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Select Research Group in Air Pollution Meteorology

Final Report

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SELECT RESEARCH GROUP IN AIR POLLUTION METEOROLOGY
Final Report

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ABSTRACT

In 1972 the Environmental Protection Agency established a five-year research program in air pollution meteorology at The Pennsylvania State University to identify long-range problems requiring solution in a five to ten year time-span and to conduct a research program to attack these problems. This report describes, in summary, the accomplishments of this interdisciplinary group effort.

The central problem identified by the group has been the development of a comprehensive mesoscale predictive transport model capable of nesting within a global scale grid system and sufficiently flexible in scale to be used for either regional or urban problems. The treatment of the boundary is sufficiently general to permit application of the model to complex terrain problems. Also included in the group's effort have been a variety of subsidiary one- and two-dimensional models for the prediction of mixed layer depth, nocturnal mixed layer evolution, and buoyantly driven convection regimes. Much work was also done on deposition processes and on facility development for measurements of air quality and model validation needs.

Summaries of the major tasks together with abstracts and references of all all published papers and dissertations produced by the research group and their students are presented.

This report was submitted in fulfillment of Grant No. R800397 by the Department of Meteorology and the Center for Air Environment Studies of the Pennsylvania State University under the sponsorship of the U.S. Environmental Protection Agency. The report covers a period from May 1, 1972 to March 31, 1978, and work was completed as of March 31, 1978.

CONTENTS

TABLES

SECTION 1

INTRODUCTION

This final report of the "Select Research Group in Air Pollution Meteorology" at the Pennsylvania State University consists of brief comments by each of the task group leaders and a complete list and set of abstracts for the many diverse scientific papers, theses, reports, etc. which have resulted from the grant support provided by the U.S. Environmental Protection agency. As such it is highly distilled. That is, it does not properly convey the multitude of individual and interactive triumphs and frustrations that a large group of diverse, but cooperating, university scientists enjoys and confronts, respectively, in the course of an extended interdisciplinary research program.

The SRG was an experiment. R. McCormick, formerly of the EPA Meteorology Research Laboratory, conceived it as an improved and innovative method for the EPA to support basic and applied research on problems which clearly required long term, and to some extent interdisciplinary, effort to progress toward a solution which could then greatly benefit the E.P.A. The development of new meteorological models and measurement techniques relevant to EPA's air quality simulation and prediction problems was one area that he felt could particularly benefit from the multi-year university grant rather than short-term contract approach.

The focus of the SRG effort was the development of a comprehensive mesoscale air quality simulation model that would serve the needs of the nation for effective air quality control programs during the foreseeable future. A considerable amount of thought went into the determination of the specifications of the model and into the various task statements that were developed to implement it. Some of the considerations are described in the following paragraphs.

It was recognized that for many purposes, such as selecting sites for new plants, existing models designed for simple terrain and making use of previously observed meteorological parameters were adequate. Moreover, a great deal of effort on the international front was being expended at that time to overcome some of the limitations of the simple models of this kind. Today, the total number of such models available for site selection and development regulation probably exceeds one hundred and certainly exceeds the number of good data sets available for validating them.

It was recognized by the SRG that many problems facing regulatory and control agencies could never be solved by simple models of the above mentioned type. One of these problems centers around the complexity of the terrain that prevails in many areas where fuels are accessible and abundant.

It was therefore apparent to the SRG that it would be necessary to formulate the boundary conditions of a comprehensive model so as to permit it to be used in highly complex terrain fields.

Secondly, the need for a predictive model was perceived. Existing models could be used only insofar as observed winds and temperature distributions were available. Sooner or later it could be anticipated that economic pressures would demand more efficient utilization of our nation's resources, including the utilization of the atmosphere, within acceptable limits, for the removal of wastes that can not otherwise be readily disposed of. The need for prediction was well stated by J.T. Middleton, Acting Commissioner of the EPA Air Pollution Control Office in his keynote speech at the Symposium on Multiple-Source Urban Diffusion Models in 1970:

> "So far as a warning scheme is concerned, the heart of any effective air pollution control strategy will be meteorological forecasts that can provide the necessary lead times and guidance required to deploy and implement abatement and control devices. The *sine qua non* of such forecasts is the capability of meteorological techniques to forecast meteorological conditions within the urban boundary layer on urban scales appropriate to the air pollution problem.
>
> "There are some meteorologists, and I must agree with them, who suggest that the utility of present diffusion models is limited by the inability to make accurate forecasts of wind and temperature profiles. I think it is abundantly clear that the accurate description within the boundary layer of the profiles of wind, temperature, and moisture and their variability in time and space as a function of surface conditions and of synoptic-scale features is a fundamental requirement for improved meteorological services not only to air pollution problems, but also to many other interests. We have an urgent need, it seems to me, for greatly improved mesoscale forecasting from the national weather services." -- Middleton (1970).

As a result of these and other perceptions, a set of criteria for the SRG comprehensive model took shape. To be capable of operating in a predictive mode, the model must have boundary conditions that are formulated in such a way that they are derivable from predictable external inputs. For example, the model must be able to operate within a larger grid framework of the global circulation models and must have a boundary layer formulation that makes use of externally imposed radiation fields. It should ultimately encompass the full range of meteorological phenomena and boundary layer processes consistent with the scale of the model. The model should embody the best physics, hydrodynamics, and chemistry consistent with present knowledge and with the limitations of present day computers. It should also be flexible enough to permit insertion of new modules as better techniques and new relationships become available. Finally it should be efficient in the sense that unnecessary sophistication of the various components would be eliminated.

Although it was tempting to think of a model that would incorporate all transport and diffusion processes and all of the chemical transformations of importance in air quality simulation and prediction, practical considerations dictated more limited goals. Many of the processes, particularly those identified with point sources and individual plumes, are simply too small in scale to be resolved on even an urban scale grid. Even though these processes could not be resolved by the model, the envisioned model would provide the parameters that allow appropriate plume models to be used in a predictive mode. Another limitation was the lack of knowledge about chemical reactions and removal processes. In principle, the envisioned model could incorporate such processes on appropriate scales, but at least initially they would have to be left out because the necessary relationships were not sufficiently understood. A third limitation was imposed by the level of support, which permitted only part-time participation of key personnel and thus required that the development effort be subordinated to other research and instructional activities. As pointed out elsewhere in this report, the integration inherent in this mixing of efforts has been responsible for an extraordinarily high level of productivity in relation to EPA's investment of funds. However, the situation inevitably set limits on the goals that could be achieved within the five-year SRG time frame.

The work expended on the development of the comprehensive model and its various subsidiary models and modules comprise tasks 1A, 1B, and 1C. Task 1A contains the major effort in the development of the model itself. Task 1B, which was in due course combined with 1A, comprised the development of a simple but efficient boundary layer module with predictive boundary conditions. Task 1C was concerned with the development of a new state-of-the-art model for boundary-layer simulation that might ultimately replace the simpler module with its recognized limitations. These efforts are described briefly in ensuing sections of this report.

Other tasks were selected by the group in recognition of the need for better knowledge of removal processes and for the acquisition of data required for the validation of a comprehensive model. Because of the limitations in the level of support available, and because of the great amount of effort being expended elsewhere on these needs, only a few limited tasks were selected.

Task 2 was originally conceived as an attack on a better understanding of the growth and evolution of aerosol particles in a regional space-time framework. This task was abandoned early in the period, with EPA approval, when it became evident that useful results could not be achieved within the effort limitations that had to be confronted.

Task 3 dealt with the removal processes. Initially wet removal processes were excluded from the taks because of work being done elsewhere; this restriction was later removed. Removal processes in the long run must play a role in air quality models that is equal to that of source distributions, and in one way or another, most of the harmful effects of pollution are identified with deposition. But the incorporation of deposition into models is presently possible only by an exceedingly crude parameterization, which depends on meteorological data, and cannot be advanced further without careful study of the processes occurring at the atmospheric-surface interface. The work done by the SRG on this problem is described briefly in an ensuing section of this report.

Along with the conception and planning of the comprehensive model came the parallel recognition of the need of data for validation. Even the very simple models that existed or were being developed in 1972 were not able to be sufficiently validated for lack of adequate data. The complexity of the SRG model would set a still greater order of magnitude in the data requirement, and even the Regional Air Pollution Study (RAPS) Experiment that was taking shape at that time could not be relied upon to satisfy all the requirements. Accordingly the decision was made to devote a portion of the effort to the development and improvement of techniques and equipment that would enable the acquisition of data over the time-space scales needed for model validation.

The Penn State Meteorology Department's research aircraft had already been instrumented for rapid collection of meteorological, navigational, and cloud physics data. Under the SRG effort this capability was enlarged to permit sampling and analysis of a variety of aerosols and pollutants and also to measure direct and indirect solar radiation fields. The enlarged capability was completed in time to contribute effectively to the RAPS (Regional Air Pollution Study) experiment, and has been employed effectively in several other large experimental programs. This effort is contained in Task 4, which is described briefly in an ensuing section.

Because of the inherent limitations of in-situ data, remote sensing systems must be relied upon to provide important model validation information. At the time of the formation of the SRG in 1972, the potential for the use of sound detection and ranging (sodar) for providing air-pollution related meteorological data was beginning to become evident and the decision was made to focus available resources on the development of better methods for quantitative analysis and interpretation of such data. The outstanding progress that has been achieved is described in the report of Task 1D.

Like all experiments, the SRG experiment has had its successes and setbacks. Each paper submitted for publication by members of the group has been subject to peer review. On two occasions the grant as a whole has been reviewed by select independent review committees. There is no question that the project's research productivity and quality has returned many times over the EPA's investment. Furthermore, because the grant contributed to the training of many masters and doctoral graduates, most of whom are continuing to work in the air pollution meteorology community, "personnel" as well as scientific returns will continue for many more years.

We believe that the most important factor contributing to the number and quality of grant "products" was that of continuity of funding beyond the normal annual or biennial cycle. Hence, long-term problems could be and were efficiently addressed. The number of Ph.D. theses produced under the aegis of the SRG grant is indicative of the level of much of the grant research work.

We hope that the reader will not as a consequence of the structure of this report be left with the impression that the project research work was primarily focused towards basic research. In fact, only one task, that of developing second order closure techniques for dynamic modeling of atmospheric turbulent transport can be clearly identified as basic research. All other aspects of the grant research were of an applied nature and, to varying degrees have been or now have immediate application to contemporary air pollution modeling and measurement problems. For example, the dynamical mesoscale model, one of the first of its kind in the world, may well become the standard against which the performance of all simplified operational models are compared, the improved atmospheric boundary layer models have already been incorporated into other operational and research atmospheric models, the mixing layer models for "free convection" situations developed in the SRG are so good, and simple, that only a good user's manual separates them from broad application in air pollution meteorology.

SECTION 2

SUMMARIES OF TASK ACCOMPLISHMENTS

1. TASK 1A. DEVELOPMENT OF GENERAL MODELS

The original goal of Task 1A was to develop general meteorological models that would be relevant for air quality prediction. Specifically, we began to develop a general, three-dimensional, fine-mesh model that could be applied to a wide variety of problems involving the transport and diffusion of pollutants on the regional scale (domains of several hundred kilometers). With minor modifications, this model would be applicable to such diverse problems as stratospheric transport of pollutants, calculation of three-dimensional trajectories under any synoptic conditions anywhere in the world, or the prediction of the transport and diffusion of contaminants within meteorologically complicated circulations such as those associated with mountainous terrain or sea-breeze circulations. The inclusion of moisture and the prediction of precipitation makes possible the estimation of washout and rainout of pollutants. The emphasis from the first proposal throughout the entire five years has been on the development of this meteorological model, i.e. specific pollutants and chemical reactions have not been included in the model. This decision was made because we firmly believe that one of the greatest limitations of current air-quality models (AQMs) is the meteorological input. A necessary condition for improving AQMs on horizontal scales larger than a city is to improve the three-dimensional meteorological input into the models. This is not to say that the meteorology is the only limitation of current AQMs; certainly the air chemistry and the emissions inventory are also major components of AQMs that must be improved. However, we felt (and still believe) that the meteorological problem is so complex that to dilute our efforts by trying to simultaneously incorporate chemical reactions and a detailed emissions inventory would seriously compromise our efforts in advancing the state of the art in mesoscale meteorological modeling. However, we have tried to always consider the possible applications of our meteorological model, as evidenced by the lengthy review papers by Anthes (1977b) and Anthes and Warner (1977a). These papers discuss the air-quality modeling problem from a meteorologist's point of view, and show how three-dimensional models are often necessary to determine the movement of pollutants.

At the end of the five-year research program we have made considerable progress toward the original goal. The major areas of research in which progress have been made are summarized in Table 1.

TABLE 1. MAJOR RESEARCH AREAS OF TASK 1A DURING THE PERIOD 1972 TO 1977. RELEVANT PUBLICATIONS, THESES AND FORMAL TALKS ARE LISTED UNDER EACH AREA

1. Development of General, Three Dimensional Meteorological Model.
   - Anthes and Warner (1973, 1978a, 1978b)
   - Anthes et al. (1974)
   - Anthes (1974b, 1975, 1978)
   - Anthes et al. (1977)
   - Busch et al. (1976)
   - Warner et al. (1977, 1978)

2. Nesting of Fine Mesh Models in Larger Scale Models
   - Sobel (1976)

3. Initialization of Mesoscale Models
   - Anthes (1974a, 1976a)
   - Anthes and Hoke (1975)
   - Hoke (1976)
   - Hoke and Anthes (1976a, 1976b, 1977)
   - Warner (1976)

4. Parameterization of Cumulus Convection
   - Anthes (1977a)

5. Development of Mixed-Layer Model
   - Anthes (1976b)
   - Keyser (1977)
   - Keyser and Anthes (1976a, 1976b, 1977)

6. Development of More Efficient Three-Dimensional Model
   - Seaman (1977)
   - Seaman and Anthes (1978)

7. Applications to Air Quality Problems
   - Anthes and Seaman (1976)
   - Anthes (1977b)
   - Anthes and Warner (1977a)

8. Verification
   - O'Lenic (1976)
   - Shaginaw (1978)

A general three-dimensional model has been developed and is currently available for application under a variety of meteorological conditions. The model has been run on horizontal meshes varying from 1 km to 120 km. There is no difficulty in running the model over larger domains (with meshes up to several hundreds of kilometers). To our knowledge, no other meteorological model has been run over such a great range of scales. The model may be run over very complicated topography, and hence is potentially suitable for the important problem of providing three-dimensional wind fields over mountainous terrain.

We recognized from the start that one of the major problems with running fine-mesh prediction models is the mathematical and physical problem of providing values of the wind, temperature, pressure and humidity around the sides of the limited-area model. A parallel study (Sobel, 1976) considered the problem and showed how the nesting of the fine-mesh model within a larger-scale model could alleviate these problems to an important degree.

A second important aspect of the fine-mesh meteorological modeling problem is the initialization process. Initial conditions of all the variables in three dimensions must be analyzed in a consistent way to begin the forecast. Important studies in this area, some under supplementary support by other agencies, are summarized by Anthes (1974a, 1976a), Hoke (1976), Hoke and Anthes (1976a, 1976b, 1977) and Warner (1976).

Under certain conditions, the vertical transport of pollutants from the boundary layer throughout the entire troposphere may be dominated by tall cumulus convection (thunderstorms). Under these conditions, it is imperative to consider cumulus convection in the meteorological model. Again with supplementary support from other agencies, significant progress has been made, and is summarized by Anthes (1977a).

The cost of general, three-dimensional models in terms of computer costs is necessarily high; however, numerical techniques are constantly being developed that may reduce the cost considerably. One such technique is the so-called "simi-implicit" technique. A semi-implicit model may run approximately four times faster than an explicit counterpart. A parallel investigation developing a semi-implicit version of the three-dimensional model was carried out during the SRG research period. The results are described by Seaman (1977) and Seaman and Anthes (1978).

A major effort of the SRG under Tasks 1B and 1C was to develop improved models of the turbulent processes in the planetary boundary layer (PBL). While waiting for the more complicated models to be developed and evaluated, we have developed (again with considerable support from other agencies) a simpler model of the PBL for use in our general mesoscale model. The model is discussed by Busch et al. (1976). Examples of its use in meteorological simulation relevant to air quality modeling are given by Anthes and Seaman (1976), Anthes (1978) and Warner et al. (1978).

While a general three-dimensional model is necessary for many air-quality problems, there are some situations on the regional scale in which a synoptic-scale capping inversion confines the pollutants to a mixed layer next to the ground. Under these conditions, a one-layer model may be used instead of the fully 3-D model. Significant improvements to the original model developed by Lavoie (J. Atmos. Sci., 1972, 1025-1040) have been made, and the improved model has been tested on a real-data case. The results from this model are described by Keyser and Anthes (1976a,b), Keyser (1977) and Keyser and Anthes (1977)

Although the major thrust of our research has not been the development and testing of specific AQMs, we have run our models under several conditions to show how the models might be applied. In Anthes and Seaman (1976), for example, the meteorological model was first run under stable and unstable conditions over complex terrain. The meteorological data generated during this simulation were then saved and used as input into a particle-in-cell transport and diffusion model to describe the behavior of a passive contaminant.

Finally, a portion of our effort was directed toward verification of the 3-D meteorological models. Case studies of specific meteorological events were conducted by O'Lenic (1975), Shaginaw (1978), and Fried (1978). These studies involved careful but time-consuming subjective analyses. They have been invaluable in gaining experience with the 3-D model and in showing the sensitivity of the model to variations in initial conditions.

It is obvious that none of the previously mentioned problems has been completely solved. Indeed, these same research topics are occupying a major portion of similar research efforts at other institutions over the world. However, we do have a working model that has had considerable preliminary testing and is suitable for some applications at the present time.

It is important to note that the three-dimensional model is not a simple tool that can be utilized by inexperienced users. The complexity of the model makes it advisable, if not absolutely necessary, for a knowledgeable meteorologist to make the adaptations for a specific study and to interpret the results. However, the amount of time and expense required for adaptation of the model to a specific use is far less than would be required for the development of a comparable model from the beginning. The ideal framework for the effective utilization of this model would be within a national facility which would have a computing facility to run the model and have trained people available to consult with individual users on specific problems. Under these conditions, many users with widely differing problems and perhaps with only limited facilities would have access to a powerful tool at a nominal cost.

Procedural aspects of the SRG concept

The original concept of an interdisciplinary effort to attack the "air-quality modeling problem" was to bring expert scientists of different specialties together to focus effort on a very complicated problem. In this idealized concept, air chemists, experts in small-scale turbulence, numerical modelers, and radiation experts would "interact" in a unified attack on the problem. Because the individual areas of specialty were so complicated, however, interactions between some of the scientists were of a superficial nature--certainly more than would have occurred without the SRG, but still on a survey level. There was simply not enough time for each specialist to teach his field to the others. Meaningful interactions did occur, however, between scientists when the need arose. The principal interactions within the SRG between the numerical modeling group and the other members of the SRG consisted of many fruitful discussions with Professors Tennekes and Blackadar on boundary layer and soil modeling, with Professor Lee on numerical modeling, Carlson on radiation problems, and Kabel when a simulation of the transport and diffusion of sulphur dioxide was made. Of course there were many interactions of our group with other modeling groups throughout the world.

