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Atmospheric Turbulence and Diffusion Laboratory

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SUMMARY OF MEETING ON MESOSCALE ATMOSPHERIC MODELLING
JUNE 14-16, 1971

Steven R. Hanna
Editor

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Meeting on Mesoscale Atmospheric Modelling, Watts Bar Dam, Tenn., 1971.

Summary of Meeting on Mesoscale Atmospheric Modelling

(held June 14-16, 1971 at Watts Bar Dam, Tennessee)

Edited by
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1. Introduction

A working meeting on mesoscale numerical modelling was held at Watts Bar Dam, Tennessee, on June 14 through 16, 1971, sponsored by the Atmospheric Turbulence and Diffusion Laboratory (ATDL) of the National Oceanic and Atmospheric Administration (NOAA). Funds were provided by NOAA to cover the travel expenses of a limited number of scientists. Persons were invited to attend who possessed working models of mesoscale planetary boundary layer air flow. A list of attendees is given at the end of this report. The purpose of the meeting was to promote the exchange of ideas, assess the state of the art of mesoscale modelling, and determine future research priorities. In order to encourage informal, uninhibited discussion, the meeting was held at a small, pleasant, isolated lakeside resort.

The meeting program was structured so that during the first half of the meeting each scientist presented a 45-minute talk outlining his model. The last half of the meeting consisted of a series of three study periods, during each of which the participants formed three groups with the assigned task of making recommendations concerning specific problem areas. After an hour or two of discussion, the groups came together and the recommendations were read before all the participants. Sections 3 and 4 contain these recommendations.

This report is being distributed in the hope that other interested persons can benefit from the discussions. We hope that the excellent communications evident at this meeting will continue.

2. Abstracts of Invited Papers

2.1 Mesoscale Modelling at the National Meteorological Center,
J. P. Gerrity, Jr.

The most comprehensive forecast model now used has been described by Shuman and Hovermale in the Journal of Applied Meteorology in 1968. The several dependent variables are carried at seven levels above each of 2964 points of a square mesh upon a polar stereographic projection of the Northern Hemisphere. The mesh spacing is 381 km at 60° north, and is smaller in terms of distance on the Earth at more southerly latitudes.

The vertical transport of momentum by eddies is estimated by a drag coefficient technique within the lowest layer of the model. The drag coefficient is based on Cressman's formulation and combines both a uniform roughness, neutral stratification estimate and a terrain height dependent estimate of so-called "form drag." The model includes sensible heat exchange between the sea and the lowest air layer based on a "thermal drag coefficient" calculation. In addition, heat, both sensible and latent, is exchanged vertically so as to maintain a convectively stable vertical profile. This is done in the manner described by Manabe and termed a "convective adjustment" process. Radiative heat transfer is highly parameterized. Solar radiation is transformed to sensible heat by direct heating of the lowest air layer. Long wave cooling at 1.5°C per day is assumed at all levels. The release of latent heat by condensation is incorporated in the lowest three layers of the model in a manner similar to that described by Smagorinsky (Physics of Precipitation).

Another version of this model which utilizes one-half the mesh size in space and time is in the final stages of check-out. The limited area, fine mesh model (LFM) is designed to provide a replacement of the current model for short-range forecasts for the contiguous U.S. A new, eight-layer model written in spherical coordinates has been designed for ultimate use as a global forecast model. The prime motivation for reducing the mesh size in our models is to lessen the truncation errors associated with both linear and nonlinear terms. Other alternatives exist, for example, the use of higher-order finite-difference approximations and the astute design of "sub-grid" scale energy or enstrophy transfer parameterization. Some research is being conducted along these lines.

The problem of short-range deterministic forecasting is thought by many to depend upon an accurate portrayal of the initial state of the atmosphere. This problem involves the analysis of observations in a manner compatible with the predictive capability of the forecast model. We tend to term this the initialization problem. Within the framework of the quasi-static equations, it is also the problem of the geostrophic adjustment. A rather considerable effort is being made in this problem area at NMC.

