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Use of Digital Terrain Data in Meteorological and Air Quality Modeling*

Examples of wind field modeling in complex terrain are presented and air quality, visibility, and other meteorological modeling are discussed.

Introduction

In recent years, an increased understanding of physical and chemical atmospheric processes that affect air quality, visibility, precipitation, and other weather phenomena has indicated a need to characterize more explicitly the topographical, geological, and vegetative features of the underlying terrain. Although surface interactions with the atmosphere have been studied for centuries, numerical simulation techniques study of mountain weather also are considered. Our aim is to provide an overview for those engaged in the production of digital terrain data of one area in which this data resource is currently being used and to identify ways in which its further use is anticipated. Our focus is primarily on atmospheric processes (wind flow patterns, pollutant transport and dispersion, precipitation, and so on) occurring over irregular or mountainous terrain because of its pronounced influence.

Abstract: *Digitized terrain data for regions of complex topography recently have been used in various modeling studies, such as in the simulation of wind flow patterns over coastal and mountainous regions in California and in the development of models for predicting visibility in remote and scenic areas. At present, available digital terrain data adequately meet the needs of many meteorological and air quality modeling analyses. The combination of terrain elevation data and ground cover information, such as the type of vegetation or soil, will facilitate further development and application of a range of air quality and visibility models.*

that can accommodate the evolving sophistication of digital terrain data have been developed only recently. In this paper, we discuss several ways in which currently available terrain data are used in air quality and meteorological analyses; potential uses of terrain and related geologic and vegetative data in air quality modeling and in the

Despite the growing interest in modeling complex terrain, a suitable definition of "complex terrain" has yet to be established. In the present context, complex terrain can be defined as topography that induces such distortion to airflow and pollutant dispersion patterns that conventional modeling approaches (such as simple Gaussian dispersion modeling or interpolation of mountain wind fields) either are inappropriate or only marginally useful. Clearly, the description of complex terrain encompasses a broad

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range of surfaces: Generic examples include isolated and multiple promontories, rolling hills, parallel ridges with intervening canyons, and rolling plains with distinct mesas or bluffs. Of course, actual terrain is composed of various surface features, many of which include more than one of these generic classes. Complex terrain occurs in every climatic zone. However, in this paper, we focus on modeling efforts in several areas of the coastal and intermountain western United States.

Acquisition of Terrain Data

An important requirement in modeling physical and chemical atmospheric processes over terrain is proper characterization of the ground surface. This requirement arises in the analysis of wind patterns, the buoyant rise of contaminant emissions (plume rise), and plume interactions with terrain features. For example, variations in the wind flow patterns near the ground are largely governed by the slope and orientation of the terrain. The ultimate height attained by emissions from power plants is meaningful only when referenced to the height of the ground underneath the plume. Depending on the configuration and location of terrain features upwind and downwind of the pollutant emissions source, diverse plume-terrain interactions, such as plume downwash, bifurcation, and impingement, might arise. Also, if terrain elevations and the heights of temperature inversion bases are known, the volume of air within which pollutant mixing can occur and a rough measure of the resulting expected pollutant concentrations can be estimated. To specify the height and geometrical characteristics of complex terrain accurately, we developed a computer code, TERRAIN, for analyzing digital terrain data.

Two methods of acquiring the necessary terrain data have been used to date. The first entails estimating mean terrain elevations from topographic maps in order to prepare manually a gridded field of elevations. Because it is tedious, this method has been used only for geographical areas typically on the order of a few tens of kilometres. The second method utilizes the digital terrain tapes available from the National Cartographic Information Center (NCIC). The data contained on these tapes have been derived by the Defense Mapping Agency Topographic Center (DMATC) from 1:250,000-scale topographic maps using a digitization procedure that produces a grid of elevation values for every 0.01 inch on each map (approximately 200 feet on the ground).

TERRAIN computes several types of data that can be resolved to user-selected grids of various sizes that are defined in terms of Universal Transverse Mercator (UTM) coordinates. These types of data include:

- Minimum, mean, and maximum ground elevations in each grid square;
- Minimum and maximum ground elevations within a user-specified number of grid squares from the square of interest;
- Mean terrain slope in each grid square;
- The percentage of terrain in each grid square that is characterized by flat terrain, valleys, ridges, or other features;
- The volume of air contained in each grid square as a function of variable inversion height above the lowest terrain elevation; and
- Standard deviations in mean terrain elevation and terrain slope (i.e., measures of terrain "complexity").