The stable funding throughout the period was appreciated by the Task 1A group and was necessary for the continuous progress made on the various projects. The problems are fundamentally difficult and the solutions in many cases are tedious to implement and test. The verification of models is extremely time consuming. Without a stable source of funding, only very limited progress could have been made. We feel that this is a positive point in the SRG concept--significant progress in the area of meteorological modeling cannot come from limited-scope, one-year contracts--a continuous dedicated effort is needed.

We must also acknowledge the support of other agencies (NOAA, National Weather Service, and the U.S. Army) in supporting research directly and indirectly related to our EPA task. Without their support, considerably less progress would have been possible. With their support, progress in all areas was accelerated. Very often a research task developed under support of one agency could be immediately used in research supported by another.

Was the program a success? From our point of view it was. From the point of view of the EPA we cannot answer. We are confident, however, that the EPA could not have achieved the equivalent research for the same amount of money by other methods, either by in-house research or by numerous smaller contracts of shorter duration.

2. TASK 1B. SIMPLIFIED BOUNDARY LAYER SIMULATION MODELS

Boundary layer simulation is required in mesoscale prediction models for two important reasons. The first is the necessity to specify realistic boundary conditions before the mean state of the atmosphere can be determined from the differential equations. The second is to provide realistic estimates of the wind transport and dispersion of atmospheric properties and pollutants. In the development of models under this task, we have chosen to emphasize simplicity and efficiency to the end that the models can be immediately incorporated into the mesoscale predictive model.

The model development has been carried out with the recognition that there exist in the atmosphere two quite different physical regimes. The first regime, which may be labeled as the nighttime regime (though it may occur at any time) is characterized by shear-driven turbulence in a stable or slightly unstable environment. The second is the convective regime marked by surface heating and large eddies that have their roots in the heated surface layer. Most of our work has been concerned with the development and testing of the nocturnal model. It has now been tested in a variety of meteorological conditions and has been well validated against real data from several different locations. The convective model has been developed and tested to the point that we know it runs realistically; however, it has not yet been tested against real data.

An important feature of both models has been the use of a simple slab model treatment of the ground layer and the demonstration that it is possible to determine the slab parameters so as to simulate accurately the amplitude and phase of the surface temperature change. By this device it becomes possible to generate the needed boundary conditions with a single equation rather than with a multilevel soil model that has heretofore been generally necessary.

3. TASK 1C. COMPREHENSIVE MODELS OF BOUNDARY-LAYER EVOLUTION

During the five years of the grant, Task 1C has produced thirty publications, four theses and twenty-nine presentations to scientific meetings. A complete list is attached.

One primary thrust of Task 1C was the effort to develop a computational model which might be used to describe pollution dispersal in an urban environment (Lumley, 1978). It was not possible to achieve this goal within the grant period. However, very substantial progress toward the goal was made. The role of buoyancy and wind shear in turbulent transport is now reasonably well understood, both as regards the dynamics of the turbulence itself and as regards the transport of a dynamically passive contaminant (Lumley, 1975; Lumley, et al., 1978; Quenette, 1977; Zeman and Tennekes, 1975; and Zeman and Lumley, 1976). One dimensional models which accurately predict the diurnal variation of the surface mixed layer of the atmosphere, and the dispersal of pollution therein, have been developed (Zeman and Lumley, 1977). The turbulence modeling itself is inherently three-dimensional; the difficulties in extending the model to three dimensions are primarily computational, relating mainly to the determination of the pressure field (Lumley, 1978). The model has been extended to two dimensions, and applied to the changes in turbulent structure which occur in the marine atmospheric surface layer due to surface waves (Zeman, 1975). Refinement of the modeling of the behavior of passive contaminants has required extensive experimental work in the laboratory (Warhaft and Lumley, 1978, 1979; Newman et al. 1979a,b). In particular, definitive work (Newman, Launder, and Lumley, 1979; Newman, 1977) has been done of the behavior of the ratio of the mechanical and thermal time scales; this ratio is involved in such quantities as the turbulent Prandtl number. In the course of this work, much better understanding has been achieved of the return to isotropy of turbulence, which influences the relative values of the component energies in shear flow (Lumley and Newman, 1978).

Considerable work remains to be done, despite the fact that a workable model has been produced. For example, there are inexplicable differences between the predictions of two-dimensional and axi-symmetric flows. Modeling which should in principle be equally applicable to both cases will predict growth rates (for a wake, say) which are correct in the two-dimensional case, and are not in the axi-symmetric case. It is extremely important that such questions be resolved relative to laboratory data, since field data involves too many uncontrolled variables to identify the source of difficulty (Lumley, 1976).

A second primary thrust of Task 1C has been inversion-rise modeling. In essence, the major theoretical problems of inversion-rise parameterization have been solved; further progress must await the results of improved observations and experiments (Tennekes, 1973, 1975, 1979; Tennekes and Zeman, 1977; Zeman, 1975; Zeman and Tennekes, 1976). It is also necessary to study the sensitivity of mixing-height forecasts to the various parameters which occur in inversion-rise models; this aspect is being examined by others.

Finally, extensive work has been done on the development of the box models for the prediction of pollution over large urban areas (Tennekes, 1976a,b; Tennekes and van Ulden, 1974). In addition to the fundamental work on box models per se. box-model statistics have been obtained using time series of wind data for Philadelphia and Harrisburg and simulated diurnal emission and mixing-height cycles (Ettorre, 1977). The program generates all variances and covariances occurring in the equation for the mean concentration in the box; particular attention is paid to the effects of different mean wind speeds and different wind speed variances.

Several years of research on inversion-rise modeling culminated in Otto Zeman's thesis. Virtually all of the results obtained by Zeman, including extensions to pollutant diffusion of the second-order modeling work done in collaboration with John Lumley, have been published. The inversion-rise parameterization paper by Zeman and Tennekes was published in the January 1977 issue of J. Atmos. Sci.. In essence, the major theoretical problems of inversion-rise parameterization have been solved; further progress must await the results of improved observations and experiments. It is also necessary to study the sensitivity of mixing-height forecasts to the various parameters that occur in inversion-rise models; the MS-thesis of Carl Benkeley (Meteorology Department, Penn State) deals with that issue.

Tennekes' work on box models for air pollution over large urban areas will be published in Volume 1 of Advances in Environmental Science and Engineering, along with contributions from the other members of the Select Research Group. This material was presented also at the Third Symposium on Atmospheric Turbulence, Diffusion, and Air Pollution in Raleigh, North Carolina last October. Under Tennekes' guidance Steve Ettorre is working on a MS-thesis which describes box-model statistics obtained with time series of wind data for Philadelphia and Harrisburg and simulated diurnal emission and mixing-height cycles. Ettorre's computer program generates all variances and covariances occurring in the equation for the mean concentration in the box; particular attention is paid to the effects of different mean wind speeds and different wind-speed variances.

4. TASK 1D. REMOTE SENSING SYSTEM DEVELOPMENT

More than six years ago during the formative stages of the "SRG", radar was the only (non-satellite) widely applied meteorological remote sensing system. Both lidar and sodar which, apparently, had outstanding potential for measurements of atmospheric particulate and turbulence, respectively, existed. But neither type of system was sufficiently well-developed to be used for quantitative air pollution-related measurements.

The objective of Task Group 1D was to undertake studies of the suit ability of various remote sensing systems for providing air pollution-related meteorological data. Because the meteorology department had made a commitment toward the development and evaluation of acoustic sounding systems, the decision was made to focus available project resources in that area.

In this final report, it is possible to only briefly summarize the outstanding progress which has been made by the SRG in the quantitative analysis of sodar measurements. For a more complete description, the reader is referred to the various referenced papers.

For convenience, the task group accomplishments have been organized according to activity: theoretical studies, systems development and field experiments.

A. Theoretical Studies

First, to assess the reliability of sodar-determined boundary layer winds, the effects of system parameters, such as bistatic geometry, and spectral signal processing techniques were examined (Przywarty, 1973; Thomson and Coulter, 1974; Thomson, 1975b; Coulter, 1976; Kristensen and Underwood, 1978). Simultaneously a complete review of published sodar research to date was prepared (Thomson, 1975a).

It was clear that sodar techniques could not provide the customary vertical temperature profiles from which, for example, static stability is normally determined. Because low level temperature inversions are often associated with high surface pollutant concentrations, we explored an alternative refractive acoustic propagation technique for determining the depth and intensity of low level inversions. Although the technique was shown, in principle, to be sound (Teufel, 1975; Greenfield et al, 1974), it was also shown to be unsuitable for operational application.

As a consequence of the refractive propagation studies, limited research was started on the behavior of gravity waves in complex terrain. Although significant progress has been made in the study of wave-terrain interactions (Greenfield et al., 1978), quantitative assessment of the role of breaking waves in the vertical transport of momentum, heat and passive pollutants is beyond the scope of the present project.

Theoretical studies of the sensitivity of Tennekes' inversion-rise model to meteorological input variables were also performed in conjunction with the sodar research (Benkeley, 1977). It was shown, among other things, that an "integrated" system of an inversion-rise model and a sodar, could provide inversion rise data suitable for most gaussian plume and box model pollutant dispersion applications.

B. Systems Development

Approximately, one-third of the financial resources required to develop the sophisticated sodar system at Penn State were provided by the EPA. The calibrated, multistatic Doppler sodar including a digital, video color display is one of the most sophisticated systems in the world (Thomsom and Scheib, 1978). It may be routinely used for quantitative measurements of planetary boundary layer winds, C_T^2, C_V^2, dissipation rate and turbulent temperature fluctuation decay rate profiles. To date, principal use of the system has been for technique evaluation studies and validation of the sodar remote sensing technique (Thomson et. al., 1978). It has also been applied for studies of powerplant high stack and cooling tower plumes (Underwood, 1978; Coulter and Underwood, 1978), and is, presently, being used for mixing layer studies in complex terrain. In 1978 the system was transported to the Risø National Laboratory in Denmark for complex terrain studies supported by the National Science Foundation. Upon its return in late 1978 it will, presumably, again be used in EPA supported research of mixing layer behavior in complex terrain environments.

For the refractive propagation studies, a 200 Hz transmitter-receiver system for 1 to 8 km paths was also developed (Teufel, 1975) and used. Upon completion of the experiments it was scrapped and insofar as possible its components used in the primary sodar systems.

C. Field Experiments

In the course of developing the sodar system, numerous limited-objective calibration and evaluation experiments were conducted. Such experiments required literally hundreds of man-hours of effort. But without them it would have been impossible to carry out research such as the sodar-aircraft intercomparison study by Thomson, Coulter and Warhaft (1978). But with this step satisfactorily completed, the existing system can now be highly confidently applied for many years to a broad class of boundary layer measurement problems. The above mentioned experiment at Risø in Denmark will, we hope, be only the first in an extended series of air pollution meteorology experiments.

5. TASK 3. NATURAL REMOVAL PROCESSES FOR AIR POLLUTANTS

The research effort in this task comprised three phases: 1) survey, 2) preliminary modeling, and 3) refinement and validation. All were quite successful and are documented in detail in the publications listed elsewhere in this report and in those publications yet to come. The emphasis here is on the accomplishments in Task 3 during the five years of the Select Research Group grant, on the context in which these accomplishments occurred, and on their role in the near future.

Much attention has been given to man's emission of pollutants into and their transport within the atmosphere. For short term, local scale objectives this was adequate. However it has become increasingly evident that for longer time periods and regional and global scales natural emissions and processes for removal must be reckoned with. Our survey covered these natural phenomena for the gaseous species SO_2, H_2S, N_2O, NO, NO_2, NH_3, CO, O_3, and hydrocarbons. It identified several interfacial and bulk removal processes. The bulk processes (typified by atmospheric reactions and precipitation scavenging) were already receiving extensive attention. By way of contrast, the interfacial processes occurring at the earth's surface (absorption by vegetation, soil, water, and stone) had been contemplated mainly in terms of damage done by pollutants to these media and were virtually ignored as removal processes. Thus our research focused on this area of ignorance. Requests for the publications of our survey results continue to arrive and we have long since run out of reprints. However the major report is available from the EPA.

Considerable preliminary modeling and semiquantitative considerations established that pollutant uptake by water bodies, vegetation, and soil was comparable in magnitude to that via the more widely studied bulk processes. The fundamental information from which quantitative models could be derived came from a diverse literature (meteorology, biology, agriculture, etc.). It quickly became clear that most authors in each of these fields viewed the pollutant transfer as being controlled by factors in their particular media. The chemical engineering literature, while having little to do historically with the natural and life sciences, did provide fundamental theory and a calculational framework to bring the methods of these diverse sciences together in a coherent manner. Our preliminary calculations showed that each of the media (Atmosphere, soil, water, and vegetation) existing at the earth's surface could play an important role in the interfacial mass transfer. Later more sophisticated analyses confirmed this and gave quantitative perspective tc the matter.

At this point, the goal became the quantitative modeling of the mass transfer characteristics (estimation of mass transfer coefficients) in each of the media separately. These individual models could be evaluated by comparison to existing data and then ultimately combined for validation with experimental observations in the field. The meteorological literature deals heavily with momentum transfer in the atmosphere, less with heat transfer, and very little with mass transfer. The major exception to this statement is the emphasis on nuclear fallout, a process not very analogous to gaseous deposition. By use of the best information available and through considerable interaction with other members of the Select Research Group, a new, multifaceted correlation for the atmospheric-phase mass-transfer coefficient was developed. It is somewhat of a break with tradition, providing considerably more physical realism than earlier related models. It enables the prediction of mass transfer to (but not across) and interface at the earth's surface. We believe this new model will prove useful as is and will give theoreticians a new starting point from which to progress.

The uptake of an atmospheric pollutant by a water body can be a valuable removal process or a water pollution problem. To model this process one needs an aqueous-phase mass-transfer coefficient as well as the previously discussed atmospheric coefficient. There had been some liquid-phase mass-transfer experiments but, in contrast to the case of the atmosphere, no predictive methods existed. Thus a model based upon wind-induced mixing of large water bodies was developed in this research. This model is being used in practical calculations at the present time and, being the only one of its kind, should provide a stimulus for further theoretical development.

Plants can exchange many gases with the atmosphere as is well known in the case of carbon dioxide, oxygen, and water. Because of their pervasiveness, their large surface area, and the atmospheric turbulence which their presence induces; they are capable of assimilating large quantities of pollutants. In this vegetative medium, as in gas and liquid media, a quantitative model has been developed to predict the resistances to mass transfer on the vegetation side of the earth surface interface. This model is a significant advance; yet we believe much more can be done and plan a chemical engineer-plant pathologist-meteorologist team to work on it.

Pollutant transfer to soil is more comp ex than the above cases and only a preliminary model resulted in the period of this grant. A follow-up collaboration between two of the SRG principal investigators (Blackadar and Kabel) should lead to an effective soil model coupled with atmospheric boundary layer models for momentum, heat, and mass transfer.

All of the above individual models have been tested to the extent possible against appropriate laboratory and field data. One outcome of these comparisons is the realization that experimenters have often failed to measure many of the critical parameters. It is hoped that our publications will guide them to obtain more appropriate data in the future. A major effort at validation which integrates much of the above material is an aircraft measurement program conducted toward the end of the project. We have measured vertical, horizontal, and longitudinal SO_2 profiles downwind of a coal fired power plant on the southeast shore of Lake Erie. This location provides all of the media addressed earlier in this report. The quantitative interpretation of the results is continuing but qualitatively it is clear that 1) natural removal of pollutants at the earth's surface is important, 2) the features of our derived models are correct, and 3) all of the indicated media can influence the removal significantly and must be considered together in a coherent calculational framework.

6. TASK 4. RESEARCH AIRCRAFT DEVELOPMENT AND APPLICATION

The principal objective of Task 4 was to modify and develop the existing Penn State Meteorology research aircraft so that it could be used for a diversity of air pollution meteorology measurements. This airborne research work was carried out independently of, but in close cooperation with EPA scientists who were involved in the St. Louis RAPS study. Penn State measurements would, thus, effectively supplement other EPA measurement efforts.

In most cases, modifications to and the subsequent application of the aircraft systems have already resulted in published scientific papers. However, interpretation of other parts of the comprehensive airborne data will be completed only as processing of the RAPS experiment data progresses, for final analysis will be dependent upon other independent surface and airborne measurements.

As quickly as resources would permit, the aircraft was equipped with comprehensive aerosol measurement instrumentation. Funding for new instruments was derived from EPA, university and other contract sources. The resulting system is summarized in Reagan et al. (1977). In the process of designing and testing the aircraft aerosol system, several "Substudies" were completed. This included the design, fabrication and evaluation of an isokinetic decelerator for airborne aerosol sampling (Pena et al, 1977). A second isokinetic probe has since been built by Penn State for the Aviation Research Facility of the National Center for Atmospheric Research. A second important study was the development of scanning and transmission electron microscope techniques for the quantitative analysis of individual aerosol particles. This research, summarized in the Ph.D. dissertation by Mamane (1977), was first applied in the definitive lidar-aircraft intercomparison study reported in Reagan et al. (1977).

Other SRG airborne aerosol and meteorological measurements are reported in Schere (1975), Schere and Thomson (1975), Mamane and Pena (1975), and Godowitch (1976).

The task of improving the aircraft turbulence measurement system was more costly in time and effort than had been anticipated. Redford (1977) has summarized the detailed boundary layer turbulence measurements made in the St. Louis urban area during two different RAPS summer programs. His results show, among other things, how vertical eddy diffusivities vary above an urban complex. The next step, incorporation of these results into an urban-scale air pollution meteorological model, was beyond the scope of the present measurements program.

A third major activity was the development of an airborne multichannel pyranometer package for urban scale radiation energy budget studies. This package was developed for Dr. J. Peterson of the EPA and was subsequently used by him during four of the major RAPS experiments.

The various aircraft projects conducted during the SRG are summarized in Table 2.

TABLE 2 SUMMARY OF EPA AIRBORNE FIELD RESEARCH PROGRAMS

Time	Location	Prin. Invest(s)	Mission	Research Flight Hours
8'73	St. Louis	Thomson, Pena	Urban PBL Turbulence and Aerosol	25
8'73	St. Louis	Moroz	Urban Plume Aerosol	15
10'73	Eastern U.S.	Thomson, Anthes	Mesoscale Meteorology	20
1'74-2'74	NY, PA	Moroz	Urban Plume Aerosol	13
7'74-8'74	St. Louis	Thomson, Pena	Urban PBL Turbulence and Aerosol	40
8'74	St. Louis	Peterson	Urban Radiation Budgets	19
11'74	Tucson	Thomson, Pena	Lidar-Aircraft Aerosol Intercomparison	42
2'75-3'75	St. Louis	Peterson	Urban Radiation Budgets	30
7'75-8'75	St. Louis	Peterson	Urban Radiation Budgets	43
6'76	State College	Thomson	Sodar-Aircraft PBL Turbulence Intercomparison	6
7'76-8'76	St. Louis	Peterson, Ching	Urban Radiation Budgets & PBL Studies	53
				306

SECTION 3

PUBLICATIONS OF THE SELECT RESEARCH GROUP

Listed below, in alphabetical order by author are titles, abstracts, and publication citation for the scientific contributions generated by the Select Research Group.