More specifically related to the subject of this conference are those programs which utilize the output of the large model to diagnose local weather. In the air pollution arena, the approach is to use the output of the model in a decision-tree framework to arrive at estimates of Air Pollution Potential (APP). Advisories are disseminated by facsimile on a routine basis delineating those portions of the contiguous U.S. over which certain criteria are satisfied. E. Gross, who is chiefly responsible for this programs automation and development, is striving mightily to glean from the literature possible techniques for parameterization of urban conditions from the essentially rural meteorological forecasts of the models.

2.2 A Single-Layer Mesoscale Model, R. L. Lavoie

There are many occasions in which a large subsiding air mass is kept sufficiently well-mixed at lower levels by strong winds and/or surface heating to give rise to a nearly homogeneous planetary boundary layer capped by an inversion. Under these conditions it may be possible to use a single-layer representation of the lower atmosphere for purposes of studying the effects of variations in terrain, in surface heating, and in surface roughness on the mesoscale distribution of weather. It may be possible to sacrifice vertical resolution in order to experiment with the consequences of horizontal asymmetries with very modest computer requirements.

The numerical model utilizes the primitive equations integrated from the top of the constant flux layer to the base of the inversion or stable layer. Fluxes of momentum, heat and moisture through the lower boundary are represented through use of drag coefficients. An attempt is made to parameterize the interactions with the overlying stable atmosphere. Convective precipitation and latent heat release are also included by parameterization.

The major application of this model has been to arctic air outbreaks over Lake Erie and the associated lake-effect storms which they spawn. Grid meshes of 6 km to 12 km have been used in these experiments. Simulation of airflow over tropical islands has also been attempted using a 1 km to 3 km grid mesh. Results encourage the view that in many cases the gross features of surface-induced disturbances on the mesoscale may be rather insensitive to the details of vertical structure of the prevailing flow.

2.3 Air Force Global Weather Central Boundary Layer Model,
Lynn L. LeBlanc

A limited area seven layer physical-numerical model for the lower tropospheric region (surface-1600 m) is described. The grid interval is half that of the standard numerical weather prediction grid used in the hemispheric, free atmospheric, operational model at the Air Force Global Weather Central (AFGWC). This model is an integral part of the complete AFGWC meso-scale (sub-synoptic) numerical analysis and prediction system. This model provides greater horizontal and vertical resolution in both the numerical analyses and numerical forecasts. It is used to predict the more detailed smaller scale atmospheric perturbations which are important in specifying sensible weather elements.

Important features of this boundary layer model include: a completely automated objective numerical analysis of input data; the transport of heat and moisture by three dimensional wind flow (including terrain and frictionally induced vertical motions); latent heat exchange in water substance phase changes; and eddy flux of heat and water vapor.

Input data are conventional synoptic surface and upper air reports. Other prediction models provide horizontal wind components at the upper boundary and an estimate of cloudiness above the boundary layer region. Forecasts for the lower boundary and surface layer are empirically derived. Despite some approximations which broadly simplify the real planetary boundary layer processes, operational use indicates the model is capable of producing detailed forecasts out to 24 hours. A winter case study is discussed.

2.4 A Planetary Boundary Layer Model, Joseph P. Pandolfo

The most general boundary layer model presently being used in several projects at the Center for the Environment and Man, Inc. solves the conservation equations for six dependent variables simultaneously over three dimensional grid arrays containing several thousand points and over integration periods of a few days. Each point within the horizontal grid array is independently specified as containing either an air-land or an air-water interface. The dependent variables are horizontal wind (and current), air temperature (and water/or soil temperature), atmospheric moisture (and salinity), and two aerosols (each of which may be particulate, gaseous, or suspended liquid water). Auxiliary equationscalculate the horizontal field of pressure, using the hydrostatic approximation equation from a specified pressure field at one vertical boundary; the grid-scale vertical velocity, using the continuity equation; the vertical Austausch coefficients, using the local Richardson number; and the radiative heating (or cooling). The radiative calculations can take into account the thermal effects of aerosols, if their optical properties are specified.

