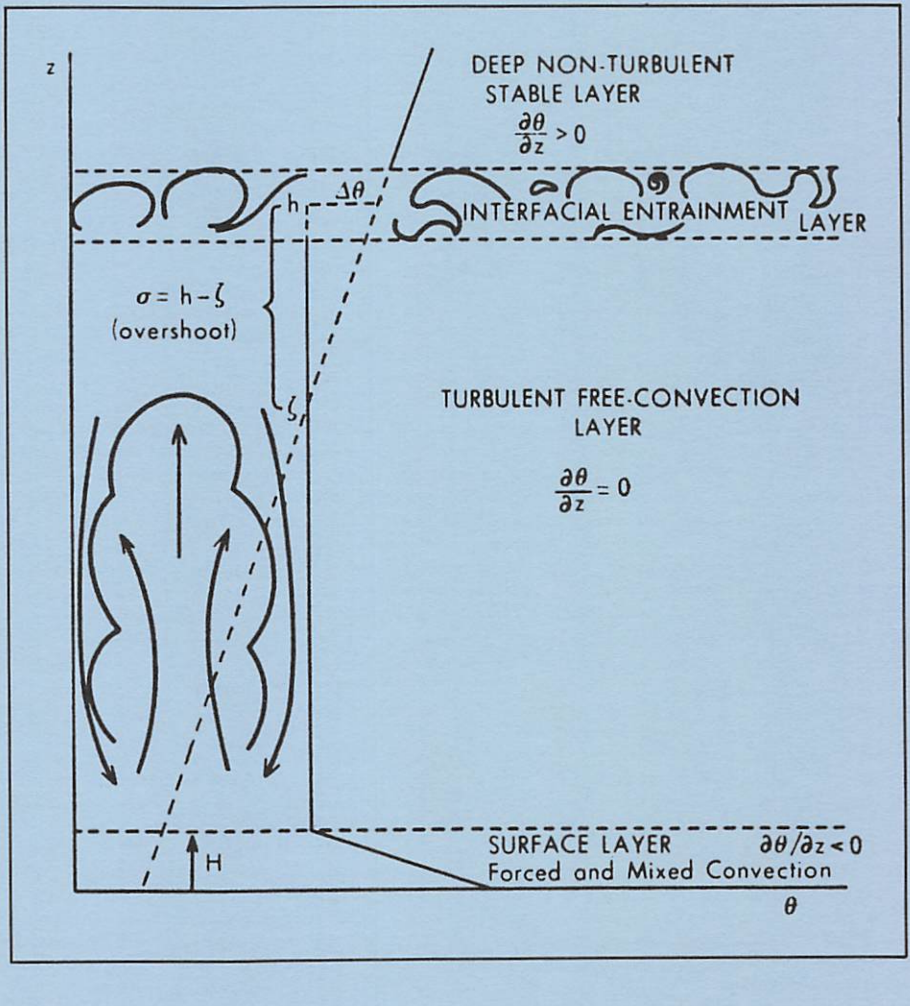
MODELING AIR POLLUTION POTENTIAL FOR MOUNTAIN RESORTS

David E. Greenland



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FOR MOUNTAIN RESORTS

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PREFACE

Increasing use of mountainous areas of the western United States for recreation and mining places great stress on all parts of the montane environment. One aspect of this environment which has received relatively little attention in the past has been the quality of mountain air - once assumed to be pristine but now, in many places, in danger from the wood-burning fires of ski resort condominiums and dust from the machines of the strip miner.

This study provides a contribution to the field of air quality maintenance in complex terrain with emphasis on the single valley case. Such sites are where vacation resorts are often located. A review of basic approaches to estimating atmospheric dispersal and subsequently air quality in complex terrain shows the box model to be useful in many cases. Its applicability would be extended if the upper limit of the 'box' could be found without making actual observations. Thus attempts are made to determine the location of the lid in the absence of on-site data. Long term National Weather Service Rawinsonde data give interesting results but none that can be used operationally. Little success is met in seeking spatial relations in short term inversion data. The most profitable approach seems to be in the use of a theoretical model of inversion rise dynamics. A box model of atmospheric dispersion is utilized in a) a standard form, b) with modeled mixing heights and c) with a tilted inversion lid. The latter does not significantly improve the performance of the basic model. However, there is evidence to suggest the flexibility of using modeled mixing height data with the box model. An interesting lag effect is noted for the model. Finally, some practical aspects with regard to air pollution potential and the land use manager are discussed.

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PART I INTRODUCTION

Background to the Study

During the past two decades many of the mountainous areas of Colorado and some neighboring states have borne a dramatic impact from recreation and energy related activities. Ten years ago, the holiday resort of Keystone, Co. did not exist. In the 1977-78 winter the 400 condominium units at this resort were occupied for an average of 25 days by between 4 to 6 people. Thus, disregarding service personnel, about 170,000 people stayed in this resort alone during the winter. The resort is not yet finished and plans to expand to 1400 units in addition to many single family dwelling units. The resort of Vail manifests a similar picture and there are plans for further entirely new resort development such as Adam's Rib. In addition to the new resorts many old mining towns such as Breckenridge and Telluride, CO have found a new lease of life in development as ski resorts. In other parts of Colorado and the west large deposits of oil shale are in the process of being developed. Oil is already being brought to the surface. As the presence of the older mining settlements would suggest, the area has been prominent in mineral and fuel production for over 100 years. However, the scale of modern mining operations far exceeds anything of which the early miners could have dreamed. Furthermore, in some areas, such as Crested Butte, Co, both vacation resort development and potential large scale mining operations are found in the same location.

All of this places tremendous pressure on the physical and socio-economic environment. All parts of the environment are effected. However, whereas some mining activities have an obvious impact on the environment, other aspects such as air quality have only recently been considered. Mountain areas have always been noted for their 'pure' air. Yet sadly, concentrations of people and resource extraction threaten to change this situation dramatically in the west.

Much of the mountainous land of the west is federal land. Within this lies large areas of national forests. Part of the responsibility of the U.S. Forest Service is to help maintain air quality of specified categories and also guard resources related to air quality. Since little is known about problems of air quality in complex terrain the Eisenhower Consortium for Western Environmental Forestry Research have sponsored the present, and other, projects.

The number of studies that have considered both planning and air quality aspects in the mountainous terrain of the west are minimal. Fox (1975) gave an introduction to the topic and pointed to some fruitful lines of investigation. Fosberg and Fox (1976) developed an effective air quality planning index that could be used, for example, to estimate the number of fireplaces allowable in a given area while still maintaining air quality standards. Marlatt and Gelinas (1975) did pioneering work in the development of a trial air quality maintenance plan for Eagle County Colorado (the location of Vail). This plan considered possible strategies which the resort developers could use to maintain air quality. Apart from this, the dual consideration of development and air quality only appears in specific Environmental Impact Statements.

Even without linking development and air quality explicitly, there is a great need for the study of air quality and its related fields of atmospheric transport, diffusion and deposition of pollutants in complex terrain. This need has been expressed most eloquently in a DOE/EPA sponsored workshop where a large scale ($15-30 million) research program was suggested (Barr et. al. 1977). The participants of the workshop outlined the benefits of such a program and showed how they would relate not just to resort areas but also "in the development of oil shale and coal energy resources particularly in the mountainous West, ... and (give) improved prediction ability for environmental problems throughout the United States in which complex terrain is a contributing factor". More recently the American Meteorological Society Committee on Atmospheric Turbulence and Diffusion have warned of the inaccuracy of present dispersion models when used in complex terrain (AMS, 1978). One of the results of the earlier workshop is the establishment of a major research program by the DOE. The program "Atmospheric Studies in Complex Terrain"-ASCOT officially began in October 1978 (DOE, 1979).

The research needs are given even more urgency by governmental legislation, particularly the National Environmental Policy Act of 1969 and the Clean Air Act Amendments of 1977. Both force developers to look to air quality. The latter specifically calls for the country to be classified into areas where different degrees of allowable air quality degradation apply. These are called class I, II and III areas. Class I are clean areas where virtually no development will be acceptable. Class II areas permit some development where the development is said to be 'insignificant', and class III includes areas that are already highly polluted and where it is necessary only to satisfy Federal and State standards. A major problem exists in complex terrain because it is likely that the quantitative differences in air quality between these classes are less than the sizes which it is possible to estimate accurately with most present atmospheric dispersal models when used in rugged landscape.

A further background factor to consider is the traditional lack of rapport between the meteorologist and the planner. The most common pattern has been for the planner to do his job and then, as a peripheral step that is often omitted entirely, to consult a meteorologist concerning possible atmospheric effects.

Part of the reason for this has been the failure of the atmospheric scientist to present results in a way which can be easily assimulated by the planner. The complexities surrounding air quality in complex terrain make it even more important for the atmospheric scientist to present clear signposts through what one planner has called "the air quality quagmire."

Bearing all this in mind the general purpose of the present study is to enhance our knowledge and understanding of meteorological theory as it affects problems of air quality in complex terrain and particularly mountain valleys. A further goal is to apply this knowledge and understanding in a practical manner to provide answers on the air pollution potential in mountain environments.

Structure of the Paper

There are five parts to this report. Following this introduction is a review of approaches to the estimation of air quality in complex terrain. In view of the lack of knowledge and particularly theory of atmospheric dispersion in complex terrain, this review takes on an importance greater than that of the normal literature review. One of the results of the review is that although there are a number of approaches to air quality modeling in complex terrain one of the most practical is the box model approach. However, one of the critical parameters of the box model (and to a certain extent other models) is the height of the atmosphere through which pollutants are mixed. The third part of the study examines methods of estimating the value of mixing height in valleys. The fourth part describes the use of the box model in mountain valleys. Finally, those aspects of this report which are of most use to the land manager are drawn together in the last part where suggestions are made as to how he or she can deal with the air quality "quagmire".

PART II. APPROACHES TO ESTIMATING AIR QUALITY IN COMPLEX TERRAIN

In this part it is shown that estimation of air quality in complex terrain is a small part of an overall air resource management program. There are several kinds of atmospheric dispersal models that can be used. Many standard models overestimate pollutant concentrations when used in complex terrain. The main reason for this is the greater turbulence in the mountain atmosphere. An examination of the special features of mountain meteorology permits a more rational selection of dispersal models. There are certain dificulties in establishing an emissions inventory for high altitude sites which also should be borne in mind.

The Decision Making Process

At the outset it is important to view the problem of air quality in complex terrain as part of an overall air resource management concept. This concept requires the making of "plans and decisions on how the atmosphere is to be used, besides as the sustenance of life" (Dicke, 1977). Such plans include the development of public policy and the technological and legal tools to carry it out, and many other steps through to an effective public information program.

It is within this framework that specific air quality maintenance programs are established. Such a program includes several stages:

1). An emisisons inventory has to be obtained for the airshed in question.

2). An atmospheric dispersal model (or models) has to be selected and applied to the inventory

3). The model must be calibrated against measured air quality

4). The emissions inventory must be projected into the future

5). The model is rerun using future emissions and the predicted air quality is compared to existing air quality standards

6). If the standards are exceeded strategies to improve the air quality must be developed and applied.

There are several weak links in this chain of events. First it is difficult to obtain an accurate emissions inventory. Second, accurate atmospheric dispersal models are not readily available, especially for complex terrain. Third, the implimentation of an air quality plan is likely to meet many practical and legal difficulties. One of the few advantages of working with air quality in complex terrain is the fewer number of governing bodies and agencies that are likely to be associated with a particular plan compared to the large number that would be concerned with air quality in a large metropolitan area. The present study concentrates mainly on the second of these areas of uncertainty; that is the dispersal model.

General Atmospheric Dispersal Models

Deardorff (1978) has listed four general approaches to modeling pollutant dispersal in the boundary layer. These are the probability distribution approach which usually utilizes a Gaussian probability function, a similarity approach which uses "simple theory or dimensional relationships possible when ... the diffusion problem is uncomplicated," a scaling approach in which results from the laboratory model can be applied to real world situations, and the diffusion equation approach which in most cases requires a three dimensional numerical model. To these should be added the mass conservation approach - or box model. On the basis of their frequency and ease of use in complex terrain it is more realistic to consider a simpler three fold classification, namely: Mass conservation or Box models, Gaussian Plume models, and Complex models.

The mass conservation or box model approach assumes emissions from the base of an imaginary box (or boxes) are instantly and equally mixed in the box volume.

If this is so then the change of mass of pollutant (M) with time (t) is given by

$$\frac{dM}{dt} = Q + Au\chi_{in} - Au\chi_{out} \qquad \text{------ 1.}$$

where Q is the source strength, A is the cross-sectional area of the box, u is the mean wind speed through the box and χ_{in} and χ_{out} are the pollutant concentrations entering and leaving the box. If χ_{in} is 0 and since χ is M/V where V is the volume of the box

$$\frac{d(\chi V)}{dt} = Q - Au\chi_{out} \qquad \text{------ 2.}$$

which has a solution of exponential form but with a finite difference solution of

$$(\chi V)^{n+1} = (\chi V)^{n} + \Delta t \left\{ Q^{n} - (Au\chi_{out})^{n} \right\} \qquad \text{------ 3.}$$

where n is the computational time step and Δt is the time interval used (Howard and Fox, 1978).

The above is a relatively simple version of the box model. The first steps to such an approach were made by Hewson (1955), Meetham (1956) and Smith (1961). The box model became well established in its theoretical basis and its practical application through the work respectively of Lettau (1970) and Reiquam (1970). It has been combined with other models, notably the Gaussian Plume model, by Johnson et. al. (1970) and Gifford (1973). Further implications of the theory of the box model have been examined by Tennekes (1976) and Venkatram (1978). The approach has also been subject to a wide range of sophistication in application from the simple level of application such as the form mentioned above to the application in a complex form by MacCracken et al. (1978).

The Gaussian Plume model operates in a three dimensional Cartesian coordinate system with the x direction aligned with the wind direction. In its simplest form, it would give a pollutant concentration at some point downwind from a continuous ground point source as

$$\chi = \frac{Q}{\Pi \sigma_y \sigma_z u} \exp(-y^2/2\sigma_y^2) \qquad \text{------ 4.}$$

where σ_y and σ_z are the standard deviations of the plume in the y and z directions. A practical application of the formula involves determining the Pasquill-Gifford stability class for the atmosphere, using graphs to obtain the value of σ_y and σ_z for any distance downwind given the specified stability class, and then applying equation 4. An example of the graphs is shown in Fig. II-1. Difficulties often arise in obtaining the stability class which is a function of insolation, cloud cover and wind speed. The formula may be extended to deal with elevated point sources and line sources. It has probably been applied to more air pollution problems than any other approach and is the dominant approach for close-in diffusion from low level point sources. Nevertheless, the approach remains essentially empirical and Deardorff (1978) has pointed out that a coherent treatment of the dependence of the spreading rates upon fundamental turbulence parameters is still lacking. Another problem is the standardization of methods for determining the stability class and other factors related to the use of these classes and the Pasquill-Gifford curves (Hanna et. al. 1978). One of the most successful uses of this type of model is in the Atmospheric Turbulence and Diffusion Laboratory (ATDL) model which can be used in an extremely simple form (Gifford, 1973).

The complex models of the present classification may take many different forms such as sophisticated statistical simulations using Monte Carlo techniques. However, probably the most common of the complex models use as their basis the

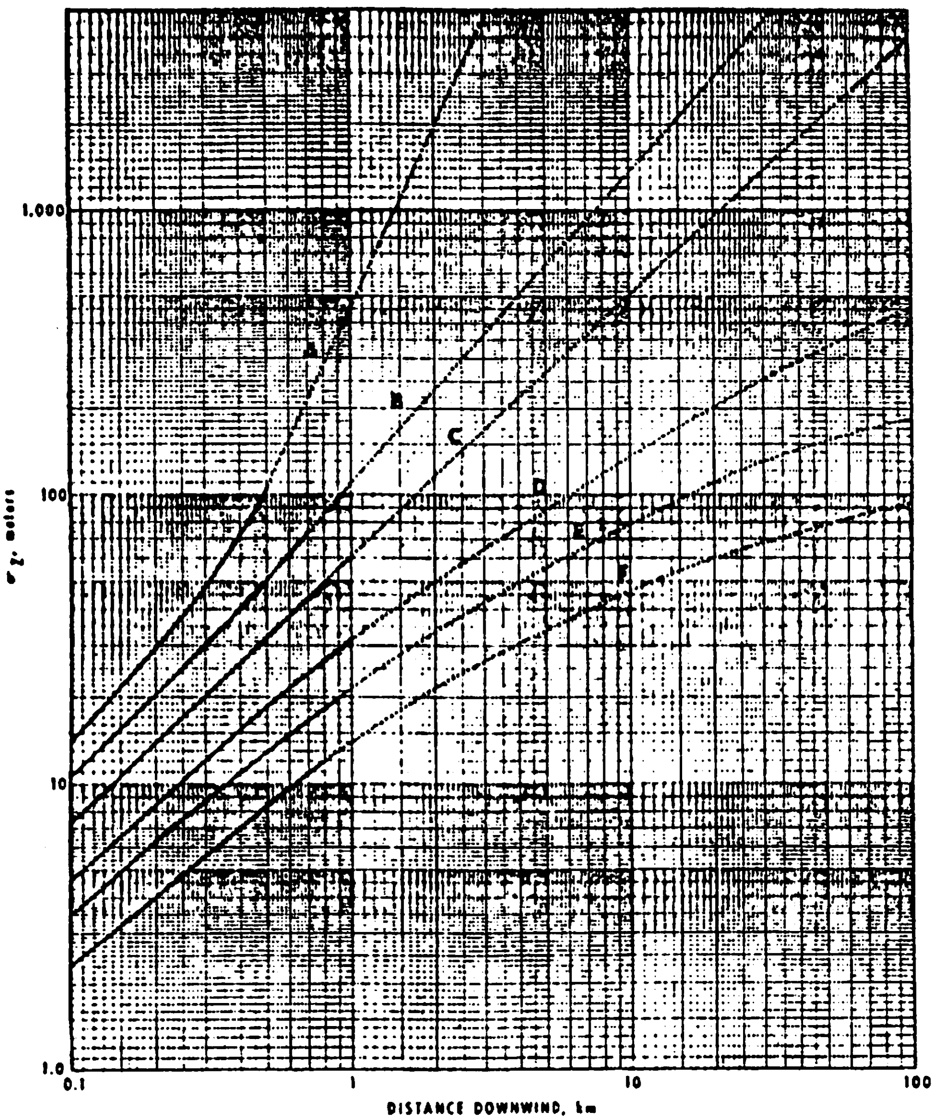


Fig. II-1. Vertical dispersion coefficient, σ_z, as a function of downwind distance from the source (Turner, 1970).

advection-diffusion equation which as described by Isaacs et al (1978) is

$$\frac{n\partial\chi}{\partial\chi} + \frac{n\partial\chi}{\partial n}\frac{\partial\chi}{\partial n} = K_y(x)\frac{\partial^2\chi}{\partial n^2} + K_z(\chi)\frac{\partial^2\chi}{\partial z^2} \qquad \text{------ } 5.$$

where n is a directional coordinate normal to a plume and K_y and K_z are the diffusivity coefficients in the y and z directions. Such formulations sometimes also have terms allowing for fallout of pollutant species. As mentioned above, they are usually applied on a three dimensional numerical modeling basis. Some of the most difficult problems arise in the parameterization of the K values.

