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MODELING THE URBAN BOUNDARY LAYER

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16. Abstract

This report is a summary and evaluation of the Workshop on Modeling the Urban Boundary Layer held in Las Vegas on May 5, 1975. The report is comprised of a workshop summary, an evaluation, and the slightly edited summaries from each of the session chairpersons. The sessions were (1) Formulation and Solution Techniques, (2) K-Theory versus Higher Order Closure, (3) Surface Heat and Moisture Balance, (4) Initialization and Boundary Problems, (5) Nocturnal Boundary Layer, and (6) Verification of Models. Hopefully, this report will be of interest for the specific topics discussed and in aiding the planning of future workshops.

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Preface

This is a summary and evaluation of the Workshop on Modeling the Urban Boundary Layer held in Las Vegas on May 5, 1975. The conference grew out of a suggestion by R. D. Bornstein, who, with R. L. Lee and R. W. Bergstrom, comprised the organizing committee. The report is comprised of a workshop summary by R. Lee, an evaluation by R. Bornstein, and of slightly edited summaries from each of the session chairpersons; it is to them that credit for this report should go. Hopefully, this report will be of interest for the specific topics discussed and in aiding the planning of future workshops.

MODELING THE URBAN BOUNDARY LAYER*

R. W. Bergstrom

Ames Research Center

1. Workshop Summary — R. L. Lee

On May 5, 1975, twenty-six atmospheric and urban boundary layer researchers attended a workshop on Modeling the Urban Boundary Layer at the Sands Hotel, Las Vegas. The main purpose of the workshop was to bring together a small group of urban boundary layer modelers in order to provide an opportunity to discuss current problems of mutual interest. It was felt that there exist various outlets for the discussion of the capabilities and accomplishments of individual modeling efforts, but few for the discussion of unresolved problems. Initially the workshop was to have been limited to urban problems, but a wide response from other interested persons led to a broadening of the scope to include more general atmospheric boundary layer topics.

The workshop consisted of six 1-hour discussion sessions interspersed with 10-15 minute presentations. A chairperson was selected for each session to act as moderator and to lead the discussion. The session topics and chairpersons were: (1) Formulation and Solution Techniques (Dr. R. Lee, Lawrence Livermore Laboratory); (2) K-Theory vs. Higher Order Closure (Dr. R. Bergstrom, Ames Research Center/NASA); (3) Surface Heat and Moisture Balance (Dr. W. Shaffer, Techniques Development Laboratory/NOAA); (4) Initialization and Boundary Problems (Dr. J. McElroy, Environmental Monitoring and Support Laboratory/EPA); (5) Nocturnal Boundary Layer (Professor A. Blackadar, Pennsylvania State University); and (6) Verification of Models (Dr. T. Yamada, Geophysical Fluid Dynamics Program, Princeton University). An introduction and summary was provided by Dr. R. Bornstein of San Jose State University.

The first session began with a discussion by Dr. R. Lee of the advantages and disadvantages of several frequently used formulation and solution techniques of the equations for urban boundary layer models. He commented that although finite difference methods have been used almost exclusively in meteorological modeling, there are alternate solution techniques which may be more accurate and perhaps better suited for large three-dimensional problems. In particular, he pointed out that the Galerkin finite element method has been used successfully in a wide variety of problems. Of special interest are problems involving complex surface geometry. Along this line, Dr. P. Long presented results of calculations made with the one-dimensional color equation using Galerkin's technique. Following this, an alternative formulation of the three-dimensional equations using two vorticities and two stream functions was discussed by Dr. R. Bornstein.

During the second session, Drs. R. Bergstrom, R. Pielke and T. Yamada made short presentations which compared results obtained from various

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*Report on a Workshop held on May 5, 1975 in Las Vegas, NE.

turbulence closure formulations. It was generally felt that the verification of turbulence models is severely handicapped by a lack of detailed observational data. In addition, it is uncertain which of the simplified or sophisticated models that have been tested for simpler flows will be appropriate for the more complex urban situation.