The following sections discuss the applications of several terrain statistics in meteorological and air quality modeling in complex terrain (hereafter referred to as complex terrain modeling).

Wind Field Modeling in Complex Terrain

The need to prescribe adequately wind flow patterns over mountains and other rugged terrain areas has become increasingly apparent in several fields of applied science and engineering. Accurate forecasting of wind patterns is essential in the deployment of resources (e.g., manpower and equipment) in response to forest fires or other destructive conflagrations. In precipitation augmentation activities, determination of the transport of seeding materials and the resultant deposition of precipitation in the target watersheds is based on knowledge of the upper air winds. Energy development (including both conversion and production) and smelting activities in the United States are rapidly being located in rural rather than urban areas and, because rural areas are often characterized by terrain-dominated airflows and dispersion patterns, accurate descriptions of the wind fields in these regions are prerequisite to successful air quality analysis. The necessity of providing safe and dependable year-round access to mountain regions has accompanied their development for recreational pursuits, retirement or second home-sites, energy development, or new transportation or commuter corridors. In this regard, knowledge of prevailing wind flow patterns is useful in dealing with and avoiding the hazards and inconveniences associated with drifting snow, avalanches, and severe winter storms (Tesche and Yocke, 1976).

A wind model suitable for application in complex terrain must account for the following physical processes:

- Mechanical blocking, channeling, and diverting due to terrain features;
- Local heating effects (because some slope aspects are warmer than others); and
- Retardation due to surface roughness elements such as stands of timber, buildings, and so on.

In this section, we present results from one wind modeling study (Tesche and Yocke, 1978) that utilized NCIC digital terrain data. (Details of the model's formulation are discussed by Yocke, Liu, and McElroy (1977).) Two uses of digital terrain data are discussed: the convenient, yet informative, use of computer renditions of terrain scenes to assist the investigator in readily comprehending the form and intricacies of the complex terrain situation of interest; and the use of these data to simulate physical atmospheric processes, in this case wind flow, over rough terrain.

The wind model was applied to geographically and meteorologically distinct regions in California. One setting—the South Coast (Los Angeles) Air Basin—represents a coastal environment and surrounding mountain ranges that exhibit significant topographic relief. The other—the high alpine zone of the Lake Tahoe air basin—is characterized by extremely rugged terrain with east-west ridges and canyons that terminate near the Sierra Nevada crest, which runs approximately north-south. In the Los Angeles application, the TERRAIN code generated mean terrain elevations based on a 3.2 km grid for that portion of the basin shown in Figure 1. Other terrain statistics (e.g., the height of and proximity to elevated terrain features of each of the grid cells) were also computed. Three-dimensional wind fields were computed for the period 0000 to 2400 PST on 4 August 1975. An example of the computed wind field at 150 metres above mean sea level during the period 1600 to 1700 PST is given in Figure 2. The channeling of flow into the San Fernando Valley and east toward Riverside is readily apparent in the figure.

In applying the model to the Lake Tahoe air basin, we focused on a 2500 km² area in the northern portion of the region, shown in perspective in Figure 3. A computer rendition of the topographic contours in the region is given in Figure 4. (Both figures were developed from NCIC digitized terrain tapes.)

On 1 January 1978, a major winter storm system approached the California Sierra Nevada; it later dropped several feet of snow at the higher elevations. Meteorological data gathered at this time were used (Tesche and Yocke, 1978) to investigate wind flow patterns over the mountains at two spatial scales—for the northern portion of the Lake Tahoe air basin, shown in Figure 5, and for the rugged Sierra Nevada terrain surrounding Lake Tahoe, shown in Figure 6. The predicted wind field (at an elevation 2050 metres above sea level) indicates the channeling of flow up the drainage basins of the North and Middle Forks of the

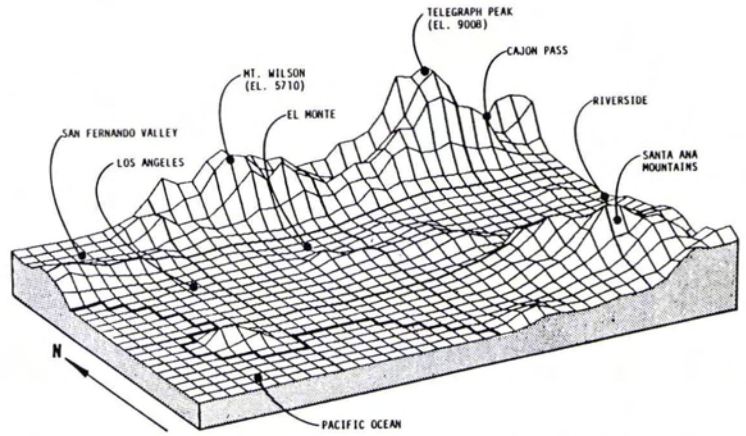

FIG. 1. Three-dimensional perspective of the South Coast Air Basin topography derived from the SAI TERRAIN code.