A simpler, one-dimensional version of the model, in which the horizontal gradients of the dependent variables are specified, is often used in experiments concerned more directly with the modelling of vertical transfer processes.

Experimental results will illustrate the effects of alternative vertical turbulent transfer formulations, of varying accuracy in the specification of initial and boundary conditions, and of the inclusion of aerosols which absorb and scatter radiation.

2.5 Mesoscale Circulations, M. A. Estoque

The present status of our studies on mesoscale circulations will be discussed. The first part of the discussion will be concerned primarily with a detailed description of the current model. Results of integrations of the model will also be presented. The second part of the discussion will deal with the results of observations which were made to determine the realism of the model. The observations were made over Grand Bahama Island in August 1970. Surface weather, aircraft, tethered balloon pilot balloon and cloud (time lapse and panoramic pictures) observations were made.

2.6 Numerical Modelling in Three Dimensions, J. W. Deardorff

This numerical approach is designed to model the energy containing eddies, especially with regard to the vertical velocity, w. Consequently, the width or length of the model is several (2 to 4) times the height, h, of the region containing the turbulence. For an unstable planetary boundary layer (upward heat flux) this height represents the level of the inversion base surmounting the mixed layer. In the neutral case, this height was chosen to be about $.5u_*/f$, with most of the turbulence being found to occur below $.3u_*/f$. All lengths were scaled by h, velocities by u_*, and time by h/u_*. If h is a kilometer, then my latest model extends over an area of only 4km x 4km and has 40x40x20 grid intervals in the respective downstream (x), cross-stream (y) and vertical (z) directions.

Motions on a scale smaller than the grid intervals give rise to sub-grid scale Reynolds stresses from which a sub-grid scale eddy coefficient, K_m', can be defined:

$$\overline{u_i'u_j'} - \delta_{ij}\,\overline{u_l'u_l'}/3 = -K_m'(\delta\bar{u}_i/\delta x_j + \delta\bar{u}_j/\delta x_i)$$

where the delta term is the average local sub-grid scale turbulence intensity, and the overbar is the local grid-volume average. K_m' was formulated by

$$K_m' = \frac{(c\Delta)^2}{\sqrt{2}} \left[(\delta\bar{u}_i/\delta x_j+\delta\bar{u}_j/\delta x_i)(\delta\bar{u}_i/\delta x_j+\delta\bar{u}_j/\delta x_i) \right]^{1/2}$$

where Δ is a representative grid interval and $c \simeq 0.2$. I've found that K_h' in the temperature equation should be set to about $3K_m'$.

I used cyclic boundary conditions in x and y, except that mean horizontal pressure gradients (invariant in height) were prescribed to have values which give no mean acceleration to the fluid as a whole when the surface stress attains an equilibrium value. Upper boundary conditions were $w = 0 = \delta\bar{u}/\delta z = \delta\bar{v}/\delta z = \delta\bar{\theta}/\delta z$, where θ is potential temperature. Lower boundary conditions were $w = 0$ at $z = 0$, but $\delta^2 \bar{u}/\delta z^2$ and $\delta^2\bar{v}/\delta z^2$ and $\delta^2\theta/\delta z^2$ prescribed at $z = 1/2\ \Delta z$ in a manner compatible with existence of a log-profile type layer below $z = 1/2\ \Delta z$.

The main results relate to the vertical profiles of mean flow and temperature, and of turbulence statistics. Because of the artificial lid imposed at $z = h$, the entrainment process and change of h with time were not modelled. Consequently, the heat-flux profile was unrealistic as $z \rightarrow h$, and rms temperature fluctuations turned out too small in the upper half of the region. Other statistics look good.