Dr. M. Estoque began the third session with an overview of the problems associated with the calculation of surface temperature and humidity by use of balance equations. Two different methods of coupling a constant flux layer with surface boundary conditions were then discussed by Dr. W. Shaffer and Mr. C. Nappo. Dr. C. Bhrumralkar presented a short discussion on the possible effects on local climate resulting from large elevated heat and moisture sources (e.g., a large power center).

Dr. J. McElroy, who chaired the session on initialization and boundary problems, noted that there are no firmly established guidelines for initialization of numerical models. He added that the inhomogeneous thermal and physical nature of urban surfaces frequently induces nonequilibrium flow conditions which make it difficult for the development and validation of models with field data. It was generally felt that the sparcity of existing urban observations also impedes these efforts. In the ensuing discussion, which included a description by Dr. F. Vukovitch of his three-dimensional urban heat island model, various problems were considered. The problems included the potential consequences and magnitudes of errors resulting from an inaccurate specification of initial conditions, the correct posing of boundary conditions in models, and difficulties in parameterization on the urban scale.

Professor A. Blackadar led off the fourth session with a review of the physical processes involved in the evolution of nocturnal surface-based radiation inversions and their associated wind profiles. Subsequently, Dr. Y. Delage showed results from a numerical model which attempts to quantitatively explain the development of a low-level jet. Recent observations of wind and temperature profiles in an urban area were then presented by Dr. B. Ackerman. In conclusion, Professor Blackadar discussed the distinction between external and internal parameters, and their role in a truly predictive model.

The final session, on the verification of models, included presentations from Drs. D. Leahey, T. Yamada, T. Yu and D. Randerson. Dr. Leahey was critical about the vague verification techniques employed by numerical modelers in general, and he suggested a possible standardization of such verification procedures. Drs. Yamada and Yu both discussed comparisons of turbulence models with observations, and Dr. Randerson discussed results produced by a simple mesoscale model which was developed for operation purposes. He cautioned that, from a practical point of view, one should question whether a complex model requiring extensive computer time could yield significantly better forecasts than a simpler model.

In summary, the one-day Workshop on Modeling the Urban Boundary Layer succeeded in providing an opportunity for urban modelers to meet and exchange up-to-date information. To what degree it accomplished the goal of discussing current problems, as opposed to successes, is not clear. Moreover,

due to the lack of time, many other problem areas worth considering had to be omitted. For example, the tailoring of urban boundary layer models to air pollution predictions, the coupling of urban models to regional or synoptic models, and the problems of cumulus parameterization were not considered. In this regard, critique forms were sent to all of the attendees of the workshop to solicit their views and suggestions for possible future workshops. The results of the critiques have been summarized and are discussed in the following section. It is hoped that such feedback will provide the necessary ingredients for improving future workshops.

2. Workshop Evaluation — R. D. Bornstein

On the basis of responses received to an evaluation questionnaire sent to each of the attendees at the Workshop on Modeling the Urban Boundary Layer, the workshop can be considered to have been a success. This evaluation is based on those responses, and is presented so that future workshops of this type can be even more successful.

The most frequently cited benefit of the workshop was the opportunity to meet with colleagues (for the first time, in many instances) for informal discussion and exchanges of ideas. Several persons expressed the thought that future workshops should be held in cities having less evening entertainment than does Las Vegas so as to encourage continued professional interactions into the evening hours.

The original concept of the workshop was that the discussions within each of the six sessions should concentrate on current problems and that they should not be a repeat of the successes that are normally reported at meetings or in the literature. Discussion leaders were selected for each of the six sessions on the basis of current research interests, and they were asked to prepare a brief summary of the unsolved problems associated with the topic to be discussed in their session. In addition, the session leaders were provided with a list of attendees who indicated an interest in making a 5 to 10 minute presentation during their session.