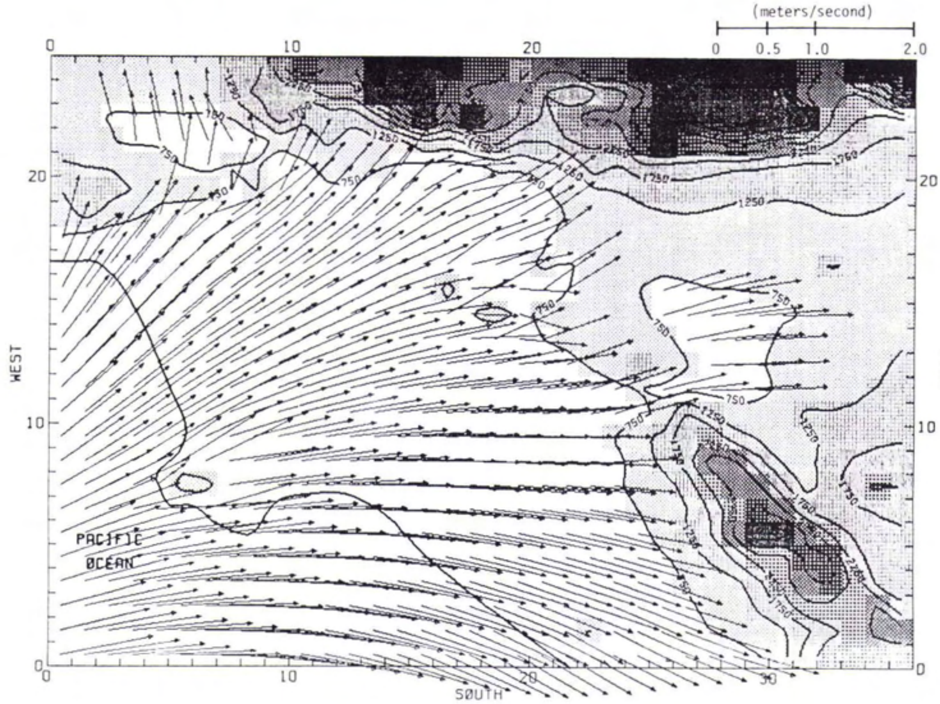

FIG. 2. Predicted wind fields at 150 metres *(msl)* over the South Coast Air Basin on 4 August 1975 at 1600 PST.

American River and the Rubicon River, as well as up the Truckee River, which then diverges out over Lake Tahoe.

At a smaller spatial scale, the wind model was applied to a 15 km² area northwest of Lake Tahoe near Donner Pass and the Sugar Bowl ski resort, shown in Figures 5 and 7. Westerly flow preceding the approaching storm is depicted in Figure 8. A ground wind convergence was predicted to the west of Mt. Lincoln, and the flow accelerates as it travels up Summit Valley and over Donner Pass.

AIR QUALTIY MODELING IN COMPLEX TERRAIN

Concern over existing or potential degradation of air quality in rural areas downwind of urban centers has led to the development of a variety of air quality models.

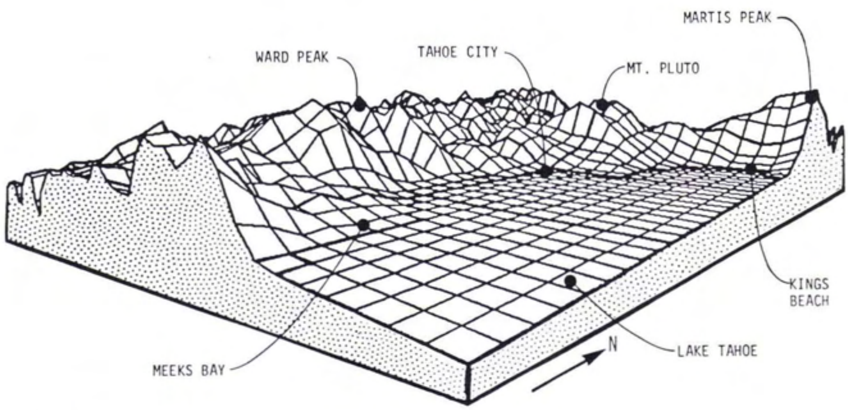

FIG. 3. The topography of north Lake Tahoe (as seen from the southeast).