In some of the numerical integrations, 800 particles were released simultaneously from a low level and tracked subsequently until thoroughly dispersed within the planetary boundary layer. Their mean height and dispersion about the release level were obtained as a function of time and of the stability parameter h/L, where L is the Monin-Obukhov length.

Such a model seems suitable for determining how fast particles released near the surface work their way upwards under various stability conditions, and also for relating the parameter h/L to a more convenient stability parameter: a bulk Richardson number.

Relevant papers: J. Atmos. Sc. 27, 1209-1211 (1970): Geophys. Fluid Dyn. 1, 377-410 (1970); J. Atmos. Sc. 26, 763-767 (1969).

2.6 Physical Modeling of Mesoscale Atmospheric Motions, J. E. Cermak

The development of physical modeling of thermally stratified flows over urban areas and regions of complex topography has been motivated strongly because of efforts to describe the advection and diffusion of air pollutants and cloud seeding materials. Scale reductions from 10^{-3} to 10^{-5} required for models of mesoscale interest introduce severe simulation problems. Research on simulation of atmospheric flows over cities and mountains in special wind tunnels of the Fluid Dynamics and Diffusion Laboratory at Colorado State University has been active during the past 7 years. Significant results from this research will be reviewed.

Exploratory efforts to simulate flow and diffusion over a 1:4000 scale model of Ft. Wayne, Indiana will be discussed. Similarities found between model data and data obtained from the Ft. Wayne field program on temperature distribution over the city, decay of ground-level concentration of tracers released from an elevated line source and vertical distributions of mean wind speed and turbulence intensities are good. The vertical scale was doubled to achieve this agreement. Additional research is required to provide a rational criterion for optimum distortion of the model and to simulate effects of the earth's rotation. The latter effects were not simulated.

The results of efforts to model flow and diffusion over Pt. Arguello, California and portions of the Rocky Mountains at scales of 1:12,000 will be compared with data obtained from field measurements. For stably-stratified flows the requirement for similarity of equal Richardson numbers produces a laminar laboratory flow. Arguments that this flow does in fact simulate the turbulent prototype flow will be presented.

2.7 Numerical Model of the Nocturnal Urban Boundary Layer, J. L. McElroy

A two-dimensional numerical model to simulate the thermal structure of the envelope of air within the nocturnal urban boundary layer is developed from a model due to Estoque. In the model, effects due to reduced city moisture, the enhanced aerodynamic roughness and the differing thermal properties of the city surface, and artificial city heat are incorporated as air of rural origin traverses the metropolitan area. Specifically, for stable meteorological conditions in the upwind rural environs, the model predicts the development of a surface-based mixed layer in the upwind residential district. The mixed layer increases with depth into the central downtown area. Beyond the downtown sector, air restabilizes, beginning at the surface. Above this stable layer, advection of warmer urban air is predicted to occur somewhat in the manner of a giant heat plume. Immediately downwind of the urban area, the thermal structure approaches that of the upwind rural settings, except for the zone occupied by the heat plume.

The model is tested on experimental data taken by the author over Columbus, Ohio, during September 1968 and March 1969. In general, the numerical simulations compare well with the measured data with respect to both the spatial changes in the thermal structure and the development of the mixed layer.

2.8 Mesoscale Modelling, P. A. Taylor

In a recent paper (Delage & Taylor, 1970) some preliminary numerical experiments were described which are part of a program which aims eventually to produce a numerical model to predict wind, temperature and turbulence fields for a "real" city. We consider that there are two extreme cases which need to be studied. One, the case where there is no regional or geostrophic wind, was looked at in the paper referred to while the other case, with strong geostrophic winds, leads to the consideration of transition zone problems (changes in surface roughness and surface heat flux or temperature) of the type considered by Taylor (1970, 1971). These can probably be treated as time independent boundary-layer problems if the geostrophic wind is sufficiently strong.