Initialization Of Mesoscale Models With Real Data

R. A. Anthes

Detailed temperature and pressure analyses on the mesoscale are not accurate enough to compute meaningful pressure gradients. Therefore, the mass field must be deduced from the wind field on this scale. However, it is often desirable to incorporate the synoptic-scale pressure gradients into the mean wind analyses through the quasi-geostrophic approximation. A method for incorporating this large-scale constraint into a mesoscale initialization scheme has been developed and tested on a strong jet stream case. Proceedings of the Sixth Conference on Weather Forecasting and Analysis, Albany, New York, May 10-13, 1976; American Meteorological Society, Boston, (1976).

Meteorological Aspects of Regional-Scale Air-Quality Modeling

R. A. Anthes

The overall problem of constructing a general, predictive air-quality model is considered, with emphasis placed on the meteorological aspects of the modeling problem.

A scale analysis of the pollutant conservation equation indicates that different physical processes are important on the urban, regional, and global scales of pollutant transport and diffusion. Thus different types of models, initial conditions and boundary conditions are appropriate for these distinct scales.

The physical and numerical aspects of predictive meteorological models on the regional scale are reviewed in detail. The major problems are associated with the measurement of the data required by numerical models, the analysis of these data, the specification of lateral boundary conditions on a limited-area domain, the modeling of the important physical processes, and the numerical solution of the finite difference equations.

Next, some general classes of air-pollution transport and diffusion models are discussed. These range from the simple box models to the complicated and expensive three-dimensional models. The limitations and potentialities of each type of model are discussed.

Finally, an example of a simple combined meteorological-air-quality model is given. The meteorological model, which is a one-layer model of the planetary boundary layer, provides detailed meteorological data for use in a particle-in-cell transport and diffusion model. A hypothetical 12-h forecast of an SO_2 plume on the regional scale is presented to illustrate the model's potential use. Advances in Environmental Science and Engineering, Vol. 1; Gordon Breach (1979).

The Height of the Planetary Boundary Layer and the Production of Circulation in a Sea-Breeze Model

R. A. Anthes

A two-dimensional mesoscale model is applied to study the evolution of the sea breeze on a stagnant base state. In contrast to previous studies, this paper considers the relationship of the planetary boundary layer (PBL), the thermodynamic structure, and the vertical circulation associated with the sea breeze in detail. An important result is that under zero geostrophic wind conditions, the return flow occurs entirely above the PBL and so pollutants emitted over land would not be carried offshore.

The development of the sea breeze circulation is studied quantitatively using the circulation theorem. The circulation in the vertical plane normal to the coast develops as a result of the solenoid term. The vertical diffusion of momentum acts as the most important brake on the developing circulation. The Coriolis term is small until six hours after the heating cycle. Late in the cycle, however, it reaches a value of 45% that of the solenoid term. Horizontal and vertical advective effects are small. Submitted to J. Atm. Sci. (1977).

Diffusion of a Passive Contaminant Over Complex Terrain Under Stable and Unstable Conditions

R. A. Anthes and N. Seaman

This paper presents forecasts of pollution under light-wind conditions over very steep terrain using a combination of a general meteorological model and a modified particle-in-cell transportional diffusion model. The meteorological model is integrated first for one hour before and two hours after sunrise. During the first hour, air near the surface is blocked by the mountain and vertical mixing is very small.

After sunrise, the planetary boundary layer begins to grow rapidly, vertical mixing increases by two orders of magnitude, and a weak mountain-valley circulation is induced by the differential heating on the mountain sides.

The wind, depth os the planetary boundary layer, and mixing coefficient data obtained from the meteorological model are then used in a 3 h forecast of pollution. This prediction is made using a particle-in-cell model modified for use over variable terrain. In this model, diffusion is accomplished on an Eulerian grid while the transport of the diffusion is done through the computation of particle trajectories. Because the winds are light in this case (generally under 1 ms^{-1}) and surface heating is strong, vertical diffusion dominates the pollution predictions.

Third Symposium on Atmospheric Turbulence, Diffusion and Air Quality, October 19-22, 1976, Raleigh, N.C. American Meteorological Society Preprint Volume, pp. 449-454, (1976).

Diffusion and Transport of a Passive Contaminant Over Complex Terrain Under Stable and Unstable Conditions

R. A. Anthes, N. Seaman, D. Keyser

This paper presents forecasts of pollution under light-wind conditions over very steep terrain using a combination of a general meteorological model and a modified particle-in-cell transport and diffusion model. The meteorological model is integrated first for one hour before and two hours after sunrise. During the first hour, air near the surface is blocked by the mountain and vertical mixing is very small.

After sunrise, the planetary boundary layer begins to grow rapidly, vertical mixing increases by two orders of magnitude, and a weak mountain-valley circulation is induced by the differential heating on the mountain sides.

The wind, depth of the PBL, and mixing coefficient data obtained from the meteorological model are then used in a 3h forecast of pollution. This prediction is made using a particle-in-cell model modified for use over variable terrain. In this model, diffusion is done on an Eulerian grid while the transport of the diffusion is done through the computation of particle trajectories. Because the winds are light in this case (generally under 1 ms^{-1}) and surface heating is strong, vertical diffusion dominates the pollution predictions. Proc. 7th International Technical Meeting on Air Pollution Modeling and Its Application, Airlie, VA, Sept. 7-10, 1976.

Prediction of Mesoscale Flows Over Complex Terrain

R. A. Anthes and T. T. Warner

A method was developed for analysis of atmospheric flows with spatial resolution on the order of a few kilometers and short-range prediction on the order of a few hours. The objective was to evaluate problems associated with development of operational mesoscale numerical prediction in the proposed Army Automatic Meteorological System (AMS). The equations of motion are written in generalized sigma (relative pressure) coordinates with provision for a variable number of levels and a variable top pressure surface. Numerical experiments were performed over very rough terrain covering a domain of almost 150x150 km. Two-dimensional experiments showed that inadequate vertical resolution produces greatest errors in the upper troposphere, and at least 14 layers appear necessary for the case of vertically propagating gravity waves in stable flow over mountain barriers. Other sources of error are a low upper model surface, proximity of lateral boundaries to steep terrain, and unsmoothed terrain elevations. The solutions from either a 2.5 or 5 km mesh showed terrain-induced perturbations of about 60 to 100% of the mean speed and on the order of a few degrees in temperature anomaly. A recommendation is made that prototype mesoscale observations be collected, under a variety of synoptically stratitied conditions, for the purpose of initialization and verification of models. Res. and Dev. Tech. Report ECOM-5532, Atm. Sci. Laboratory, White Sands Missile Range, NM 88002, 101 pp.

Applications of General Meteorological Models to Air-Quality Problems

R. A. Anthes and T. T. Warner

Some of the potential applications of general meteorological models to air-quality problems of mesoscale flows are discussed. Although general models are relatively expensive, they are easily modified to treat many complicated problems that are not amenable to solution by simpler methods.

Results from two meteorological models are presented to illustrate the versatility of the models. The first is a relatively simple model of the atmospheric mixed layer. A 6-h real-data forecast is shown. The second model is a more general three dimensional model which is capable of treating a variety of meteorological problems. A 12-h real-data forecast of flow and precipitation over the U.S. is summarized. Then the model is applied to a regional-scale simulation of light wind conditions. Finally, the model is applied to small-scale flow under stable conditions over complex terrain. Conference on Air Quality Meteorology and Atmospheric Ozone, Boulder, Colorado, Aug. 1-6, 1977.

The Development of Mesoscale Models Suitable For Air Pollution And Other Mesometeorological Studies

R. A. Anthes and T. T. Warner

The development of a general, predictive hydrostatic meteorological model is described. The model is three-dimensional and is suitable for a wide variety of problems, ranging from the synoptic scale to the small end of the mesoscale. The model contains provisions for variable terrain, a moisture cycle, sensible heat addition at the earth's interface, and high- and low-resolution boundary layer physics.

This paper presents the mathematical and numerical formulation used in the various options of the model. The basic equations are written for a Lambert Conformal projection. The horizontal and vertical grid structure and the finite-difference equations are described. The energetics of the three-dimensional model and its two-dimensional analog are discussed. The problem of the lateral boundary conditions for limited area forecasts is considered, with emphasis on the effect of the lateral boundary conditions on the mean motion over the domain.

Two options for including the frictional and diabatic effects at the earth's surface are presented. These include a bulk parameterization and a high-resolution model of the planetary boundary layer. Both models use a predictive surface energy equation developed by Blackadar to determine the time-dependent surface heat flux.

The water vapor cycle and the parameterization of cumulus convection is summarized. Both stable, nonconvective (grid-scale relative humidity equal to 100%) and unstable, convective (grid-scale relative humidity less than 100%) precipitation are parameterized.

Several preliminary simulations with the two-dimensional analog are presented. These investigate the sensitivity of the model to the finite-differencing scheme, the treatment of the upper boundary condition, and the effect of the horizontal diffusion on the solutions forced by moderate flow over steep terrain. The energetics of the model are examined for these flows. The model is shown to be energetically consistent to a good approximation, and capable of simulating hydrostatic mountain waves realistically. Three-dimensional experiments are discussed in a separate paper by Warner et al. Submitted to Monthly Weather Review, (1978).

Development and Testing of a Mesoscale Primitive Equation Model at Penn State University

R. A. Anthes, T. T. Warner, A. L. McNab

Two numerical experiments that were performed using the Penn State mesoscale primitive equation model are described. We intend here only to summarize the basic characteristics of the two versions of the model used as well as briefly describe the situations in which they were applied.

A moist version of the mesoscale model was used to simulate the atmospheric conditions prevailing over the eastern United States during the period 12Z, 16 October 1974 to 00Z, 17 October 1974. The area was covered by a mesh of 30 x 35 points spaced approximately 111 km apart. The vertical coordinate (σ, normalized pressure) was divided into six layers between the surface and the top of the model at 250 mb. Lateral boundary conditions were open, where the dependent variables at the boundaries were specified by linearly interpolating in time between the observed conditions on the boundary at the initial and final times. Initial conditions on temperature were obtained from the nondivergent component of the winds through the use of the balance equation. Initial winds consisted of the sum of the nondivergent component and a small divergent component obtained from an omega equation. Figures 1 through 14 depict the initial and final observed conditions as well as some of the forecasted quantities.

A second version of the model that contained a high resolution planetary boundary layer was used to study mesoscale perturbations to a uniform low wind speed flow. Mesoscale circulations were produced by orographic forcing, differential heating and differential friction. The domain, defined by a 30 x 30 mesh, covered the northeastern United States and encompassed most of the complex terrain of the Appalachian Mountain range.

The grid increment was approximately 60 km and the model was divided in the vertical into 12 layers of unequal depth. The layers within the planetary boundary layer had a depth of about 160 m. During the first 18 hours of integration, the flow was allowed to adjust to the terrain. At 18 hours a differential surface roughness was introduced and at 24 hours a six hour heating cycle was begun. Between 24 hours and 30 hours the surface heat flux increased from zero to a value equivalent to 15% of the solar constant. By dividing the integration into these three segments, we are able to separate the effects of the three forcing mechanisms in terms of the perturbations they impose on the initially uniform flow. Figures 15 through 18 show the conditions at the end of the last segment of the integration. Proc. Third Conference on Numerical Weather Prediction, Omaha, Nebraska, April 26-28, 1977; American Meteorological Society, Boston, (1977).

Modeling The Nocturnal Boundary Layer

Alfred K. Blackadar

The model discussed in this paper was designed to provide in the simplest manner possible the time height distribution of temperature and wind during the course of the night given the thermodynamic and mechanical properties of the surface, and the geostrophic wind. The model provides, indirectly the vertical distribution of exchange coefficient, which may prove useful in estimating the vertical dispersion of surface sources of contaminant whose aerial distribution is given; it also incorporates the best methods available for predicting the distributions of σ_w and σ_v that are useful in predicting the dispersions of elevated plumes.

From the point of view of predicting the interactions with the atmospheric layer, however, it is necessary only to know the soil surface temperature as a function of time. As a result, it is possible to reduce the number of levels in the soil very greatly. For a pure sinusoidal heat input at the surface, the surface temperature amplitude and phase can be exactly calculated with a simple model consisting of a uniform slab resting on a substrate of constant temperature. Preprints, Third Symposium on Turbulence, Diffusion and Air Quality, Oct. 19-22, 1976, Raleigh, NC, Amer. Meteor. Soc., Boston, (1976).

High Resolution Models of the Planetary Boundary Layer

A. K. Blackadar

The great number of air quality simulation models that have evolved within the last few years differ rather fundamentally in the way information is expected to become available. In the simplest class of models, it is merely assumed that the required wind distribution is provided directly from observations or less directly through some interpolative analysis of observations made at a number of places. The models comprising the most complicated class provide for the prediction of the complete mean wind distribution from an observed antecedent state and from boundary conditions based on predictable external physical features of the environment such as solar radiation, soil characteristics, and surface roughness. Models are also required to give information about the diffusion of contaminants or other properties into or out of the path of the mean wind. The demands that must be met by models are of two different kinds: diffusion transports that are required for the determination of contaminant distributions; and those that are needed for the correct modeling and prediction of the mean wind distribution. Both demands must be kept in midn when planning how the boundary layer and the boundary conditions are to be treated.

In this paper the formulations of many models are compared and analyzed in the light of some results of second-order closure approximations. Advances in Environmental Science and Engineering, Vol. 1, Gordon Breach, (1978).

A Multi-Level Model of the Planetary Boundary Layer Suitable for Use with Mesoscale Dynamic Models

N. E. Busch, S. W. Chang, and R. A. Anthes

In this paper a simple model of the planetary boundary layer (PBL) is proposed. The surface layer is modeled according to established similarity theory. Above the surface layer a prognostic equation for the mixing length is introduced. The time-dependent mixing length is a function of the PBL characteristics, including the height of the capping inversion, the local friction velocity and the surface heat flux. In a preliminary experiment, the behavior of the PBL is compared with observations from the Great Plains Experiment. J. Appl. Meteor., V. 15, pp. 909-919, (1976).

Pollutant Transfer Into Water Bodies

W. J. Brtko and R. L. Kabel

Although considerable effort has been devoted to the development of air pollution models, little has been done to incorporate natural mechanisms capable of removing pollutants from the atmosphere. One important process is the uptake of atmospheric pollutants by water bodies. In this paper, a calculational scheme to quantify this transport process is presented. In particular, two models characterizing wind induced turbulence in a water body are invoked to estimate the liquid phase mass transfer coefficient. A priori specification of parameters yielded predictions well within an order of magnitude of experimental evidence in both the laboratory and the field. Water, Air, and Soil Pollution, Vol. 6, pp. 71-95, (1976).

Transfer of Gases at Natural Air-Water Interfaces

W. J. Brtko and R. L. Kabel

The natural exchange of gases across an air-water interface is an important mechanism that can be quantified. The mass transfer coefficients characterizing the liquid phase can be predicted using certain models representing the liquid phase turbulence. Methods have been developed to approximate the necessary input parameters. Predictions of the models yielded liquid-phase mass-transfer coefficients well within an order of magnitude of experimental data at air-water interfaces. Submitted to J. Physical Oceanography.

Potential Application of Satellite Temperature Measurements in the Analysis of Land Use Over Urban Areas

T. N. Carlson, J. A. Augustine, and F. E. Boland

Satellite-derived surface temperature maps of Los Angeles are presented for a day-night pair of orbits as an illustration of how the satellite may be used to study urban heating patterns, which are strongly influenced by human use of the land. Bulletin of the American Meteorological Society, Vol. 58, pp. 1301-1303 (1977).

Indirect Sensing of the Urban Heat Island by Satellite and the Measurement of Substrate Parameters Responsible for its Formation

T. N. Carlson, J. A. Augustine, and F. E. Boland

Satellite-derived temperature analyses are presented for a day-night sequence over Los Angeles during October 1976. Relatively warm temperatures appear over the downtown area, industrial sections, and medium rise high density suburbs; cooler temperatures are observed over the less populated suburbs and over wooded terrain. Such thermal contrast is clearly related to the surface layer heating and reflects the nature of land use and the character of the ground surface. We outline a method whereby a numerical surface layer temperature/heat flux model may be used to obtain by inversion, quantitative estimates of the thermal inertia and moisture availability which are essentially responsible for the formation of the urban heating pattern. Proc., 4th Conference on Sensing of Environmental Pollutants; Amer. Chemical Soc., (1978).

A Model For Computing Surface Heat Flux And Temperature And Its Application To The Analysis Of The Urban-Rural Substrate

T. N. Carlson and F. E. Boland

A one-dimensional numerical model, capable of simulating surface temperature and heat flux, is described in terms of the effective atmospheric and terrain variables. The two model parameters which are most responsible for the formation of important temperature variations in the horizontal over the urban-rural complex are the thermal inertia (thermal property) and moisture availability, the former being most responsible for shaping the nighttime temperature pattern while the latter has a greater effect during the day.

The controlling substrate variables are not easily determinable by direct measurement over a surface consisting of an inhomogeneous agglomerate of elements. We present one method whereby surface temperature, a more readily obtainable quantity, can be used in conjunction with the surface model to determine by numerical inversion of the latter the effective values of moisture availability and thermal inertia and thereby provide a quantitative framework for analysis of complex terrain and for an evaluation of the surface energy budget.

A Model for Dispersion from Area Sources in Convective Turbulence

G. Crane, H. A. Panofsky, and O. Zeman

Vertical mixing coefficients have been computed by integrating vertically changes of concentrations of nonreactive pollutants along horizontal trajectories, during convective conditions.

Mixing coefficients are obtained for three separate periods, and analyzed according to the hypothesis of convective similarity. It was found that normalized mixing coefficients could be represented as "universal" functions of the ratio of the height to the mixing depth. These functions were small at small z and large z and reach a maximum at about half the mixing depth. In fact, the K-coefficients are so large in the middle of the boundary layer, that the concentrations there are effectively independent of height.

In the surface layer, the mixing coefficients agree with the hypothesis that mixing coefficients for contaminants equal mixing coefficients for momentum (eddy viscosity). The observed universak functions also agreed fairly well with predictions made by Lumley and Zeman from second-order closure theory. However, laboratory measurements indicate larger mixing coefficients. It is suggested that K-values estimated both from second-order closure theory and from Los Angeles measurements are systematically underestimated. Nevertheless, it seems likely that K-theory is useful for determining pollutant concentrations from large, continuous area sources at the ground, under convective conditions. Atmospheric Environment, Vol. 11, pp. 893-900. Pergamon Press (1977).