Overestimation of Dispersal Models in Complex Terrain

Classic studies in the early 1970's related to the impact of a coal-fired power plant on air quality in Huntington Canyon, Utah were the first to point out the overestimation of standard, especially Gaussian Plume, techniques of estimating dispersal in complex terrain (Van der Hoven et. al., 1972). At this site Start et. al. (1973) using Sulfur Hexaflouride and oil smoke tracer studies and employing a Gaussian Plume model with flat terrain parameters found a) little difference between flat and canyon terrain for daytime lapse conditions; b) a five times greater dilution for canyon aerial concentrations compared to flat terrain concentrations for neutral stability; and c) center line dilutions 15 times greater than the flat land case under strong atmospheric inversions. Since these studies there have been several others indicating the same kinds of results (Roffman, et. al. 1976; Start, et. al., 1974; Lantz et. al., 1976; and Spangler, et. al., 1978). The overestimation need not always occur as long as the terrain variation is not very pronounced. This is demonstrated for a case in West Virginia where the vertical topographic variation is less than 200 m

(Bowers and Cramer, 1976). However, studies by Smith and Ruch (1978) demonstrate that overestimation of pollution concentration is definitely possible in this kind of terrain. Furthermore, they show that it is not only the simple Gaussian Plume models that overestimate but overpredictions were also noted for the EPA models called MODCDM and VALLEY. The latter in particular is supposedly adapted to a complex terrain situation.

Part of the explanation for the greater dispersal rates that are most marked in stable and neutral atmospheres over complex terrain, lies in some of the atmospheric factors that are unique to mountain meteorology. It is helpful to examine some of these factors not only because it helps explain model performance but also because such an examination is important for the selection of an atmospheric dispersal model and the modification of those already in existence.

Aspects of Mountain Meteorology Affecting Dispersal Rates

The discussion in this section will be divided into three parts. First will be examined terrain induced airflow phenomena near the terrain itself. Then present knowledge on mountain and valley thermal wind systems will be reviewed. Third, attention will be given to the interaction between valley and upper airflow.

There are many terrain-induced airflow phenomena occurring near the terrain itself. Many of them have been identified by Barr et. al. 1976 who point to the following:

1). Deformation of streamlines - airflow around and over obstacles produces confluence and bending of streamlines. This has large implications for pollutant concentration and dispersal acting through the processes of entrainment, turbulence and plume rise.

2). Separated Flow - high pollutant concentrations may be found at the point where a detached or separated flow reattaches itself to the lee side of an obstacle. In other parts of the separated flow dilution of pollutants may occur.

3). Slope flows - These are thermally produced and may contain smaller features such as pulses. The whole system is difficult to model (Bergman, 1969) and may produce double pollution doses where pollutants originally formed at the valley bottom are carried upslope during the day and down again in the evening.

4). Plume Impaction - although in the theory of hydrodynamics there should be no streamline impact on a surface, in reality, plumes and airflows do impact onto rugged terrain (Start et. al. 1976) and this can be incorporated into modeling procedures.

5). Internal Gravity Waves - these can be caused by the vertical deflection of flow by hills and ridges. They can lead to maximum concentration of pollutants in certain cases where downward limbs of waves coincide to bring pollutants to earth. Stull (1976 a, b) also treats the gravity waves occuring at an inversion base.

6). Secondary Flows - There are a number of secondary airflows that have been observed in certain circumstances. These include the wake flows around obstacles noted in Huntington Canyon (Start, et. al. 1973) and helical motion examined by Angell et. al. (1968). Most of these would generally increase dilution of pollutants.

7). Enhanced Convection - occurs mainly due to differential solar heating of slopes. It can give rise to small scale convection currents (Hahn, 1977) or mesoscale currents sometimes initiating moist convection. At either scale pollutants might be injected into upper level flow and dispersed or can be returned to the ground at high concentrations.

8). Forest Canopy Effects - Barr et. al. (1977) also point out the possibility of forest canopies scrubbing an impacting plume. Little is known about this but it is probably important owing to the frequency of forested slopes in mountain areas.

Probably the most frequently quoted aspect of mountain meteorology is that of the mountain and valley thermal wind systems. The simple system of upslope, downslope, upvalley and downvalley winds driven by solar heating of slopes during the day and cold air drainage at night was first described comprehensively by Defant (1951). It is possible in this simple system for pollutants to be carried upslope and/or upvalley during the day only for some of them to be returned at night. Further studies of the phenomenon however have revealed important complications and inconsistencies. Modeling of the system such as Thyer's (1966) work is essentially diagnostic rather than predictive. Even complex models of more simple flows such as over a single ridge (Fosberg, 1967) come into the same category. Observational studies sometimes show counter currents above the surface flows in valleys (Buettner and Thyer, 1966; Tyson and Preston-Whyte, 1972) sometimes not (Davidson and Rao, 1963); McKee and Whiteman, 1978 pers. comm.). Important from the point of view of dispersal is not only the possiblilty of the break up of an inversion from the top as described by Whiteman and McKee (1977) but also dissipation of a valley-plain wind from the top (Davidson and Rao, 1963). Both cases would give rise to a relatively longer period of pollutant exposure assuming the dissipation of the valley plain wind is followed by more turbulent conditions derived from solar driven convection or the influence of upper air currents. Studies such as those of Hahn's (1977) and Fox et. al. (1976) show that conventional knowledge of mountain and valley airflow cannot be applied in detail in any particular valley. Even more disturbing from the dispersal point of view are the findings of Kao et. al. (1975) that the kinetic energy of mean and turbulent motions and the rate of diffusion in the Salt Lake valley changes in time and space in a non-systematic and non-Gaussian manner. This undercuts one of the basic assumptions of the Gaussian plume approach.

Finally in this review must be considered the interaction between the valley flow and the airflow above the ridge tops. Even less is known about this than the topics already examined. One thing that is well established is the channeling effect which topography asserts on the upper air flow if it does reach the surface (Davidson and Rao, 1963). Another commonly reported effect is the development of a rotor in a vertical plane in a valley parallel to the upper air wind when the latter is perpendicular to the general alignment of the valley or terrain itself (Clements and Barr, 1976; Ruff, 1978). Banta and Cotton (1978) have reported a most interesting interaction between the upper air and surface wind regimes for the lee of a ridge situation. Studies in summer in South Park, Colorado showed a diurnal change composed of three regimes - a nocturnal drainage wind, a morning upslope wind and a surfacing of gradient winds aloft descending in the same direction as the drainage winds. The last regime is potentially extremely effective in flushing out pollutants that might be found in the lee location. Yet more extreme down slope winds originating in the upper air, such as those reported by Brinkmann (1973) would be even more effective in pollutant flushing. Limited observational evidence suggests a wide range of interaction between upper level and valley winds between virtually complete decoupling of the systems as some of Hahn's (1977) data show to those cases where it is possible to compute the momentum transport to and from the two regimes (Fox et. al., 1976). However, there is a great need for further studies in this area.

Strategies for Dispersal Modeling in Complex Terrain

Clearly the lack of knowledge and understanding of atmospheric factors in complex terrain poses immense problems for those who would model atmospheric dispersal. In the face of these problems the strategies adopted by scientists are many and are often site and/or problem specific. The strategies may be grouped into three classes for the sake of discussion. First there is the empirical and/or semi or fully theoretical alteration of standard models such as the plume model. Second, there is the option of increasing the complexity of the already complex models in order to gain a better approximation to reality. Third, there is the use of models such as the box model which incorporate in a "black box" fashion many of the complex processes that occur.

Several methods have been suggested for the alteration of plume model for use in complex terrain. Probably the simplest method is to alter the Pasquill-Gifford stability class. Shearer and Minott (1977) have suggested that if the downstream direction of airflow over rolling terrain at night can be predicted, then a plume approach can give approximate results by shifting the stability class one category towards neutral. In 1978 Minott and Shearer showed how observational studies could be used to redraw the lines representing the stability classes. This study was based on results from a steep-sided fjord in Norway and indicated large differences in σ_z values between the fjord case and the standard flat terrain case. A different approach has been used by Egan et. al. (1978) where they provide the rationale for calculating the effect of reflection when a plume directly impacts on an area of elevated terrain. Fosberg et. al. (1976a) have provided a third approach in which the Gaussian plume method has been modified for mass divergence influences.

The application of the above modifications is likely to be satisfactory for the point source in complex terrain but will be less appropriate for area sources such as vacation resorts and large scale mining operations.

There is virtually no limit to the degree of complexity which can be incorporated into the complex models. A full treatment of this topic cannot be given here but some examples can point the directions which the complex modeling systems appear to be taking. (A more thorough review has been given by Egan, 1978.)

One area of very active research, as indicated in an earlier section is to apply the advection-diffusion equation usually in a conservation form. Most attention is given to the following difficulties:

1). It is difficult to parameterize the eddy diffusivities for mountainous terrain. Limited observations have demonstrated the non-stationarity of these features in time and space (Kao et. al., 1975).

2). The success of this approach also depends on good meteorological input especially with regard to the wind field. Many different approaches have been made to obtaining an accurate wind field as exemplified by the work of Fosberg, et. al. (1976b), Dickerson (1978) and Mason (1978).

3). Inherent in wind field modeling and other parts of complex modeling are the analytical mathematical difficulties involved in choosing boundary conditions and subsequent solutions to the relevant differential equations. Following this there is the necessity for using appropriate numerical methods for computer solutions. One of the practical results of these difficulties is that according to Deardorff (1978) present models cannot resolve terrain features smaller than a few kilometers in scale. Furthermore, "a mesoscale model with sufficient horizontal resolution to capture the important local terrain influences would be too expensive to utilize" (Deardorff, 1978).

Probably one of the most advanced models of its kind is the LIRAQ-2 model developed by MacCracken et. al. (1978) for the San Francisco Bay area. This also is one of the few models for complex terrain that attempts to include photo-chemical reactions. It is likely that the research and development costs for this model were very high, and it is unknown at this time how easy and costly it would be to apply this model in other areas of complex terrain.

It would seem that in the long run the improvement of the complex models is the only truly scientific way of tackling the problem of predicting dispersal in complex terrain. However, the modeling problems are enormous and it is likely to be several decades before adequate inexpensive numerical models are developed.

In the meantime, it is more pragmatic to turn to models which are simple to use because they treat the complex meteorological processes of complex terrain in a black box fashion. There may well be a case for applying some of the simpler versions of the ATDL model to valley situations (Gifford, 1973). This is because it assumes narrow upwind segments of pollutant sources and also because it effectively becomes a box model at some distance from the source. Apart from this the box models themselves have found considerable favor for use in complex terrain, especially valleys. They are particularly suitable for area sources such as a ski resort. Also in some respects they are more suitable for application in rugged terrain than in flat terrain. This is attributable to 1) the assumption on instantaneous mixing throughout the volume of the box is more likely to be true in rugged terrain because of the greater turbulence, and 2) it is much easier to define the volume of the box in a valley with real sides than it is in flat terrain. With respect to 2) the only problem becomes to define the lid of the box. It is possible to solve this with the operational use of sodar and there may be other ways to define the lid. This problem is examined in the next part. Another advantage of the box model is its flexibility. Its use can be extended to any number of airsheds an investigator cares to designate. Furthermore, Whiteman and McKee (1977a) have shown how the model can be applied in a cross-valley fashion - in their particular case to explain inversion descent.

The overall conclusion of this section is that unless almost unlimited research and development funds are available the most appropriate strategies for air quality modeling in complex terrain are the use of a modified Gaussian plume technique for point sources and a box model approach for area sources. The present study with its emphasis on vacation resorts will examine the use of the latter.

Comments on Emissions Inventories and Projections

Although it is not the purpose of this study to examine emissions inventories, as mentioned earlier, they are an integral part of the air quality planning process, and a few comments are in order. First, no matter how good the atmospheric dispersal model used is, its accuracy will be limited ultimately by the accuracy of the input emissions. Second the establishment of an emissions inventory for a mountain resort carries some advantages and disadvantages compared to a similar excercise for a large metropolitan area in flat terrain. The main advantage is that mountain resorts are usually small and provide no great source sampling problems. Often a complete list of sources e.g. restaurants can be compiled. The main disadvantages are related to altitudinal effects. Very little research has been done on these and it remains standard practice, as in the inventories for Vail and Aspen, Colorado (Aspen, 1977, Vail, 1978) to apply low altitude emission factors as supplied by EPA (1973). Many of these will not be applicable to high altitude. There are certain fallaceous climatological assumptions as well. So, for example, in the computation of suspended fugitive dust emissions, Thornthwaite's potential evapotranspiration method is used. This method does not work well at high altitude because it is temperature rather than net radiation dependent.

Similar advantages and disadvantages apply to the projection into the future of emissions. Mountain resorts suffer the same doubt as lowland sites concerning future emission factors for automobiles and the projected use of automobiles given uncertainty in fuel supply. However, it is usually much easier to predict the growth of resorts because, owing to their size, their planning is usually centralized and fairly rigorously controlled.

In general judging by the high quality of the emissions inventories already assembled by Vail and Aspen it is probable that they are quite adequate for and compatible to the available atmospheric dispersal models. The same is probably true in the case of mining operations as well.

PART III ESTIMATING MIXING HEIGHTS IN VALLEYS

Introduction

It is quite clear that an adequate determination of mixing height is important in the application of box type models of air quality prediction. It is less important, though implicit, in many other types of models. Furthermore, mixing height has often been used together with wind speed as an indicator of air pollution potential (e.g. Holzworth, 1972). Most often the mixing height is taken as being defined by the temperature structure. Usually the air level of inversion base is assumed to be the mixing height. Olsson et. al. (1974) showed that this was not strictly true, at least for Western Oregon. They found the inversion base only to mark the beginning of a rapid decline in pollutant concentration. Observations from the United Kingdom also suggest there is some mixing within an inversion layer (Readings et al., 1973). Russell and Uthe (1978) indicate that the top of a ground based stable layer provides a measure of the upward limit of weak mixing. In this study it will be assumed as first approximations that the mixing height is synonymous with the height of an inversion base for elevated inversions. At certain points, especially when there are ground based inversions, inversion tops will also be examined.

Data summaries from NWS synoptic stations were first examined to see what they showed with respect to mixing heights and complex terrain. This data set summarized 5 years data. Next, shorter term data from Colorado was investigated in a search for spatial relations among mixing heights at different locations. Finally theoretical models of inversion rise dynamics are used to suggest the form the mixing layer might take across a valley.

Rawinsonde Derived Information

Summaries of routine rawinsonde measurements have been made for the EPA by Holzworth (1974, a,b) considerable information is available from this work but the most useful indices for the present study are: the frequency of ground based inversions, the frequency of elevated inversions with the most frequent height (by class) of their base, and the inversion thickness of greatest frequency. The rawinsonde data is taken approximately 45 minutes before the standard synoptic observation times of 0000 and 1200 GMT. Data for the stations used in the present study are summarized for the 5 year period 1960-1964.

Summaries are available for 79 stations in all. Nineteen stations were initially selected as potentially being in valley sites. The locations of these stations was examined using U.S.G.S. topographic maps and it was found that only 4 stations were actually in valleys of any significance. All the other stations although near valleys were usually at airports situated on plateau above the valley itself. The stations finally selected were Albany, NY, Caribou, MN, Grand Junction, CO and Medford, OR. The topographic characteristics of each site are summarized in table III-1. It was hoped that a much larger number of stations in valleys would be available so that the effects of topographic differences could be examined. This was not possible with only four stations. However, it was still possible to investigate the effect of valley sites compared to flat land sites with respect to mixing heights. Consequently three further stations were chosen for mixing height comparisons. These stations were Portland, MN in the same time zone as Caribou and Albany; Denver, CO, for comparison to Grand Junction; and Winnemucca, NV which shares Pacific Standard Time with Medford.

Table III - 1. PHYSICAL CHARACTERISTICS OF VALLEY RAWINSONDE STATIONS

Station	Valley Ht from floor to lowest ridge. m.	Valley Width ridge to ridge at narrowest point. m.	Vertical dist. of station from valley floor. m.	Valley Ht/Width ratio x 10^2
Albany, NY	49	2092	0	2.34
Caribou, MN	79	3862	65	2.05
Grand Junction, CO	407	26,393	84	1.54
Medford, OR	323	15,449	0	2.09

In each case, the flat terrain station was the one with comparable data nearest to the valley stations. Where heights are quoted they refer to the lowest height of the layer classes chosen by Holzworth and indicated in the sample summary output given as appendix I.

Dealing with the early morning soundings first,Table III-2 shows there are no consistent differences between the parameters examined for the valley stations of Albany and Caribou. However, contrasting these two stations with Portland shows the latter station to have more surface based inversions all the way through the year. Conversely, Portland has less elevated inversions. Possible explanations for these facts are that firstly there is greater turbulence in the aerodynamically rough mountain terrain breaking up the surface inversions and/or secondly the orientation and slopes of the valley stations are leading to enhanced convection. Comparing morning sounding data for Denver and Grand Junction (Table III-3) shows little difference through the year in the frequency or thickness of surface based inversions but Denver consistently has more elevated inversions. This might be attributed to the heat island effect operating at Denver. Contrasting the data summaries for Winnemucca and Medford, like Portland, the flat terrain station consistently has more surface based inversions and less elevated inversions throughout the year (Table III-4). Again the same features as were suggested to occur in the northeastern valley stations might be speculated to also occur at Medford. In this case, possible complications due to land and sea breeze effects at Portland will not operate at Winnemucca. Another possible explanation for the higher frequency of ground based inversions at Winnemucca is the drier air and decreased cloud cover to be expected at the Nevada station.

Table III - 3. Inversion Statistics for Denver, CO and Grand Junction, CO. Heights and Thickness in m. Early morning sounding 1200 GMT 0415 MST.

	DENVER, CO	GRAND JUNCTION, CO
WINTER		
% Surface Inversions	79.6	84.6
% Elevated Inversions	14.2	6.7
Most frequent Ht of Elev. Inv.	500	500
Thickness of most frequent surface Inv.	250	250
SPRING		
% Surface Inversions	78.4	78.0
% Elevated Inversions	15.7	3.3
Most frequent Ht of Elev. Inv.	1500	2500
Thickness of most frequent surface Inv.	250	250
SUMMER		
% Surface Inversions	87.0	86.3
% Elevated Inversions	8.2	1.9
Most frequent Ht of Elev. Inv.	500	250
Thickness of most frequent surface Inv.	500	500
FALL		
% Surface Inversions	86.3	87.1
% Elevated Inversions	10.8	2.9
Most frequent Ht. of Elev. Inv.	1500	1500
Thickness of most frequent surface Inv.	250	250
YEAR		
% Surface Inversions	82.8	84.0
% Elevated Inversions	12.3	3.7
Most frequent Ht. of Elev. Inv.	1500	500 and 1500
Thickness of most frequent surface Inv.	250	250

Table III - 2. Inversion statistics for Albany Ny, Caribou, MN, and Portland, MN. Heights and Thickness in m. Early Morning Sounding 1200 GMT 0615 EST.

