is present, CTDM accounts for how the changed flow alters the way in which plume material can reach the surface. Obviously, the path of the plume can change as the flow spreads over or around the hill so that there is a shift in the relative position of a receptor and the center of the plume. The rate at which the material diffuses toward the surface is also changed, and the center of the plume is allowed to impinge on the surface of the hill. As a result, peak concentrations expected on terrain are increased beyond those concentrations that would have been expected for the same meteorological conditions on level terrain.

In the absence of stratification, all streamlines in the flow pass over a hill as modeled by CTDM. The centerline of a plume in this flow follows the streamline that passes through the source of that plume. As the plume grows in the vertical and horizontal directions (in the plane perpendicular to the flow), plume materia diffuses across adjacent streamlines eventually reaching the set of streamlines that marks the surface of the terrain Distortions in the flow which are induced by the hill change the position and relative spacing of the streamlines from their initial distribution over level terrain and therefore change the shape of the plume as it passes over the hill. In CTDM, the plume stretches in the horizontal as it passes over the crest of a simple three-dimensional hill and this stretching produces a wide concentration footprint over the hill. In addition, spacing between streamlines is reduced in the vertical and expanded in the horizontal, while the speed of the flow increases over the crest. These changes tend to increase the diffusion in the vertical and reduce it somewhat in the horizontal, thereby affecting the magnitude of the predicted concentrations on the hill.

The nature of the flow change dramatically when the flow is very stabl stratified. A two-layer structure develop in which the flow in the lower laye primarily deflects around the hill, whil the flow in the upper layer travels ove the top of the hill. A critical height H defines the boundary of these two layer in CTDM. In the layer above H_C, th approach flow has sufficient kineti energy to transport a fluid parcel up an over the hill against the density gradien of the ambient stratification. In the laye below H_C, the approach flow ha insufficient kinetic energy to push the parcel over the hill, so that the flow below H_c is restricted to lie in a nearly horizontal plane, allowing little motion in the vertical. Consequently, plume material below H_c travels along and around the terrain rather than over it.

Adjusting receptor positions while keeping the trajectory of the plume a straight line simplifies the mathematics of CTDM a great deal. Rather than keeping track of the actual boundary of a hill and the deformed trajectory of each of the segments of the plume, concentrations are computed at receptor points in a coordinate system along the plume trajectory. The resulting equations are only slightly more complicated than those for flat terrain. A similar adjustment of receptor positions is employed for receptors above H_c. When the deflection of each streamline is removed, and the distortion in the plume is scaled out, an equivalent plume-receptor geometry is obtained.

Many of the concepts contained in CTDM are not present in complex terrain screening models currently in use for regulatory assessments. Partitioning of plume material about H_c in the vertical and about the stagnation streamline in the horizontal is unique to CTDM. This partitioning is fundamental to describing the transport of plume material in the flow field around hills. Furthermore, the treatment of the effect of the hill on the dispersion process for material above H_c, avoids the use of the plume height correction factor found in other models. This factor is typically applied as a function of stability and receptor height only, and it leads to an inconsistent treatment of reflection of plume material from the lower boundary. In the screening models, the height of the plume above the ground is constant all of the way from the source to a receptor, but this height varies from receptor to receptor. Hence, adjacent receptors at unequal terrain elevations are modeled *with two very different plumes. If an* impingement computation is invoked, this treatment produces a concentration equal to twice that at the center of the plume in the absence of terrain. In CTDM, the impingement concentration is equal to that at the center of the plume.

The method used to specify the rate of plume growth also differs from the other models. Both σ_y and σ_z functions depend on the turbulence intensity, rather than stability class. In the case of σ_z, the function describing the rate of growth with time also depends on the scale of the mixing processes, which depends on the elevation of the plume above the surface, and on the stratification and turbulence near this elevation. In contrast, the other models incorporate a fixed rate-of-growth function for each stability class, and do not contain the influence of processes at plume height.

CTDM Evaluation Analysis

CTDM and other complex terrain models used for rural applications, COMPLEX I and RTDM, were evaluated at five sites. These sites included the three CTMD sites (CCB, HBR. FSPS) as well as two other sites with conventional SO_2 data for a one-year period (the Westvaco Lake paper mill and the Widows Creek steam generating station). A large part of the CTMD data base (CCB, HBR, FSPS) was used in the development of CTDM, so the overall results for CTDM at these three sites do not represent an unbiased test of CTDM versus COMPLEX I and RTDM.

A series of statistical tests were run on the models for data sets both paired or unpaired in time and/or space. These tests examined the models' overprediction or underprediction bias as well as the root-mean-square (RMS) error, and the percentage of predictions within a factor of two observations.

Another aspect of the evaluation analysis involved an examination of the spatial distribution and magnitude of CTDM concentrations for each hour at the three CTMD tracer sites. CTDM performance in the LIFT and WRAP components was assessed by examining the behavior of hourly patterns of predicted and observed concentrations.