A Method for Measurement of Temperature Profiles in Inversions from Refractive Transmission of Sound

R. J. Greenfield, M. Teufel, D. W. Thomson, R. L. Coulter

A method is described for estimating temperature profiles in the lower troposphere during conditions including a surface-based or elevated inversion layer. The method uses acoustic energy transmitted over paths of the order of 10 km in length. Measurements are made at approximately 1-km intervals extending radially outward from the transmitter. The vertical temperature profile is modeled as two constant temperature gradient layers. The first layer extending from the surface to height H_1 has a temperature gradient T_1 (usually negative upward). The second-layer temperature gradient T_2 is strongly positive upward. For temperature profiles of this type, ray paths arrive with a high intensity at a caustic, and no rays return to earth between the source and the caustic. The method requires that H_1 be determined by some other means such as vertical acdar sounding. The T_1 and T_2 are then simultaneously determined by measuring the range to the caustic and the wave propagation tiem. Even if the propagation time cannot be measured, useful estimates of T_2 can be obtained from observations of H_1 and the caustic distance. For a ground-based inversion no caustic occurs. However, the temperature profile can be determined by measuring the wave propagation time. Since horizontal wind shear produces the same effect on ray paths as a vertical temperature gradient, the proposed method obtains the sum of the effects of the wind shear and the temperature gradient. In conditions including significant wind shear, corrections for it must be made. J. Geophysical Research, Vol. 79, pp. 5551-5554, (1974).

Atmospheric Impact on Nutrient Budgets

R. L. Kabel

The objective of this work is to find the flux of a gas between a gas and a liquid phase. The method which will be shown can work in either direction, i.e. one can have a gas absorbing in a liquid from a gas phase or one can have the transport of a dissolved gas from the liquid phase to a gas phase. The approach that will be used in this disucssion is first, to obtain a deposition velocity, i.e. a coefficient to characterize the mass transport in the gas phase. Second, a liquid mass transfer coefficient will be obtained to characterize the mass transport in a liquid phase. And third, these two will be linked by characterizing the equilibrium which exists at the gasliquid interface. Finally, and illustrative example of the calculation of the flux of nitrogen dioxide from the atmosphere to a fresh water lake will be presented. In this way it is intended to show the state of the art in predicting mass transport of gases between gas and liquid bodies. It should be made clear that the work which is presented here is only partly complete in all three of the aspects. However, it should be sufficient to give a feeling for what can be done in this field and also the potential of the various approaches for practical calculations in the future. Proc. First Specialty Symposium on Atmospheric Contribution to the Chemistry of Lake Waters. International Association for Great Lakes Research, Sept. 28 - Oct. 1, 1975.

Deposition of Atmospheric Pollutants

R. L. Kabel

Removal of atmospheric pollutants at the earth's surface can be an important boundary condition in air quality simulation models. This interfacial process is equally critical in quantifying the pollution of water bodies via atmospheric deposition. This paper provides a macroscopic approach to the specification of this boundary condition.

An overview of sources and sinks of gaseous pollutants is presented. This is followed by consideration of various natural mechanisms for gaseous pollutant removal. Focus is ultimately placed on air-earth interface processes, that is, removal by water, vegatation, soil, and rock.

A procedure for computing the pollutant flux at the interface is outlined. It is based on the use of mass transfer coefficients for the atmospheric and nonatmospheric phases and upon equilibrium concepts to characterize the interface. The gas phase mass transfer coefficient is closely related to the familiar deposition velocity and can be predicted from ocrrelations in the meteorology and chemical engineering literature. The prediction of the aqueous phase mass transfer coefficient, based upon correlations from the chemical engineering and oceanography literature, is discussed. Third Symposium on Atmospheric Turbulence, Diffusion, and Air Quality, Oct. 26-29, 1976, Raleigh, NC; Amer. Meteorological Soc., Boston (1976).

Natural Removal of Gaseous Pollutants

R. L. Kabel

Removal of atmospheric pollutants at the earth's surface can be an important boundary condition in air quality simulation models. This interfacial process is equally critical in quantifying the pollution of water bodies via atmospheric deposition. This paper provides a macroscopic approach to the specification of this boundary condition.

An overview of sources and sinks of gaseous pollutants is presented. This is followed by consideration of various natural mechanisms for gaseous pollutant removal. Focus is ultimately placed on air-earth interface processes, that is, removal by water, vegetation, soil, and rock.

A procedure for computing the pollutant flux at the interface is outlined. It is based on the use of mass transfer coefficients for the atmospheric and nonatmospheric phases and upon equilibrium concepts to characterize the interface. The gas phase mass transfer coefficient is closely related to the familiar deposition velocity and can be predicted from correlations in the meteorology and chemical engineering literature. The prediction of the aqueous phase mass transfer coefficient, based upon correlations from the chemical engineering and oceanography literature, is discussed. Third Symposium on Atmospheric Turbulence, Diffusion, and Air Quality, Oct. 26-29, 1976, Raleigh, NC; Amer. Meteorological Soc., Boston (1976).

Sensitivity Tests with a Parameterized Mixed-Layer Model Suitable for Air Quality Simulations

D. Keyser and R. A. Anthes

Several modifications to the one-layer mesoscale numerical model which Lovoie developed and applied to Great Lake snowstorms are formulated and tested. The model atmosphere consists of a parameterized constant-flux layer of fixed depth, as well-mixed layer capped by an inversion, and a deep layer of stable air overlying the mixed layer. Time-dependent calculations of the horizontal components of the wind velocity, potential temperature and the height of the base of the inversion are performed over a mesoscale grid. Since the mixed-layer assumption eliminates the dependence of the prognostic variables on height, the low-level mean flow can be predicted far more cheaply than with multi-layer models.

The major refinements introduced in this paper lie in the parameterization of the effects of the stable layer on the mixed-layer, the entrainment of mass, heat and momentum into the mixed-layer by subgrid-scale eddies, and the erosion of the inversion by heating. The sensitivity of the model solutions to the initial inversion height and strength, the stability of the upper layer, the vertical shear of the geostrophic wind, and the height of the undisturbed level in the overlying stable layer is investigated. These tests are performed for an east-west cross-section for moderate flow over complex terrain. EPA Conference on Modeling and Simulation, Cincinnati, Ohio, April 20-22, 1976.

Diabatic Heating Experiments With a Mixed-Layer Model Suitable for Air Quality Simulations

D. Keyser and R. A. Anthes

The single-layer model of a well-mixed PBL has been applied to three different physical situations where sensible heating at the surface may significantly modify mesoscale flows. The sensible heat flux has been shown to exert considerable control in the vertical development of the PBL through the entrainment process in all cases. Furthermore, when the synoptic-scale pressure gradient force is absent, differential heating is the primary process governing the evolution of PBL flows.

The assumption of vertical homogeneity is the most severe limitation of the model. Even with this limitation, the model is able to depict some of the gross features of a sea breeze, although it cannot resolve the detailed structure. The performance of the model in the case of the urban heat island appears realistic. This result is encouraging because the flow patterns induced by an urban heat island are indeed germane to air quality modeling efforts. Third Symposium on Turbulence, Diffusion, and Air Quality, Oct. 26-29, Raleigh, NC; Amer. Meteorological Soc., Boston (1976).

The Applicability of a Mixed-Layer Model of the Planetary Boundary Layer to Real-Data Forecasting

D. Keyser and R. A. Anthes

The mesoscale numerical model of the planetary boundary layer (PBL), which Lavoie applied to lake-effect snowstorms and the airflow over the Hawaiian Islands, is modified and utilized to assess the feasibility of producing short-range real-data forecasts of low-level flow patterns. The dry model atmosphere comprises three layers. A parameterized surface layer of fixed depth (50 m) follows the variable terrain and allows vertical fluxes of heat and momentum to affect the flow in the overlying PBL or "mixed layer." The horizontal wind velocity and potential temperature, both prognostic variables, are assumed to be independent of height in the mixed layer. The height of the top of the mixed layer is an additional prognostic variable. A parameterized stable layer, characterized by a vertically constant potential temperature lapse rate, overlies the mixed layer. Synoptic-scale patterns of pressure and potential temperature are specified at the top of this uppermost layer as upper boundary conditions. Energy-conserving parameterizations for the entrainment of heat and momentum from the upper stable layer into the mixed layer and for convective adjustment are introduced. The simplifications in the atmospheric structure provide for considerable computational efficiency while preserving a high degree of physical realism under the assumed conditions of a well-mixed PBL.

Experiments with a cross-section version of the model are performed for a domain containing a smoothed Appalachian terrain profile and adjacent coastal waters in order to economically assess the model's response to variable terrain, differential heating, and differential roughness at the coast. The terrain profile produces a perturbation in the quasi-steady-state westerly flow pattern that exhibits subsidence and higher wind speeds over a ridge in qualitative agreement with mountain-wave theory. While differential roughness causes subsidence at the coast, differential heating engenders a maximum of upward motion around 40 km inland that is considered to be a crude representation of a sea breeze superimposed on the westerly flow. The results of the cross-section experiments are used to aid in interpreting a real-data simulation of the daytime PBL over the MIddle Atlantic States on 16 October 1973. The model resolves a lee trough in the flow east of the Appalachians, a surface pressure trough in eastern Virginia and eastern North Carolina, and realistic vertical motion patterns along the coastal regions and the Chesapeake Bay. Verification statistics are provided for the sea-level pressure and surface potential temperature patterns. Submitted to Monthly Weather Review.

Pressure-Strain Correlation

J. L. Lumley

It is shown that the separation of the pressure-strain correlation into a transport and a deviatoric term is not unique, and that the customary separation appears likely to be the wrong choice. Phys. of Fluids, Vol. 18, p. 750 (1975).

Modeling Turbulent Flux of Passive Scalar Quantities in Inhomogeneous Flows

J. L. Lumley

It is suggested that, in an inhomogeneous turbulent flow, the flux of a passive scalar admixture should be modeled to first order by a linear combination of gradient transport and convective transport, where the convective transport coefficient is proportional to the gradient of the (gradient)-transport coefficient. A simple model is presented which allows determination of the coefficient of proportionality. Phys. of Fluids, Vol. 18, 619-621 (1975).

Simulation of Turbulent Transport in Urban Air Pollution Modeling

J. L. Lumley

Urban air pollution models are classified into K-theory types (including Gaussian plume and Lagrangian models) and second order models. It is shown that the K-theory models cannot predict the countergradient heat, contaminant and other fluxes which are observed in convective situations. The second order models are examined in detail: recent questions raised regarding accuracy requirements in second order models are put to rest, and settling down times discussed; the response to rapid change of mean conditions, realizability conditions, large Reynolds number behavior and buoyant transport are described as areas in which many second order models fail. A schedule is presented for verification of second order models by reference to a sequence of laboratory flows embodying selected phenomena in various combinations. Advances in Environmental Science and Engineering, Vol. 1, Gordon Breach (1978).

Modeling of Turbulent Fluxes of Momentum and Heat in a Stratified Flow

J. L. Lumley and B. Khajeh-Nouri

This paper is based upon two related methods which make possible the generation of models of all orders of the third moments and of all orders in the Reynolds number in a straightforward manner (Lumley and Khajeh-Nouri, 1973). The technique is equally applicable to stratification, pollution dispersal, chemical reactions, etc. In addition, the method is not terribly expensive. Many of the terms the technique generates are those suggested by others. But in the case of the third order transport terms we will find that it is inconsistent within the model not to allow the flux of one second order quantity to be produced by gradients of all the others. This is much like the molecular flux of salt that can be produced in a liquid by a temperature gradient and vice versa. This leads to the important possibility of upgradient diffusion which is a process that occurs in atmospheric modeling. This is unlike the situation in kinetic theory where the corss diffusion coefficients are ordinarily small, because the turbulent cross diffusion coefficients may be substantial. The forms obtained under the artificial situation of constant eddy viscosity and constant structure reduce to the classical forms assumed by other authors on their ad-hox basis. Translated from Lzvestiya Akad. Nauk, SSSR, Fizika Atmosferi i Okeana, Vol. 10, 636-645 (1974).

Computational Modeling of Turbulent Transport

J. L. Lumley and B. Khajeh-Nouri

We present two related techniques which make it possible to generate, in a consistent and straightforward manner, models of all orders of the third moments, and of all order in Reynolds number. The technique is equally applicable to stratification, to pollution dispersal, to chemical reactions, etc. Many of the terms generated are essentially those suggested by other authors on an ad hoc basis. However, in the case of the third order transport terms, we find that it is inconsistent within the model not to allow the flux of one second order quantity to be produced by gradients of all the others, much as a molecular flux of salt can be produced in a liquid by a temperature gradient, and vice versa. This opens the possibility of up-gradient diffusion, an important process in atmospheric modeling. Unlike the situation in kinetic theory, where the cross-diffusion coefficients are ordinarily small, the turbulent cross-diffusion coefficients may be substantial. However, in the (artificial) situation of constant eddy viscosity and constant structure, the forms obtained reduce to the classical forms assumed by other authors on an ad hoc basis. Advances in Geophysics, Vol. 18, 169-192; Academic Press, New York (1974).

The Influence of Buoyancy on Turbulent Transport

J. L. Lumely, O. Zeman, and J. Siess

Turbulent transport of fluctuating turbulent energy, turbulent momentum flux, temperature variance, turbulent heat flux, etc. in the upper part of the atmospheric boundary layer is usually dominated by buoyant transport. This transport is responsible for the erosion of the overlying stably stratified region, resulting in progressive thickening of the mixed layer. It is easy to show that a classical gradient transport model for the transport will not work, because it transports energy in the wrong direction. On the other hand, application of the eddy-damped quasi-Gaussian approximation to the equations for the third moments results in a transport model which predicts realistic inversion rise rates and heat flux profiles. Submitted to J. Fluid Mech.

Aerosol Measurements Over St. Louis: Some Preliminary Results

Y. Mamane and J. A. Pena

Simultaneous measurements of aerosol, turbulence, solar radiation and state parameters were taken over St. Louis, during summer, 1974, using the PSU Meteorology research aircraft (Aerocommander 680E) as a platform.

The body of information presented in this paper is directed to scientists and air pollution agencies interested in the urban atmospheric aerosols.

Vertical and horizontal flight soundings were designed to map in two dimensions, i.e., vertical cross sections along the wind direction or horizontal mapping of the metropolitan area of St. Louis at different levels, below and above the mixing layer. Flights were taken during different parts of the day and in various meteorological conditions.

This paper describes vertical and horizontal variations of the particle concentration (.5μ dia.), the scattering coefficient, the particle mass concentration, and the concentration of condensation nuclei. These parameters were measured, respectively, using a Particle Counter Royco 225, an Integrating Nephelometer MRI 1550, a Particle Mass Monitor Thermal Systems 3200A, and a Condensation Nuclei Monitor Environment One Rich 100. The air for the instruments was sampled using an isokinetic probe. To eliminate humidity effects on some of the measurements, a heater was placed in the sampling inlet of the Particle Counter and the Particle Mass Monitor.

A preliminary analysis of the aerosol data indicates the following:

(1) The vertical distribution of the particle concentration, the scattering coefficient, and partially the relative humidity are highly affected by the temperature lapse rate.

(2) Comparison of three crosswind horizontal legs shows that downwind of St. Louis particle concentration, concentration of condensation nuclei and scattering coefficient are much higher than those obtained upwind of St. Louis.

(3) No large variations in aerosol profiles did happen during the same day.

(4) The ratio of condensation nuclei concentration to large particle concentration varies between 8-200 under polluted conditions in comparison to 100-5000 under "clean" conditions.

Proc. 68th Meeting, Air Poll. Contr. Assoc., Boston, Jun 15-20, 1975.

A Model for Uptake of Pollutants by Vegetation

R. A. O'Dell, M. Taheri, and R. L. Kabel

A mass transfer approach is used in developing a practical mathematical model of gaseous pollutant uptake by leaves in which a series of resistances is summed across a concentration difference. The body of information presented in this paper is directed to plant pathologists or physiologists in the field of vegetal-pollutant effects and to people interested in the natural removal of air pollutants by vegetation. Correlations are given to calculate the aerodynamic and the stomatal resistances to uptake, while both a qualitative investigation and quantitative estimates are made of the mesophyllic resistance. The factors which control the aerodynamic resistance, r_a, are leaf size and wind speed, while the leaf physiology is the determinant of the stomatal resistance, r_s. It is noted that the chemical reaction rate and pollutant diffusivity in the mesophyll controls the mesophyllic resistance, r_m, through the overall gas phase mesophyllic resistance, Hr_m, is strongly a function of pollutant solubility in water. Finally, the overall model is compared to earlier experimental work on vegetal uptake of SO_2. J. Air Pollution Control Assoc., Vol. 27, pp. 1104-1109 (1977).

Isokinetic Sampler for Continuous Airborne Aerosol Measurements

J. A. Pena, J. M. Norman and D. W. Thomson

For aerosol measurements, especially those concerned with the aerosol particle size distribution, it is important to sample in isokinetic conditions. Most available instrumentation for aerosol measurements is intended for use on the ground under light wind conditions; intake air speeds rarely exceed a few meters per second. If the same instrumentation is used onboard an aircraft, the air must be decelerated 60 or more m/sec before it is sampled by individual instruments.

On the Pennsylvania State University Meteorology research aircraft, the air for all aerosol instruments is decelerated in a single isokinetic sampler located above the roof of the cabin outside the aricraft boundary layer. The air enters the sampler through a carefully designed circular intake. Its velocity is reduced as the cross section increases along a 7° conical diffuser. The expansion cone terminates in a cylindrical chamber in which the air velocity is 1/16 the aircraft speed. Behind the sampling chamber the air is accelerated in a second conical section to an end exhaust port. Exhaust port "pumping" is used to compensate internal losses and, thus, helps preserve the isokinetic nature of the sampler.

Tubes leading to individual instruments are located in the sampling chamber and may be individually adapted to match the air sampling velocity with the local air speed inside the sampling chamber. The level of turbulence ($u_{rms}/\bar{u}$) in the sampling section is ≈0.05.

The sampler has been thoroughly wind tunnel and flight tested and successfully used in August and November, 1974, for field programs in the St. Louis and Tucson metropolitan areas, respectively. J. Air Pollution Control Association, Vol. 27, pp. 337-341 (1977).

Global Emissions and Natural Processes for Removal of Gaseous Pollutants

K. H. Rasmussen, M. Taheri, R. L. Kabel

This review briefly illustrates the state of the art in the recognition of the various sources and natural sinks of gaseous pollutants. The removal mechanisms include absorption by vegetation, soil, stone, and water bodies, precipitation scavenging, and chemical reactions within the atmosphere. The nature and magnitude of anthropogenic and natural emissions of the gases (H_2S, SO_2, N_2O, NO, NO_2, NH_3, CO, O_3, and hydrocarbons), along with their ambient background concentrations and information on their major sinks identified to date, are discussed. Air, Water, and Soil Pollution, Vol. 4, pp. 33-64 (1975).