	ALBANY NY	CARIBOU MN	PORTLAND MN
WINTER			
% Surface Inversions	47.7	53.0	64.4
% Elevated Inversions	47.9	43.5	32.0
Most Frequent Ht. of Elev. In.	500	500	250
Thickness of most frequent Surface inversion	250	250	250
SPRING			
% Surface Inversions	35.9	41.0	47.0
% Elevated Inversions	52.1	50.5	43.0
Most Frequent Ht. of Elev. In.	500	500	250
Thickness of most frequent surface inversion	500	500	250
SUMMER			
% Surface Inversion	36.5	30.5	44.9
% Elevated Inversions	47.8	49.7	41.8
Most Frequent Ht. of Elev. In.	500	250	250
Thickness of most frequent surface inversion	500	500	500
FALL			
% Surface Inversion	60.8	52.8	63.9
% Elevated Inversion	31.9	38.4	29.1
Most Frequent Ht of Elev. In.	1500/500	500	500
Thickness of most frequent surface inversion	500	250	250
YEAR			
% Surface Inversions	45.1	44.2	55.0
% Elevated Inversion	45.0	45.6	41.6
Most Frequent Ht. of Elev. In.	500	500	250
Thickness of most frequent surface inversion	500	500	250

Table III - 4. Inversion Statistics for Winnemucca, NV and Medford, Or. Heights and Thickness in m. Early Morning sounding 1200 GMT. 0315 PST

	WINNEMUCCA, NV	MEDFORD, OR
WINTER		
% Surface Inversions	86.1	71.7
% Elevated Inversions	6.1	20.7
Most frequent Ht of Elev. Inv.	250	750
Thickness of most frequent surface Inv.	250	250
SPRING		
% Surface Inversions	81.2	68.8
% Elevated Inversions	5.2	13.1
Most frequent Ht of Elev. Inv.	2500	2000
Thickness of most frequent surface Inv.	250	250
SUMMER		
% Surface Inversions	94.3	85.4
% Elevated Inversions	0.7	9.6
Most frequent Ht of Elev. Inv.		2000
Thickness of most frequent surface Inv.	250	250
FALL		
% Surface Inversions	91.6	80.7
% Elevated Inversions	3.8	12.6
Most frequent Ht. of Elev. Inv.	2000	1500
Thickness of most frequent surface Inv.	500	250
YEAR		
% Surface Inversions	88.3	76.7
% Elevated Inversions	3.7	13.9
Most frequent Ht. of Elev. Inv.	250 and 2000	250 and 2000
Thickness of most frequent surface Inv.	500	250

Both factors would contribute to more effective radiational cooling at the Nevada station compared to that at Medford, Oregon. Overall, the western stations (both in valleys and on flat terrain) manifest a consistently higher frequency of ground based inversions. This might be expected in the summer because of the earlier effectiveness of solar heating at the eastern stations. However, the difference is consistent throughout the year, and may possibly also be associated with greater radiational cooling in the drier air of the west.

The nationwide pattern of results for the afternoon and early evening sounding data shows the east to have consistently higher number of surface based inversions through the year but especially in winter. This is undoubtedly due to the onset of the nocturnal inversion already having started in the east. At most stations (except Medford) leftover elevated inversions from the previous night are most often found at about 1500 m. The detailed results again show interesting contrasts between the valley and flat land stations. There is little difference seen between the summaries for Albany and Caribou (Table III-5) but Portland has more surface based inversion in summer and winter and more elevated inversions throughout the year. Once more it is tempting to suggest that the more turbulent mountain airflow breaks up inversions more often over the complex terrain than occurs in the less turbulent air over Portland. Contrasting Denver and Grand Junction, Denver consistently shows a higher frequency of surface based inversion (Table III-6). This may be due to the earlier onset of sunset and nocturnal inversions at Denver; a suggestion supported by the effect being more marked in the winter season. The pattern with respect to elevated inversions is not clear. It is noteworthy though that in winter a 47.3% frequency of elevated inversions whose base is most often at about 500 m suggests some stagnation of

Table III - 5. Inversion statistics for Albany, NY, Caribou, MN, and Portland, MN. Heights and Thickness in m. Afternoon and Early Evening Sounding 0000 GMT. 1815 EST

	ALBANY, NY	CARIBOU, NY	PORTLAND, MN
WINTER			
% Surface Inversions	37.1	44.6	52.0
% Elevated Inversions	56.0	50.5	58.7
Most frequent Ht of Elev. Inv.	1500	1500	1500
Thickness of most frequent surface Inv.	250	250	250
SPRING			
% Surface Inversions	17.0	29.0	27.7
% Elevated Inversions	51.0	49.6	56.4
Most frequent Ht of Elev. Inv.	2500	--	250
Thickness of most frequent surface Inv.	250	250	250
SUMMER			
% Surface Inversions	13.0	14.6	25.4
% Elevated Inversions	39.8	36.7	50.7
Most frequent Ht of Elev. Inv.	2500	2500	250
Thickness of most frequent surface Inv.	250	250	250
FALL			
% Surface Inversions	53.5	44.0	51.0
% Elevated Inversions	32.1	44.1	50.6
Most frequent Ht. of Elev. Inv.	1500	--	1500
Thickness of most frequent surface Inv.	250	250	250
YEAR			
% Surface Inversions	30.0	32.9	38.9
% Elevated Inversions	44.7	45.2	47.4
Most frequent Ht. of Elev. Inv.	1500	1500	250
Thickness of most frequent surface Inv.	250	250	250

Table III - 6. Inversion Statistics for Denver, CO and Grand Junction, CO. Heights and Thickness in m. Afternoon and Early Evening Sounding. 0000 GMT. 1615 MST.

	DENVER, CO	GRAND JUNCTION, CO
WINTER		
% Surface Inversions	39.2	11.5
% Elevated Inversions	32.2	47.3
Most frequent Ht of Elev. Inv.	750 and 1500	500
Thickness of most frequent surface Inv.	250	250
SPRING		
% Surface Inversions	1.7	2.0
% Elevated Inversions	21.8	11.1
Most frequent Ht of Elev. Inv.	2000	3000
Thickness of most frequent surface Inv.	--	--
SUMMER		
% Surface Inversions	5.9	1.1
% Elevated Inversions	8.7	2.2
Most frequent Ht of Elev. Inv.	2000	--
Thickness of most frequent surface Inv.	250	--
FALL		
% Surface Inversions	15.6	3.3
% Elevated Inversions	26.3	19.8
Most frequent Ht. of Elev. Inv.	1500	2500
Thickness of most frequent surface Inv.	250	100
YEAR		
% Surface Inversions	15.5	4.5
% Elevated Inversions	22.2	20.0
Most frequent Ht. of Elev. Inv.	1500	500
Thickness of most frequent surface Inv.	250	100

air at Grand Junction in this season. Comparison of summaries from Winnemucca and Medford (Table III-7) show both stations to have low values of surface based inversions because both stations are in daylight and probably the air above them is experiencing strong convection at the time of the soundings (1515 PST). Winnemucca consistently has less elevated inversions especially in the summer. When they do occur their elevations are higher at Winnemucca than at Medford. this suggests stronger convectional currents over the hot surface of the Nevada desert.

The most important result to come out of this analysis from the point of view of the present study is that in most cases there are marked differences between inversion statistics from stations in valley and complex terrain and those from nearby stations in flat terrain. The explanations offered here for the details must be regarded as speculative and are worthy of further study concentrating especially on the mesoscale climatology of the stations involved. None of the results quoted here could be used on an operational basis. However, it is encouraging that there appear to be consistent differences between data from complex and flat terrain.

Spatial Relations in Short Term Inversion Data

If there is some kind of spatial coherence between mixing height data taken at one location and that at another then it might be possible to examine spatial relations among mixing heights in different plance and determine the effect of topography. There are many data sets in the literature that suggest the existence of spatial coherence among mixing heights on differing scales. Fisher (1977) analysed the rawinsonde data summaries of Holzworth on a nationwide basis and found many large geographic areas where the inversion parameter values changed

Table III - 7. Inversion Statistics for Winnemucca, NV, and Medford, OR. Heights and Thickness in m. Afternoon Sounding. 000 GMT. 1515 PST.

	WINNEMUCCA, NV.	MEDFORD, OR.
WINTER		
% Surface Inversions	4.7	10.4
% Elevated Inversions	59.2	61.4
Most frequent Ht of Elev. Inv.	500	250
Thickness of most frequent surface Inv.	250	750
SPRING		
% Surface Inversions	0.4	0.7
% Elevated Inversions	26.8	33.7
Most frequent Ht of Elev. Inv.	2500	2000
Thickness of most frequent surface Inv.	-	-
SUMMER		
% Surface Inversions	0.4	0.4
% Elevated Inversions	7.4	24.4
Most frequent Ht of Elev. Inv.	3000	2500
Thickness of most frequent surface Inv.	-	-
FALL		
% Surface Inversions	1.5	3.7
% Elevated Inversions	38.1	50.0
Most frequent Ht. of Elev. Inv.	2000	250
Thickness of most frequent surface Inv.	250	250
YEAR		
% Surface Inversions	1.8	3.8
% Elevated Inversions	34.5	42.3
Most frequent Ht. of Elev. Inv.	2000	250
Thickness of most frequent surface Inv.	250	250

only slowly. Most mesoscale studies of mixing height have occurred in large metropolitan areas. Although these studies give evidence for a rise of mixing height as air passes from the rural area to the center of the built up area (Oke and East, 1971; Spangler and Dirks, 1974) again, when scale is taken into account there are no abrupt changes in mixing height.

This being the case an examination was made of mixing height data taken from those areas in Colorado. NWS daily rawinsonde data for winter (December - January) 1975/76 and summer (June - August) 1976 were obtained for Grand Junction and Denver (Stapleton International Airport). Also a limited amount of data from June and July, 1976 was made available by the U.S. Geological Survey for two sites at the Piceance Creek area near Rifle, CO. The latter data are taken from tethersonde and acoustic sounding apparatus. One of the Piceance stations (020) at which a meteorological tower exists was situated approximately 5 km to the south and 194 m higher. The Piceance sites are about 80km NNW of Grand Junction and the latter is 320 km west of Denver.

It is most difficult to say something meaningful about the spatial variation of inversion bases. This is because of the high frequency of ground based inversions at 0415 MST at all sites. Table III-3 shows, for example, that the lowest frequency of ground based inversions at Grand Junction and Denver is 78% at the former station in spring. 78% is also the annual value for two years data taken at the tower site at Piceance 1974-1976 (Ashland Oil et. al. 1976). Also most of the days for which tethersonde data at Piceance are available show ground based inversions at 0415 MST at both sites. Piceance data for four days where there is a clear rise of the ground based inversion are plotted in Fig. III-1.

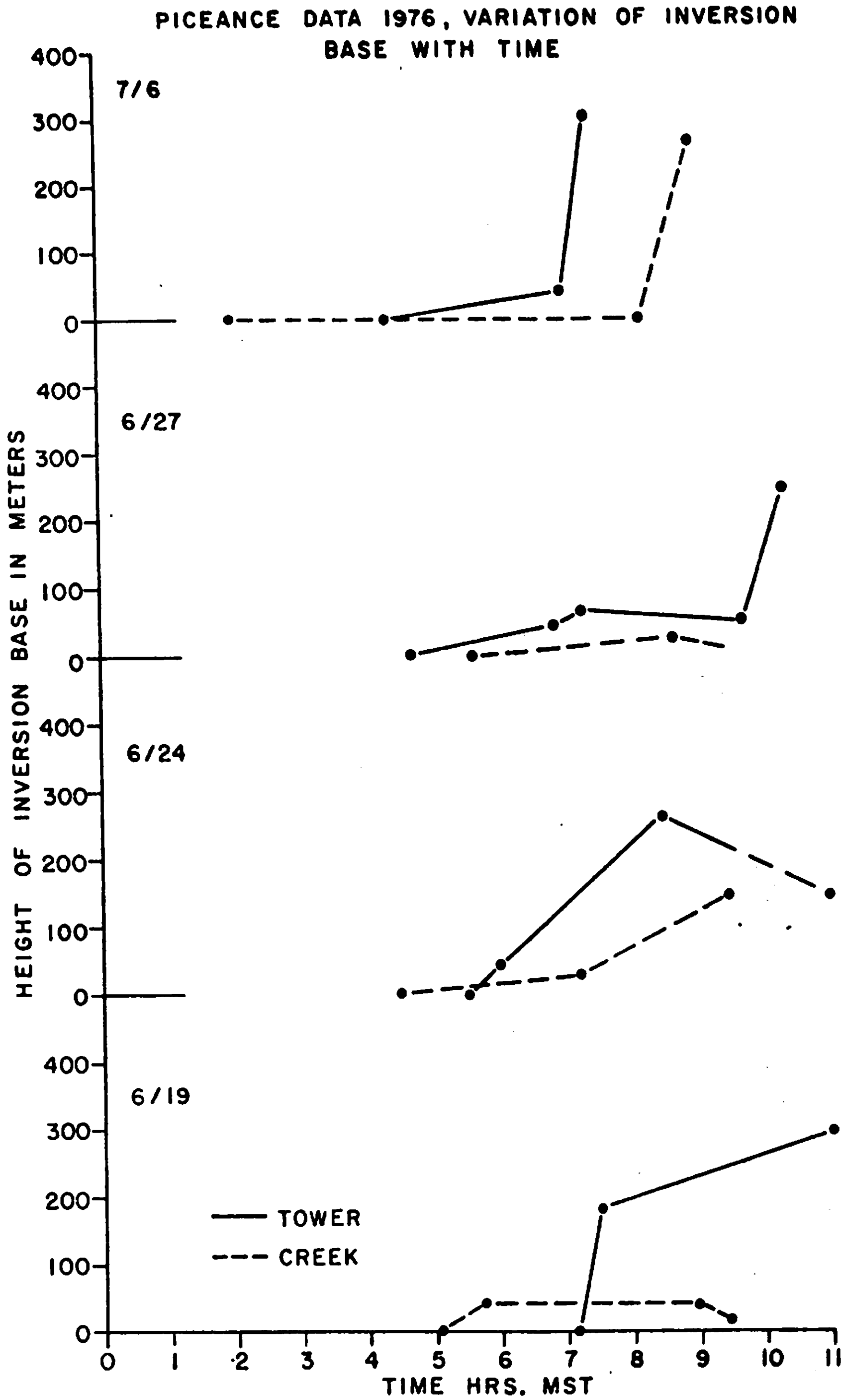

PICEANCE DATA 1976, VARIATION OF INVERSION BASE WITH TIME
HEIGHT OF INVERSION BASE IN METERS
7/6
6/27
6/24
6/19
0
100
200
300
400
TOWER
CREEK
0 1 2 3 4 5 6 7 8 9 10 11
TIME HRS. MST

Fig. III-1

These data show that, although starting later on two of the four occasions, inversions at the tower site rose more rapidly than at the creek site.

In an attempt to gain freedom from the synoptic reporting times a variation of Ludwig's (1970) method of computing mixing height variation during the day was applied to Grand Junction data. The method of computation is described in appendix II. The results, shown in Table III-8, indicate that there is certainly no one to one correspondence between the mixing heights at the two places when computed this way. A linear regression between the data sets yields

$$h_{PC} = 0.0381h_{GJ} + 41.46 \text{ meters}$$

where h_{PC} and h_{GJ} are the inversion heights at Piceance Creek and Grand Junction respectively and the correlation coefficient between them is 0.448. This is really not high enough to be used on an operational basis. Furthermore it is interesting to note from Table III-8 that if the observed Grand Junction inversion height is taken as the maximum mixing height it does not bear a very close relationship with the h_{max} estimated by the Ludwig (Holzworth) method.

Finally, with respect to inversion base, the winter Denver and Grand Junction rawinsonde data were examined for correspondence. The morning soundings showed that on all except one occasion elevated inversions at Denver were accompanied by ground based inversions at Grand Junction and vice versa. The afternoon soundings showed evidence of the same inverse relationship with respect to ground based inversions but no clear pattern when both locations had elevated inversions.

It is therefore difficult to determine any meaningful spatial relationships for inversion bases in the data used here.

Table III - 8. Computed Mixing Heights at Grand Junction at times when an elevated inversion occurs at Piceance Creek. Heights in m.

Day	Time MST	Inv. Base in Piceance Creek	Computed G.J. Inv. Ht.	Observed G.J. Inv. Ht. at 1615 MST	Computed G.J. max mixing Ht.
6-18	0720	12	1212	4210	4000
6-19	0500	5	201	none	3110
	0530	42	301		
	0900	41	1304		
	0930	19	1405		
6-21	0700	43	1207	none	4074
	0725	102	1358		
6-22	0950	171	289	none	481
6-23	0215	77	307	3236	3988
	0330	123	307		
	0550	21	638		
	0940	169	2454		
	0950	238	2454		
6-24	0700	37	668	32 and 5043	3475
	0720	36	1069		
	0950	154	2005		
6-26	0933	154	3357	none	5371
6-27	0830	35	2753	none	4982
7-6	0830	271	1952	5	5466

The tops of ground based inversions typically show considerable variation in height with time on a daily basis. An example of this is seen in the acoustic sounding data for June 1976 taken at the Tower site at Piceance (Fig. III-2). Given uncertainties in the actual time, i.e., minute, of rawinsonde ascent, it would be unlikely to find spatial relationships among the inversion tops. However, for a limited amount of data, the regression relationships appearing among tops of ground based inversions at 0415 MST found in Table III-9. With 12 or less available data pairs no firm conclusions can be drawn from this analysis. Some surprisingly high correlations coefficients are apparent but all have doubt cast upon them by the absolute lack of statistical correlation seen between mixing heights at the two Piceance stations. Many more data pairs are available for the heights of inversion tops when ground based inversions occur at 0415 in December 1975 and January 1976 at Grand Junction and Denver. Nevertheless, the scatter of the data is very wide and it is doubtful if any useful relationship can be drawn.