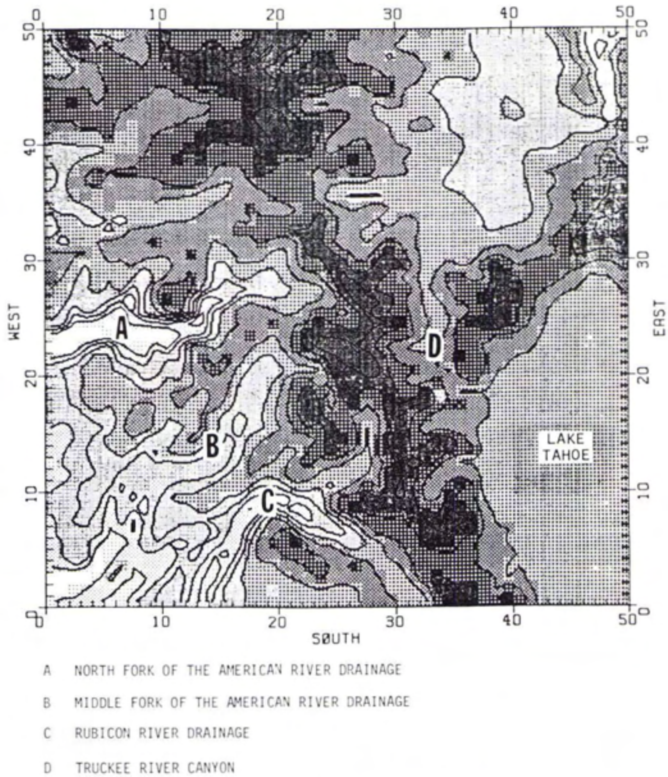

FIG. 4. Contour map for the Lake Tahoe wind modeling region. Countours are shown in 150-metre intervals; Lake Tahoe is at 1926 metres above mean sea level.

Basically, these models are designed to account for the transport, dispersion, chemical reaction, and ultimate fate of pollutants emitted from urban source complexes or from other sources, such as smelters or power plants, that may be located in rural settings. The availability of terrain data facilitates the application of air quality models in several ways. Clearly, terrain data are important to the specification of wind fields over complex terrain. In addition, these data are useful in examining terrain-temperature inversion interactions, pollutant dispersion rates, and the surface removal of airborne contaminant gases and particulates.

In general, persistently high levels of air pollutants are associated with so-called

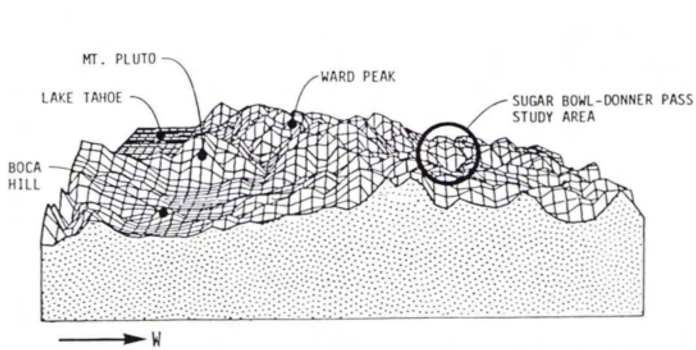

FIG. 5. The topography northwest of Lake Tahoe (as seen from the north).