Atmospheric Particulate Properties Inferred from Lidar and Solar Radiometer Observations Compared with Simultaneous, In-Situ Aircraft Measurements: A Case Study

J. A. Reagan, J. D. Spinhirne, D. M. Byrne
D. W. Thomson, R. Pena, Y. Mamane

Particulate size and height distributions, complex refractive index, and mass loading have been measured and inferred from direct aircraft and indirect lidar-solar radiometer observations made during a unique joint experiment conducted the week of 18 November, 1974 in Tucson, Arizona. The aircraft and lidar-solar radiometer measurements were first analyzed independently and the results were then intercompared. Vertical profiles of particulate extinction obtained from the lidar (monostatic) and aircraft measurements were found to be in excellent agreement on both a relative and absolute basis. Lidar (bistatic and monostatic) inferences of particulate mass loading agreed favorably with the aircraft mass monitor measurements. The aircraft and lidar (bistatic) size distribution determinations were found to be similar in shape and agreed in absolute value within an order of magnitude. The mean particle refractive index inferred from the lidar (bistatic) measurements (n = 1.40 - 10.000) agreed with the index of a significant fraction of the particles identified by electron microscope analysis of impactor samples collected with the aircraft. J. Applied Meteorology, Vol. 16, pp. 911-928 (1977).

Vertical Profiles and Size Distributions of Particulates Over St. Louis, Missouri

K. L. Schere and D. W. Thomson

Vertical profiles and size distributions of the aerosol burden upwind, over, and downwind of the St. Louis metropolitan area were studied concurrently with the 1973-74 Regional Air Pollution Study (R.A.P.S.). High

resolution airborne data were obtained in the 0.5-8.0 μm range using a light-scattering particle counter (ROYCO Model #225) adapted for airborne sampling. Vertical profiles of the particulate number density (d_p > 0.5 μm) were measured upwind and downwind in different air mass types and at different times during the day. A marked homogeneity is evident in particulate number density within the mixed layer, especially during afternoon hours. Although this feature is present in air masses of differin; origin, the magnitude of the particulate number concentration is observed to differ by more than an order of magnitude from one air mass to another. Many individual profiles exhibit the masking influence of near-by anthropogenic sources on the normal dispersion patterns.

Airborne estimates of the size distributions of the aerosols were also obtained. Five finite intervals between 0.5 μm-dia. for each size distribu- were used. A power law was found to fit the data well. Each size spectrum was thus characterized by a relationship of the form $dN/d(\log r) = ar^{-\beta}$, where the coefficient "a" is indicative of the total particle loading and β represents the slope of the distribution. Both "a" and β were found to vary substantially from the mixed layer to the layer immediately above. Within the mixed layer "a" appears to be most sensitive to the air mass type, while β was generally about 3. The effects of the changing proportions of large and small particles on the size spectra are seen to affect the slope of the size distribution. Representative size distributions are presented in power law form for each of two distinct air masses and altitudes. Proc. 68th Annual Meeting, Air Pollution Control Assoc. Boston, June 15-20, 1975.

A comparison of Haurwitz Wave Forecasts With One-Way and Two-Way Interacting Nested Grids

J. P. Sobel and R. A. Anthes

A technique for constructing a two-way interacting, moving nested grid that is suitable for the prediction of extratropical waves is presented. The technique conserves horizontal fluxes of mass and momentum across the interface of the meshes and utilizes varying time steps on each mesh.

The two-way meshed system is tested on Haurwitz waves in which there is strong flow across the interface. A one-way interacting meshed system, in which the equations on the coarse mesh grid are integrated independently of those on the fine mesh grid and then used to provide boundary conditions for the fine mesh is also tested. When long waves (relative to the coarse mesh) exist, both meshed systems produce adequate and similar results. When short waves (relative to the coarse mesh) exist on both meshes, the skill of the forecast deteriorates rapidly with time. Again, both meshed systems produce similar results. However, when a long wave exists on the coarse mesh and the fine mesh contains both the long and a shorter wave, the two-way interacting system produces superior results. Submitted to J. Applied Meteorology.

Circulations Associated with a Jet Streak in Nested Grid Models

J. P. Sobel and R. A. Anthes

A three-dimensional nested grid model is constructed in order to study mesoscale atmospheric circulations. The model is tested on a jet streak which propagates across the fine mesh grid. The two-way interacting nested grid system handles this case of strong flow normal to the boundary well. In contrast, a one-way interacting nested grid system shows considerably more numerical noise, and is therefore judged inferior.

The vertical circulations induced by the jet streak are studied in some detail. During the first three hours of the forecast, a two-cell vertical motion pattern develops across the jet streak in response to the supergeostrophic nature of the streak. After the initial adjustment period, however, there is a tendency to develop a four-cell pattern in the vertical motions in agreement with Riehl's equivalent barotropic jet stream model. Submitted to J. Applied Meteorology.

A Model for the Dynamics of the Inversion
Above a Convective Boundary Layer

H. Tennekes

The differential equations governing the strength Δ (a potential temperature difference) and the height h of inversions associated with dry penetrative convection are considered. No assumptions on the magnitude of the downward heat flux at the inversion base are needed to obtain an algebraic equation that relates h and Δ to the heating history of the boundary layer and to the initial conditions. After the nocturnal inversion has been filled in by heating, the inversion base generally grows linearly with time in the morning, but is proportional to the square root of time in the afternoon. The variation of Δ with time differs greatly from case to case. J. Atmos. Sci., Vol. 30, pp. 558-567 (1973).

Reply

H. Tennekes

In a letter to the author, Zilitinkevich proposed a parametric expression for the temporal term in the turbulence energy budget at the inversion base of a mixed layer. In this reply, the Zilitinkevich scheme is discussed and limiting cases of the mixed layer development are investigated. J. Atmos. Sci., Vol. 32, pp. 992-995 (1975).

Observations on the Dynamics of Simple Box Models with a Variable Inversion Lid

H. Tennekes

Mixing-height parameterization is an integral part of the boundary-layer and cumulus-cloud parameterization schemes needed in advanced numerical weather predictions on regional and synoptic sales.

The mixing height limits vertical dispersion over relatively long distances. The effects of an inversion lid can be studied best if an air quality simulation model that includes the mixing height as an explicit variable is used. A box model for pollution in a large urban area with distributed sources appears to be ideally suited for this purpose. This paper explores some of the problems associated with the effects of mixing-height variations on box models. Third Symposium on Turbulence, Diffusion, and Air Quality, Oct. 26-29, 1976, Raleigh, NC; American Meteorological Society, Boston (1976).

The Effects of Mixing-Height Variability on Air Quality Simulation Models

H. Tennekes

Recent progress in inversion-rise parameterization suggests that the simple schemes developed by Betts, Carson, Deardorff, and Tennekes are quite adequate for applications to air-pollution meteorology. Diurnal and seasonal cycles of the mixing height now can be predicted with confidence. It is thus timely to ask how mixing-height variations affect the pollutant concentrations predicted by air quality simulation models. This paper considers that question by exploring the role of mixing-height changes in simple box models. It is found that the variations of the mixing height have significant effects on the climatology of box models, and that the behavior of a box model during episodes of poor ventilation is modified profoundly by the amplitude of the diurnal cycle in the mixing height. Advances in Environmental Science and Engineering, Vol. 1, Gordon and Breach (1978).

Short Term Forecasts of Temperature and Mixing Height on Sunny Days

H. Tennekes and A. P. van Ulden

This paper reports on studies made at the Roayl Netherlands Meteorological Institute since the spring of 1973. In the first part of the paper, the inversion-rise model of Tennekes (1973) is used for forecasts pertaining to a fairly large number of days in 1971; in the second part, six representative forecasts are discussed in detail, and in the third part, progress in the determination of boundary conditions, initial conditions, and adjustable numerical coefficients is reported. Proc., Symposium on Atmospheric Diffusion and Air Pollution, Santa Barbara, CA; American Meteorological Society, Boston (1974).

Parameterization of the Turbulent Energy Budget at the Top of the Atmospheric Boundary Layer

O. Zeman and H. Tennekes

The budget of turbulent kinetic energy at the base of the inversion which caps the atmospheric boundary layer depends on the lapse rate of potential temperature in the air aloft. The principal gain term in the energy budget is turbulent transport of kinetic energy, the principal loss term is buoyant conversion of kinetic energy into potential energy. The contributions made by these and other terms in the energy budget need to be parameterized for applications to inversion-rise prediction schemes. This paper contains a detailed analysis of the effects of anomalous dissipation near the inversion base, which leads to reduced entrainment if the air aloft is very stable. The parameterized energy budget also includes the Zilitinkevich correction, the influence of mechanical energy production near the inversion base, and modifications needed to incorporate cases in which the surface heat flux is negligible . Extensive comparisons of the theoretical model with experimental data indicate that a simplified treatment of the energy budget is adequate for forecasts of the development of convective mixed layers. The parameterization scheme is also applicable to thermocline erosion in the ocean; in that case, however, some of the minor terms in the energy budget often play a major role. J. Atmos. Sci., Vol. 34, pp. 111-123 (1977).

Acdar Meteorology: The Application and Interpretation of Atmospheric Acoustic Sounding Measurements

D. W. Thomson

Quantitative estimates of atmospheric structure have been derived from refractively propagated sound signals for more than 50 years. For example, data from both natural and artificial explosions have been used to estimate mean tropospheric and stratospheric temperature and wind profiles (see eg. 1, 2 or rev. art. 3). Acoustic refraction measurements still are being researched. Recently, Chang (4) and Greenfield et al (5) investigated the use of infrasonic and sound signals, respectively, for measuring winds and temperature gradients in the planetary boundary layer (PBL).

During the last decade, however, some of the most exciting research in indirect atmospheric probing has been in the area now generally known as "acdar meteorology." That is, in the development and application of Acoustic Detection And Ranging systems for a wide variety of experimental and routine atmospheric measurements. Although Gilman et al (6) were the first in 1944 to make acdartype atmospheric measurements, and Kelton and Bricout had successfully made wind velocity measurements in 1964 (7), it was not until 1968 when McAllister (8) published vertical time sections of range-compensated acdar signals back-scattered in the lower troposphere, that the meteorological community recognized the tremendous potential of acdar observations. Shortly thereafter, Little's review paper (9) and a more complete report by McAllister et al (10) provided the basic information required for many groups to begin acdar research. Today, individual sounders are as diverse in sophistication, type, geometric configuration, operating frequency, and pulse length and repetition frequency as their contemporary microwave radar counterparts. Most monostatic (common transmit-receive antenna) systems, including commercially available units, provide a vertical time section of scattered signal intensity as a function of height. Because the turbulent velocity and temperature fluctuations which scatter the acoustic energy may be associated with identifiable atmospheric structural features, monostatic sounders may be used to observe phenomena such as waves, variations in the height of the mixing layer and thermal plumes. More sophisticated phasecoherent monostatic and bistatic (separated transmit-receive antennas) systems also output as a function of range the scattered signal Doppler frequency. Hence, depending upon the system configuration, they may be used to sense one or more components of the vector wind as a function of height. Third Symposium on Meteorological Observation and Instrumentation, Feb. 10-13; pp. 144-150 (1975).

The Select Research Group in Air Pollution Meteorology

D. W. Thomson

The Select Research Group is one of the University's largest continuing interdisciplinary research programs. The program is coordinated jointly by the Department of meteorology and the University Center for Air Environment Studies, and there are participating faculty and students in the Departments of Meteorology, Aerospace Engineering, Geosciences, Chemical Engineering, Chemistry, and Mechanical Engineering. Earth and Mineral Sciences, V. 44, pp. 59-60; The Pennsylvania State University (1975).

Analysis and Simulation of Phase Coherent Acdar Sounding Measurements

D. W. Thomson and R. L. Coulter

The phase surface geometry and its dependence upon system and atmospheric parameters for both monostatic and bistatic acadar sounders is discussed. The observed Doppler frequency shift is shown to be a consequence of the motion with respect to the equiphase surfaces of many distributed atmospheric scatters. Because acdar measured average Doppler frequencies and Doppler spectra are integral functions of system-related and atmospheric structure-dependent weighting functions, application of simple models that assume signal scattering only along the antenna beam axis may result in significant wind velocity measurement errors. It is further shown that accurate quantitative estimates of C_T^2 and C_V^2 for thin turbulent layers require detailed analysis of the bistatic acdar common volume. Two techniques, based on distributed acdar signal phase and amplitude fluctuations. J. Geophysical Research, Vol. 79, pp. 5541-5549 (1974).

Simultaneous Measurements of Turbulence in the Lower Atmosphere Using Sodar and Aircraft

D. W. Thomson, R. L. Coulter, and Z. Warhaft

Simultaneous measurements of C_T^2 and C_V^2 were made using a calibrated Doppler sodar and a research aircraft equipped with meteorological and turbulence sensors. In each experiment a region of specific interest was identified using the sodar and then the aircraft vectored into it using air-ground radio. Measurements were made in both "layers" (with and without detectable turbulence and "waves") and in convective plumes. In each case the spectra of turbulent temperature and velocity fluctuations derived from the in-situ observations showed a well developed inertial subrange. Excellent agreement was found between the magnitude of the in-situ aircraft C_T^2 and C_V^2 values and those derived from the sodar signals interpreted using the Tatarski scattering theory.

Examples are shown of how sodar may be used for real-time, quantitative estimates of the dissipation rate of turbulent kinetic energy ε, and the rate of destruction of temperature variance N. On the present Penn State sodar system the operator may select a display of C_T^2, C_V^2, ε, N or winds derived from signal Doppler shifts. Either time series at selected heights, vertical time sections on a color, digital video display or conventional printed or graphical output may be produced. J. Appl. Meteor., V. 17, 723-734 (1978).

Improved Display Techniques for Sodar Measurements

D. W. Thomson and J. P. Sheib

Improved quantitative display techniques, including digital false-color systems, for use with sodar or other similar remote probing systems are discussed. With sodar the use of a false-color system greatly facilitates real-time measurements of temperature and velocity structure functions, the dissipation rates of turbulent kinetic energy and temperature variance in the planetary boundary layer of the atmosphere, and the vertical wind and wind shear profiles. Bulletin American Meteorological Society, Vol. 59, pp. 147-152 (1978).

The Initial Growth of Data-Related Errors in Mesoscale Weather Prediction Models

T. T. Warner

A set of stochastic-dynamic equations was utilized to investigate the error-energy transfer that occurs during the initial adjustment phase of numerical models. The results were interpreted in terms of mesoscale data accuracy requirements, the general mesoscale predictability problem, and the use of various initialization techniques.

Synoptic-scale experiments showed the existence of an equilibrium value of the initial standard error of the north-south wind component v, of about 1.2 ms^{-1}, for an initial standard error in the temperature data of 1°C. Any value of the initial v error lower than the equilibrium value produced a net flux of uncertain energy into the v component, thereby increasing the variance back toward the equilibrium level. Conversely, an initial v error larger than the equilibrium value caused a net flux of uncertain energy out of the v component, which again caused the variance in v to adjust back toward the equilibrium value.

It was shown that, on the mesoscale, small mass and momentum initial data errors are not strongly coupled in the sense that there is very little transfer of error-related energy or uncertainty from one variable to another. The nature of the adjustment process on the mesoscale effectively insulates the velocity field from mass field data errors. Conversely, the mass field is only very slightly perturbed by velocity field data errors because the magnitude of the displacement of the fluid required to produce a mass field in balance with the velocity errors is minimal. The energy in the initial mass field errors is partitioned to the gravity-inertia wave modes which, in most realistic mesoscale models, propagates out of the forecast domain through open boundaries or is damped by special time-differencing schemes. This initial error-energy is thus only a temporary contaminant of the forecast. Except for the fact that the amplitude of the gravity-inertia waves would be proportional to the magnitude of the initial mass field error, the magnitude of the uncertainty in these data is relatively unimportant, within reasonable bounds. The velocity errors, however, maintain their amplitude and location during the adjustment phase of the forecast, and thus are clearly the most crucial on the mesoscale.

These results indicate that the predictability of a mesoscale forecast will be degraded most in situations where existing instabilities or near - instabilities are related to the velocity field rather than the mass field. The perturbations in the mass field, associated with initial mass field data errors, tend to produce only transient gravity-inertia waves. However, the velocity errors persist in time and thus provide the most probable origin for the unrealistic suppression of generation of unstable flow patterns.

Certain initialization procedures were shown to have definite advantages when viewed in terms of the error-energy transfer characteristics of the mososcale adjustment process. The use of initialization methods which determine the velocity field from the mass field, results in an initial velocity field with a very high error variance even though the fields may be dynamically balanced. This problem may be serious since the large errors are produced in the very variables which are unable to dissipate their error-energy by partitioning it to the gravity-inertia wave mode during the adjustment process. On the other hand, methods which diagnose the mass field as a function of velocity observations (e.g., through the use of a balance equation) do not suffer from this problem. The initial velocity errors produce only small amplitude anomalies in the mass field which are rapidly eliminated. Third Symposium on Turbulence, Diffusion, and Air Quality, Raleigh, NC, Oct. 26-29, 1976; American Meteorological Soc., Boston (1976).

Numerical Simulations with a General, Three-Dimensional Mesoscale Model that is Suitable for Air Pollution and Other Mesometeorological Studies

T. T. Warner, R. A. Anthes, A. L. McNab

For the past four years, the Pennsylvania State University (PSU), under the support of the Environmental Protection Agency (EPA), has been developing time-dependent dynamic models for use in air pollution and other meteorological studies. PSU is developing a general, hydrostatic model suitable for forecasting flows with characteristic horizontal wavelengths of approximately 10-2500 km under a variety of meteorological conditions (see Anthes and Warner, 1977 and Warner, et al., 1977). For example, the model may be applied either as a coarse - resolution urban model (grid spacing - 2.5 km) or as a subsynoptic - scale regional model (grid size - 200 km). In particular, we are modeling perturbations to the synoptic flow induced by terrain variations, land-water contrasts, convective systems such as squall lines and clusters of cumulonimbi, frontal systems, and propagating upper-level disturbances such as jet streaks.

The primary goal of EPA in developing the above model lies in utilizing the model as a research tool capable of providing meteorological information that is necessary for rational decision making over questions concerning air quality standards. Specifically, information such as expected flow patterns and concentrations of pollutants under a variety of weather conditions at diverse locations is required in the preparation of environmental impact statements that are now required before proposed actions such as nuclear power plant construction are approved. Joint Conference on Applications of Air Pollution Meteorology, Salt Lake City, Utah, Nov. 28 - Dec. 2, 1977.