One other indirect method of isolating the effect of topography on mixing heights was attempted. It was reasoned that if some relationships could be determined between mixing heights and commonly observed surface meteorological parameters, then a difference in such relationships from one valley to another might be related to topographical differences. A stepwise multiple regression analysis was undertaken between various mixing height parameters and atmospheric pressure, cloud cover, cloud height, wind speed, wind direction, wet and dry bulb temperatures and dew point depression. This was done for the morning and afternoon sounding data and corresponding surface data for Grand Junction and Denver

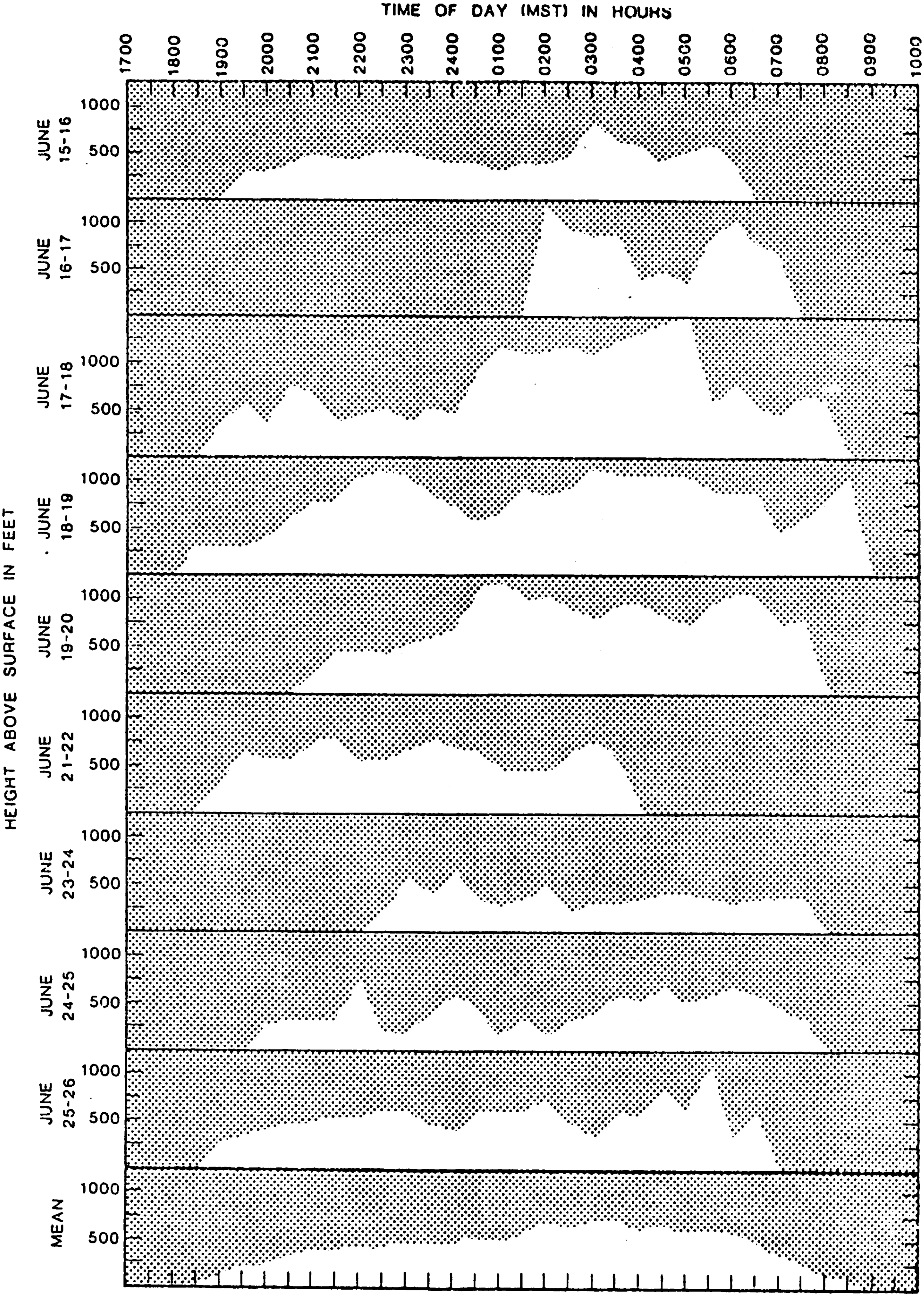


FIG. III-2. Typical inversion-top time histories (Station 023) tower site Piceance. (From Ashland Oil Co. et al. 1976.)

Table III-9

Regression relationships between 0415MST heights of groundbased inversion tops at Grand Junction (GJ), Denver (DEN), and Piceance Creek (PC), and Tower Sites (PT).

Regression Equation	Correlation Coefficient
$h_D = 1.05\ h_{GJ} + 85.43$	0.72
$h_{PC} = -7.32\ h_D + 327.56$	0.26
$h_{PT} = 0.33\ h_D + 35.02$	0.92
$h_{PC} = 3.89\ h_{GJ} + 283.00$	0.10
$h_{PT} = 0.25\ h_{GJ} + 110.00$	0.36
$h_{PT} = -0.05\ h_{PC} + 154$	-0.05

in December-January 1975/76 and June-August 1976. The actual mixing height parameters used as dependent variables were inversion base and top heights, inversion thickness and inversion intensity. The major aspects of the results of this analysis are listed in Appendix III. The only really high correlations occur when the number of cases is very small. Also no one or two independent variables are entered consistently into the equations in the first few steps. As a result this method of attempting to isolate the effect of topography on mixing heights was abandoned.

Utilization of Theoretical Models of Inversion Rise Dynamics

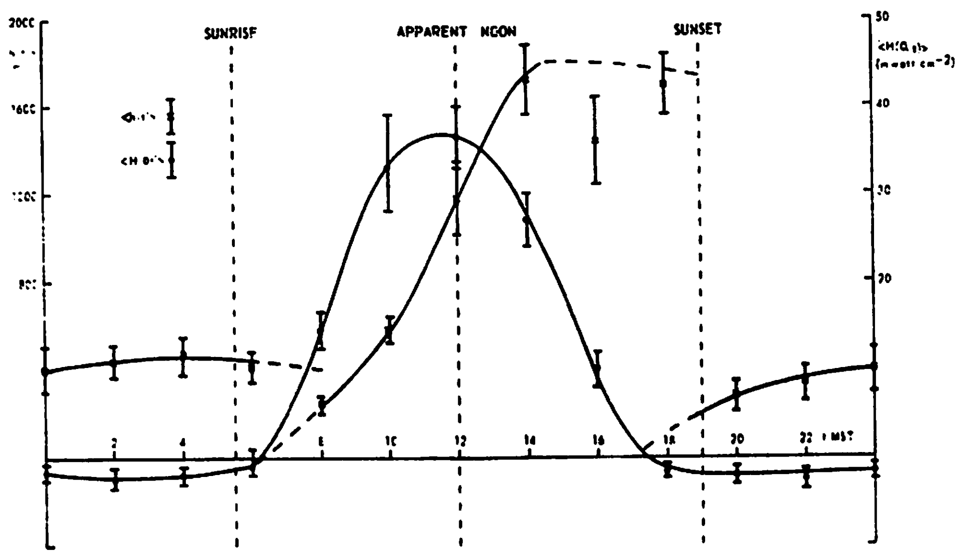
One of the major reasons for the lack of success of the analyses of the previous two sections in finding a method of determining mixing height in valleys for use on an operational basis is the entrance paucity of comparable data. It is not uncommon to suffer a data scarcity in mountain meteorology and a frequent method of overcoming this problem is in the use of modeling techniques. No models of inversion rise have been developed for complex terrain but several have been formulated for flat terrain. It is the purpose of this section to enquire what such models can tell us concerning the form of mixing heights in complex terrain.

The seminal paper in inversion rise dynamics was presented by Ball (1960) who first pointed to the energetics involved in the entrainment of air from the stable layer above the inversion base. Tennekes (1973) used a simplified version of the enthalpy balance equation and shows how the change in inversion height may be related to the heating history of the boundary layer and to initial conditions. Carson (1973) independently derived a rather similar model which also indicated the importance of entrainment. Zilitinkevich (1975) and Tennekes (1975) considered some special cases not examined in Tennekes (1973) model, while Mahrt and Lenschow (1976) estimated how large the vertical shear must be for mechanical production of turbulent kinetic energy budget to be important. Much more generalized and sophisticated parameterizations of the turbulent kinetic energy budget have been given by Stull (1976a, b) and Zeman and Tennekes' procedure has been developed by Rubenstein (1974) for predicting mixing heights in East Africa. Recent attempts at operationalizing inversion rise models have been made by Benkley and Schulman (1979) and Yamada and Berman (1979). Zeman and Tennekes (1977) conclude that under light winds the more simple 1973 model of Tennekes is adequate. This will be the model considered mostly in this study but it will be shown where appropriate why the more sophisticated models need not be applied to the present problem in its initial examination. The 1973 Tennekes model has been used in two other applications. Tennekes and Van Ulden (1974) tested its use for operational forecasts of mixing heights in the Netherlands and found it adequate as long as synoptic weather conditions were unchanging. Tennekes (1976) further applied the inversion rise model when he incorporated it into a box model of air quality prediction.

The typical case of inversion rise in conditions of relatively low wind speed is shown in Fig. III-3 using data from O'Neill, Nebraska. Some of the physics of the situation are schematically represented in Fig. III-4. The framework in which the Tennekes 1973 model works is given in Fig. III-5 where t is time, Δ is the inversion strength, Θ is potential temperature, w is vertical wind velocity, h is the height of the inversion base and $(\overline{\Theta w})_i$ and $(\overline{\Theta w})_o$ are the turbulent sensible heat fluxes at the inversion base and ground surface respectively. The model essentially considers the enthalpy balance at the inversion base and is expressed as

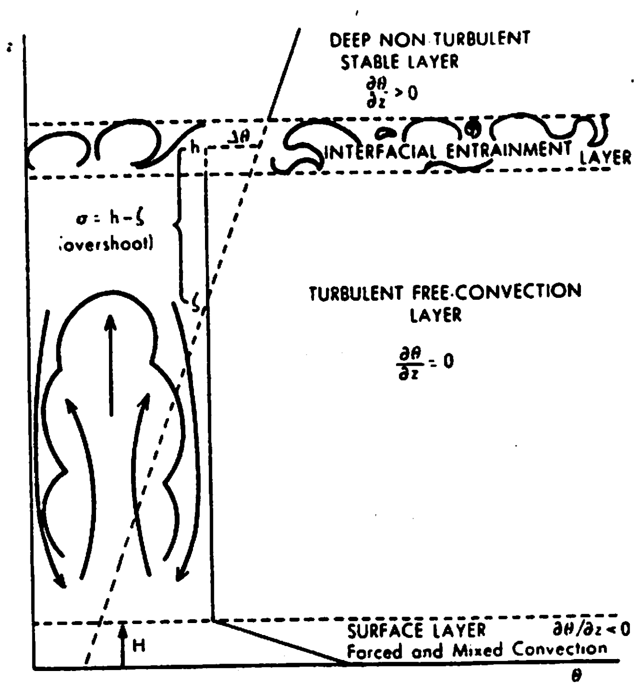
$$-(\Theta w)_i = \Delta \frac{dh}{dt} \qquad \text{----- 1.}$$

and $$\frac{d\Delta}{dt} = \gamma \frac{\partial h}{dt} - \frac{(\overline{\Theta w})_o}{h} + \frac{(\overline{\Theta w})_i}{h} \qquad \text{----- 2.}$$



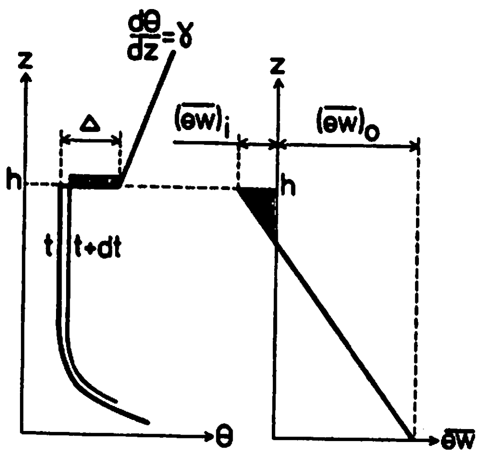
The mean boundary layer thickness, <*h*(*t*)>, and the sensible heat flux at the surface, <*H*(0,*t*)>, deduced for the O'Neill data and plotted with standard errors as functions of time of day, *t*, in Mean Solar Time.

Figure III-3. Reproduced with permission of the Royal Meteorological Society from Carson (1973).



Schematic representation of the developing convectively unstable boundary layer and the adopted potential temperature profile, $\theta(z)$.

Figure III-4. Reproduced with permission of the Royal Meteorological Society from Carson (1973).



The vertical distributions of potential temperature and turbulent heat flux in and above a convective boundary layer.

Figure III-5. Reproduced with permission of the American Meteorological Society from Tennekes (1973).

These equations can be solved and integrated to

$$h\Delta - h_o\Delta_o = \frac{1}{2}\,\gamma\,(h^2 - h_o^2) - \left[\Theta w\right]_o t \qquad \text{------ 3.}$$

where it is important to note that the subscripts 0 on all terms except $(\overline{\Theta w})_o$ refer to a time zero at the beginning of inversion rise. Equation 3 holds for the linear period of inversion rise starting a few hours after sunrise and, in Tenneke's terminology, called the post morning transient period or morning convection period. In the first few hours after sunrise when surface heat flux is assumed to increase linearly with time and the inversion rise increases only slowly with time equation 3 is rewritten as

$$h\Delta - h_o\Delta_o = \frac{1}{2}\,(h^2 - h_o^2) - \frac{1}{2}\,\frac{(\Theta w)_n t^2}{\tau} \qquad \text{------ 4.}$$

where $(\Theta w)_n$ is the surface heat flux at noon and τ is the time scale of initial heat flux with time which Tennekes takes as about 3 hrs or 10800 secs.

Before going further with this model it is necessary to consider the role of radiative heat fluxes. Tennekes suggests that radiative fluxes (by which he implicitly means longwave thermal radiative fluxes) will be relatively unimportant as long as penetrative convection is vigorous. In this case, the turbulent flux will dominate the radiative one. Tennekes also suggests that a radiative flux tends to decrease the net heating rate of the air in the boundary layer and can be incorporated into the model by making a small reduction in the surface heat flux $(\Theta w)_o$. This is because the net longwave flux represents a cooling of the surface and the atmosphere. The amount of such cooling could be affected by the longer lasting inversion conditions sometimes existing in stagnant valley air, and/or by thermal radiation from valley sides. However, preliminary calculations using radiative transfer computational routines developed by Cox et. al.

(1976) showed the presence of an inversion to make only a slight difference to the net radiative cooling. Furthermore, computations by McKee and Whiteman (1977) for a model valley with steep sides showed that in the most extreme case net loss of longwave radiation at the valley floor was reduced by 24% over the net loss that would have occurred in flat terrain. Hence, if longwave radiative heat flux were to be incorporated into the Tennekes model an even smaller reduction of $(\overline{\Theta w})_o$ would be required for a valley case than in a flat land case. Thus Tennekes' decision to neglect the longwave radiative heat flux is even more sound in application of his model to a valley than in its original application to flat terrain. It will be seen later that it is a different matter with regards to incoming short wave radiation.

Returning now to Tennekes model it is possible to list some of the results that can be derived from it and which may have application to the valley situation.

First with regard to the <u>morning convection</u> period:

1). <u>An approximation of h in a steady state is given by</u>

$$h^2 = h_o^2 + \frac{2}{\gamma} (\overline{\Theta w})_o t \qquad \text{----- 5.}$$

which comes from equation (3), carries a possible 20% error and assumes $h\Delta \ll h^2$ and $h_o\Delta_o \ll h_o^2 + \frac{2}{\gamma} (\overline{\Theta w})_o t$.

2). <u>An approximation of $-(\Theta w)_i$</u> is given by

$$-(\overline{\Theta w})_i = 0.2\ (\overline{\Theta w})_o \qquad \text{----- 6.}$$

which applies when h<100m, and assumes the kinetic energy dissipation rate at the inversion base is small, the kinetic energy flux convergence near the inversion to be proportional to the cube of the standard deviation of w divided by h, and the dominance of free convection.

3. An approximation of the relation between Δ and h is given by

$$\Delta \sim \frac{\gamma h}{7} \qquad \text{----- 7.}$$

for $h > 2h_o$ and intense convection occurrence.

4. A further approximation of h is given by

$$h^2 \simeq 2\,\frac{(\overline{\Theta w})_o\, t}{\gamma} \qquad \text{----- 8.}$$

assuming h_o to be unimportant and equation 7 holds. This also shows that it is unnecessary to know Δ. It also follows that when there is no surface heat flux the entrainment rate and inversion rise is very slow. In fact with

$$(\overline{\Theta w})_o = 0 \quad \frac{dh}{dt} \rightarrow 0. \qquad \text{----- 9.}$$

Second, dealing with the morning transient period, the most important desirable result for the present study is

An approximation of h given by

$$h \simeq \left\{ \frac{7}{5}\, \frac{(\Theta w)_n}{\gamma\ \tau} \right\}^{\frac{1}{2}} t \qquad \text{-----10.}$$

which assumes $h > 3h_o$.

The implications of this model for inversion rise in a valley case have to be investigated in two parts dealing with the morning transient and the morning convective period.

a) Morning Transient Period

Following Tennekes, helpful insights are gained by putting numbers into equation 10. For example, by taking values of $0.5^oK.m.\ sec^{-1}$ for $(\overline{\Theta w})_n$, $5^oK\ km^{-1}$ for γ and 10^4 sec or 2.8 hrs for τ, dh/dt becomes 425 m hr^{-1} (not 300 m hr^{-1} as stated in Tennekes' paper). In the case of a valley with one side receiving direct shortwave radiation and the other side receiving only diffuse radiation, assuming γ of $5^oK\ km^{-1}$ to apply in both cases the values might be as follows:

For the sunny side assuming $(\overline{\Theta w})_n$ to be 0.6^{o}K.m. sec^{-1} and τ to be 2 hrs or 7200 secs dh/dt is 550 m hr^{-1}. For the shaded side assuming $(\overline{\Theta w})_n$ to be 0.2^{o} km sec^{-1} and τ to be 2 hrs dh/dt is 317 m hr^{-1}. In other words the inversion base might be expected to rise at almost twice the rate on the sunny side of the valley as it does on the shaded side. The following questions now arise: what are the limiting extreme conditions for the $(\overline{\Theta w})_n$ and τ values and how do these values change with topography and season?

Once more some actual values can point to the answer to the first question. Table III-10 shows some of the few actual observations of surface heat flux taken on different slopes in mountain terrain over a surface that is not ice. These data were collected by Dr. A. Brazel in the Chittistone Pass area in south-east Alaska at 61^{o}N and about 1830 m elevation and are averaged from an 11 day sequence from July and August (Brazel and Outcalt, 1973). The sunny side of the pass has a value of $(\overline{\Theta w})_n$ about three times as large as that on the shaded side. It is also noteworthy that the sensible heat flux was not directed away from the surface until about 0930 on the shaded side in contrast to about 0630 on the sunny side. This implies that if τ is taken to be 2½ hours the morning transient regime will last throughout the entire period of increasing solar heating on the more shaded side. The sensible heat fluxes in these data will not of course be the maximum possible because of the high latitude and the slope orientation not being due north and south. Since it is relatively straightforward to compute the potential direct shortwave radiation (K↓) on a slope if an assumption can be made about how much of this goes into the sensible heat flux then it would be possible to approximate the latter. For the three sites 1, 4, and 5 of the Chittistone data the ratio $(\overline{\Theta w})_n/K{\downarrow}_n$ is 0.24, 0.28, and 0.25, respectively. These values compare well with those from some other observational studies of surface

Table III-10

Values of sensible heat flux at the surface for three locations in the Chittistone Pass area, Alaska. (After Brazel and Outcalt 1973)

Site Number	Slope Degrees	Exposure/ Orientation Degrees	Noon Surface Sensible Heat Flux Wm^{-2}
1	0	0	91
4	34	125	125
5	28	315	43

energy budgets in mountainous terrain in mid-latitudes, e.g., Greenland (1973). It is thus not unreasonable to assume a value of 0.25 for the $\overline{(\Theta w)}_n/K{\downarrow}_n$ ratio as a first approximation.* Using this assumption and computing K↓ for a flat surface at lat. 23.5S with a solar declination of -23.5^o a possible limiting value of $\overline{(\Theta w)}_n$ might be about 230 Wm^{-2} or 460 Wm^{-2} if a dry unvegetated surface was considered. In the latter case this would translate to an inversion ascent rate of about 398 m hr^{-1}. The lower extreme value of $\overline{(\Theta w)}_n$ is much easier to estimate. Since some slopes never receive direct radiation at certain times, assuming K↓ is the only source of heat for $\overline{(\Theta w)}_n$, then when K↓ → 0 so will $\overline{(\Theta w)}_n \rightarrow 0$.