There were a number of general comments from the attendees concerning the content of various sessions. Some felt that a few summaries and presentations contained material which the speakers should have assumed would have been familiar to the workshop group, while others felt that some of the material was a preview of that to be presented at the formal conference. In light of these comments, future workshop organizers should work very closely with their discussion leaders so as to ensure the optimum use of the very limited time available at such workshops.

The workshop was originally to have been limited to problems concerning the urban boundary layer, but enthusiastic responses from other interested persons led to a broadening of the scope so as to include more general atmospheric boundary layer topics. However, some of the attendees felt that 26 participants were a bit too many for everyone to have an opportunity to directly participate in each of the sessions. In addition, others felt that by broadening the scope of the workshop, too little time was spent in discussing urban boundary layer problems.

Under the format followed at the one-day workshop, six topics were covered in six 1-hour sessions, and it was suggested by a number of attendees that more time should have been spent in discussing each topic. This could have been accomplished at a one-day workshop by any or all of the following: (1) have four topics discussed in sessions of 90 minutes in duration; (2) have attendees break into smaller groups whose deliberations could then be reported back to the larger group; or (3) have additional sessions during the hours after dinner. Alternatively, the workshop could have been longer, and most of the attendees felt that an optimum length would have been two or three days.

A two- or three-day workshop would have to be held on its own, as opposed to being held in conjunction with a meeting of the American Meteorological Society, as was done with the present workshop. About half of the attendees felt that future workshops should be held on their own, while most of the remaining persons felt that they should be held in conjunction with "specialty" AMS meetings. In the latter case, the most convenient situation would occur when a one- or two-day workshop would be held in conjunction with a three- or four-day specialty meeting. This would help ensure that as many interested persons as possible would be available for the workshop and it would also keep travel expenses to a minimum.

There is, however, another possibility, and that is to hold a series of workshops in conjunction with the annual meeting of the AMS. These meetings have been experiencing declining participation over the last few years due to the increase in the number of specialty meetings that have been sponsored by the society. The AMS could hold the workshops, say, during the afternoon hours on several days during the annual meeting. In addition, two types of workshops could be sponsored, i.e., one for those persons actively involved in research in a particular area and one for those persons who are interested in future research in that area (like the Workshop on Micrometeorology held in Boston in June 1972). Several of each of these types could be held simultaneously, if they covered topics in widely separated areas of the atmospheric sciences.

In summary, the Workshop on Modeling the Urban Boundary Layer was successful in that it provided an opportunity for a small group of researchers to hold informal discussions on the current status of their various research efforts in the area of boundary layer modeling. This brief evaluation reviewed some of the comments collected from the attendees on how to improve future workshops. In particular, suggestions have been put forth on how the American Meteorological Society might sponsor future workshops in conjunction with either specialty or annual meetings, and comments to the AMS on these suggestions are welcome.

3. Sessions Reports

Session 1: Formulation and Solution Techniques

Chairman: R. L. Lee

The purpose of this session was to discuss the advantages and disadvantages of current and new formulation and solution techniques for the model equations used in urban boundary layer prediction.

The first discussion was by Dr. R. L. Lee, who summarized the necessary steps taken by a numerical modeler, including (1) formulation, (2) discretization and numerical integration, and (3) display of output. At the onset, the modeler has to make various decisions as to what the model hopes to predict. Typical questions which arise are two vs. three dimensions, time dependent vs. steady state, primitive equations vs. vorticity-stream function, etc. Dr. Lee indicated that although finite difference methods have been used almost exclusively in meteorological modeling, there exist alternate solution techniques which have shown promise. The best known of these alternate techniques is the Galerkin Finite Element Technique, which is a subclass of the more general Method of Weighted Residuals.