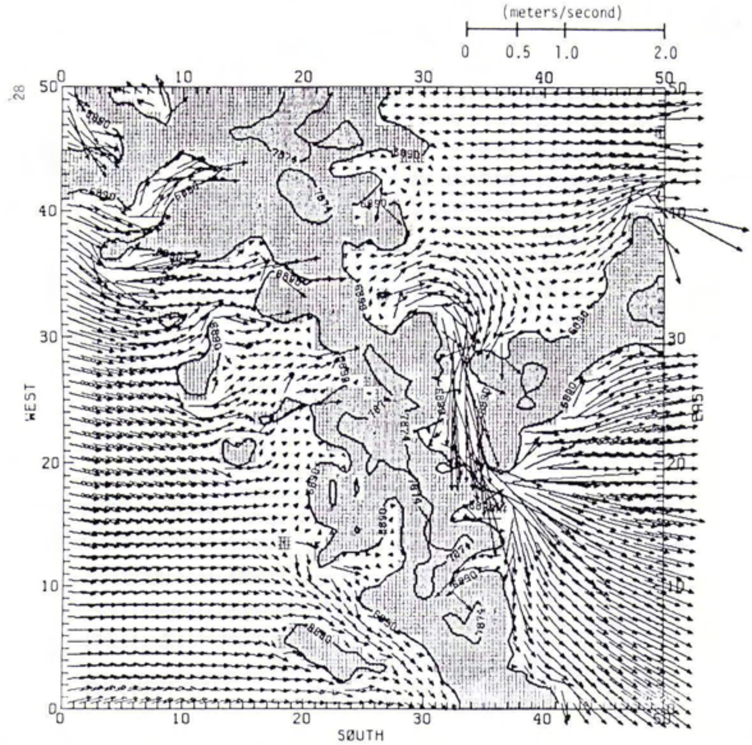

FIG. 6. Predicted wind field at 2050 metres (*msl*) over north Lake Tahoe on 1 January 1978 at 1300 PST.

temperature inversions.* In regions of complex topography, the relationships between terrain configurations (including height, slope, and aspect) and the height of inversion layers are both complicated and, at present, poorly understood. Nevertheless, the significance of temperature inversions in air quality modeling in complex terrain has been recognized by several investigators. Inversions are important phenomena in air pollution studies because of their inhibiting effects on pollutant dispersal. Contaminants released into a surface inversion experience very little diffusion because the air is stably stratified. In contrast, pollutants released below an elevated inversion may diffuse rapidly upward to the base of the inversion, which often acts as a "lid" on the well-mixed layer of air next to the ground.

* An inversion can be loosely defined as a layer of air within which the ambient temperature remains constant or increases with height—hence, the name "inversion layer." When the bottom of such a layer coincides with the ground, it is called a "surface inversion"; otherwise, it is called an "elevated inversion."

The joint occurrence of temperature inversions and pollutant emissions in complex terrain can potentially lead to adverse air pollution levels. For example, if the underlying terrain is flat and the plume from a smelter or power plant is sufficiently elevated, none of the emitted pollutants may reach the ground until they are diluted to very low concentrations. But, if hills or ridges extend up to the average plume height, then, under certain wind direction and speed conditions, the plume may impinge on a hillside, leading to large pollutant concentrations within a small area. In the event of low heights of emissions sources and attendant plume rises, emissions from power plants in complex terrain may likely impinge on surrounding hills under certain conditions. Also, if pollutants have been emitted into the stable, nonturbulent inversion layer during the nighttime, then when solar heating of the ground has later eroded that portion of the inversion below the general elevation of the plume, air contaminants will be carried rapidly downward, leading to increased ground-level concentrations.

When an elevated inversion occurs, it can

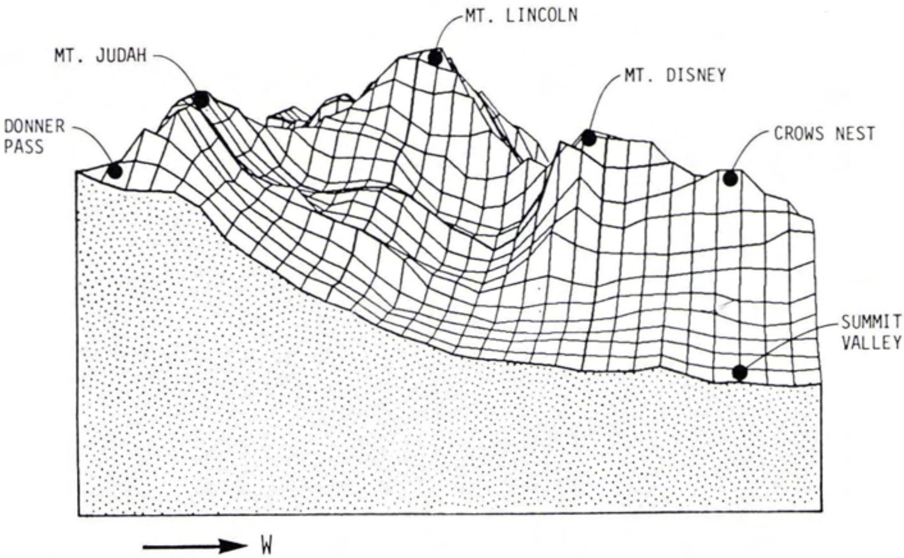

FIG. 7. Complex terrain of the Sugar Bowl (as seen from the north-northwest).