It is fairly safe to assume that γ will remain constant or near constant in the horizontal plane above and across the valley. However, in order to utilize equation 10 the limiting values and changes in τ should be considered. Tennekes defines τ as the "time scale of initial increase of flux with time" and he takes his value (of 3 hrs) from data of Deardorff (1967). Unfortunately, Deardorff's data are rather vague about the beginning and ending points of the τ period. Two areas of certainty are however: 1) the beginning of the period cannot be before sunrise and 2) the end of the period is likely to be about 30-60 minutes before noon unless the heat flux had a 'late start' because of shading. As seen above, in the latter case τ will go from local effective sunrise to solar noon.

*Note this value carries with it the assumption of more or less equal partitioning of a net radiation value (that is itself about half the direct radiation value) between the latent and sensible heat fluxes. Changes of vegetation type or surface cover and/or moisture conditions might require a change in the value of this ratio. For example, the value could exceed 0.50 over a dry unvegetated surface and will increase as the Bowen ratio increases.

Thus for computational purposes τ may be taken as 2.8 hrs (following Tennekes) for all cases unless because of shading it is taken from effective sunrise to solar noon. For simplicity τ will also be used as the length of the morning transient period.

Stull's (1976b) approach might be briefly introduced at this point. Instead of concentrating only on the surface heat flux term, Stull points out that if entrainment due to cloud induced subsidence and synoptic scale subsidence may be ignored, dh/dt will be a function of four factors. These are: 1) the sensible heat flux at the surface or buoyancy contribution; 2) energy due to wind shear at the earth's surface; 3) turbulent kinetic energy due to wind shear at the inversion base; and 4) energy losses due to internal gravity waves. If we assume light winds as are common in stable conditions in mountain valleys then only term one will be of great importance. Thus the Tennekes model in use is a special case of the more general Stull model.

b) Morning Convection Period

During the morning convection period, Stull's (1976b) results (see especially his Fig. 7) indicates that dh/dt, as shown by the entrainment rate, varies proportionally with the bouyant contribution term. At the same time at the surface and the inversion base tend to vary in opposite directions thus cancelling out their effect on the rate of entrainment. Thus once again in initial modeling of this period, Tennekes' particular solution, rather then Stull's general solution to the inversion rise problem may be taken.

The most useful of Tennekes' relationships for application to this period is equation 8 above. With respect to the valley case γ is again likely to be constant all the way across the valley since it is a function of the upper air conditions only. If this is true, the equation may be written as:

$$h = \simeq \left\{ B(\overline{\Theta w})_o t \right\}^{\frac{1}{2}} \qquad \text{----- 11.}$$

where $B = 2/\gamma$ and h will essentially vary in space (the horizontal dimension on x y plane) with the square root of $(\overline{\Theta w})_o t$. It is therefore expected that the same kinds of variation of dh/dt with different valley slopes will occur for the morning convection period as for the morning transient period but the rates of increase of h and the height difference of h across a valley will be less since the square root of $(\overline{\Theta w})_o$ is taken rather than the full value of $(\overline{\Theta w})_n$. Inserting representative numbers into the sample maximum case used above where $(\overline{\Theta w})_{on}$ is 460 Wm^{-2} and $\gamma = 5^oK\ km^{-1}$, at solar noon h would be at 2648 m. Once more the lower limiting case would be when $(\overline{\Theta w})_o \rightarrow 0$ then $h \rightarrow 0$. For the sake of simplicity it is further assumed that the inversion does not rise further after solar noon.

It is necessary to mention three practical points with regard to the computations using the Tennekes model. First, the calculation giving the maximum value of h as 2648 m assumes similar conditions to the calculations made for the morning transient period. Second, in applying equation 11, a time averaged value of $(\overline{\Theta w})_o$ as opposed to the noon value of the term is required. Assuming a sinusoidal increase in $(\overline{\Theta w})_o$ during the pre-solar noon period, the time averaged value for insertion into equation 11 is approximated by 0.7071 $(\overline{\Theta w})_{on}$.

Finally, there is a problem of dimensions. In Tennekes' derivation of enthalpy balance $c_p\rho$ (specific heat of air at constant pressure times air density) appear on both sides of the equation and cancel. Hence the use, in this case of $(\overline{\Theta w})$, in $^oK\ m\ sec^{-1}$ for sensible heat flux which refers to unit area. When deriving sensible heat flux from K↓, which is in cal $cm^{-2}\ min^{-1}$ or Wm^{-2}, $c_p\rho$ must be brought back into the computation and K↓ must also be divided by $c_p\rho$. In doing this an assumed value of ρ of 1.049×10^{-3} gm cm^{-3} valid, according to the

U.S. Standard Atmosphere, for air at 6000 ft or 835 mb, is used together with a value of c_p of 0.24 cal gm^{-1} $^oK^{-1}$. This gives results in cm min^{-1} ^oK if K↓ is in cal cm^{-2} min^{-1}. Thus the procedure is to convert Wm^{-2} to cal cm^{-2} min^{-1}, and divide by $c_p\rho$ and then divide by 6×10^3 to allow for the change from cm min^{-1} to m sec^{-1}. Therefore to convert values of K↓ in Wm^{-2} to values of $(\overline{\Theta w})$ in ^oK m sec^{-1} a multiplication by 9.4865×10^{-4} is required.

Using the above theory and assumptions the following steps are necessary for a practical application.

1. Determine representative values of slope angle and orientation for each valley side and valley floor. Also determine representative values for solar declination, latitude, atmospheric transmissivity and the solar constant.

2. Using the above values compute the potential incoming shortwave radiation on each slope and multiply by the appropriate factors to obtain $(\overline{\Theta w})_n$ in ^oK m sec^{-1}. Potential radiation on a slope at solar noon may be computed using the method given in Appendix IV.

3. Determine time of start of sun on slopes. The computer program MAPSUM written and described by Williams et al. (1972) whose listing is available on request from the author will make this computation. Take the length of the morning transient period as being 2.8 hours following effective sunrise, and take the morning convection period as being the remainder of the time up until solar noon.

4. Assume a constant value for γ, say 0.005 ^oK m^{-1} and then apply the equations.

$$h = \left\{\frac{1.4 \times (\overline{\Theta w})_n}{50.4}\right\}^{\frac{1}{2}} 10080 \qquad \text{----- 12.}$$

for the morning transient period, and

$$h = \left\{400 \times 0.7071(\overline{\Theta w})_{on} \cdot t\right\}^{\frac{1}{2}} \qquad \text{----- 13.}$$

for the morning convection period where t is the length of the period in seconds.

5. The final value of h for noon is obtained by adding the two values of h to the elevation of a point half-way up the slope.

As an alternative application h can be determined at most times during the rise period by inserting the appropriate number of seconds for either 10080 or t.

Comparison with Observation

As with any studies of mixing heights in rugged terrain at the present time, observational data are very scarce. Further difficulties arise because many assumptions have to be made in the application of the theory and the available data that the theory requires. With this in mind the rate of inversion rise in the vertical plane only will be examined. The only published data on inversion height variation in the horizontal plane in a valley obtained by Russell and Uthe (1978a, 1978b) for the Santa Clara valley is not suitable because of general large scale subsidence conditions existing at the times of observations. Such conditions conflict with assumptions in the inversion rise theory. Even with sophisticated inversion rise models most observational verification is limited to one or two individual day case studies. Two recent studies have improved matters somewhat. The studies of Benkley and Schulman (1979) and Yamada and Berman (1979) used 30 and 22 days of data respectively. Nevertheless, the longest term verification study in the literature at present remains that of Tennekes and van Ulden (1976) who used 58 days. Their results, for de Bilt in the Netherlands, showed the Tennekes 1973 model to perform fairly well but rather better in predicting the maximum temperature of the mixing layer than the mixing height itself.

The best available data for testing the present application of the model come from the town of Vail in the Gore Valley, Colorado, and are for December 1976 to

March 1977. These accoustic sounder derived data were kindly supplied by Dr. D.G. Fox. The inversion rise model was applied to conditions that would exist on December 21, January 15, February 14, and March 21. The following assumptions and approximations were made in addition to those listed in the last section in order to operationalize the model:

1. The average atmospheric transmissivity was taken as 0.95.

2. For times when there was no direct radiation on the slopes the mixing height was approximated by the Benkley and Schulman (1979) relationship, namely

$$h \approx 125u$$

This relationship gives h in m when u, the windspeed at 10 m is in m sec^{-1}. It assumes that only mechanical turbulence, as opposed to both mechanical and convectional, is operative.

The Vail data are not ideal for model verification. During the hours of darkness it is likely that the accoustic sounder is looking at the top of a surface based inversion and is therefore not measuring mixing height. During the day the limited vertical range of the sounder, approximately 500 m, means that inversion levels higher than this cannot be detected. When there is mixing data due to this feature, a value of 1300 m is inserted when the monthly mean accoustic sounder data was computed. The value of 1300 m was deliberately chosen to match the Tennekes model prediction. Thus 'observed' and modeled data are coupled.

Bearing in mind this high degree of colinearity between observed and modeled data, all that it is possible to say about the results of the application of the model is that they give some grounds for encouragement. Figure III-6 shows modeled and averaged 'observed' mixing height data by hour for the month of January. Correspondence for the other months is similar. It can be seen that the predicted rise rate is roughly the same as that shown by the Vail data except that it is out of phase by about two hours. Part of the phase difference is probably due to the insertion of 1300 m for missing data and the consequent averaging procedure. The only time period where direct comparison can be made between model and observation is between about 9.0 a.m. and 10.0 a.m. Here agreement is good. More valid verification of the model will have to await better observational data. However, it should be mentioned that successful use of dispersal models with the modeled data would also lend support to the inversion rise modeling system used here.

Application of the model to slopes other than that of the valley floor in the Gore Valley suggests that as long as inversion rise is controlled by solar radiation forcing the rise would be more rapid over slopes more directly exposed to radiation. Maximum mixing height values predicted by the model for Vail indicate a mixing height 180 m above that over the valley floor for the northernmost (south-facing) slope.

Conclusions

Quite clearly knowledge concerning the values of mixing height in complex terrain is in its infancy - a situation almost entirely due to lack of data. Information from NWS rawinsonde stations located in valleys is interesting and shows consistencies in differences between valley and non-valley stations. Further study is needed to identify the precise causes for these differences. Furthermore there are not enough NWS stations located in valleys for findings derived from them to be used on a operational basis. An investigation of Colorado data to find spatial relationships in mixing heights proved unsuccessful. So also did the application of Ludwig's method of estimating diurnal change of mixing height and a search for

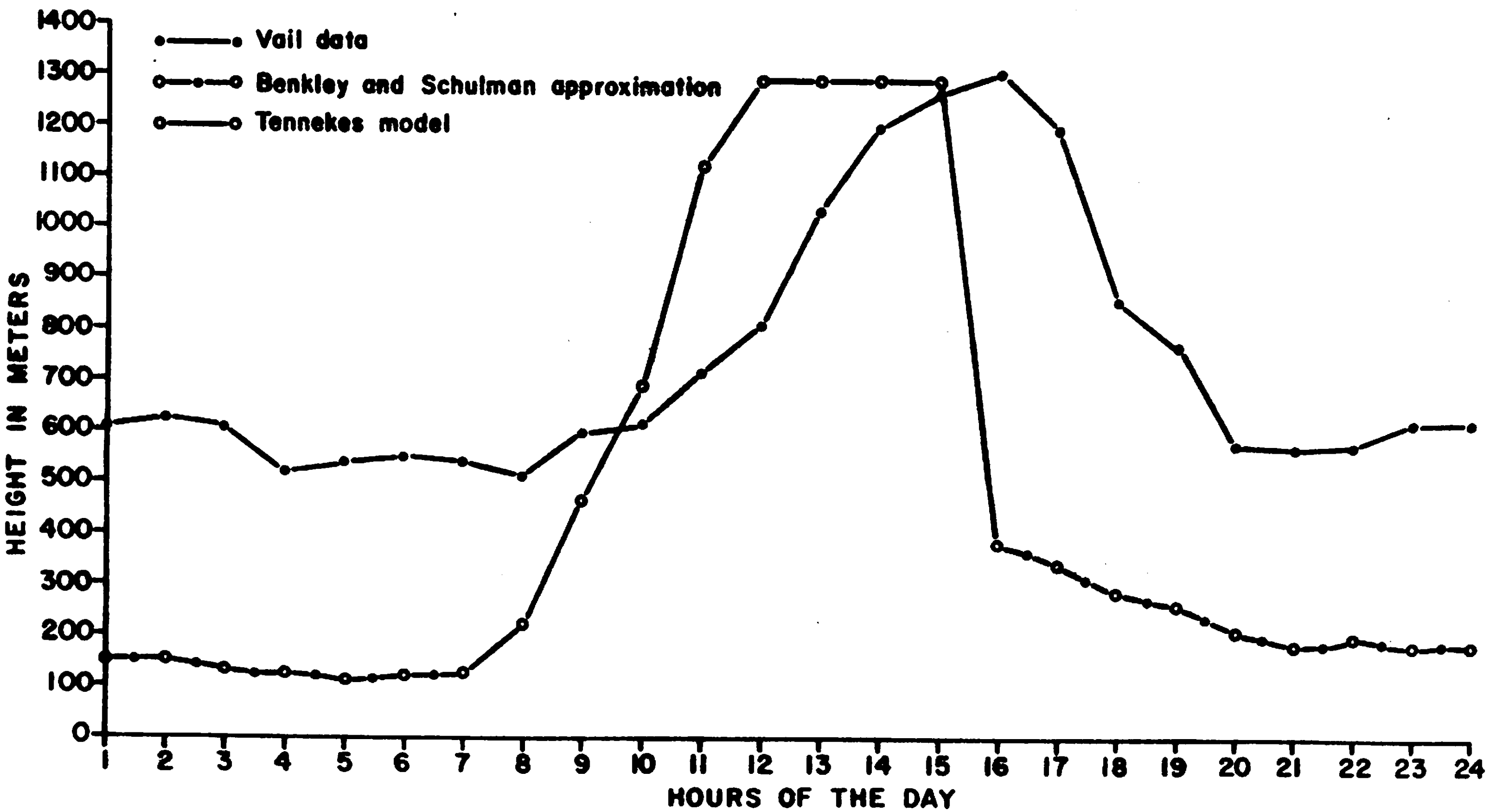


FIG. III-6. Data for inversion rise model verification for January.

relationships between mixing heights and meteorological parameters commonly observed at the surface. Rather more promising is the application of the inversion rise model of Tennekes. It appears that by refining the method of application and input data some useful results can be obtained for the estimation of mixing height in valleys on an operational basis.

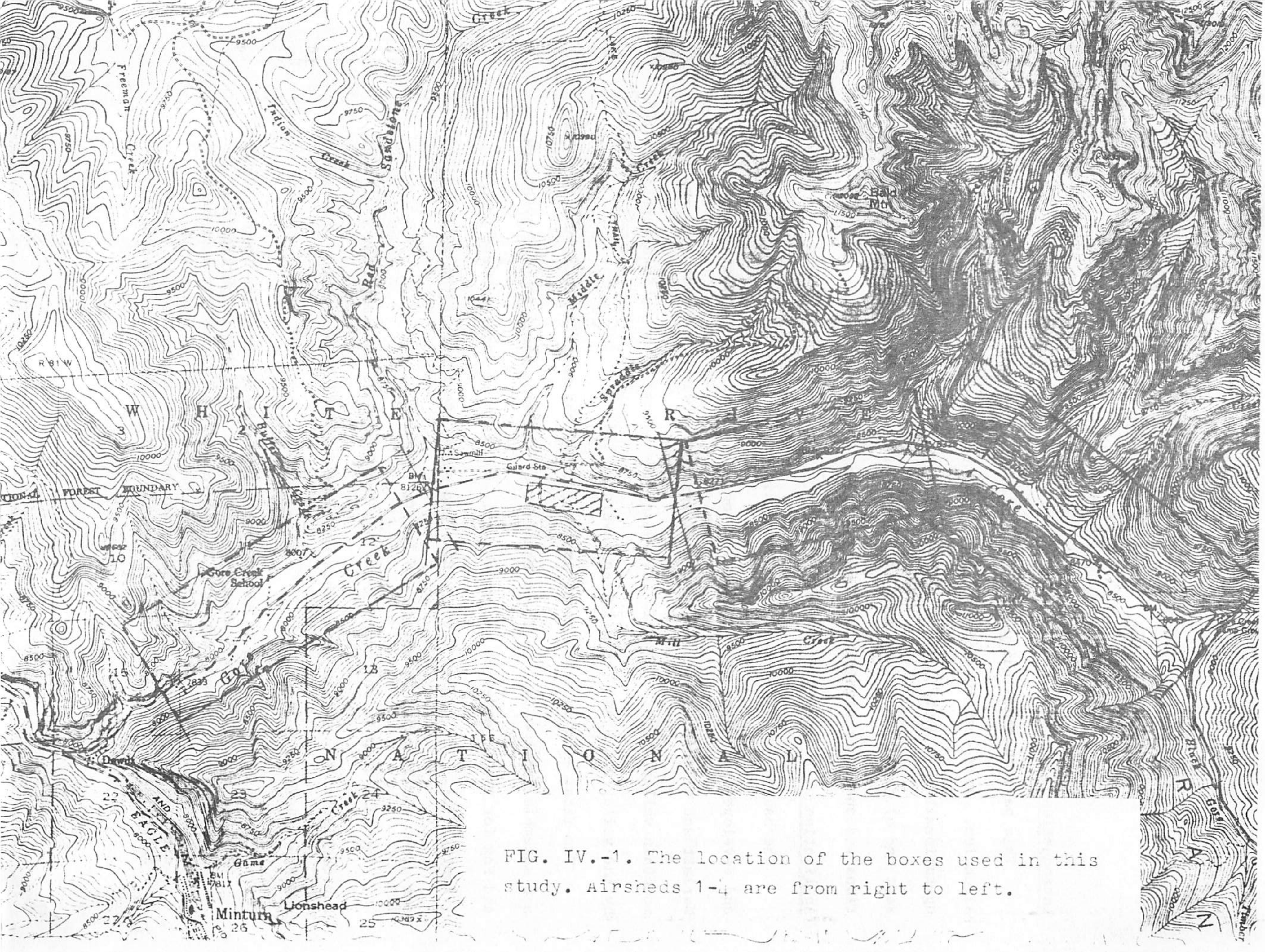


FIG. IV.-1. The location of the boxes used in this study. Airsheds 1-4 are from right to left.

PART IV. THE USE OF THE BOX MODEL IN MOUNTAIN AREAS

Introduction

This part examines the utility of the box model for use in a mountain valley situation. As a starting point the box model used by Howard and Fox (1978) is operationalized. Modifications are then made by a) using modeled mixing height data and b) tilting the inversion lid of the box. The effect of these modifications and one other significant phenomenon that appears are discussed.

Application of the Basic Box Model

The basic box model that is used in this study is that described in part II and developed by Howard and Fox (1978) from an earlier version compiled by Marlatt and Gelinas (1975). The main difference between an urban "box" and a mountain valley "box" is that in the valley the volume is prescribed more definitely by the valley sides and (usually) an inversion lid.