Finite element techniques have essentially replaced finite difference methods in structural problems and have recently been used very successfully in fluid mechanics. Among the major advantages of finite element techniques are: (1) ability to handle boundary conditions easily; (2) adaptability to domains with complex boundary geometry; (3) straightforward algorithms to generate higher accuracy. Results from numerical experiments with the one dimensional color equation were shown to interested attendees. These experiments showed distinctly that the lowest order (linear) finite element method is more accurate than a typical second-order finite difference scheme.

Dr. Paul Long discussed his numerical experiments with linear chapeau functions (equivalent in one dimension to linear finite elements) on telescoping grids, constant grids and outflow boundary points. Chapeau functions are used in the Techniques Development Laboratory's (NOAA) three dimensional boundary layer model. The difficulties which arise with fixed outflow boundary points and points of abrupt transition in mesh spacing (coarse → fine) result from the rapid propagation of noise from these points upstream. Using one-sided chapeau functions at these points greatly reduces the reflected noise. Chapeau functions are also useful for solving vertical turbulent transfer equations without recourse to ad hoc flux boundary conditions.

Finally, a brief discussion was made by Dr. R. D. Bornstein on his formulation of a hydrostatic, three-dimensional vorticity-stream function boundary layer model. In two dimensions, it is known that the vorticity-stream function approach is natural and tends to yield slightly 'smoother' solutions than the primitive equation counterpart. However, many of the conveniences offered by the stream function approach in two dimensions become lost due to mathematical complexities in defining a stream function in three dimensions. On

the other hand, if the flow can be assumed to be hydrostatic, the three-dimensional equations reduce to a form similar to a two-dimensional case.

Session 2: K-Theory Versus Higher Order Closure

Chairman: R. W. Bergstrom

The purpose of the session was to discuss the advantages and disadvantages of various ways of predicting the turbulent transport properties of the urban atmosphere. The most widely used method has been to prescribe "turbulent diffusivities" (called K-theory). However, in the last several years considerable effort has been spent on more sophisticated methods (see, for example, *Advances in Geophysics*, Vols. 18A and B; or *Turbulence Transport Modeling*, AIAA Selected Reprint Series, Vol. XIV). These more detailed methods (often called "Higher Order Closure" Schemes) promise greater accuracy and generality at the expense of computational effort. However, the question of interest to someone who is not closely involved in the construction of turbulence models, but only wants to use one, is: "What method should I use for X percent accuracy in Y situation for Z computational expense?" Unfortunately, for a number of different reasons the information necessary to answer the question does not appear to be available.

The session presentations consisted of the results of three investigators who have looked at a particular aspect of the question. Dr. Bergstrom presented a comparison of results from a K-theory formulation and a higher order closure scheme for a Wangara Day 33 simulation. Results were also compared to other investigators and showed that for the temperature predictions during the day, the K-theory agreed very well with both the observations and predictions of other higher order schemes.

Dr. Pielke presented results which were also for a Wangara Day 33 simulation. His results (contained in a paper to be published in JAS) similarly showed that a K-theory model does remarkably well for the daytime predictions indicating that daytime conditions are perhaps easily predicted. The exchange coefficients used by Dr. Pielke were functions of the distance above the ground, rather than coefficients dependent only on local gradients. For the case studies examined thus far, K-theory results are as accurate as with the higher-order closure schemes.

Dr. Yamada presented results contained in an earlier paper with G. Mellor (JAS, *31*, 1791-1806, 1974) where three turbulence models were compared with each other for diurnal cycle predictions. The three models performed similarly and the authors concluded that their level 2 model was a good compromise. However, they made no attempt in this work (but see Session 6 summary) to compare with observations.

The discussion during the session indicated the serious problem of verification of turbulence models for urban flows. Frequently, models have been developed for simplified flow situations (constant "flux" layer, steady flow, etc.) and later applied to different flow situations where their applicability

is unknown. Much work in turbulent modeling is being done for simplified flows (for example, decay of isotropic turbulence) and it remains to be seen how much will be appropriate for urban models.