The case with no geostrophic wind is clearly very similar to the sea and lake breeze problems, studied by Estoque (1961) and Moroz (1967). We must ask what is the basic mechanism which gives rise to a circulation? One explanation (Pearce, 1956) is that the air above the heated surface expands and causes a tidal or 'gravity wave' flow aloft from, in this case, the city to the countryside and the circulation pattern develops from there on. Clearly for this mechanism to work the model must include a layer of the atmosphere which is stably stratified - the mechanism will not work if the model only deals with a neutral atmosphere. If the overall stratification is stable the upper boundary condition (on p or W) has little or no effect on the predicted flow. For constant eddy transfer coefficients we obtain satisfactory results for the 2D heat island. In 3D there are some problems in the axially symmetric case.

At this stage I must confess to a rather serious error in section 8 of Delage & Taylor (1970), which deals with a "variable-K" model. There we use what is essentially a mixing-length model with the mixing-length, $\ell \propto z$ near the ground - no z_0. We get some numbers out but these are entirely dependent on the finite difference scheme used. This has led to an investigation of finite difference schemes for the planetary boundary-layer and we find (Taylor & Delage, 1971) that the schemes used by several authors are unsatisfactory. A scheme using an expanding grid based on the form used for mixing-length is proposed.

References

Delage Y. & Taylor P. A. (1970) Boundary-Layer Meteorol. 1, p. 201

Estoque M. A. (1961) Q.J. Roy. Meteorol. Soc. 87, p. 136

Moroz W.J. (1967) J. Atmos. Sci. 24, p. 337

Pearce R.P. (1956) Q.J. Roy. Meteorol. Soc. 82 p. 239

Taylor P.A. (1970) Boundary-Layer Meteorol. 1, p. 18

Taylor P.A. (1971) 'Airflow above changes in surface conditions; an extension to include the stable case', to appear in Boundary-Layer Meteorology.

Taylor P.A. & Delage Y. (1971) 'A note in Finite Difference Schemes for the Surface and Planetary Boundary-Layers'. Subm. to Boundary-Layer Meteorol.

3. Recommendations of Study Groups

Nine group discussions took place, each including five or six persons and lasting about one hour. A few sentences describing the discussion topic were given to the person designated as reporter in each group who guided the informal discussion. He then reported the recommendations of his group to the rest of the groups, so that additional suggestions could be included in the final reports. The topics for discussion and the recommendations and comments are as follows.

3.1 Physical Models

In view of the instrumental problems and cost of large field experiments and the theoretical and numerical difficulties of numerical models of mesoscale flow, it may be useful to employ physical models to study mesoscale flows. This study group considered the possible advantages and limitations of physical models. The following recommendations were made:

3.1.1) No general rules can be set with respect to whether a given facility can meet similarity criteria. If the emphasis is on terrain features, urban heat islands, or Great Lakes' snow storms, different similarity criteria apply in each case. In present facilities (e.g.

the wind tunnel at Colorado State University), similarity of turbulence _and_ mean flow can be satisfied for scale reductions of 1 : 5,000 or less, corresponding to atmospheric scales up to 10 km. Using the same facility, similarity of mean flow can be achieved for stably stratified flows over complex terrain at scale reductions of 1 : 10,000. For the study of general mesometeorological problems, the size of physical models should be increased by a factor of ten.

3.1.2) Little advantage results from using water rather than air for mesoscale modelling since small surface features will require exaggeration of the vertical scale for both fluids if the model surface is to function as an aerodynamically rough surface. The small gains in geometrical scaling appear to be offset by the increased difficulty and cost of achieving thermal similarity. Physical models in open fields are not satisfactory alternatives to laboratory models since no control of the flow and thermal conditions is possible.

3.1.3) The neglect of Coriolis accelerations is not permissible for simulating stable (nighttime) flow in the planetary boundary layer. For a fully mixed layer with negligible wind turning, the neglect of Coriolis forces is permissible.