act as a barrier to the upward motion of material released below it, depending on the height of the inversion base and the surrounding topography. Accordingly, in order to assess the possibility of large pollutant concentrations downwind of sources located in complex terrain, it is necessary to determine, among other things, the behavior

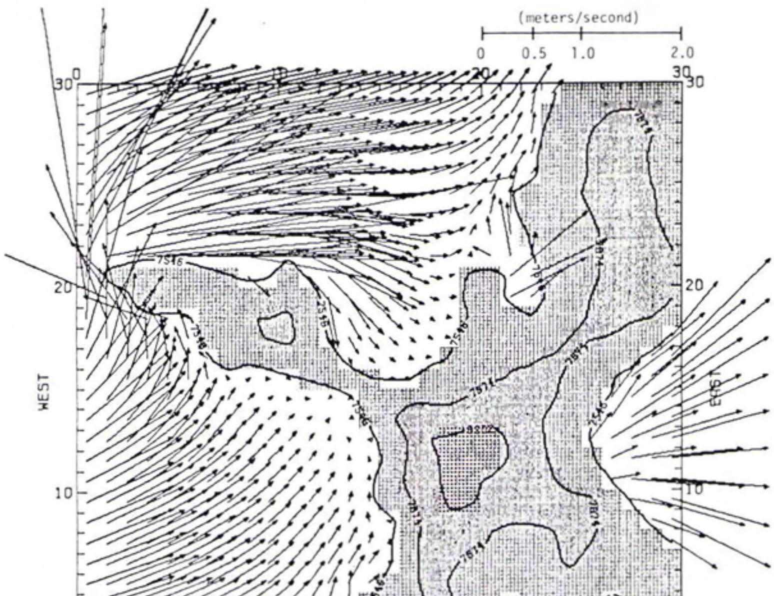

FIG. 8. Mountain wind field over Sugar Bowl at 2250 metres (*msl*) on 1 January 1978 at 1300 PST.

of inversions over rugged topography and the geometrical characteristics of the topography itself. With respect to the latter, digital terrain data fulfill this need. If the geometrical features of an enclosed air basin located in mountainous terrain (e.g., the Lake Tahoe air basin) can be well defined from available terrain data, then it is possible to estimate the approximate volumes of air beneath a temperature inversion within which air pollutants might be emitted and trapped. Simple box models, which assume uniform mixing of air pollutants within a volume of air—in this case defined by the inversion base and the underlying three-dimensional terrain—are examples of air quality analysis techniques whose usefulness can be enhanced by detailed terrain data.

Modeling studies of pollutant transport and dispersion over rugged terrain require estimates of the rate at which pollutants are diffused by atmospheric turbulence. Because the intensity of turbulence in the lower layers of the atmosphere is strongly governed by the characteristics of the underlying terrain, prescription of diffusion rates is made easier if topographic variations are known. Here, digital terrain data are useful in developing statistics that characterize the complexity of the terrain. For example, consider the application of a regional air quality model for the Lake Tahoe region. It is clear from Figures 3, 4, and 5 that over some portions of the region, particularly the lake, the surface is very flat; in other areas, extreme topographic relief exists, such as the mountain peaks and valleys west of the lake. With the detailed data available from the NCIC digital tapes, it is possible to compute not only the mean terrain elevation for any subarea (useful for wind modeling), but also the standard deviation from the mean elevation. This latter quantity is directly related to the ruggedness of the terrain and hence can be valuable in estimating the spatial variations in diffusion rates.