Numerical Simulations with a Three-Dimensional Mesoscale Model

T. T. Warner, R. A. Anthes, A. L. McNab

Four numerical experiments are conducted using a mesoscale primitive equation model developed at the Pennsylvania State University. The experiments illustrate the broad spectrum of applications made possible by the model's flexibility in treating subgrid-scale parameterizations, lateral boundary conditions, and physical processes appropriate to the scale of each simulation. One experiment uses real synoptic-scale data to produce a 12-hour forecast that is compared to the observed circulation and precipitation patterns. The other experiments are initialized with idealized flows over areas ranging in size from regional to small mesoscale. The idealized flow simulations produce qualitatively realistic features such as lee side troughs and sea, lake, and mountain-valley breezes resulting from differential thermal forcing. Submitted to Monthly Weather Review.

A Second-Order Model for Buoyancy Driven Mixed Layers

O. Zeman and J. L. Lumley

A second-order modeling technique for stratified turbulent flows with application to buoyancy driven mixed layers is presented.

The models of pressure terms, dissipation, and destruction of temperature variance are to a great extent based on invariant techniques. The unknown constants in these models were determined empirically. The turbulent transport model, based on solutions to the approximated rate equations for the third order turbulent moments, incorporates buoyancy effects. The buoyancy contributions to the third moments were found to be crucial to modeling the dynamics of entrainment. The numerical results presented illustrate the capability of the model to realistically predict the structure of the entraining mixed layer including the vertical flux of turbulent energy and the downward heat flux at the mixed layer-inversion interface.

The second-order technique is also applied to the process of vertical diffusion of a passive contaminant released from a distributed source near the mixed layer surface. Proceedings, ICHMT International Seminar, "Turbulent Buoyant Convection," Dubrovnik; Hemisphere Publ. Co., Washington, D.C., pp. 65-76 (1976).

Modeling Buoyancy Driven Mixed Layers

O. Zeman and J. L. Lumley

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Turbulence and Diffusion Modeling in Buoyancy Driven Mixed Layers

O. Zeman and J. L. Lumley

In this paper we develop a second order model for buoyancy-driven mixed layer (hereafter BDML), i.e. the family of entraining flows where the energy input is provided by a prescribed surface heat (density) flux.

The entrainment of stable fluid into the well-mixed turbulent region takes place within a narrow region: the erosion layer, at the mixed layer top. The process of entrainment entails destruction of turbulent energy. In order to maintain the entrainment process the erosion layer has to be supplied with enough turbulent energy through turbulent transport. Hence, modeling the entrainment process realistically is predicated on a realistic model of the third-order turbulent fluxes.

In the past, second-order models for atmospheric entraining layers were developed by Wyngaard and Coté (1975), Lewellen and Teske (1975), and Yamada and Mellor (1975). These models utilize simple gradient transport for the third order fluxes. We have found that traditional gradient transport models are inadequate and that buoyancy effects have to be accounted for in the transport if the entrainment mechanism is to be predicted realistically.
Third Symposium on Atmospheric Turbulence, Diffusion, and Air Quality, Oct. 26-29, 1976; Raleigh, NC: American Meteorological Society, Boston (1976).

Buoyancy Effects in Entraining Turbulent Boundary Layers: A Second-Order Closure Study

O. Zeman and J. L. Lumley

A second-order modeling technique is used to investigate the structure of turbulent boundary layers under stable, neutral and unstable conditions. Special attention is paid to the evening transition from a convective to a stable regime of an atmospheric entraining boundary layer capped by an inversion.

The second-order closure scheme utilizes the turbulent transport model which incorporates buoyancy effects (Zeman and Lumley, 1976). The importance of the buoyancy contributions in the turbulent transport model for the process of entrainment and for the turbulence decay during the evening transition is discussed. Proceedings, Symposium on Turbulent Shear Flows, The Pennsylvania State University, University Park, PA, pp. 6.21-6.28 (1977).

A Self-Contained Model for the Pressure Terms in the Turbulent Stress Equations of the Neutral Atmospheric Boundary Layer

O. Zeman and H. Tennekes

In this paper we develop an abbreviated model for the pressure-gradient velocity correlation terms in the equations for the Reynolds-stress components in the neutral boundary layer. The model contains three terms: a nonlinear return-to-isotropy term, a mean strain-rate term, and a mean vorticity term. There are three free constants in the model, which are determined with the aid of experimental results on the ratios between the Reynolds-stress components in the neutral surface layer. Since three independent equations are involved, the model is self-contained. Through its mean vorticity term, the model incorporates the effects of a rotating coordinate system. The application of the model to a neutral Ekman layer give realistic results. J. Atmos. Sci., Vol. 32, pp. 1808-1813 (1975).

Parameterized Energetics of Boundary-Layer Growth in the Atmosphere and the Ocean

O. Zeman and H. Tennekes

The height of the mixed layer in the atmosphere and the depth of its counterpart in the upper ocean are of great concern in regional- and large-scale studies of air and water pollution. The rate of growth of these layers into their stably stratified environments is parameterized with the aid of the energy budget at the inversion base or thermocline. The principal term is the conversion of turbulent kinetic energy into potential energy, but terms representing temporal changes, anomalous dissipation, and mechanical energy production near the interface are also accounted for. There are indications that the flux divergence of gravity-wave energy may lead to slower entrainment in some cases. The theoretical model has been compared with data from a wide variety of sources; it appears to be capable of handling most parameter combinations that occur in nature. For convective boundary layers in the atmosphere, the present model supports the simple parameterization developed by Betts, Carlson, Deardorff, and Tennekes. In most other conditions, however, it is not advisable to work with a drastically simplified energy budget. Proc. Third Symposium on Atmospheric Turbulence, Diffusion, and Air Quality, Raleigh, NC; October 26-29, 1977; American Meteorological Society, Boston, pp. 397-402 (1976).

SECTION 4

CONTRIBUTION TO EDUCATION AND MANPOWER

One of the key elements of the SRG concept has been its involvement in the training of men and women for careers in interdisciplinary fields of importance to air quality control. A substantial fraction of the SRG effort has involved students, and more than 30 candidates for the M.S. and Ph.D. degrees cooperated in the group's research.

Listed below are abstracts of six Ph.D. and 23 M.S. theses that were completed by students whose assistantships were supported by the SRG grant.

Detailed Analysis of Urban Ground Temperatures Using High Resolution Satellite Measurements

J. A. Augustine

A diverse system has been developed for application to various types of satellite data. Its capabilities include variable smoothing, character mapping, contouring, subsetting, and geographical location.

After development the system was implemented to analyze effects of urbanization on surface temperature patterns. Both day and night VHRR data of the Los Angeles area under clear atmospheric conditions were used. To correct for absorption by water vapor in the IR channel, a parametric formula, which gives the temperature deficit between the measured and actual surface temperatures as a function of integrated water vapor, was applied.

The surface of the Los Angeles basin has been greatly influenced by man. Construction of buildings and other artificial structures or surfaces inhibit evaporation and also serve as strong conducting media for the retention of heat. The built up area, because of increased roughness, shadowing, and high thermal inertia shows daytime surface temperatures that are somewhat lower than those of the flat industrial regions. But after sunset, because of high storage during the day, the built up inner city area reveal a maximum in surface temperature - reflecting the urban heat island. Flat desert areas, on the other hand, whose thermal inertia is much lower than that of the city, gain and loose heat at a more rapid rate, consequently, a higher diurnal temperature variation results. Vegetated regions, where higher moisture content inhibits a large partition between sensible and stored heat, exhibit small temperature variations. This effect is illustrated quite well in the wooded regions of the Santa Monica Mountains. Just after sunset or when the sun's elevation is low, slope characteristics of the terrain tend to briefly override other determinants of surface temperature causing anomalies of two to four degrees Celsius to occur on the southern slopes. Surface albedo was found to be of second order importance.

In the future, diurnal surface temperature differences derived from HCMM data will be used in conjunction with an inverted boundary layer model to obtain surface and substratic properties of urban areas. M.S. (1976).

Model of Planetary Boundary Layer Growth Using Sodar Validation: Applications to Pollutant Dispersion

C. W. Benkley

A three-part computer program is constructed. First through consideration of the magnitude of terms in the surface energy budget, the time-dependent surface heat flux is estimated. Using this heat flux, the time-dependent mixed layer height is estimated using the "Zeman-Tennekes" model. Finally, using the mixed layer height as the upper boundary for Gaussian point-source dispersion, surface-level pollutant concentrations are predicted.

The sensitivity of the Zeman-Tennekes model to the surface heat flux, the lapse rate, lapse rate errors, and other factors, is shown through consideration of carefully designed hypothetical cases. This analysis is pursued further in order to establish error bars for model prediction of real, measured mixed layer growth rates. For this validation, Sound Detection And Ranging (sodar) is used to provide precise, continuous measurements of mixed layer heights.

To demonstrate the general applicability of the approach, surface-level pollutant concentrations are predicted for hypothetical elevated and ground-level sources using as an upper boundary condition the best-fit mixed layer rise prediction of one of the measured growth curves. M.S. (1977).

A Model for Determining Surface Temperatures and Sensible Heat Fluxes Over the Urban-Rural Complex

F. E. Boland

Because of the need for improved weather forecasting as well as pollutant forecasting over an urban area, it is imperative that a detailed knowledge of boundary-layer processes be obtained. An essential part of determining atmospheric interactions in this layer lies in accurately measuring surface-layer fluxes and the surface temperature. Without a detailed knowledge of these parameters, one cannot hope to specify pollution transport, mixed-layer dynamics, and the quality of the urban atmospheric environment. Surface heating over a complex urban area is a major forcing function for circulation patterns over and around a city, and it plays a role in human comfort.

Due to the increasing concentration of population in urban agglomerations over the last hundred years, interest in studying the urban microclimate has expanded greatly. From the earliest investigations to present-day endeavors, it has been recognized that cities alter their surrounding climate. As urbanization increases, these effects will become more and more pronounced and widespread. Indeed, in just a few years, it not already, extensive urban structure may significantly alter the larger-scale atmospheric motions. In the past decade, especially, numerical models of increasing sophistication have been developed to try to quantify the degree to which urban areas have modified their environment.

Given the importance of urban atmospheric research, why have meaningful results been relatively scarce? The anser lies in the remendously complex structure and varied surface features of cities. It is extremely difficult to measure surface-layer processes on so small a scale. For example, it is nearly impossible to predict interactions of turbulent fluxes in areas between buildings and houses. Urban features affecting atmospheric motions are so varied that even if meaningful relations could be established for one specific area, it is doubtful whether they would apply to any other area. For study of urban meteorology it has been necessary to modify traditional concepts of scales of analysis. Models which attempt to deal with cities are hampered by a paucity of data for verification and a necessity to make limiting assumptions in the interest of simplicity. Even so, models offer the best hope of understanding the urban microclimate. Benefits of such understanding could include distributional planning of contaminating sources in order to minimize regional air pollution, and the creation of parks and housing developments for maximizing human health and comfort benefits. M.S. (1977).

Mass Transfer at Natural Air-Water Interfaces

W. J. Brtko

Although considerable effort has been devoted to the development of air pollution models, little has been done to incorporate natural mechanisms capable of removing pollutants from and/or adding pollutants to the atmosphere. One important process is the transfer of atmospheric pollutants across natural air-water interfaces. In this thesis, a calculational scheme to quantify this transport process is presented. In particular, two models characterizing wind induced turbulence in a water body are invoked to estimate the liquid phase mass transfer coefficient. A priori specification of parameters yielded predictions well within an order of magnitude of experimental evidence in both the laboratory and the field. Finally, in order to facilitate use of the models, criteria for choosing the better model have been presented, the limitations of the models have been identified and attempts to resolve these limitations have been developed. The relative importance of the limitations are then quantified by performing a parametric sensitivity analysis on the models. M.S. (1976).

System Geometry and the Interpretation of Sodar Data

R. L. Coulter

The characteristics of acoustic signals scattered in the lower layers of the atmosphere depend both upon the space-time varying acoustic scattering cross section and the geometry of the region from which the signal is derived. This thesis discusses, primarily, the effect of systems geometry upon meteorological measurements derived from Doppler sodar signals.

Establishing the exact region of space contributing to the sensed signal return at any instant is shown to result in a signal amplitude which varies over several orders of magnitude as a pulse of energy traverses the common volume in a bistatic acoustic sensing system. The so-called system function is shown to be highly dependent upon the system parameters, in particular the transmitter and receiver beamwidths and the relative pointing angle. The effect of the system function upon the evaluation of the sensed atmospheric scattering cross section is discussed.

Due to the relatively large beamwidths associated with acoustics, the equiphase surfaces (loci of points such that the number of wavelengths between transmitter and receiver via scatterer is constant) have a change of curvature within the "instantaneous" scattering volume. This curvature is shown to lead to a spectrum of Doppler frequencies, any one of which may be sensed at a given instant. For a monostatic system this spectrum is derived under assumed conditions of isothermal atmosphere, with constant wind speed and with linear wind speed variations with height. The effects of a Gaussian antenna weighting are included.

For the bistatic system, the peak and halfwidth of the spectrum can be defined in terms of the intersection of the transmitter and receiver beams in space. The variation of peaks and halfwidth is derived as a function of the system parameters. They are found to have a marked height dependence, and two sign reversals as the common volume is traversed. The halfwidths determined in this way show the spectra to be highly asymmetric in the first and last parts of the volume. The inclusion of wind shear causes the peak vs. height curves to change dramatically and may cause a narrowing of the spectrum at intermediate ranges.

Finally, the characteristics and initial use of the Penn State sodar system are discussed and data obtained with it, including correction for the system function variations, are compared with double theodolite wind profile measurements. Ph.D. (1976).

Aircraft Measurement of the Removal of Sulfur Dioxide at Natural Air-Land and Air-Water Interfaces

A. J. DeCaria

Aircraft measurements of vertical concentration profiles of SO_2 above land and water surfaces were conducted in an attempt to differentiate removal at the air-water interface from removal at the air-land interface. Numerical models coupled with models for surface removal were also studied. Significant surface resistances to mass transfer were found to exist at both surfaces. The models showed that removal at a surface covered with vegetation can be as much as an order of magnitude higher than removal at a water surface. Aircraft measurements confirmed the existence of significant surface resistances at both land and water surfaces, although the relative magnitude of these resistances was difficult to assess. M.S. (1978).

The Application of a Box Model with Variable Mixing Height in Air Pollution Meteorology

S. Ettorre

The purpose of this research is to examine the dynamics of the box model which contains the variable mixing height and random wind speed as explicit variables. Depending on the amount of advection by the wind, the entrainment process can serve as a means of diluting the pollution already in the box or capture yesterday's contaminants. The wind speed is a random element in the system, prohibiting the application of deterministic methods of solution. M.S. (1977).

Case Studies of Aircraft and Helicopter Temperature Measurements Over St. Louis, Missouri

J. M. Godowitch

Aircraft have been used for many years to obtain both synoptic weather observations and special purpose meteorological measurements. During the first major conflict to include long distance airborne operations, World War II, reconnaissance flights were extensive. Since then, specially equipped airplanes have been employed to survey atmospheric characteristics from, essentially, the surface to the fringes of outer space. Special fleets, such as the "Hurricane Hunters," have been used to probe severe weather systems like hurricanes and thunderstorms. Since the early 1950's airplanes have also been used for measurements and seeding in all the major weather modification experiments.

The development of improved instrumentation, such as inertial navigation systems, and sophisticated data acquisition systems, like those based on mini-computers, for aircraft and helicopters has prompted renewed interest and attention in airborne meteorological measurements (GATE, 1972). The versatility of an airplane makes it a useful and unique sensor platform capable of gathering high resolution data over extended distances in the atmosphere. Studies such as the one by Lenschow (1970) showed how well the detailed thermal structure through the planetary boundary layer could be obtained using an aircraft. Lenschow also estimated vertical fluxes from temperature and wind velocity measurements collected during horizontal flight runs at various altitudes within the boundary layer. Useful state of the art reviews of contemporary research aircraft techniques, instrumentation and applications are made in numbers 1 and 7 of Atmospheric Technology, 1973 and 1975, respectively.

Airborne flights were planned and conducted during the St. Louis Metromex (Metropolitan Meteorological Experiment) program to investigate the inadvertant modification by the urban area on the weather and climate. For example, Spangler and Dirks (1974) deduced the temporal and spatial mesoscale variations of the planetary boundary layer inversion from aircraft soundings and horizontal runs across the St. Louis region.

An instrumented helicopter is uniquely suited for flights at altitudes below which aircraft are not permitted, particularly within urban areas. It is well-known that urban influences may substantially modify the thermal structure over a city, especially during nocturnal periods, to form the so-called urban heat island. A helicopter is also sufficiently mobile so that ascent or descent spirals may be made at many selected limited area sites in an urban area. Thus, spatial variations as well as temporal changes in the thermal structure above a city may be observed.

This thesis consists of selected case studies which depict the detailed temperature structure over St. Louis from both aircraft and helicopter measurements. Emphasis is upon the temporal and spatial temperature variations during the morning and evening transitional periods.

The observations for this study were made in conjunction with the larger multi-year Regional Air Pollution Study (R.A.P.S.) in the St. Louis area. The R.A.P.S. field program is supervised and funded by the U.S. Environmental Protection Agency and depends on the cooperation and participation of many diverse scientific groups and specializations. The overall goal of R.A.P.S. is the development and validation of air quality simulation models so that least-cost air pollution control strategies may be planned (Pooler, 1974). To achieve this goal, a major objective is to acquire an extensive data bank of emission, air quality and meteorological data.

The Penn State Meteorology aircraft has participated in a number of special R.A.P.S. studies and has collected a variety of special airborne data. Meteorological and aerosol sampling flights were conducted during the summer of 1973. Emphasis during the summer flights in 1974 was upon measurements of atmospheric aerosols (Schere, 1975; Mamane and Pena, 1975) and turbulence in the region (Redford, 1976). Other flights in 1974 and 1975 included special multi-wavelength visible and infrared radiation measurements. All the helicopter and aircraft data discussed in this thesis were obtained in summer, 1973 experiments. M.S. (1976).

Meteorological Parameters Affecting Nocturnal Air Quality

D. A. Kellermeyer

A one-dimensional boundary layer model is used to investigate which of the external physical and meteorological parameters are most important in determining the development of the nocturnal boundary layer. Specifically, the sensitivity of the inversion height and the ventilation to varying values of external parameters was studied.

The ventilation rate, defined as the mean wind speed times the height of the mixed layer is proportional to the third power of the geostrophic wind speed and is inversely proportional to the rate of net heat loss at the surface. This conclusion has been verified by model experiments and comparisons with actual cases. M.S. (1976).

Sensitivity Tests and a Real-Data Forecast for the Planetary Boundary Layer Using a Mixed-Layer Model

D. Keyser

Advances in computer technology in the past ten years have made numerical solution of the primitive equations governing atmospheric flow possible on increasingly finer, three-dimensional grids. It is becoming possible to deterministically resolve phenomena characteristic of the meso-β (horizontal scale 25-250 km) and meso-γ (horizontal scale 2.5-25 km) scales (Orlanski, 1975) with contemporary versions of mesoscale numerical models. Because these scales are shorter than that of the upper-air observational network in North America (400 km), mesoscale models provide not only a theoretical data base, but practical predictions of phenomena such as nocturnal low-level jets, squall lines, mountain-valley circulations, sea breezes, and urban heat-island flows.