Attempts at verification by comparison to observations are also hazardous because often one doesn't know if the test is of the turbulence model or the other assumptions involved in the numerical model. Verification against observations is only meaningful when there are enough large scale measurements (time dependent pressure gradients, upwind conditions, etc.) to provide inputs for the model. Then the results from several turbulence models could be compared against the observations. To date, however, observations with such detailed information do not exist. Perhaps for the present, the best advice is to use models which have been tested against laboratory flows with the understanding that the model has not been "verified" for flow in an urban area.

Session 3: Surface Heat and Moisture Balance

Chairman: W. A. Shaffer

Professor Mariano Estoque of the University of Miami began the discussions with an overview of the problem of specifying surface temperatures and humidities. For a predictive model, it is desirable to *predict* surface temperatures and humidities and Prof. Estoque felt that the energy balance method offers the best approach. He then reviewed the general formulation of a surface energy-flux balance.

Dr. Wilson Shaffer of the National Weather Services Techniques Development Laboratory then discussed the way he couples a contact layer to the surface in a forecast model that he and Dr. Paul Long (now at DuPont's Savannah River Laboratory) are jointly developing. The soil heat flux term is based on an analytic solution, and requires no computation levels within the soil, while surface moisture is calculated by assuming that the ratio of actual evaporation to potential evaporation remains constant for an entire day. Dr. Shaffer then showed some results obtained from the method. He demonstrated that errors in the initial soil temperature profile have a minimal effect upon the forecast temperatures. However, a poor estimate of soil moisture (and thus evaporation) can produce large differences in the resulting temperatures.

As an extension of the usual energy balance method, Mr. Carmen Nappo of the Atmospheric Turbulence and Diffusion Laboratory presented an approach which includes consideration of vegetative cover. The method combines a "constant flux" layer, a vegetative layer, and a soil layer. New profile relationships have been obtained for the atmospheric layer immediately above the vegetation, but these relationships require specification of some constants relating to the moisture transfer. This method, still in the developmental stage, eliminates the need to know the detailed structure within the vegetative layer.

Another problem facing urban meteorologists today is the injection of large amounts of heat and moisture into the atmosphere — not at the surface,

but aloft. Stanford Research Institute's Dr. Chandrakant Bhumralkar presented some order of magnitude estimates of these inputs from power parks. A few possible consequences of these inputs were mentioned: restriction of sunlight due to shadowing by a visible plume, deposition of detrimental chemicals in cooling water onto surrounding areas, restriction of visibility by a plume reaching the ground, and changes in the precipitation patterns near the power parks.

Session 4: Initialization and Boundary Problems

Chairman: J. McElroy

In his introductory remarks, the session chairman noted that the initialization process for urban meteorological models is basically similar to that established over the past two decades for their synoptic scale counterparts. An initial data field consistent with the specific model equations must be developed, and a mechanism must be set up for the rejection of invalid data. This data field, for instance, may be (1) idealized to apply to a simplified meteorological situation or to fit the model equations, (2) "smoothed" or filtered observed data, (3) the result of a solution of a simplified version of the model equation or a hierarchy of systems of such equations, or (4) result from an iterative process involving an initially prescribed observed data field and subsequent solutions of model equations.

Thus, as the above possibilities illustrate, there are no firmly established guidelines for initialization. The initialization process typically involves a considerable amount of experimentation or improvisation. For the same model, the process may vary strikingly according to the particular weather situation.

However, the diurnal forcing functions involving the heat, momentum, and radiative fluxes at the earth-air interface are far more significant for urban models than for the synoptic scale counterparts. In fact, these forcing functions influence the model solutions for the former to such a degree that a highly precise or stable initialization may not be required. The successful simulation of gross urban atmospheric features by comparatively simple advective models is at least a partial verification of this hypothesis.