Finally, the type of surface cover influences the deposition rate of certain pollutants. Because pollutants react differently with various types of ground cover (soil, rocks, water) and vegetation, a major sink for airborne pollutants is thereby provided. Thus, ground cover information is important to the study of pollutant transport over large distances. At present, gridded data on surface vegetation and ground cover on a comparable level to the NCIC digitized terrain data are not available. However, Craighead (1976) has shown that it is possible to develop digitized ground cover information. In a study of the location and extent of grizzly bear habitats in the western United States, Craighead derived color photomosaic renditions of 13,225 square miles of territory in western Montana from Landsat data. On the basis of these data and ground-truth field studies, he was able to classify rock and vegetation complexes to a spatial resolution as fine as one acre. Ground-truth verification experiments were, remarkably, 88 percent accurate in classifying the ground cover according to eight categories: vegetated rock, sandstone and argillite, large limestone, talus slope, subalpine parkland, whitebark pine forest, alpine meadow, and coniferous forest.

These results indicate the possibility of obtaining gridded ground cover data at a scale commensurate with the spatial resolution of regional air quality models. These data could be used in such models in two ways. The surface characteristics could be used to prescribe spatial variations in the rate of surface uptake of pollutants such as ozone, SO_2, and sulfate. Also, since mounting evidence points to the need to consider natural emissions of reactive hydrocarbons (from coniferous forest, for example) in modeling studies of the long-range transport of photochemical oxidant (Whitby and Coffey, 1977), the distribution of natural hydrocarbons emissions over a region as a function of vegetation type, time of day, season, and so on could be estimated.

Visibility Modeling in Complex Terrain

The establishment of general visibility and scenic vistas in remote areas such as national resources requiring protection (through recent amendments to The Clean Air Act) has led to initiation of the development of visibility models, in which complex terrain must be considered. A visibility model comprises a wind field model, an air quality model, and an atmospheric optics calculation. Terrain data play an essential role in the calculation of the effects of air pollution on visibility.

Two problems must be considered in treating visibility. The first is the "near-source" or "plume blight" problem, which is caused by a plume of pollutant emissions from a particular source visible from or lying within a remote area. An example is the potential impact of proposed large power plants in the Southwest on the wilderness (or Class I) areas nearby. The second is the "regional problem" (corresponding to the problem of long range transport of pollutants in air quality modeling), which involves a source (or source complexes) that contributes to the overall degradation of visibility. An example is the general hazy appearance of warm air masses that accumulate small sulfate particles as they move from the Midwest to the East Coast of the United States, causing poor visibility by the time they reach the coast.

With respect to the plume blight problem, the atmospheric optics calculation entails determining whether the light intensity and color in a particular direction have been altered enough by the plume to cause it to be visible. The degree of color alteration depends on the background against which the plume is viewed. For example, a plume may be more noticeable in front of a white cloud than a dark mountain. Terrain data and ground cover information (perhaps derived from Landsat imagery) can be used to prescribe the background scene for a particular area. At present, the SAI TERRAIN code is being used in a study of the plume blight (near-source) problem in the case of the Navajo Power Plant in Page, Arizona. Various projections of the power plant plume will be graphically displayed on background vistas to examine the visibility of the plume, and comparisons of the projections with photographs will indicate the veracity of the method. If this technique proves successful, it should be useful in determining the necessary emissions controls for power plants in meeting possible visibility standards.

For the regional problem, terrain data can help define scenic backgrounds of interest. A complete visual scene can be constructed using the following steps:

- Define the elevation data as a three-dimensional field (x, y, z),
- Locate the observer viewing positions,
- Compute the projection of the elevation points onto the viewing plane,
- Connect the elevation points,
- Remove hidden lines,
- Define surface elements,
- Compute the intensity and color of the elements, and
- Predict the effects of airborne contaminants in obscuring the scene.

A preliminary example of this approach is shown in Figure 3, which embodies the first five of the above steps. Work is currently under way to define the various surface characteristics and to identify their colors. When it is completed, an air quality model (incorporating an atmospheric optics submodel) can be used to estimate the amount of visibility-reducing materials in the atmosphere between an observer and any given background vista. Hopefully, application of this technique will be useful in displaying the effects of regional air pollution on scenic vistas.

Other Potential Uses of Terrain Data in Meteorological Analyses

Terrain data might also be useful in such fields as precipitation enhancement and mountain hydrometeorology. Because the availability of water plays a critical role in developing and sustaining the economy and quality of life in the western United States, weather modification has been considered as a potential tool for augmenting existing water supplies, particularly during periods of drought. In fact, emergency drought relief weather modification projects are under way in Washington, Oregon, California, Nevada, Utah, and Colorado in response to the recent western drought (Foehner, 1977). Whether the modification activity is intended to produce or to augment rainfall or snowfall, the basic goal remains the same—to enhance precipitation events and to ensure that the resultant precipitation can be retained in reservoirs or mountain snowpacks for later delivery and use.