The first step in a practical application of the model is to define the boxes and assemble input data. In the present study the same boxes as used by Howard and Fox for the Gore Valley, in which Vail, Colorado is located, were used (Figure IV-1). The valley floor widths and slope gradients of the valley sides are given in the paper by Howard and Fox (1978).

The next step is to establish values for emissions for each hour of the day for each box. The way in which this was done for Vail is described by Howard and Fox (1968) as follows

> Emissions data used in this paper were developed from the Town of Vail Air Quality Emissions Inventory. Table 2 is a listing of particulate emissions in the four airsheds in the Vail area. Automobile emissions were apportioned on the basis of an annual daily traffic estimate with a diurnal distribution. Fireplace emissions were apportioned in time according to the following percentages: 0800-1200 (2%), 1200-1600 (1%),

1600-2000 (54%), and 2000-2400 (43%), based upon an extensive survey of uses (Romero 1977). Average fireplace use (Romero 1977) in terms of kilograms of wood per burn and hours per burn resulted in a determination that 54 days of burning per fireplace was an appropriate estimate. The fireplace emission factor applied was 21.2 gm/kg (PEDCo 1977), which was determined from a limited measurement program in the Vail area. This number is about twice as much as fireplace emission estimates made at sea level. No attempt was made to relate emission to occupancy rate in the hotels, although this is surely related. Restaurant emissions were apportioned on a diurnal basis according to information determined by usage (Murphy 1978). The cycle used was 0700-1100 (15%), 1100-1400 (35%), and 1600-1900 (50%).

It should be noted that considerable effort is needed to complete this part of the process.

Wind data were provided for Vail by the U.S. Forest Service. Wind speed and direction from a 10 m mast in the center of the third box (airshed) were reduced to the form of hourly mean wind speeds and a directional index describing simply up and down valley wind directions. Wind speeds in the other boxes are calculated using the principle of air mass continuity in which case the wind speeds in the other boxes u_j are given by

$$u_j = u_3 \quad \frac{w_3 + \frac{h}{2}(\cot \alpha_3 + \cot \beta_3)}{w_j + \frac{h}{2}(\cot \alpha_j + \cot \beta_j)} \qquad \text{------1.}$$

where w_j is the base width of the jth box cross section and α and β are the slope angles defined in Figure IV-2.

Mixing height (h) data were obtained from an accoustic sounder, and provided in an hourly average format. In the initial application of the box model when there was no mixing height indicated by the sounder the mixing height was set at 1000 m. Mixing height is a critical input to this model. Fox (1975) has shown, for example, that for a steep sided valley a factor of 2 change in mixing depth

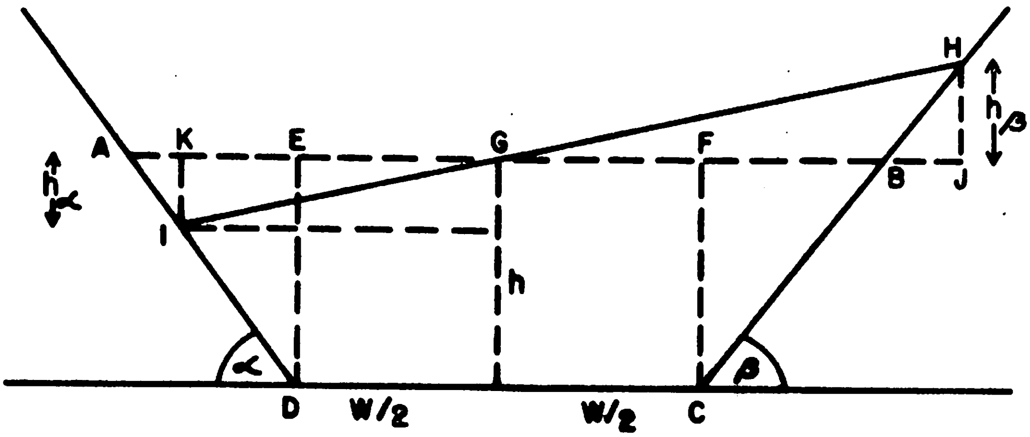


Figure IV-2. The geometry for the cross section of a box used in a box model.

leads to a factor of 4 change in mixing volume.

The box model used in this study uses a Eulerian finite differencing scheme and gives the mass of the pollutant (M_j) in a specified air volume (V_j) as

$$M_j^{n+2} = M_j^n + \Delta t \left\{ q_j^n + \left(uA\,\frac{M}{V}\right)_{j-1}^n - \left(uA\,\frac{M}{V}\right)_j^n \right\} \qquad \text{------2.}$$

where q is the emissions and Δt is the time step used. The basic time scale step taken is 1 hour but internal to each hour the main computation is performed in 5 min. time steps. Practically one computer program computes the hourly pollutant concentrations for each box and a second program computes daily averages and other statistics from these data. Both programs VAIL1 and NEWAVE are listed in appendix V. The first was kindly provided by Dr. D. G. Fox and the second was generously given by Mr. G. Korrell.

In summary, the input data needed are hourly emissions (grams/sec), hourly wind speed (miles per hour), hourly mixing heights (fifths of meters), the box base width and length (meters) and slope angles in degrees. Hourly pollutant concentrations are given which are summarized to daily averages by NEWAVE. The original form of the model assumes winds are only either directly up or down the valley, that the background pollutant concentration is zero, that input and output is only through endwalls, that mixing height is constant across the valley and that the "default" mixing height is 1000 m.

An example of the output of NEWAVE when the box model is used in the form described above is shown in Table IV-1. The model was run on data for the period Dec. 21, 1976 to Mar. 25, 1977. Four day running means of concentrations of Total Suspended Particulates (TSP) in airshed 3 are shown in Figure IV-3. These repeat

TABLE IV-1. Sample Output from the Program NEWAVE

VAIL BOX MODEL - TSP CONCENTRATIONS

DAY	BOX 1	BOX 2	BOX 3	BOX 4
15	66.0	114.4	125.4	85.2
16	13.2	32.1	51.9	50.1
17	2.9	4.7	7.3	7.5
18	26.7	57.0	95.9	95.2
19	61.1	75.2	87.1	62.6
20	65.0	65.1	59.6	33.2

VAIL BOX MODEL - TSP CONCENTRATIONS

	ARITHMETIC		GEOMETRIC	
	AVERAGE	ST.DEV.	AVERAGE	ST.DEV.
BOX 1	51.7	34.2	37.5	2.6
BOX 2	68.4	41.5	52.8	2.3
BOX 3	78.9	45.8	62.3	2.2
BOX 4	58.5	35.3	45.8	2.2

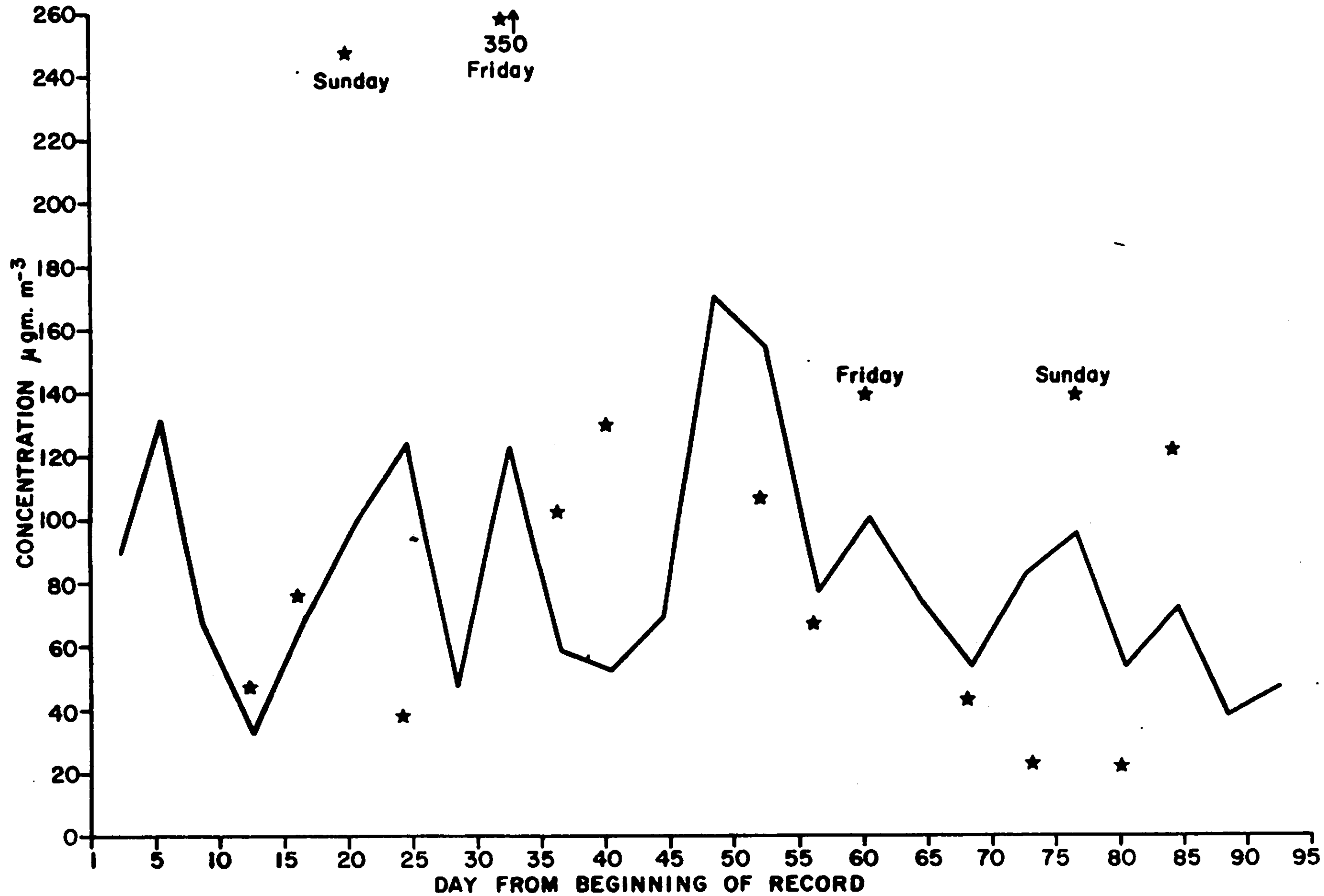


FIG. IV-3. Four-day average concentration of TSP from the original model and observations (*) from a high volume sampler.

the results already given by Howard and Fox (1978). Small differences occur because of a slightly different averaging procedure used in the present study. Figure IV-3 also shows the measured values of TSP obtained in airshed 3 by a high-volume sampler used every four days throughout the period with the exception of a few days with missing data. The results are discussed in the next section.

<u>The Basic Box Model with Modeled Mixing Heights and a Tilted Inversion Lid</u>

Several variations of the basic box model were made in order to find out more about its applicability. The variations included the use of synthetic mixing height data and a tilted inversion lid. A lag effect was also noted and briefly examined. The variation will be described, then all of the results will be considered together.

It is unlikely that in most cases data on mixing heights will be available. Thus it is interesting to see how the box model performs when mixing height data are themselves synthesized. As a first approximation an average diurnal change of mixing height was constructed based on the considerations in the last part of this study. The data period, by chance, was fairly suitable for the application of the inversion rise model from the point of view meeting the requirement of only slowly changing weather: 65 of the total of 94 days in the period were dominated by anticyclonic weather; 20 days occurred when the location was under cyclonic flow and only on 7 days did fronts actually pass over Vail. The inversion rise modeling system was applied to four subperiods: December 21-31, 1976, January 1-31, February 1-28, March 1-25 with $K{\downarrow}_n$ values for December 21, January 15, February 14, and March 21 being taken as representative of these periods. The atmospheric transmissivity was assumed to be 0.95. The model was worked with $(\overline{\Theta w})/K{\downarrow}$ ratios set at 0.25. Night mixing heights were approximated following the method of Benkley and Schulman (1979) mentioned previously.

One feature arising from the examination of mixing heights was that because solar heating is stronger on sunny slopes the inversion rise is likely to be faster in these locations. When E-W aligned valleys are considered the inversion lid may well be higher on the northern side of the valley than the southern side. The inversion base may be considered to be in the form of a flat plane in order to model this effect. In this case with reference to Figure IV-2 the cross section area of the valley becomes the original area ABCD minus the area of triangle AIG plus the area of triangle GBH. Assuming the h_β and h_α are the heights of the inversion base half way up the valley sides respectively above and below an inversion level that is itself half way across the valley floor, and other distances are as shown on Figure IV-2 then it can be shown that the new cross sectional area Δ is given by

$$\Delta = hw + \frac{1}{2}\left\{ h\left(\frac{h}{\tan\alpha} + \frac{h}{\tan\beta}\right) - \left(\frac{h_\alpha h}{\tan\alpha} + w\right) + \left(\frac{h_\beta h}{\tan\beta} + w\right)\right\} \qquad \text{------3.}$$

Equation 3 applies when the distance h_α is less than h. If h_α is greater than h as could happen when part of the valley floor is shaded then the geometry of Figure IV-4 is applied. In this case the valley cross section area will be the original area ABCD plus the area of triangle GBH minus the area of AGQD. The latter area is computed as the area of triangle ALG minus the sum of the area of triangle DNL and QNL. The new cross sectional area is then given by

$$\Delta = \frac{1}{2}\left\{ h_\alpha\left(\frac{w}{2} + \frac{h}{\tan\alpha}\right) - \frac{(h_\alpha - h)^2}{\tan\alpha} - (h_\alpha - h)\left(\frac{w}{2} - \frac{(h_\alpha - h)}{\tan\alpha}\right)\right\} \text{-----4.}$$

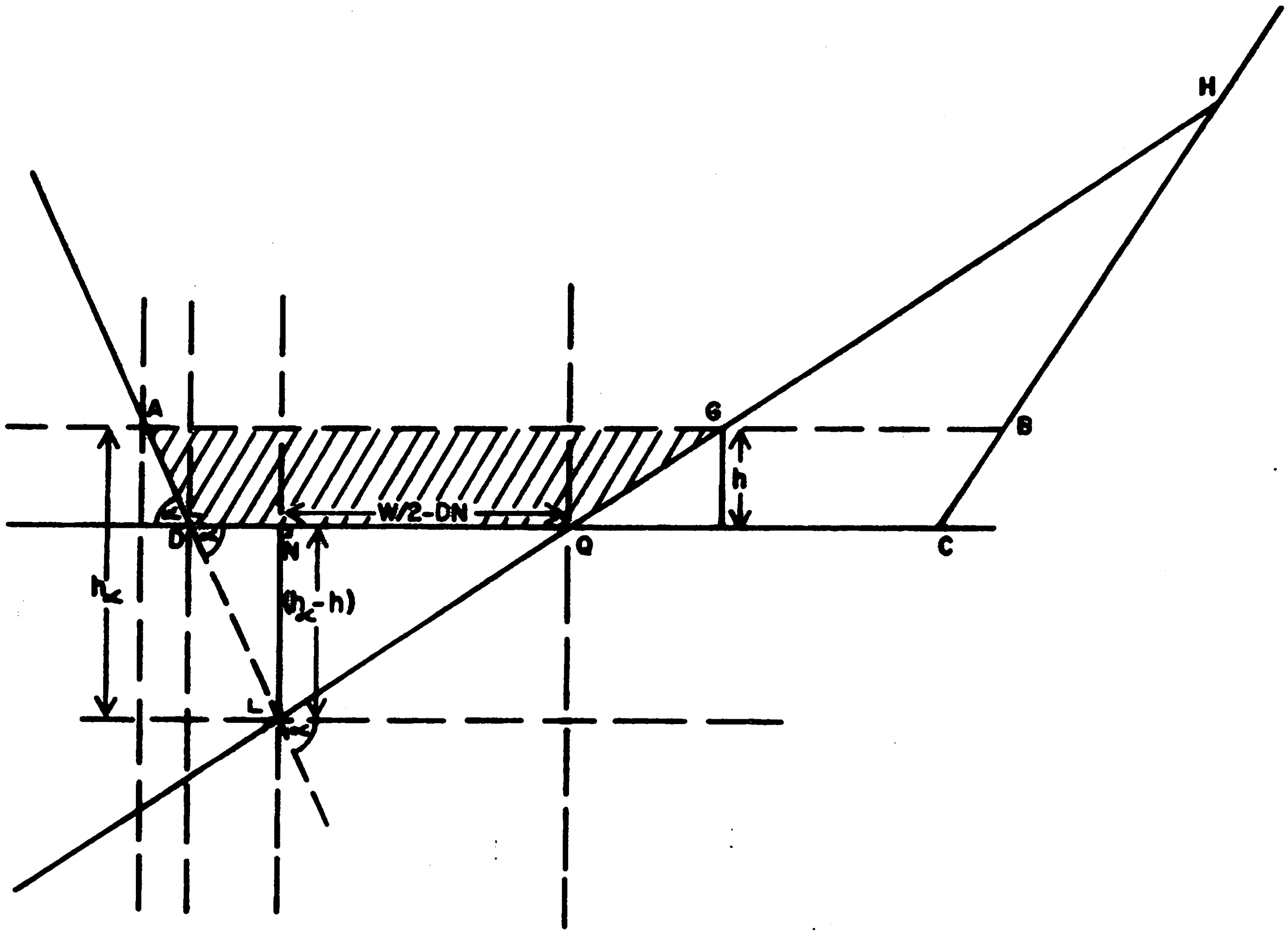


FIG. IV-4. The geometry of the box cross section for cases when $h_\alpha > h$.

Another possible variation most often due to the fact that the inversion rise is starting from a higher elevation owing to topography, is shown in Figure IV-5. In this case a new height h_γ, defined in the figure is introduced. The cross sectional area required to be added to the left hand side of the box is the area of SRG minus SRA. This additional area is given by

$$\frac{1}{2} h_\gamma \left\{ (h_\gamma + h/\tan\alpha) + (w/2) - h_\gamma^2/\tan\alpha \right\} \qquad \text{-----} \; 5.$$

The additions to the original program required to allow for the first two variations of a tilted inversion base are listed in Appendix V.

Howard and Fox (1978) found that closer agreement between model and observed results could be achieved if the four-day running means of the model results were taken. Thus for comparative reasons values of four-day running means were computed for the original version of the model results and five*-day running means were taken of the results of the variations to the original model.

One of the weakest assumptions in the derivation of mixing heights is that of the ratio of surface sensible heat flux to incoming solar radiation. It could be argued, for example, that if all slopes are snow covered all of the time, a value of 0.25 for this ratio is inappropriate. Indeed under such circumstances surface sensible heat flux is usually directed downwards and could not force inversion rise. In order to encompass this case one set of mixing height data was formed assuming only mechanical turbulence and employing the approximation of Benkeley and Schulman (1979). The box model was also used with these data.

*It was easier to apply five rather than four day running means since the day to which the mean applied was less equivocal.