Unfortunately on the other hand, the inhomogeneous thermal and physical character of the urban surface may necessitate a rather complex formulation for the spatial portion of such forcing functions. This inhomogeneity will cause considerable "noise" to exist in observed data. Additionally, it may mean that equilibrium flow cannot be established anywhere over an urban area (if internal boundary layer theory is valid). This in turn will make it difficult for the development and validation of urban models with field data.

Dr. F. Vukovich then described his mathematical modeling of an urban heat island for both idealized situations and for the St. Louis, Missouri area. The ensuing discussion was primarily confined to specific problems encountered by various workshop attendees in their modeling efforts. For instance, the

consequences of using various boundary conditions were discussed. Effects of pressure gradients and friction on the structure of the urban heat island were described as determined by modeling studies by several investigators. The difficulty of parameterization on the urban scale in initialization, as well as in other aspects of modeling, was touched upon briefly. Additionally, the attendees considered the potential consequences and the magnitudes of possible errors resulting from errors in the specification of initial conditions.

Session 5: Nocturnal Boundary Layer

Chairman: A. Blackadar

Professor A. Blackadar led off the discussion on nocturnal boundary layers by outlining several problems, and then proceeded to review the physical processes involved in the evolution of nocturnal inversions and associated wind profiles. During the afternoon hours, convection deprives the lower boundary layer of momentum, and the wind deviates considerably from the geostrophic wind. As a radiation inversion begins to form in the lowest 10-20 meters, the air layers above are temporarily detached from the surface and begin executing an inertial oscillation which, if unchecked, would result in supergeostrophic winds several hours later. However, as the winds increase, the shear of the surface layers increases and the Richardson number falls below its critical value (probably about 0.25). As a result, turbulent motion is produced and modifies both the temperature and wind distribution. The nocturnal inversion is thus viewed as a well-, but often intermittently-, mixed layer growing upward during the night, frequently displaying a jet-like wind speed maximum at its top. The height of the mixed layer and the evolution during the night are strongly controlled by the geostrophic wind distribution in height and time. Dr. Y. Delage then presented some results from his numerical study of the nocturnal atmospheric boundary layer (Q.J.R.M.S., *100*, 351-364, 1974) which gave strong support to early qualitative explanations of the low-level jet phenomenon and which showed that the height of the mixed layer increases rapidly early in the evening and then stabilizes at a height that depends uniquely on the rate of surface cooling and the geostrophic wind speed.

Dr. Bernice Ackerman presented some recent observations of wind and temperature profiles measured in various locations upwind, downwind, and inside of the city of St. Louis, Mo. Wind profiles displaying a jet-like maximum occur frequently at night, and tend to be higher over the city than upwind of it. Also, analyses based on measurements made at four city sites indicated horizontal convergence below 350 m and divergence above. Two types of crossover effects were discussed: one in the wind, and the other in the temperature. In the latter effect, the surface temperature is highest over the city, while the temperatures above 50-100 m are higher over the country. This effect is generally believed to result from enhanced turbulent mixing over the city, but there was no agreement about the relative importance of surface roughness vs. surface heating as the mechanism for producing the increased surface temperature. Oke had pointed out in 1972 (Conference on Urban Environment and 2nd Conference on Biometeorology, Philadelphia) that the heat island

forms very rapidly early in the evening but does not increase significantly after midnight. Others present confirmed this fact and attributed it to the observation that rural temperatures fall rapidly after sunset, while urban temperatures fall very little if at all during the early evening. This effect might be explained by the higher heat capacity of the urban surface materials and by the daily variation in the anthropogenic heat sources.