Central to effective weather modification is the knowledge of where and when seeding agents must be delivered to the atmosphere, how they will be transported with the moving storm system, and, ultimately, where the induced precipitation will fall. Since the early 1970s, sophisticated numerical models have been under development for combining the microphysics of precipitation formation and the dynamics of wind flow over mountainous terrain. Terrain data are useful in application and refinement of this type of numerical models.

Management of the water resources of the western United States requires an understanding of the hydrology of high elevation ecosystems. Because mountain snowpacks are a primary source of recoverable water, research has been increasingly directed toward the description of winter snow accumulation, wintertime mountain energy balances, the "condition" of the snowpack throughout the winter and spring, and the amount and timing of the incipient snowmelt. With respect to snowfall accumulation in mountainous areas, mathematical models requiring topographic inputs have recently been used in Colorado to forecast the locations and amounts of snowfall (see, for example, Rhea and Grant (1973)); it seems quite reasonable to expect that greater modeling capabilities for simulating the various processes involved in the weather modification and natural precipitation events will bring a corresponding increased dependence on the detailed characterization of the underlying terrain.

Once on the ground, snow undergoes continued metamorphic changes in response to wind, sunshine, temperature, rain, additional snowfall, and other factors. Among other things, these changes affect the time(s) at which snow melts and delivers water to impoundments. Because of the obvious importance to water supply managers of knowing when and where snowmelt is anticipated and in what amounts, attempts have been made to model the complicated hydrometeorological processes occurring in high elevation water-sheds.

Leaf and Brink (1973) developed a computer model for a sub-alpine watershed in Colorado as a means of investigating the ramifications of forest management practices and weather modification activities on mountain snowpacks. The concept upon which the early model is based (and also the later refined model of Solomon *et al.*,(1976)) is that the mountain snowpack behaves as a dynamic heat reservoir. Among the energy transfer processes parameterized in the model are heat input due to rain or snow, heat input due to radiation, heat loss due to nighttime radiation and/or conduction to the atmosphere, and so on. Temperatures within the snowpack are computed on the basis of unsteady heat transfer theory. Leaf and Brink applied this model to the 667-acre Deadhorse Creek watershed at the Fraser Experimental Forests and reported close agreement between observed and simulated melt rates. They concluded that the model concept was a useful tool in watershed management. Because Leaf and Brink's snowmelt simulation model was applied to a small area, the slope and the aspect of the watershed could be treated as single values. However, in extending the modeling concept to the spatial scales that are meaningful to water resources planners—areas on the order of several thousand square kilometres—spatial variations in mountain terrain must be taken into account.

Terrain data are essential in the application of snowmelt simulation models for several reasons. First, radiation heat transfer is a key component in the dynamic snowpack heat balance. Because the incident shortwave radiation depends largely on slope aspect, south-facing slopes will receive greater insolation than north-facing slopes, resulting in differential melting of the overall snowpack. A second and related reason is that when the pack approaches the final melt period, portions of the mountain become either free of snow or covered by thin snow layers. This leads to numerical problems with existing computer model formulations (Solomon *et al.*, 1976), but they could be resolved by analyzing portions of a watershed seperately according to their terrain features. Finally, if a large region (composed of many distinct watersheds) were to be modeled, areas at lower elevations would experience different energy balances than those at the higher elevations.

From the above discussion of weather modification and hydrometeorology, it appears that the availability of high-resolution digital terrain data will be useful in the development and application of simulation models for use in water resource planning endeavors. As the demand increases for greater accuracy and precision in estimating the water yield from snowpack and the location and prospective efficiency of augmented precipitation, the need for reliable terrain data is expected to increase as well.

Summary

At present, characterizations of surface topography in regions of complex terrain that were developed with digitized data are being used in the application of models to predict wind flow patterns and pollutant dispersion. Terrain data currently available from the National Cartographic Information Center are of sufficient spatial resolution to support most of these modeling efforts. However, with the growing need for simulation techniques applicable to studies of the fate of pollutants over regional scales, and the potential resultant degradation of visibility, the need arises for developing digitized data pertaining to surface composition and coloration at a spatial resolution roughly commensurate with the present terrain elevation data. Other uses, not yet fully explored, of currently available terrain data include the study of precipitation enhancement due to weather modification and simulation of wintertime mountain energy balances affecting snowpack accumulation and water yield.

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