Conclusions

The Complex Terrain Model Development program objectives have been met. The Complex Terrain Dispersion Model, CTDM, is the primary product of the effort. This model displays *considerable improvement over the* models that EPA has been using in regulatory practice, especially on an event-by-event basis. It also shows improved performance over RTDM, a model EPA is adopting as a third- level screening model and which benefited from the early findings of the CTMD program on the importance of the dividing streamline concept to understanding stable flows.

CTDM is an improved and versatile refined air quality model for use with elevated point sources in high terrain settings during stable conditions. Its improvements over the screening models currently used in complex terrain applications can be attributed to several factors:

- its ability to use observed vertical profiles of meteorological data (rather than just one level) to obtain plume height estimates of these variables;
- computation of plume dispersion parameters, σ_y and σ_z, directly from turbulence measurements rather than indirectly from discrete stability classes.

Despite these advances, CTDM still contains several limiting assumptions:

- Its framework is a steady-state Gaussian model. It is not designed for extreme light-wind conditions with highly variable wind directions.
- The mathematical depiction of terrain shapes is simplified from actual shapes.
- Flow interactions among different terrain features are not explicitly accounted for.
- Meteorological data can be input to the model for only one x,y location.
- Flow deformation is treated with linearized equations of motion for steady-state Boussinesq flow, with higher order terms neglected. These assumptions are not valid for applications involving steep terrain (greater than about 15°) or strongly stable flow (Froude number less than 1) if the LIFT module is used.

CTDM can be used for regulatory applications involving a long series (e.g., a full year) of model simulations. Several of its limitations are related to the desire to keep the computer execution time reasonable.

An operational limitation of the current version of CTDM is that it provides concentration estimates only for stable hours. For multi-hour concentration averages involving nonstable conditions, a second model must be run to augment the CTDM predictions. CTDM also presents operational challenges to the user. *Detailed terrain and meteorological* data must be provided. "Isolated" terrain elements need to be defined, and this task can be complicated by superimposed and/or interconnected features. The considerable demands for meteorological input, while necessary, represent a significant increase over those for current models that use a single level of data.

The CTDM user must be careful in obtaining the proper meteorological data for input to the model. CTDM can be very sensitive to errors in wind direction, for example. Plume σ_y and σ_z calculations are critically dependent upon on-site *turbulence measurements* at plume height. The evaluation results show thet use of low-level or poor vertical resolution measurements will degrade the performence of CTDM on an event-by-event basis. The use of tall towers or doppler acoustic sounders will be necessary to obtain representative wind and turbulence data. The capability for accurate remote temperature sensing is still being developed, but representative ΔT measurements are *essential* for obtaining accurate concentration estimates. Such measurements can be obtained from two levels on a tall tower or two separate (but electronically linked) shorter towers (one on a hill) if instruments are placed well away from the ground (e.g., 50 meters or higher) on each tower.

It is useful to compare CTDM's normalized mean square error values with those of EPA refined models as listed in Appendix A of the *Guideline on Air Quality Models (Revised),* 1986. CRSTER has been tested at tracer sites in Illinois (flat site) and Tennessee (moderately hilly site). These experiments, sponsored by the Electric Power Research Institute, featured several weeks of data collection at a network of 150-200 tracer samples. ISC was tested with tracer data bases collected by the American Gas Association (AGA) at two natural gas compressor stations. The comparison shows that CTDM's performance at the CTMD tracer sites is comparable to those of EPA-designated refined models in similar test environments.

CTDM, while showing good performance at the evaluation sites, also exhibits an overprediction tendency at most sites tested; this is important for regulators who are interested in protecting air quality through the use of analytical modeling techniques. The most serious underprediction result, at Hogback Ridge (CF_3Br), is associated with mobile crane tracer releases close to the ridge, while using meteorological data from the main tower farther from the ridge. This supports the concept that the *location* as well as the vertical resolution of the meteorological data must be designed with care for CTDM use.

The data analyses performed during this program effort support the concept that there are inherent limits to our ability to predict measured or observed air quality concentrations. Improvements to models, such as those accomplished in this effect, establish confidence that a model is properly accounting for the physical phenomena involved, and is therefore "fair" in its application to different situations. It is especially noteworthy in this regard that CTDM consistently performed well with all of the data sets used, in contrast to the other models tested. Nevertheless, the effort has not resulted in a "breakthrough" in reducing statistical uncertainty associated with individual predictions versus observations. The use of a high resolution profile of meteorology measurements with height resulted in improvements to CTDM's performance. It is apparent from case-study analyses that further model performance improvements would emerge from an increase in the information on horizontal as well as vertical variations in meteorological data.

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The complete report, entitled "EPA Complex Terrain Model Development: Final Report," (Order No. PB 88-162110/AS; Cost: $38.95, subject to change) will be available only from:

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