Dr. Blackadar continued the discussion by emphasizing the dominant influence played by such parameters as geostrophic wind and surface net radiation on the wind and temperature distribution, not only during the night but in the daytime as well. The former are examples of *external* parameters, while parameters such as surface temperature and surface wind speed are *internal* parameters (or independent and dependent parameters). It is important to recognize the difference between the two. External parameters are the true forcing functions of predictive models while internal parameters are consequences of the forcing. External parameters are in general predictable from events going on outside the system: geostrophic wind from the global circulation; solar radiation at the top of the model from astronomical and upper atmosphere considerations; surface soil characteristics from laboratory analyses and moisture inventories; and SO_2 emissions and depositions from surveys and other prediction methods. Many feedbacks occur and must be programmed into any realistic model. Most present-day models are dependent to some degree on internal parameters. For this reason, they are not truly predictive.

After considerable discussion several points were agreed upon: (1) one of the most important immediate objectives of mesoscale models should be that of determining the relative sensitivity of the boundary-layer evolution to the many different external parameters, and by so doing to guide the design of more efficient field-measurement programs; (2) operational models are essentially predictive in nature and should, therefore, be designed in such a way as to be independent of internal parameters, except through feedback processes; and (3) quantitative prediction of exchange processes can only be achieved if there are measurements of *both* wind and temperature profiles, together with the significant external parameters.

Session 6: Verification of Models

Chairman: T. Yamada

Introduction. Every numerical model should be verified. But how? This was the topic discussed during the session on the verification of models.

The following are summaries of the presentations of D. Leahey, D. Randerson, T. Yamada and T. Yu, and of the subsequent discussions arising during the session. In order to make this summary more accurate, each speaker was asked to submit to the chairman a brief summary of the content and conclusions of his talk. Thus this report may contain not only discussions held during the workshop, but also some thoughts developed at the time of the writing, which was about six weeks after the meeting.

Summary of presentations. Dr. Leahey criticized the vague verification techniques employed by numerical modelers in general. He suggested the following as a possible standardized guide for the verification of models (in addition to the conventional visual comparisons of the computed results with observations):

(a) Standard errors or RMS values of estimates should be supplied and discussed.

(b) When possible, correlation coefficients should be given and explained.

Dr. Yamada discussed the results of a paper, "A simulation of the Wangara atmospheric boundary layer data" (with G. Mellor and published in J.A.S.). The model is based on a simplified version of a turbulence closure model which is required to solve the turbulence energy and temperature variance equations. Computed nocturnal low-level jet wind speeds are correct in magnitude and location in comparison with the observation of days 33 to 35 of the Wangara experiment.

Dr. Yu conducted extensive comparisons of various formulations of eddy diffusivities which have appeared in the literature by utilizing a one-dimensional planetary boundary layer model of the Techniques Development Laboratory. Yu found that satisfactory results were obtained (in the case of the convective boundary layer) when the diffusivity was specified by O'Brien's K-cubic formula capped by Deardorf's mixed layer height formula. He recently added a turbulent energy model into his comparisons and found that for the wind speed this model obtained the best agreement with the observations.

Dr. Randerson presented the results obtained with a series of mesoscale models that he and John Cornett have developed. The individual models are based on the following: (1) advection of horizontal vorticity, (2) advection of absolute vorticity, (3) inertial terms in the equation of motion, (4) ageostrophic terms, and (5) a complete model consisting of inertial motion, vertical mixing and ageostrophic acceleration. The complete model has yielded the best forecasts in terms of RMS errors among the models tested, but only by a small amount. From an operational viewpoint, however, Dr. Randerson commented that we should ask ourselves if complex models requiring extensive computer time yield significantly better forecasts.

Remarks. Drs. Yamada and Yu utilized one-dimensional models because of simplicity and the availability of data, but further verification of models must be conducted using three-dimensional observations. Fortunately such data may be available in the near future, for example, from project METROMEX and from the New York Air Pollution Dynamics Project.

The session chairman is grateful to Drs. Yu, Randerson and Leahey for their kind and prompt replies to his request for their summaries. This report was partially based on the summaries submitted by those speakers. The session chairman is, however, responsible for any incomplete reproduction of their presentations in this report, since the original summaries have been shortened by over 50 percent due to space limitations.

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