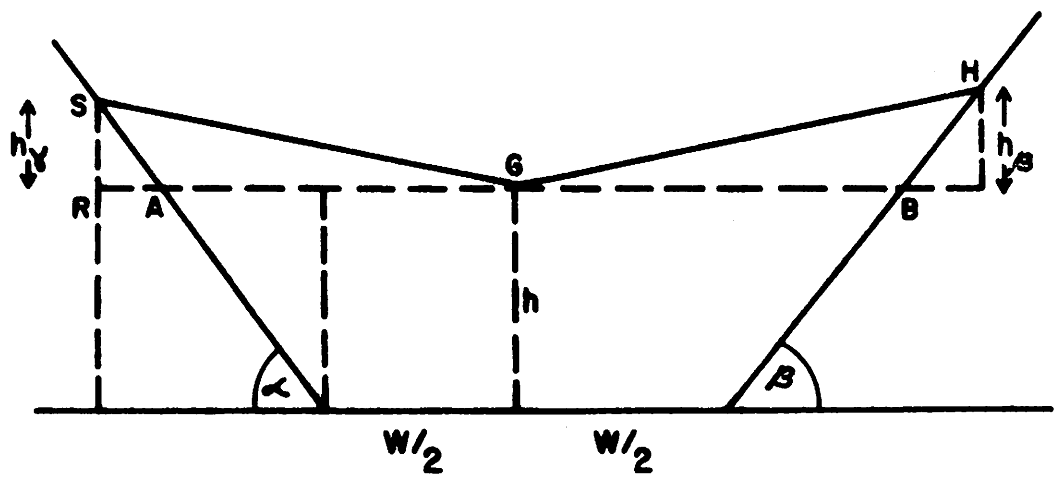


FIG. IV-5. The geometry of the box cross section for case when $h_\gamma > 0$.

A previous version of the mixing height synthesis which assumed modeled convectively forced mixing heights based on half-way through the total day period, a default mixing height of 1800 m and a night-time mixing height of 450 m was also used with the box model.

When the results of the above alterations were being compared to observed data it was noticed that better agreement could be reached between model and observed data if a lag of one day in the model results after the observed data values was considered. Thus all the models were also tested using their results for the day following the recorded observations.

Table IV-2 summarizes all the variations of the models that were tested against 16 daily averages of TSP from a high volume sampler operated during the period by the Colorado Air Pollution Control Division.

Discussion

The comparison of 4-day running mean values from the Howard and Fox model with observed values of TSP for individual days in Figure IV-3 is encouraging. Howard and Fox (1978) showed in their original publication that almost all the modeled points fall within limits given by modeled maximum and minimum 24-hour running average concentrations within the respective 12 hours around 0000-1200. The only major discrepancies between the model and the observations fall on week-end days. On weekends ski traffic is very high at Vail. Additionally many people light wood burning fires. Since all versions of the model use only average emission data it might be expected that these extreme cases would be underpredicted.

The results of the correlations of the various model versions (Table IV-2) show that on an actual day basis none of the schemes gives significant correlations between predictions and observation. There are presumably many reasons for this but judging by the higher correlations when lagged values are used, an important

TABLE IV-2. Correlations between observed data and results from various box modeling schemes.

	Correlation coefficient	Significance
Howard and Fox model with 1000 m default mixing heights and actual day values	0.23	0.1918
Howard and Fox model with 1000 m default mixing heights and 4 day running mean values	0.46	0.0368
Howard and Fox model with 1000 m default mixing heights and 1 day lagged values	0.77	0.0002
Howard and Fox model with 1000 m default mixing heights and 2 day lagged values	0.41	0.0565
Howard and Fox model with 1000 m default mixing heights and 3 day lagged values	0.37	0.0802
Box model convection and mechanical modeled mixing heights with horizontal lid and actual day values	0.29	0.1417
Box model convection and mechanical modeled mixing heights with horizontal lid and 1 day lagged values	0.50	0.0252
Box model convection and mechanical modeled mixing heights with tilted lid and actual day values	0.27	0.1559
Box model convection and mechanical modeled mixing heights with tilted lid and 1 day lagged values	0.45	0.4230
Box model mechanical modeled mixing heights only with horizontal lid and actual day values	0.26	0.1612
Box model mechanical modeled mixing heights only with horizontal lid and 1 day lagged values	0.51	0.0210
Box model convective modeled mixing heights by day, assumed by night with horizontal lid and actual day values*	0.29	0.1358
Box model convective modeled mixing heights by day, assumed by night with horizontal lid and 1 day lagged values*	0.54	0.0154
Box model convective modeled mixing heights by day, assumed by night with tilted lid and actual day values*	0.23	0.1942
Box model convective modeled mixing heights by day, assumed by night with tilted lid and 1 day lagged values*	0.53	0.0177
Howard and Fox model with tilted lid and 1 day lagged values*	0.78	0.0002

*These applications assume modeled mixing heights based on half-way through total data period, a default mixing height of 1800 m and a night-time mixing height of 450 m.

reason must be the memory of the box model. This memory is demonstrated well by the correlations shown by the original Howard and Fox model when applied to actual day predicted values and 1, 2 and 3 day lagged predicted values. High correlation significant at the 95% level is found with the 1 day lag and then there is a decrease in correlation with increasing lag.

Tennekes (1976) was first to point out the memory of the box model. He called it a 'fading memory' and suggested two processes which might be at work. One is the possible entrainment of polluted (or non-polluted) air from above that has been left over from the day before. This then becomes an additional source of air daily. The other process occurs when the mean daily wind speed multiplied by 24 hours is less than twice the box length and internal storage effects come into play. In the present study available data for the period investigated show that this latter factor does not apply for the monthly mean although it might apply to certain times within the data period. A clear explanation of the box model memory has been given by Venkatram (1978) in analytical terms. He shows that the solution of the basic box model equation (Part II, equation 2) has a solution of the form:

$$\chi h = (\chi h)_o \exp(-t/T_f) + QT_f (1 - \exp(-t/T_f)) \qquad \text{----- 6.}$$

Here T_f is the flushing time of the box, i.e., box length/mean wind speed. Examination of this equation shows that even if Q is zero (i.e., emission sources are shut down) then the concentration does not become immediately zero but decays exponentially. After time T_f the concentration is still only reduced to 37% of its initial value. Thus the "model has a great deal of inertia." The most simple way of dealing with this is by taking the lagged values as in this study. Venkatram (1978) has suggested another approach but more work is required to make this approach applicable to the multiple box model situation. Bearing all of the above in mind the succeeding discussion will refer to the 1 day lagged predicted values.

Modeling the box volume with a horizontal or tilted lid appears to make little difference in the present instance. Where direct comparisons can be made there is a decrease in the correlation coefficient of 0.01 between the horizontal and tilted lid cases respectively. Only with the use of the original Howard and Fox model is there an increase, also of 0.01, but since a different default mixing height was used in both applications the higher correlation coefficient of 0.78 with the tilted lid model cannot be definitely attributed to the tilt itself. There is little work available to help resolve this problem. The data of Russell and Uthe (1978a, 1978b) tentatively suggest a concave downwards inversion lid for the wide Santa Clara valley, California. Observations in a similar size valley, the Gunnison valley in Colorado, have suggested a concave upwards shape to the lid (Marlatt, 1979, pers. comm.). It is suggested that further theoretical studies on this point be postponed until more observational data are available, and that until that time a horizontal lid should be assumed.

Since there will never be enough mixing height data for points from the valley the use of modeled mixing height data is particularly important. Table IV-2 shows that all of the applications of the box model with synthesized mixing heights were successful with correlation coefficients ranging from 0.50 to 0.54 all significant at at least the 97% confidence level. The small range of these coefficients suggests that it is difficult to choose between the various mixing height modeling schemes attempted here. However, the highest coefficient is found where the convective (Tennekes) modeling system is used by day and a 450 m height is assumed by night. This in turn gives tentative evidence to suggest that the Benkley and Schulman, mechanical turbulence forced mixing height method, is giving underestimates of the mixing height both by night and by day. Another way of interpreting this suggestion is to say that instead of the mixing height being underestimated the dispersal rate is being underestimated, which as seen earlier, is not uncommon in complex terrain. It might be possible therefore in the future to adjust the Benkley and Schulman approximation in a way analogous to the adjustment of Gaussian dispersal coefficients for complex terrain. Overall, however, the use of modeled mixing height data is very promising, as long as the box model is being used for planning, as opposed to day to day prediction, purposes.

Conclusions

It is seen that the box model can be applied very usefully to the individual valley situation. This is especially so when the memory characteristic of the box model is taken into account. The model can give 'postdictions' of pollutant concentrations which are accurate enough for use in overall air quality planning. The alteration of the box model for use with a tilted lid does not give significantly more accurate results, and further investigation of this point will have to await the availability of more observational data. Most importantly it does seem feasible to use the box model with modeled mixing height data. Since little real mixing height data are available for mountain valleys this finding is of considerable value.

PART V. AIR POLLUTION POTENTIAL AND THE LAND USE MANAGER

On Friday, February 9th, 1979, the director of planning for Crested Butte, Colorado called a meeting of various persons in the state who were interested in air quality. Faced with a problem of population increase due to recreational development of the town at a rate of 20% per year and the possibility of massive mining operations the planning authorities were rightly worried about future air quality of the area. They were however confused about the steps to take to forestall the problem.

Crested Butte, like many other western resort areas, needs an air quality maintenance plan which, because of the town's limited financial resources, needs to be produced with the minimum of expense. The steps for the development of such a plan were outlined at the beginning of part II of this study. The two most important steps, apart from plan implementation, are a) the development of an adequate emissions inventory and its future projection and b) the selection and application of an adequate atmospheric dispersal model.

The value of the present research to the land manager or planner is essentially three fold:

1) It is made clear that an adequate simple atmospheric dispersal model--the box model--is available for use as a planning tool.

2) Further it is demonstrated that mixing heights which are expensive to observe can be modeled to a degree of accuracy necessary for the box model.

3) If the manager wants to delve deeper into the problems of atmospheric dispersal modeling, the review of part II will be available.

Some comments on these points are in order. It was mentioned earlier that there has been a traditional lack of rapport between the meteorologist and the planner. To the extent that this is due to the barriers of complexity of technology the box model will overcome the difficulty. The essential concept of the box model as a mass of air with inputs and outputs is easy to grasp. It is only subject to mishandling in two areas; the use of an invalid emissions inventory and the lack of clear definition of the lid. The latter problem will have to be treated by a meteorologist but by refining the methods outlined in the present study, it should not present too much difficulty. With regard to the third point above, it is likely that the planner will be besieged by a variety of agencies and organizations each with varying points of view on atmospheric dispersal models. The review of part II should help to sort out the planner's priorities in this instance, bearing in mind that the more complex the model the more costly it is likely to be to apply.

In an even more practical vein, what are the actual steps planners should take when they find themselves in the situation of those of Crested Butte? The most important step in anticipation of the development of an air quality maintenance plan is to commence data collection as soon as possible. The essential data are those on emissions and wind speed. If funds are available data on mixing heights would be of help in the modeling procedure. The units in which all these are collected are not critical but time will be saved if the model input units listed in the last part are used.

Wind speed and direction are probably easiest to obtain. There are many commercial brands of instruments to measure these. Guidance can be obtained by looking at the advertisements in the Bulletin of the American Meteorological Society. A ten meter mast should also be obtained for mounting the instruments.

The location of the mast should be as close as possible to the center of the most important box--if several boxes are used. Adequate funds should be set aside for data reduction and maintenance. It is a common mistake to purchase instruments and not insure a program of continued operations and data processing. As much data as possible are ideal but two year's data would probably be enough to give a satisfactory picture of the local wind climatology for air quality modeling purposes.

The data most difficult to obtain are those for emissions. The planner should be prepared to employ an environmental consultant firm or graduate student(s) to work on compiling an adequate emissions inventory. There are several standard EPA documents of help in this procedure. Some were quoted earlier. However not much is known about emissions factors at high altitudes. Consequently whosoever is compiling the inventory should make personal contact with the EPA and other experts to ensure that the most up to date information on techniques is available. Another helpful strategy for the planner is to review the major pollutant sources and present local ordinances and make sure, that if it is not already mandatory, to have legislation enacted requiring the reporting of all new potential pollutant sources such as fire places or new types of grills or air filtering techniques in restaurants. A list of major pollutants can be found in Marlatt and Gelinas (1975) or the inventories for Aspen (1977) and Vail (1978). By far the greatest proportion of the planners budget should be given to the compilation of a satisfactory emissions inventory and to obtaining information allowing the projection of the inventory into the future.

In the best of all possible worlds mixing height data would be obtained by accoustic sounders for low altitude, lidar ("lasar beam radar") for high altitudes backed up by instrumented balloons, both tethered and untethered and possibly aircraft and helicopter data gathering systems. In the real world the planner should try to organize obtaining as much mixing height data as possible. The more that is available for a particular location the more accurate the mixing height modeling procedure will be.

When the time comes for performing the modeling a computer facility is needed. The model runs can be made by private companies, or some universities. In some cases , the state air pollution control division will handle the mechanics of this. Little or moderate cost should be involved at this stage.

Another aspect that should be on the mind of the planner is to obtain air quality sampling data to which the initial runs of the models can be compared. Several agencies, federal and state government, have mobile equipment for taking and analyzing air quality samples. The use of these facilities would probably be just adequate. However, if there is some extra source of funds the local planning authority would be well advised to investigate the purchase of sampling equipment--at least for total suspended particulates and carbon monoxide.

Almost all of the above are necessary steps towards the eventual development of an air quality maintenance plan. In some ways they represent the rather crude state of the art at the present time. Very little is known, for example, concerning atmospheric chemistry or deposition at the high altitudes where most resorts are found.

The initial reaction of planners when informed of all the stages outlined above is that the whole process is more involved and more expensive than anticipated.

There are three factors to be considered when confronted with this view. First the case of a small resort settlement is infinitely simpler than the case of a large metropolitan area. Second, it is not necessary to complete all the stages simultaneously. No modeling can be done without data. Similarly it is not necessary to fund the complete program from any one source or in any one year. Aspen and Vail are fine examples of what can be done toward establishing air quality maintenance plans over several years. Third, since federal and state law require attention be given to air quality and since instrumentation, private, state and university aid are all subject to the same laws of cost inflation it would be wise to initiate planning for air quality as soon as possible. Otherwise a vital component of the attraction of mountain resorts--the atmosphere--will be ruined.

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APPENDIX I

Sample Output from the Holzworth Rawinsonde Statistic Summaries

DENVER

STATION 23062 TIME 12 SEASON 12-02 PER CENT TEMPERATURE FREQUENCY OF OCCURRENCE 1

DELTA HEIGHT		SURFACE	1- 100	101- 250	251- 500	501- 750	751-1000	1001-1500	1501-2000	2001-2500	2501-3000	TOTAL	NONE	GRAND TOT	MISSING
		BASE OF INVERSION													
1- 100	A	.2			.2				.2			.7			
	B	.2										.2			
	C	2.0								.2		2.2			
	D	2.7			.2	.2						3.1			
	E	2.0										2.0			
101- 250	A	1.5	.2					.4		.2		2.4			
	B	2.2		.2		.2	.4	.4		.2		3.8			
	C	8.6 } 34.0		.2		.2						9.1			
	D	16.4										16.4			
	E	5.3			.2							5.5			
251- 500	A	.9		.7	.7				.7	.2		3.1			
	B	.9			.2			.2	.4			1.8			
	C	13.9 } 27.4		.4	.2			.2				14.8			
	D	10.6		.2	.4	.2		.4				11.9			
	E	1.1										1.1			
501- 750	A	.2							.2		.4	.9			
	B	2.2		.4	.2							2.9			
	C	4.0					.4					4.4			
	D	.9										.9			
	E														
751-1000	A	.4			.2							.7			
	B	.9			.2	.4	.2					1.8			
	C	.9	.2	.2		.2						1.5			
	D														
	E														
1001-1500	A	.2		.2	.4		.2					1.1			
	B	.4					.2					.7			
	C	.4										.4			
	D														
	E														
>1500	A	.2										.2			
	B	.2										.2			
	C														
	D														
	E														
TOTAL		79.6	.4	2.7	3.3	1.5	1.5	1.8	1.5	.9	.4	93.8			
SFC-BASE OF INVER	A			.2	.4			.2	.4			1.3			
	B		.2	1.1	1.5	1.1	1.5	1.5	1.1	.9	.4	9.5			
	C			.9	1.1	.4						2.4			
	D			.2	.2							.4			
	E		.2	.2								.4			
NONE	A		1.3	1.3	.9	.9	.4								
	B		3.8	4.0	4.9	4.2	4.6	4.9							
	C		.7	.9	.4	1.1	1.1	1.3							
	D														
	E		.4										6.2		
GRAND TOTAL														100.0	
MISSING															

DELTA T/H INVERSION LAYER
A 0.0000 - 0.0047 C/M D 0.0263 - 0.0600
B 0.0048 - 0.0114 C/M E > 0.0600
C 0.0115 - 0.0262 C/M

DELTA T/H NO INVERSION
A <0.0000 TO -0.0040 D -0.0121 TO -0.0160
B -0.0041 TO -0.0080 E < -0.0160
C -0.0081 TO -0.0120

Appendix II

A Variation of Ludwig's Method of Estimating the Diurnal Change of Mixing Height.

The method may be resolved into five stages.

1). The early morning sounding data are plotted onto a psuedo-adiabatic chart.

2). The maximum mixing height for the day h_{max} is taken as the intersection of the dry adiabat from the maximum daily surface temperature with the morning sounding.

Computation of height is made in pressure units and changed to meters using the hydrostatic equation in the form

$$h = 8.129 (T + T_s + 913.3) \, l_n \left\{ \frac{Ps}{Ps - \Delta P} \right\}$$

where T is temperature at level h, Ts is the surface temperature both in ^{o}F Ps is surface pressure and P is the pressure difference between the surface and level h, both pressures being taken in mb.

3). The minimum mixing height h_{min} is taken as that shown by the early morning sounding and h_{min} is taken as constant throughout night-time hours.

4). The mixing height (h_t) at any time in the morning before h_{max} occurs is given by an interpolation based on surface temperature as follows:

$$h_t = \left\{ \frac{Tt - Tmin}{Tmax - Tmin} \right\} (h_{max} - h_{min}) + h_{min}$$

5). The mixing height at any time after h_{max} occurs is taken by linear interpolation between h_{max} and the next h_{min}.

Appendix III: Results of Regression Analysis Between Inversion Parameters and Surface Meteorological Observations.

Key to variables: INBASE=Inversion base; INTOP=Inversion top; INTHIK=Inversion thickness; INTENS=Inversion intensity; COV=cloud cover; HT=cloud height; DIR=Direction; SP=wind speed; WB, DB=Wet and dry bulb temperature; DP=Dew point depression; PRESS=Atmospheric pressure; DEN=Denver; GJ=Grand Junction.