Although high-resolution mesoscale models can realistically simulate complex flow patterns, their application is formidably expensive. The excessive cost of producing forecasts has restricted the use of these models to research ventures. That high-resolution three-dimensional mesoscale models will be operationally employed is unlikely until the advent of faster and larger computers.

After considering some of the drawbacks involved with high-resolution mesoscale models, one finds a simpler model, which requires less computing power while duplicating the main results of a complicated model, a tempting alternative. Almost ten years ago, Lavoie (1968) hypothesized an idealized atmospheric structure leading to a viable compromise between desired physical realism and imposed computational restrictions. In particular, he claimed that a well-mixed atmospheric boundary layer can be described adequately by a single level of data. The following section considers the implications of this assertion. M.S. (1977).

Predictions of Mass Transfer to Air-Land and Air-Water Interfaces

R. L. Kraft

In the development of air pollution models, it is highly desirable to allow for natural processes which are capable of removing pollutants from the atmosphere. One important removal mechanism is the transfer of pollutants to air-land and air-water interfaces. It is the purpose of this work to quantify this process so that specification of such meteorological conditions as wind and temperature profiles, and type of surface (bluff, fibrous or water), and the pollutant concentrations at a specific height in the atmosphere and at the surface will enable the calculation of pollutant flux to the earth's surface.

In this research, a model is proposed in which the mass transfer to the surface is obtained from a partial analogy with the momentum transfer to the surface. In particular, this model enables the calculation of the mass transfer coefficient as a function of the meteorological and surface conditions. combining this mass transfer coefficient with its corresponding concentration driving force produces estimations of the pollutant flux at the surface.

Various constants in the models are determined by comparison with wind tunnel data taken by Chamberlain (1966) and (1968) and Owen and Thompson (1963). For atmospheric situations it is expected that mass transfer to rigid surfaces such as rocks, gravel, cities, etc. may be predicted within a factor of 2.2. For fibrous surfaces such as grass, wheat, etc. and water surfaces mass transfer coefficients may be predicted within 50%.

Models to predict mass transfer from momentum transfer are proposed in the literature by many investigators. The proposed models in this research are compared to the models suggested by the literature and are shown to be physically more realistic than the former models. Finally, the importance of various parameters such as wind speed, roughness length, surface geometry, pollutant species and stability terms in the model are presented graphically in a parametric study.

A Quantitative Method for the Detection of Individual Submicron Sulfate Particles

Y. Mamane

A quantitative method for the analysis of individual submicron sulfate particles has been developed. The method is based on the reaction of the sulfate ion with barium chloride and can be applied only to soluble sulfates. The result of the reaction is a characteristic halo easily recognized under the electron microscope. In addition, this method yields the size distribution of submicron sulfate particles.

The method is specific for sulfates. Soluble carbonates, nitrates and sulfites do not cause interference. It enables one to distinguish between ammonium sulfate and sulfuric acid particles and provides some information on mixed sulfates. The method is reproducible and quantitative: by measuring the size of the halo and knowing the ratio of halo to particle diameter, the size of the original particle can be obtained.

The method is not affected by the background of the collecting surface, in this case a thin film of carbon mounted on electron microscope screen.

The lower limit of detection for the method as it was applied in this study is 0.03 μm for sulfuric acid and 0.06 μm for ammonium sulfate particles. However, if the thickness of the barium chloride film is reduced this limit could be extended to lower values.

The method requires short sampling times on the order of minutes or for very polluted areas seconds.

Because of its high resolution this method should be especially useful in studies of hourly variations of sulfate in the atmosphere, variations with air masses, changes brought about by precipitation, or in studies of plumes where the sampling time is reduced to seconds. In addition it can be applied to studies of transformation of sulfur dioxide to sulfate, transport of sulfates, laboratory investigation of submicron sulfates, and in other studies where short sampling times are required.

The method has been applied to samples of atmospheric aerosol representing very different environments: a power plant plume, rural area, and southwestern U.S. urban location. The analyses provided, besides the percentage and size distribution, some information about the nature and the origin of the sulfate particles. In particular, it was possible to observe the existence of mixed particles which could be the result of heterogeneous nucleation of sulfur dioxide on foreign particles. Ph.D. (1977).

Second Order Modeling and Statistical Theory Modeling of a Homogeneous Turbulence

G. R. Newman

In this investigation, the Test Field Model (Kraichnan, 1971a) is applied to the study of the decay of isotropic, passive-scalar turbulence. Predicted velocity and scalar energy, dissipation and transfer spectra and second and third order velocity, scalar and velocity-scalar correlations are shown to provide moderate agreement with heated grid turbulence data (which exhibit near-unity levels of the ratio of velocity to scalar time scales, r) at moderate Reynolds and Peclet numbers. Self similar decay resulting from the simulations exibited an asymptotic approach to a value of unity for r and to values of 4.0 for the normalized decay rates of the velocity and scalar dissipation rates, ψ and ψ_θ respectively. This predicted level for ψ agrees fairly well with levels of ψ observed in grid turbulence data over the experimental range of Reynolds numbers. On the other hand, the predicted asymptotic approach to $\psi_\theta = 4.0$, $r = 1.0$ is at variance with existing heated grid turbulence data (in which $r \neq 1$) in which ψ_θ and r remain invariant in time at their initial values. These disparities are discussed in the context of equilibrium decay of concomitant, nearly-isotropic scalar and velocity fields, and a consistent picture is proposed in which the predicted results for ψ, ψ_θ and r are viewed as equilibrium decay values, appropriate for moderate and large Reynolds and Peclet numbers, which might be observed asymptotically in heated grid turbulence flows. Further grid turbulence studies are needed to evaluate this premise. Also, it is suggested that a further investigation using the Test Field Model approach but with initial spectral forms set to agree more closely with those observed in heated grid flows might provide predictions which better reproduce the ψ_θ and r behaviors observed in the data. Finally, the implications of the Test Field Model results for second-order closure schemes are discussed. M.S. (1977).

The Mechanism and Prediction of Gaseous Pollutant Uptake by Vegetation

R. A. O'Dell

The objective of this research is to investigate the various mechanisms and factors which control gas uptake by vegetation and to develop quantitative method for predicting the uptake rate. Sulfur dioxide (SO_2) is used as an example pollutant of interest. First, the three resistances to uptake - aerodynamic, stomatal, and mesophyllic - are described and then characterized in terms of controlling parameters. This approach to gas exchange has been used by plant physiologists since Gaastra (1959) or earlier.

Factors which control the individual leaf aerodynamic resistance, r_a, are wind speed, leaf size and geometry, and gas viscosity and diffusivity. The stomatal resistance, r_s, is a function of the stomatal opening, which in turn is affected by water deficit, CO_2 concentration, and light intensity.

The mesophyllic resistance, r_m, is related to gas solubility in water, gas-liquid diffusion, and ultimate removal of the gas by leaf hydrodynamics and chemical reactions.

The three resistances, which are based on the leaf surface, are summed and divided into the atmospheric gas concentration difference to yield the uptake rate per unit leaf area. Therefore, if the leaf characteristics and environmental parameters which control the resistances - wind speed, atmospheric moisture, temperature, and light intensity - are known, the gas uptake rate by the leaf can be estimated. As an initial test of the model, estimates of gas uptake by vegetation are compared with published results.

When the uptake rate by leaves is known, the removal of SO_2 or other pollutant gases over vast vegetated tracts may be calculated. Then, the impact of vegetation, considered as a natural sink for atmospheric pollutants, can be assessed. M.S. (1977)

Mesoscale Interactions Between a Cold Front and the Planetary Boundary Layer

E. A. O'Lenic

On October 16 and 17, 1973 a low-level outbreak of cold air, accompanied by a strong upper-level front, swept southeastward over the eastern United States. This thesis investigates the mesoscale circulations in the cold, low-level flow over the Great Lakes, the Appalachians, and the Piedmont-coastal region during this period. It emphasizes the role of the three-dimensional synoptic environment and the diurnal variations of surface heating in determining the persistence, nature, and location of the mesoscale perturbations which appear in the planetary boundary layer (PBL) on 16-17 October.

The structure of the planetary boundary layer was summarized by Hoxit (1973) in terms of a two-layer structure. The momentum boundary layer, in which mechanical turbulence destroys kinetic energy, is the layer nearest to the ground. The adjustment time for the flow in this layer is of the order of that for turbulent motions. The momentum boundary layer reaches its greatest depth in the late afternoon. After sunset, a new momentum boundary layer, comprised of the lowest stable layer, forms next to the ground below the old momentum boundary layer. In the old boundary layer, called the "inertial boundary layer," surface friction does not affect the flow, kinetic energy dissipation is small, and the adjustment time is a half pendulum day.

According to Deadorff (1974), the PBL modifies the free troposphere through entrainment, convergence, and penetration by convection. These processes modify the momentum, heat, and moisture content of both the PBL and the atmosphere above the PBL.

The results of Ball (1960), Rayment and Readings (1973), and Tennekes (1973) indicate that the PBL grows mainly through heating and convection, with large upward heat flux near the ground, and downward heat flux near the base of the inversion.

Although relatively simple in structure under horizontally homogeneous conditions over flat terrain, the PBL and the processes determining its structure become extremely complex when synoptic-scale variations in the wind and the stability interact with the PBL over variable terrain. Synoptic studies and numerical modeling, using observations representative of various synoptic conditions, may be the most promising approaches to studying the PBL circulations under these conditions. This thesis investigates the mesoscale structure of the lower troposphere during a period of fast northwesterly flow over the northeastern United States. Significant perturbations to the low-level flow were induced by the Great Lakes, the Appalachian Mountains, and the land-sea contrasts along the Atlantic coast and Chesapeake Bay during this period. M.S. (1976).

Numerical Studies of Atmospheric Acdar Sounding

R. C. Przywarty

During the past few decades many types of radio and optical systems have been developed for remote atmospheric probing. In fact, one of the first methods for atmospheric sounding was analysis of long distance sound propagation in the atmosphere. Since the early studies of "anomolous" sound propagation, the results of many important acoustic experiments have been published. But although the technology necessary to design relatively sophisticated acoustic sounders has existed for more than 20 years, few systems were constructed. Perhaps it was the lack of spectacular technological advances (in contrast to, e.g., satellite meteorology) that inhibited potentially fruitful research into indirect acoustic probing techniques. Now as a consequence of contemporary studies of the troposphere's planetary boundary layer, interest in acoustic sounding has been revived. The potential usefulness of acoustic "radars" is greatest for indirect measurements of temperature and wind in the lowest few kilometers of the troposphere.

Several research groups have during the past five years developed the so-called acadar (acoustic detection and ranging) systems and employed them for a variety of different atmospheric experiments. Yet, with few exceptions, although the acdar observations have provided meteorologists with a new "aualitative" perspective of the lower atmosphere, much remains to be done before the various systems can be effectively utilized for "quantitative" atmospheric measurements.

One difficult problem is that of determining the "response" of a propagating acoustic signal to particular changes of meteorological variables along the total propagation path. In effect, the complete history of the propagating acoustic wave as it is modified by space-time atmospheric temperature and wind variations must be determined. Because the atmosphere is, in general, both an uncooperative and extremely complex laboratory, such experiments can often now be more efficiently conducted using a physically sound model and a large computer.

This thesis develops a theoretical numerical model which can be used to "predict" the nature of received acdar signals for specified atmospheric conditions.

Presently, the model is two-dimensional. A wave front of transmitted acoustic energy is reduced to ray components. The individual rays are then propagated through a refracting, non-scattering atmosphere to and into a scattering layer. The characteristics of the scattering layer including scatterer density, size and velocity may be specified. If an individual ray intercepts a scatterer, the scattered energy is returned to the receiver along that ray's propagation path. At the receiver the signal phase and amplitude of each intercepted ray is calculated. The total resultant vector signal phase and amplitude is then computed. Next, the scattering layer is shifted horizontally a specified distance (time) to simulate scatterers being translated with a mean wind.

It is thus possible to estimate the resultant signal phase and amplitude as a function of time. Because a special technique is used to remove the 2π ambiguity from the signal phase variations, it is also possible to compute longer term trends in the signal phase and thus extract average Doppler shifts from the received signals. M.S. (1973).

A Comparison of Several Methods for Predicting Scalar Transport in the Atmospheric Surface Layer

R. Quenette

This thesis reports several calculations of vertical eddy diffusivity, i.e., exchange coefficient, in a horizontally homogeneous, buoyancy-driven, mixed layer. Calculations of a pollutant concentration field are obtained using different distributions of eddy diffusivity in a numerical solution of the diffusion equation.

The first part of the thesis describes observations of passive contaminants made during the Los Angeles Reactive Pollutant Project (LARPP). Based on a profile of eddy diffusivity obtained experimentally, an approximation of the distributions of eddy diffusivity is made.

In the second part of the thesis, we use second-order techniques by modeling second-order moment equations of the contaminant field. An expression for the eddy diffusivity is deduced and three different profiles of eddy diffusivity are obtained using two approaches of second-order modeling and a set of self-similar equations.

The last part consists of numerical computations of distributions of pollutant concentration, calculated from a numerical solution of the diffusion equation, using the preceding distributions of the mixing coefficients. The simulations based on LARPP and the two approaches of second-order modeling give accurate distributions, while the case using self-similar equations does not behave as expected. M.S. (1977).

Sources and Natural Removal Processes for Some Gaseous Atmospheric Pollutants

K. H. Rasmussen

This report has attempted to illustrate what the "state of the art" is in the recognition of the various sources and sinks of gaseous pollutants. This information, summarized in Table I, outlines the nature and size of anthropogenic and natural emissions for the various gases (H_2S, SO_2, N_2O, NO, NO_2, NH_3, CO, O_3, and hydrocarbons), along with their ambient background concentrations and a listing of their major sinks identified to date. All information in this table is expanded upon in the text and is supplemented with any quantitative data on removal rates available.

The quantitative information given in this paper has, in most instances, been subject to conversion of units. The conversions were made to attain some consistency among the data and with the International System (IS) of Units. Because many people are not yet acquainted with this system, formerly used concentration dimensions, such as parts per million, are given in parentheses.

The amount of information available on gaseous source and sink strengths has blossomed the last several years. In fact, our knowledge in some areas has increased so much that much of the information in Robinson and Robbins' (1968) original work on trace gases in the atmospheric environment is now outdated. Contrary to belief of just a few years ago, for instance, it is now obvious that natural carbon monoxide emissions play an important role in determining the atmospheric background concentration of this gas.

A comprehensive search for natural pollutant removal mechanisms is presented. The following processes have been identified:

(1) foliar absorption
(2) soil absorption
(3) absorption by natural water bodies
(4) absorption by natural stone
(5) rainout and washout (scavenging)
and (6) chemical reactions in the atmosphere.

Quantitative modeling of most of these mechanisms is found to be in its infancy. M.S. (1974).

Airborne Measurements of Boundary Layer Turbulence Over St. Louis, Missouri, and Adjacent Rural Terrain

T. G. Redford, Junior

About 150 years ago, near the beginning of the Industrial Revolution, man began burning fuel in such large quantities that the effluent affected the local environment. As industry grew, centers of industry experienced a population expansion which still continues today. The smoke and soot of industry thickened and spread to outlying areas. Chimneys grew into smoke-stacks in order to carry the smoke away from the large urban centers which now surrounded the industrial plants. As population increased, space became precious, giving rise to today's architectural giants, the skyscrapers.

While tall isolated structures had been built centuries earlier, the concentration of such buildings, stacks, and towers found in today's cities began only 50 to 100 years ago. By increasing effective surface roughness these structures have changed the wind and turbulence patterns around cities (Landsberg, 1961). Additionally, many square miles of pavement and masonry have radically altered the radiation absorption-emission characteristics of the surface. The effect of this alteration is to increase the surface heating of the air, thus producing buoyant turbulence in larger quantities than surrounding rural areas. Consequently the diffusion and dispersion of pollutants emitted by the city are affected. M.S. (1977).

Application and Interpretation of Digital Display Techniques to Sodar Returns

J. P. Scheib

This study is a comparison of visual display techniques for use in remote sensing sodar systems. Sodar (Sound Detection and Ranging) is a remote atmospheric probe that used acoustic energy scattered by turbulent temperature and velocity fluctuations to sense atmospheric structure. In most systems, the received and processed acoustic signals are displayed visually on some type of graphic recorder. The display unit must be capable of presenting three pieces of information in only two (x,y) dimensions. The final visual product, thus, must illustrate the range at which acoustic scattering occurs, the intensity of the returned signals and the time evolution of the scattering.

The intensity of scattered acoustic signals is dependent on the strength of fluctuating temperatures and velocities in the atmosphere. The characteristics of the acoustic propagation depend, of course, upon the spatially and temporally varying acoustic refractive index which is determined by fluctuating meteorological parameters. Details of the interaction of turbulence and sound waves have been studies by many researchers. Little's (1969) review of theoretical work relevant to sound propagation in the atmosphere summarized the relationship between the parameters C_T^2, D_V^2 and the scattered acoustic energy.

$$\sigma(\theta) = .03\ k^{1/3} \cos^2\theta \left[\frac{C_V^2}{C^2}\cos^2\frac{\theta}{2} + .13\frac{C_T^2}{T^2}\right]\left(\sin\frac{\theta}{2}\right)^{-11/3}$$

where σ is the scattered power per unit volume per unit incident flux per unit solid angle at an angle θ from the initial direction of propagation, C_T^2 and C_V^2 are structure functions and are defined by

$C_T^2 = \overline{(T_1 - T_2)^2}/r^{2/3}$ and $C_V^2 = \overline{(V_1 - V_2)^2}/r^{2/3}$ where T_1 and T_2 and V_1 and V_2 are temperatures and velocities respectively at two points separated by the distance r. One can show using arguments analogous to those used in Bragg scattering that the turbulent eddies that scatter sound have a characteristic wave number that corresponds to one half the wave number of the difference between the incident and scattered wave. Therefore, the amplitude of back scattered sodar returns is indicative of the intensity of turbulence of eddies of a size L equal to one half the wave length of the transmitted sound wave. Note also that monostatic (coaxial transmitter and reciever) sodar returns are only dependent on the turbulent temperature structure ($\cos^2\theta/s = 0$). An appropriate visual presentation of the sodar returns can thus illustrate diabatic processes and help an observer develop a "physical feel" for the variations that occur in the region probed by a sounder.

The most common display technique used for sodars is a "vertical time section" displayed on a facsimile recorder. The facsimile recorder is an intensity modulated x-y plotter where the x axis is time, y axis range, and the charring of the facsimile paper is proportional to returned signal strength. This display method has several serious limitations. A vertical time section will at best show only the turbulent structure that has been advected through the sounding volume. But a more serious fundamental limitation, presently, is that the available facsimile recorders have a limited dynamic range of response and are not generally able to resolve the full range of scattering phenomena.