Depend Var.	Place	In Type	AM/PM	Season	R^2	Order of Variables entered	Cases	Sig.
INBASE	GJ	GB	AM	Winter	.041	COV DP SP DIR PRESS	60	.801
"	"	EL	"	"			1	
"	"	GB	"	Summer	.091	WB PRESS SP DIR COV HT	88	.241
"	"	EL	"	"			3	
"	"	GB	PM	Winter	.238	PRESS DIR COV EB DB SP HT	56	.057
"	"	EL	"	"	.352	COV WB DIR DP HT PRESS SP	34	.091
"	"	GB	"	Summer	.339	HT COV SP PRESS DP DB	32	.084
"	"	EL	"	"	.701	DP HT DIR DB SP PRESS COV	19	.027
INBASE	DEN	GB	AM	Winter	.337	HT WB SP DIR COV	57	.001
"	"	EL	"	"	.414	WB HT PRESS DP COV SP	11	.805
"	"	GB	"	Summer	.311	HT SP COV WB DIR PRESS	89	.000
"	"	EL	"	"	.852	COV DB HT DP PRESS SP	12	.053
"	"	GB	PM	Winter	.169	SP DIR WB COV DP HT PRESS	41	.478
"	"	EL	"	"	.329	SP DIR DP PRESS HT COV DB	26	.324
"	"	GB	"	Summer	.312	SP DP DIR HT COV PRESS	21	.432
"	"	EL	"	"	.158	SP HT PRESS DP COV WB	15	.946
INTOP	GJ	GB	AM	Winter	.097	HT COV DP DB PRESS SP	60	.468
"	"	GB	"	Summer	.063	DP SP DIR COV PRESS HT DB	88	.616
"	"	GB	PM	Winter	.255	PRESS HT DIR SP WB COV DB	56	.028
"	"	EL	"	"	.440	COV WB DIR HT DB SP	34	.010
"	"	GB	"	Summer	.338	PRESS COV HT SP DP DB	32	
"	"	EL	"	"	.689	DP HT DIR DB PRESS SP COV	19	.032
INTOP	DEN	GB	AM	Winter	.407	HT PRESS SP DP DIR COV	57	.000
"	"	EL	"	"	.464	HT BD PRESS DIR WB SP COV	11	.874
"	"	GB	"	Summer	.276	HT SP DP DIR COV PRESS WB	89	.000
"	"	EL	"	"	.846	COV DB HT WB PRESS DIR	12	.058
"	"	GB	PM	Winter	.165	SP DB DIR WB HT COV PRESS	41	.495
"	"	EL	"	"	.262	SP DIR PRESS HT DB WD COV	26	.519
"	"	GB	"	Summer	.3.9	SP DP DIR HT COV PRESS	21	.414
"	"	EL	"	"	.154	SP HT PRESS DP COV WB	15	.949
INTHIK	GJ	GB	AM	Winter	.097	HT COV DP DB PRESS SP	60	.466
"	"	GB	"	Summer			3	
"	"	GB	PM	Winter	.214	HT COV SP PRESS DIR DB	56	.056
"	"	EL	"	"	.180	HT DIR COV PRESS DB	34	.321
"	"	GB	"	Summer	.600	PRESS DIR SP DB COV DP HT	19	.553

epend Var.	Place	In Type	AM/PM	Season	R^2	Order of Variables entered	Cases	Sig.
:NTHIK	DEN	GB	AM	Winter	.235	WB HT DIR SP PRESS COV DP	57	.056
"	"	EL	"	"	.405	WB DP PRESS DIR COV HT SP	11	.918
"	"	GB	"	Summer	.095	COV DP DIR DB HT PRESS	89	.213
"	"	EL	"	"	.870	PRESS DB SP DIR WB HT COV	12	.106
"	"	GB	PM	Winter	.346	DR DP COV SP DIR HT PRESS	41	.036
"	"	EL	"	"	.415	DB DIR WB COV SP PRESS	26	.083
"	"	GB	"	Summer	.430	DB HT PRESS DIR SP COV WB	21	.285
"	"	EL	"	"	.457	HT DB SP PRESS COV DIR	15	.428
INTENS	GJ	GB	AM	Winter	.092	COV WB DIR DB SP HT PRESS	60	.631
"	"	GB	"	Summer	.		3	
"	"	GB	PM	Winter	.085	HT SP DIR DP COV PRESS DB	56	.724
"	"	EL	"	"	.058	DP HT SP COV WB PRESS	34	.944
"	"	GB	"	Summer	.377	HT DP COV PRESS SP DIR DB	19	.599
INTENS	DEN	GB	AM	Winter	.311	DP HT COV PRESS DIR SP	57	.004
"	"	EL	"	"	.875	DIR DP HT PRESS SP COV DB	11	.198
"	"	GB	"	Summer	.401	DP HT WB PRESS COV DIR	89	.022
"	"	EL	"	"	.740	DP PRESS SP DIR COV HT	12	.180
"	"	GB	PM	Winter	.242	WB PRESS COV SP DB DIR	41	.127
"	"	EL	"	"	.217	DIR PRESS DP COV SP	26	.531
"	"	GB	"	Summer	.284	DB DP DIR COV HT SP PRESS	21	.645
"	"	EL	"	"	.614	SP DB COV DIR DP PRESS HT	15	.278

Appendix IV - Method for Computing Incoming Potential Direct Solar Radiation at noon on slopes.

This method follows Garnier and Ohmura (1968).

Potential direct shortwave radiation ($K\downarrow$) on any slope is given by

$$K\downarrow = G^{Q1} \times QT \times SOL$$

where G is the atmospheric transmissivity

$$Q1 = 1/(\cos\delta \cos\phi \cos H + \sin\delta \sin\phi) \text{ and must } \neq 0$$

$$QT = -\sin B \sin A \sin H \cos\delta + (-\cos A \sin B \sin\phi + \cos B \cos\phi)\cos\delta$$

δ is solar declination, ϕ is latitude of site

H is hour angle which is 0 for noon time computation, A is the slope azimuth and B is the slope gradient, SOL is the solar constant.

At solar noon since $H = 0$

$$Q1 = 1/(\cos\delta \cos\phi + \sin\delta \sin\phi)$$

$$QT = (-\cos A \sin B \sin\phi + \cos B \cos\phi)\cos\delta$$

Q1 has to be altered to express the optical air mass by means of the secant approximation. This may be done graphically but at solar noon the alteration is minimal.

The use of a programmable desk calculator in the present application made the computation simple.

Appendix V. The Programs VAIL1, NEWAVE, and the alterations required for using VAIL1 with a tilted lid.

```
UNIVERSITY OF MINNESOTA FORTRAN COMPILER (VERSION 5.4 - 79/03/01) ON THE 6400 UNDER KRONOS 2.1.0 ON 79/05/17 AT 15.33
UNIVERSITY COMPUTING CENTER - UNIVERSITY OF COLORADO

            MNF.

000000B          PROGRAM VAIL1(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,TAPE1,TAPE2,
                .TAPE3,TAPE4)
012411B          REAL M
012411B          INTEGER DIR
012411B          DIMENSION Q(4,24),TH1(4),TH2(4),BL(4),BW(4),M(4,2),CHI(4)
012411B          DIMENSION U(24),H(24),DIR(24),QT(4),AT(4),VT(4)
012411B          DIMENSION UT(4)
012411B          DATA TH1/32.,29.,14.,19./
012411B          DATA TH2/22.,25.,18.,22./
012411B          DATA BL/3000.,2*3700.,4300./
012411B          DATA BW/2*500.,2*600./
012411B          PI = 3.1415926536
012735B          IHR = 0
012736B          IDAY=0
012737B          DO 1 I=1,4
012741B          TH1(I) = TH1(I) * PI / 180.
012743B          TH2(I) = TH2(I) * PI / 180.
012744B          CHI(I) = 0.
012744B        1 M(I,1) = 0.
012747B          DO 2 I=1,4
012750B        2 READ(5,500)(Q(I,N),N=1,24)
012765B        9 CONTINUE
012766B          IHR = IHR + 1
012767B          IF(IHR .EQ. 25) IHR = 1
012772B          IF(IHR .NE. 1) GO TO 3
012773B          READ(4,400)(U(N),N=1,24)
013003B          IF(EOF(4).NE.0.)STOP44
013010B          READ(3,300)(H(N),N=1,24)
013017B          IF(EOF(3).NE.0.)STOP33
013024B          IDAY=IDAY+1
013025B          READ(2,200)(DIR(N),N=1,24)
013035B          IF(EOF(2).NE.0.)GO TO 20
013040B          DO 4 N=1,24
013042B          U(N) = U(N) * 1609. / 3600.
013044B        4 H(N) = H(N) * 5.
013047B        3 CONTINUE
013047B          DO 5 J=1,4
013050B          QT(J) = Q(J,IHR) * 1.E6
013052B          HT = H(IHR)
013053B          IF(HT .EQ. 0.) HT =1000.
013060B          AT(J) = BW(J) * HT + 0.5 * (HT*HT/TAN(TH1(J)) + HT*HT/TAN(TH2(J)))
013075B        5 VT(J) = AT(J) * BL(J)
013103B          UT(3) = U(IHR)
013104B          CON = UT(3) * AT(3)
013106B          UT(1) = CON / AT(1)
013107B          UT(2) = CON / AT(2)
013111B          UT(4) = CON / AT(4)
013112B          DT = 300.
013114B          DO 7 N=1,12
013116B          J = 1
013116B          IF(DIR(IHR).EQ.0) J = 4
013123B          M(J,2) = M(J,1) + DT * (QT(J) - UT(J)*AT(J)* M(J,1))/VT(J))
013131B          DO 6 JNDX = 2,4
013133B          J = JNDX
013133B          IF(DIR(IHR) .EQ. 0) J = 4 - JNDX + 1
```

```
 55.   013140B          JM = J - 1
 56.   013141B          IF(DIR(IHR).EQ.0) JM = J + 1
 57.   013144B          M(J,2) = M(J,1) + DT * (QT(J) + UT(JM)*AT(JM)* M(JM,1)/VT(JM)  -
                     .      UT(J) * AT(J) *  M(J,1)/VT(J))
 58.   013156B        6 CONTINUE
 59.   013161B        7 CONTINUE
 60.   013164B          DO 8 J=1,4
 61.   013166B          CHI(J) = M(J,2)/VT(J)
 62.   013167B          WRITE(1,100)CHI(J)
 63.   013176B        8 M(J,1) = M(J,2)
 64.   013202B          GO TO 9
 65.   013202B       20 WRITE(6,600) IDAY
 66.   013207B      600 FORMAT(10X,*DAY NO*,I6)
 67.   013207B      100 FORMAT(E12.4)
 68.   013207B      500 FORMAT(12F6.0)
 69.   013207B      400 FORMAT(4X,24F2.0)
 70.   013207B      300 FORMAT(6X,24F3.0)
 71.   013207B      200 FORMAT(24I1)
 72.   013207B          END
ALTERATIONS FOR TILTED LID.
  7.   012411B          DIMENSION HALPHA(4),HBETA(4)
  8.   012411B          DIMENSION GHJ(4),BHJ(4),GBH(4),GKI(4),AKI(4),AGI(4)
  9.   012411B          DIMENSION AGQD(4)
 10.   012411B          DIMENSION AGL(4),DNL(4),QNL(4)
 11.   012411B          REAL QNL

                  C     ADD IN VALUES OF HBETA AND HALPHA
 16.   012411B          DATA HALPHA/532.9,589.3,237.5,343.3/
 17.   012411B          DATA HBETA/124.1,220.4,182.2,135.2/

                  C     TO ALTER CROSS SECTION AREA
                  C         RIGHT HAND BOX GBH
 48.   013155B          GHJ(J)=0.5*HBETA(J)*(0.5*BW(J)+(HT/TAN(TH2(J)))+(HBETA(J)/TAN(TH2(
                       1J))))
 49.   013171B          BHJ(J)=0.5*HBETA(J)*(HBETA(J)/TAN(TH2(J)))



 50.   013200B          GBH(J)=GHJ(J)-BHJ(J)
                  C         LEFT HAND BOX AGI
                  C     FOR HALPHA LT HT
 51.   013201B          IF(HALPHA(J).GE.HT) GO TO 21
 52.   013204B          GKI(J)=0.5*HALPHA(J)*(((HT-HALPHA(J))/TAN(TH1(J)))+(BW(J)*0.5))
 53.   013217B          AKI(J)=0.5*HALPHA(J)*(HALPHA(J)/TAN(TH1(J)))
 54.   013226B          AGI(J)=GKI(J)+AKI(J)
 55.   013227B          AT(J)=AT(J)+GBH(J)-AGI(J)
 56.   013232B          GO TO 22
                  C     FOR HALPHA GT HT
 57.   013233B       21 AGL(J)=0.5*HALPHA(J)*((BW(J)/2.0)+(HT/TAN(TH1(J))))
 58.   013245B          DNL(J)=0.5*(HALPHA(J)-HT)*((HALPHA(J)-HT)/TAN(TH1(J)))
 59.   013255B          QNL(J)=0.5*(HALPHA(J)-HT)*((BW(J)/2.0)-((HALPHA(J)-HT)/TAN(TH1(J))
                       1))
 60.   013271B          AGQD(J)=AGL(J)-(DNL(J)+QNL(J))
 61.   013275B          AT(J)=AT(J)+GBH(J)-AGQD(J)
 62.   013300B       22 CONTINUE
```

UNIVERSITY OF MINNESOTA FORTRAN COMPILER (VERSION 5.4 - 79/C3/01) ON THE 6400 UNDER KRONOS 2.1.0 ON 79/05/17 AT 16.36
UNIVERSITY COMPUTING CENTER - UNIVERSITY OF COLORADO

MNF.

```
000000B       PROGRAM NEWAVE (OUTPUT,TAPE6=OUTPUT,TAPE1)
003131B       DIMENSION SUM(4), SUML(4), SUM2(4), SUML2(4)
003131B       DIMENSION AAVE(4), GAVE(4), ASD(4), GSD(4)
003131B       DIMENSION CHI(4,24), AVE(4)
003131B       N=0
003335B       NDAY=355
003336B       IKNT=0
003337B       DO 1 J=1,4
003341B       SUM(J)=SUML(J)=SUM2(J)=SUML2(J)=0.0
003341B     1 CONTINUE
003346B       READ(1,100) (CHI(J,24), J=1,4)
003355B     2 NDAY=NDAY+1
003356B       DO 3 I=1,24
003360B       READ(1,100)(CHI(J,I),J=1,4)
003371B       IF(EOF(1).NE.0) GO TO 6
003371B     3 CONTINUE
003376B       N=N+1
003377B       DO 5 L=1,4
003401B       AVE(L)=0.0
003401B       DO 4 I=1,24
003404B       AVE(L)=AVE(L) + CHI(L,I)
003404B     4 CONTINUE
003413B       AVE(L)=AVE(L)/24.0
003414B       IF(AVE(L).EQ.0) AVE(L)=0.0000001
003417B       AVEL=ALOG(AVE(L))
003422B       SUM(L)=SUM(L)+AVE(L)
003424B       SUML(L)=SUML(L)+AVEL
003426B       SUM2(L)=SUM2(L)+AVE(L)*AVE(L)
003430B       SUML2(L)=SUML2(L)+AVEL*AVEL
003432B     5 CONTINUE
003435B       IF(NDAY.EQ.367) NDAY=1
003441B       IF(IKNT.EQ.0) WRITE(6,605)
003445B       IF(IKNT.EQ.0) WRITE(6,606)
003451B   605 FORMAT(////,1H1,16X,*VAIL BOX MODEL - TSP CONCENTRATIONS*)
003451B   606 FORMAT(8X,*DAY*,7X,*BOX 1*,7X,*BOX 2*,7X,*BOX 3*,7X,*BOX 4*)
003451B       WRITE(6,600) NDAY, (AVE(L), L=1,4)
003461B       IKNT=IKNT+1
003462B       IF(IKNT.GE.25) IKNT=0
[illegible]   GO TO 2
003464B     6 RN=FLOAT(N)
003466B       DO 7 L=1,4
003470B       AAVE(L)=SUM(L)/RN
003471B       GAVE(L)=EXP(SUML(L)/RN)
003476B       ASD(L)=SQRT((RN*SUM2(L)-SUM(L)*SUM(L))/(RN*(RN-1.0)))
003507B       GSD(L)=EXP(SQRT((SUML2(L)-((SUML(L)*SUML(L))/RN))/(RN-1.0)))
003522B     7 CONTINUE
003525B       WRITE(6,605)
003530B       WRITE(6,607)
003533B       WRITE(6,608)
003536B       DO 8 I=1,4
003537B       WRITE(6,609) I, AAVE(I), ASD(I), GAVE(I), GSD(1)
003554B     8 CONTINUE
003556B   100 FORMAT(E12.4/E12.4/E12.4/E12.4)
003556B   600 FORMAT(/,1H ,I10,4F12.1)
003556B   607 FORMAT(//,19X,*ARITHMETIC*,14X,*GEOMETRIC*)
003556B   608 FORMAT(15X,*AVERAGE    ST.DEV.      AVERAGE     ST.DEV.*)
003556B   609 FORMAT(/,8X,*BOX*,I2,F8.1,F10.1,5X,F8.1,F10.1)
```

INSTITUTE OF ARCTIC AND ALPINE RESEARCH
OCCASIONAL PAPERS

Numbers 1 through 5, and 9, 11, 12, 17, and 23 are out of print. A second edition of Number 1 is available from the author. Numbers 2, 3, 4, 5, 9, and 11 are available from National Technical Information Service, U.S. Department of Commerce. For details, please write to INSTAAR.

6. *Guide to the Mosses of Colorado.* By W. A. Weber. 1973. 48 pp. Order from the author, University of Colorado Museum, Boulder, Colorado 80309. $2.50.

7. *A Climatological Study of Strong Downslope Winds in the Boulder Area.* By W.A.R. Brinkmann. 1973. 228 pp. Order from the author, Institute for Environmental Studies, University of Wisconsin, 1225 West Dayton Street, Madison, Wisconsin 53706.

†8. *Environmental Inventory and Land Use Recommendations for Boulder County, Colorado.* Edited by R.F. Madole. 1973. 228 pp. 7 plates. $6.00.

†10. *Simulation of the Atmospheric Circulation Using the NCAR Global Circulation Model With Present Day and Glacial Period Boundary Conditions.* By J.H. Williams. 1974. 328 pp. $4.75.

†13. *Development of Methodology for Evaluation and Prediction of Avalanche Hazard in the San Juan Mountains of Southwestern Colorado.* by R.L. Armstrong, E.R. LaChapelle, M.J. Bovis, and J.D. Ives. 1975. 141 pp. $4.75.

†14. *Quality Skiing at Aspen, Colorado: A Study in Recreational Carrying Capacity.* By C. Crum London. 1975. 134 pp. 3 plates. $5.50.

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†18. *Century of Struggle Against Snow: A History of Avalanche Hazard in San Juan County, Colorado.* By B.R. Armstrong. 1976. 97 pp. 11 plates. $4.50.

†19. *Avalanche Release and Snow Characteristics, San Juan Mountains, Colorado.* Edited by R.L. Armstrong and J.D. Ives. 1976. 256 pp. 7 plates. $7.50.

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†24. *Avalanche Hazard in Ouray County, Colorado, 1877-1976.* By B.R. Armstrong. 1977. 125 pp. 32 plates. $4.50.

†25. *Avalanche Atlas, Ouray County, Colorado.* By B.R. Armstrong and R.L. Armstrong. 1977. 132 pp. 34 plates. $6.00.

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†30. *Synoptic Climatology of the Beaufort Sea Coast of Alaska.* By R.E. Moritz. 1979. 176 pp. $6.00.

†31. *The North Pacific Oscillation and Eigenvectors of Northern Hemisphere Atmospheric Circulation during Winter.* By J.C. Rogers. 1979. 177 pp. $6.00

†32. *Modeling of Air Pollution Potential for Mountain Resorts.* By D.E. Greenland. 1979. 96 pp. $5.00.

†33. *Baffin Island Quaternary Environments: An Annotated Bibliography.* By M. Andrews and J.T. Andrews. 1980. 123 pp. $5.50.

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