The subject of this investigation is to evaluate several alternative display techniques for sodar. Two paths are considered: improvements in the display of vertical time sections and the use of other types of display techniques which have been developed for radar but might be applied to sodar. Not all of the latter may prove to be suitable for sodar as a consequence of the relatively slow phase velocity of sound (as compared to electromagnetic waves). Furthermore, some techniques are extremely costly. An attractive feature of sodar is that it is a relatively inexpensive probe and thus is available to a wide range of users.

The low cost and wide availability of mini-computers now allows practical development of computer enhanced displays of vertical time sections. For example, the computer facilitates use of a diversity of pulse-to-pulse averaging techniques which can "smooth" a noisy signal return. Gray shading analysis produced on a line printer can produce multiple "digital" levels of gray scale. This can greatly enhance the dynamic range of vertical time section displays. Another recent development is the interfacing of color cathode ray tubes (CRT) to computers and micro-processors, to enhance, for example, satellite data for cartographic studies. Techniques have been devised as a part of this study to adapt such systems for sodar displays, where the "false" color contrast allows an observer to more easily recognize sodar signatures of various turbulent features in the atmosphere. M.S. (1977).

Characteristics of the Ambient Atmospheric Aerosol Structure Over St. Louis, Missour

K. L. Schere

"Aerosol" is the generic term applied to all dispersed solid or liquid matter in a gaseous medium. Aerosols normally consist of particles of many different sizes and shapes and of a variety of different chemical compositions. In the earth's atmosphere, on a global scale, nature produces about 90 percent of the particulates, or aerosols. Aerosols produced by man's activities are a distant second. However, in the vicinity of industrialized urban areas, such as St. Louis, Missouri, man's proportion of the atmospheric aerosol burden may easily surpass nature's. In fact, it is normally safe to assume that urban aerosols are totally dominated by anthropogenic material.

From an air pollution standpoint aerosols are important for several reasons. Chronic exposure to high concentrations of particulates may be harmful to an individual's lungs. The synergistic role of the aerosols with certain gaseous pollutants, such as SO_2, produces known biologically toxic effects. Esthetically, the aerosol burden increases atmospheric turbidity and, hence, reduces visibility, particularly in urban areas. The possibility also exists that aerosols are affecting the energy balance of the earth through changes in albedo or radiation absorption. Scattering of solar radiation can be a factor in reducing the solar heating in the lower levels of an aerosol layer. One study showed that aerosols may produce radiative temperature changes larger than those caused by water vapor (Atwater, 1971). Anthropogenically produced particles are known to affect the microstructure of clouds in their path. These particles may enhance or hinder the precipitation mechanisms of the cloud depending upon the cloud type and particle characteristics (SMIC, 1971). In order to better understand these effects it is first necessary to study the characteristics of the structure of aerosols.

This study describes the characteristics of urban aerosols over the St. Louis region by investigating, in particular, vertical profiles of the particulate concentration (d_p >0.5 μm) from the surface through 3000 meters above ground level (a.g.l.) at various locations around the region. The size distribution of the particulates is also studied within a range from 0.5 μm-diameter to approximately 8.0 μm-diameter. This size range is one which is especially deleterious to the lungs since natural removal mechanisms for particles of these sizes are particularly inefficient (Williamson, 1973).

The size distribution of the aerosols is an important parameter in that by using it one may be better able to understand from which sources different proportions of various aerosol sizes are emanating. For instance, if a significantly higher proportion of smaller particles over larger particles is found than is normally associated with "background" size distributions it is likely that anthropogenic sources are adding significantly to nature's share of the smaller particulates. Examples of this type of effect will be shown. In this thesis, both vertical profiles and size distributions in two separate air masses of differing type are analyzed.

Observations for this were obtained as part of a larger continuing field measurement program by the Penn State Meteorology Department in the Regional Air Pollution Study (R.A.P.S.) of the St. Louis, Missouri, area. R.A.P.S. is a five year project, supervised and funded by the U.S. Environmental Protection Agency, which is bringing many diverse scientific groups and disciplines together with the goal of better understanding, and eventually, accurately numerically modeling urban air pollution. As part of the 1974 effort Penn State contributed to the field study by making airborne measurements of atmospheric aerosols and turbulence over St. Louis during the period 31 July 1974 to 22 August 1974. M.S. (1975).

The Development of a Mesoscale Semi-Implicit Numerical Model

N. L. Seaman

A mesoscale three-dimensional semi-implicit numerical model was derived from the Navier-Stokes equations of atmospheric flow. Complex terrain was included in the model, but several other physical effects, such as diabatic heating, moisture, and surface friction, were neglected. The neglected terms were not crucial to the basic development of the model.

A set of finite difference equations in the x, y, and σ coordinate system, where σ is a nondimensional vertical coordinate based on pressure, was derived from the basic system of primitive equations. To obtain computational stability with long time steps, terms primarily responsible for gravity wave flow were linearized by a perturbation method and treated implicitly. All other terms, including the small perturbation portions of the wave-propagating terms, were explicitly differenced. Substitutions reduced the system to a family of Helmholtz equations in terms of pressure and vertical velocity, which was solved by successive over-relaxation methods.

An explicit three-dimensional model was used to verify the semi-implicit model results in lieu of real data predictions. The semi-implicit model was tested in a variety of experiments to determine the most stable form of the finite difference equations. The use of a nine-point Miyakoda Laplacian for the successive over-relaxation cycles reduced generation of short wave-length noise. The internal balancing of differenced terms within the thermodynamic equation was also crucial to the stability of the model. The model was most stable when the thermodynamic equation was differenced in advective form. All other equations were differenced in flux form.

The introduction of complex terrain was made possible by treating the orographically induced portion of the pressure gradient explicitly to be consistent with the orographic portion of the geopotential gradient. Most of the dynamically induced pressure and geopotential gradients were included in implicit terms. Residual short wavelength noise was generated by the ill-posed open boundary conditions. The use of the Asselin time filter controlled the residual noise. The resulting three-dimensional semi-implicit model produced accurate forecasts, compared to a similar explicit model, with time steps six times those of the explicit scheme. The computational efficiency advantage of the model was about 3:1. Mass and energy conservation characteristics were comparable to those of the explicit model.

Further experimentation with a cross section version examined the details of the semi-implicit model's response characteristics. The relatively minor effect of the boundary conditions in the cross section allowed a time step ratio of 8:1 to be used. The semi-implicit model was about four times as efficient as the explicit model for this time step ratio. The cross section model was stable with time step ratios as large as 20:1. However, temporal truncations began to seriously degrade the quality of the solutions when very large ratios were employed.

The propagation speed of gravity waves is crucial to the correct adjustment of mass and velocity fields in a numerical model. The phase speeds of external gravity waves in the semi-implicit model were reduced to 50 percent to 85 percent of the true analytical phase speeds for waves of length $8\Delta x$ to $30\Delta x$, respectively. Larger time step ratios caused greater reductions in phase speed. High resolution, 16-layer cross section experiments were performed to determine if the phase speed loss seriously affected the adjustments of the mass and momentum fields. Experiments simulated adjustment for forced flow over a high mountain range of 10 km half-width and for an initially unbalanced upper tropospheric jet stream. In both cases the semi-implicit model produced results comparable to those of the explicit model in terms of both the statistical characteristics and physical similarity to atmospheric systems. Despite the reduced gravity wave phase speeds, root mean square error calculations showed almost no difference in the adjustment rates between the two models. This was attributed to the fact that even the most rapidly propagating meteorological features rarely exceed speeds of about 50 m s^{-1} (17 percent of the analytical external gravity wave speed). The verification that the semi-implicit model produces adjustments between the wave phase speed reductions, is an important step in insuring that the semi-implicit technique can be successfully applied to mesoscale forecasting. Because the periods of mesoscale meteorological systems are closer to those of atmospheric gravity waves than are those of synoptic scale waves, the applicability of the semi-implicit technique to the large scales is also supported. Thus, the research has been successful in verifying and extending the use of the semi-implicit technique in the field of numerical atmospheric modeling. Ph.D. (1977).

Nested Grids in Numerical Weather Prediction and an Application to a Mesoscale Jet Streak

J. P. Sobel

This dissertation discussed the development and application of a technique for meshing numerical grids of differing horizontal resolution. The technique used modified finite difference forms to compute the tendencies at the interface of the coarse mesh (CMG) and the fine mesh (FMG) and thus allowed mutual interactions between the two grids. In addition, the technique has the advantageous property of conserving fluxes across the internal interface.

The equations were integrated on a horizontally staggered grid by the "box" method. Because the variables were staggered it was not possible to maintain uniformly shaped boxes for the momentum variables. Special finite difference forms were required along each edge of the internal interface and at the four corners.

A two-dimensional barotropic model was used to compare the mutually - interacting nesting technique to a one-way interacting approach in which the boundary points of the FMG were specified from an independent forecast of the CMG. For Haurwitz waves of various sizes, little difference was found between the techniques when a single-scale disturbance was present. With either technique, the difference in numerical wave speeds across the interface eventually led to the generation of noise which contaminated the forecasts. However, both meshing techniques produced forecasts with considerable skill for the first 12 hours.

When there was a distinct separation of the scales of motion on the CMG and FMG, the mutually-interacting meshing technique was superior. Experiments with a moveable FMG centered over a short-wave moving into a long-wave on the CMG showed that the two-way technique produced forecasts much closer to a control experiment on a uniform FMG.

Finally, a baroclinic, multilevel model was used to study the vertical circulations about a mesoscale jet streak. For this physical situation, the mutually-interacting technique was superior to the oneway interacting technique. After only three hours, considerable computational noise developed on the outflow boundary of the FMG when the specified boundary approach was used, the forecasts were smooth and well-behaved even after 12 hours.

Two sets of jet streak experiments were run. In the first the streak was present only in the wind field and thus was entirely super-geostrophic. In the second, an attempt was made to geostrophically balance the height and temperature fields. In the "unbalanced" case an indirect two-cell vertical motion pattern developed initially. This result was consistent with quasi-geostrophic theory that predicts an indirect circulation in the super-geostrophic portion of a propagating jet streak. As the integration continued, the model adjusted so that the exit region became sub-geostrophic.

After six hours the classic four-cell vertical motion pattern developed with a direct circulation in the entrance region and an indirect circulation in the exit region. In the "balanced" case, the result after three hours was again predominantly a two-cell indirect circulation. This was apparently due to the initialization scheme which did not produce an exact geostrophic balance between the initial mass and wind fields. While the initial conditions were closer to a balanced state, the ageostrophic motion was such that a two-cell pattern was dominant. However, as in first experiment, after six hours a four-cell pattern developed as the system reached a more balanced state. Ph.D. (1976).

Application of a Long Baseline Bistatic Acoustic Sounder to the Study of Temperature Inversions Near the Earth's Surface

M. R. Teufel

A long baseline bistatic acoustic sounder operating at 200 Hz has been successfully tested, over ranges up to 10 km, during atmospheric inversion conditions. Experimental determination of caustic positions (regions of high sound intensity) has been partially successful. A recording micromicrobarograph was also constructed and operated. Fluctuations in signal level were observed on both the sounder and barograph records. The amplitude spectra computed for these two types of signals give an indication that the sounder fluctuations are the result of the same atmospheric motions which cause the pressure variations.

A unique pressure record was recorded of a wave with a 40 minute period. This wave persisted from 10:10 p.m. until 6:45 a.m. The wave-form was distorted from a sinusoidal shape. The frequency domain coefficients determined for this wave were compared to the theoretical coefficients predicted by Hunt (1961) for a large amplitude internal gravity wave, which interacts in a non-linear manner with the earth's surface. The comparison indicates that Hunt's theory is basically able to explain the observed waveform distortion. M.S. (1975).

Comparative Verification of Two Atmospheric Boundary Layer Models

S. A. Vigeant

In this study, three one-dimensional mathematical models of the stable nocturnal boundary layer are compared and verified. This is done to aid in developing a computationally efficient, predictive model which is capable of providing detailed information on the behavior of the stable nocturnal boundary layer. Such a model can be utilized in conjunction with a larger mesoscale model.

All three models employ K-theory to characterize the turbulent mixing occurring in the boundary layer. The B-model, developed by A. K. Blackadar, D. Kellermeyer, and the author, derives the formulation of the mixing coefficient K from second-order closure theory. The BC and BCM-models, originated by N. E. Busch, S. Chang, and R. A. Anthes, derive the expression for K from the energy equation.

A comparative verification of the models' predictions under various geostrophic wind speed conditions is presented in tabular form. Key parameters predicted by each model are compared with field data from the Wangara Experiment and the Great Plains Turbulence Field Program.

The results indicate that the models are able to provide fairly realistic predictions of the behavior of the stable nocturnal boundary layer if the proper adjustments are made to the model formulation. It is also shown that the B-model is more efficient computationally than the other models.
M.S. (1978).

The Initial Growth of Data-Related Errors in Mesoscale Numerical Weather Prediction Models

T. T. Warner

A set of stochastic-dynamic equations was utilized to investigate the error-energy transfer that occurs during the initial adjustment phase of numerical models. The results were interpreted in terms of mesoscale data accuracy requirements, the general mesoscale predictability problem, and the use of various initialization techniques.

Synoptic-scale experiments showed the existence of an equilibrium value of the initial standard error of the north-south wind component v, of about 1.2 ms^{-1}, for an initial standard error in the temperature data of 1°C. Any value of the initial v error lower than the equilibrium value produced a net flux of uncertain energy into the v component, thereby increasing the variance back toward the equilibrium level. Conversely, an initial v error larger than the equilibrium value caused a net flux of uncertain energy out of the v component, which again caused the variance in v to adjust back toward the equilibrium value.

It was shown that, on the mesoscale, small mass and momentum initial data errors are not strongly coupled in the sense that there is very little transfer of error-related energy or uncertainty from one variable to another. The nature of the adjustment process on the mesoscale effectively insulates the velocity field from mass field data errors. Conversely, the mass field is only very slightly perturbed by velocity field data errors because the magnitude of the displacement of the fluid required to produce a mass field in balance with the velocity errors is minimal. The energy in the initial mass field errors is partitioned to the gravity-inertia wave modes which, in most realistic mesoscale models, propagates out of the forecast domain through open boundaries or is damped by special time-differencing schemes.

This initial error-energy is thus only a temporary contaminant of the forecast. Except for the fact that the amplitude of the gravity-inertia waves would be proportional to the magnitude of the initial mass field error, the magnitude of the uncertainty in these data is relatively unimportant, within reasonable bounds. The velocity errors, however, maintain their amplitude and location during the adjustment phase of the forecast, and thus are clearly the most crucial on the mesoscale.

These results indicate that the predictability of a mesoscale forecast will be degraded most in situations where existing instabilities or near-instabilities are related to the velocity field rather than the mass field. The perturbations in the mass field, associated with initial mass field data errors, tend to produce only transient gravity-inertia waves. However, the velocity errors persist in time and thus provide the most probable origin for the unrealistic suppression of generation of unstable flow patterns.

Certain initialization procedures were shown to have definite advantages when viewed in terms of the error-energy transfer characteristics of the mesoscale adjustment process. The use of initialization methods which determine the velocity field from the mass field, results in an initial velocity field with a very high error variance even though the fields may be dynamically balanced. This problem may be serious since the large errors are produced in the very variables which are unable to dissipate their error-energy by partitioning it to the gravity-inertia wave mode during the adjustment process. On the other hand, methods which diagnose the mass field as a function of velocity observations (e.g., through the use of a balance equation) do not suffer from this problem. The initial velocity errors produce only small amplitude anomalies in the mass field which are rapidly eliminated.

Wind Fluctuations at Two Meters Using a Laser Space Averaging Anemometer

T. L. Wilfong

Small scale density fluctuations resulting from atmospheric turbulence produce variations in the atmospheric optical refractive index. The turbulence generated scintillation pattern is often seen for it produces the quivering or twinkling of stars, and contributes to the "dancing" or an image observed across a hot highway.

When a laser beam traverses these refractive index disturbances, at a distant receiver, a "drifting" scintillation pattern may be observed. A laser space averaging anemometer is configured so as to measure the speed at which scintillation related disturbances pass across the laser beam. Since the refractive disturbances travel with the wind, the laser anemometer can be used to derive a spatially averaged wind transverse to the laser path.

The laser anemometer system used in this study consists of a low powered laser and the CA-9 Space Averaging Anemometer. It is manufactured by

Campbell Scientific, Inc. The laser is aimed across at least a 300 meter path to the CA-9 which then computes a path averaged mean speed.

The purpose of this study is to compare the relationship of short term fluctuations ($\leq$15 min.) in the time series measured by the laser anemometer to those measured by conventional anemometers placed at selected points along the laser path. M.S. (1976).

The Dynamics of Entrainment in the Planetary Boundary Layer: A Study in Turbulence

O. Zeman

In this thesis the dynamics of horizontally homogeneous entraining mixed layers is studied. Parameteric and second order models of these entraining layers are developed.

The parametric model is based on the one-layer model of Tennekes. In the model the temporal term of Zilitinkevich and a dissipation term were incorporated. The dissipation term was found to be proportional to the Brunt-Vaisala frequency and the mixed layer height, and inversely proportional to the characteristic turbulence velocity. The effect of mechanical turbulence production at the top of the mixed layer is included as a correction to the dissipation term. Wind shear-generated turbulence is taken into account through the friction velocity and a geostrophic friction law.

The second order model was developed for buoyancy-driven mixed layers. The models of pressure terms, dissipation, and destruction of temperature variance are to a great extent based on invariant techniques. The unknown constants in these models were determined empirically. The constants in the dissipation model were optimized by fitting the model predictions to the data in homogeneous plane shear and plane strain flows. The transport term models are based on solutions to the approximated rate equations for the third order turbulent moments. Buoyancy effects were taken into account. The buoyant transport model gives realistic profiles of the vertical fluxes of second-order turbulence quantities and realistic values of the downward heat flux at the top of the mixed layer. Ph.D. (1975).

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16. ABSTRACT

An interdisciplinary program in air pollution meteorology at the Pennsylvania State University lasting from May 1, 1972 to March 31, 1978 identified as a central problem, the development of a comprehensive mesoscale predictive transport model capable of nesting within a global scale grid system and sufficiently flexible in scale to be used for either regional or urban problems. The treatment of the boundary is sufficiently general to permit application of the model to complex terrain problems. Also included in the group's effort have been a variety of subsidiary one- and two-dimensional models for the prediction of mixed layer depth, nocturnal mixed layer evolution, and buoyantly driven convection regimes. Work was also done on deposition processes and on facility development for measurements of air quality and model validation needs.

This final report presents summaries of the major tasks, together with references and abstracts of published papers and dissertations produced by the investigators and their students.

17. KEY WORDS AND DOCUMENT ANALYSIS

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