3.1.4) Physical models should be used as input to numerical models. Comparisons of surface drag and other boundary conditions should be made. The mathematical model being compared should not contain the effects of precipitation and Coriolis forces, however.

3.1.5) Physical models can assist field programs by guiding the location of meteorological instruments and interpreting anomalous results of existing towers.

3.1.6) There should be close cooperation between physical and mathematical modellers and field researchers.

3.2 Boundary Conditions

In most mesoscale numerical models, changes at the boundaries cause changes in the air flow. Therefore, methods of introducing these changes are important. Also, the boundary conditions must be consistent with the physical assumptions. The conclusions of the study group are:

3.2.1) There is a problem of parameterizing sub-grid scale terrain variations by means of a roughness length that perhaps a physical model could help to solve.

3.2.2) In a dry model, a surface energy balance should be used to determine surface temperature. It is easier to add artificial heat when the flux method is used.

3.2.3) The division between sensible and latent heat flux needs further investigation. Perhaps subsurface moisture fluxes should be included.

3.2.4) The upper boundary conditions for pressure p and vertical speed w present problems if the stratification is not stable near the top of the model. When the stratification is stable, it is usually possible to assume that w equals zero on this boundary. However, when gravity waves form this approximation is not valid.

3.2.5) Initial values are a critical problem when models are to be used for predicting detailed conditions at some point and time. If the flow is not in equilibrium with respect to initial data, local accelerations or differences can cause unrealistic forecasts of these details from the model. For this purpose, it may be necessary that the initial data be smoothed or forced into equilibrium.

3.3 Radiational Cooling

Numerical procedures to solve the equations for radiational cooling often take most of the computer time of models. Are our present techniques satisfactory for handling radiational cooling? Is parameterization possible?

3.3.1) In stable conditions with small mixing coefficients K, present models are capable of generating multiple inversion layers. The intensity of the inversion produced by an aerosol depends on the size distribution, chemical properties, absorption characteristics, and concentration of the aerosol. Little is known about these particular properties of aerosols. Pandolfo found that the additional cooling of an air layer due to the presence of a typical aerosol was about 1°C per day.

3.3.2) For predictive purposes, radiational cooling can and is being satisfactorily parameterized. However, for research purposes, as much detail as possible is desired.

3.3.3) Analogue computers may be very well suited for simulating radiational cooling, which involves frequent vertical integrations. It would be fruitful to further explore the uses of hybrid computers for mesoscale mathematical models.

3.4 Optimum Grid Spacing and Parameterization of Sub-Grid Scale Processes

Because it is necessary to employ finite grid spacing, the sub-grid scale processes must be accurately parameterized. The conclusions of this group are:

3.4.1) For research purposes, the number of grid points should be as many as the computer can handle and the sponsor can afford. An expanding grid is most efficient when limitations are necessary. In this case, the grid distance is the smallest near regions where large gradients are expected. It is imperative that the expanding coordinate system be affected through use of a coordinate transformation which brings additional terms into the governing equations.

3.4.2) In the vertical direction an expanding grid should be used with the lowest point well up in the constant flux layer. The use of constant flux layer formulations rather than multiple grid points near the surface leads to more accurate results.

3.4.3) In order to parameterize sub-grid scale motions, it is first necessary to determine the variation or spectrum of these motions. Thus the results of theoretical work or numerical experiments with a much finer grid must be studied.

3.4.4) Parameterization of counter-gradient fluxes, which include upward heat fluxes through stable layers, is necessary.

3.4.5) Parameterization techniques for cloud cover need to be improved.

3.5 Light Wind Cases

The nighttime urban heat island circulation is characterized by very light winds. During these conditions, the calculated mixing coefficient K approaches zero. The following recommendations were made by this study group:

3.5.1) Many models do not permit K to be less than some arbitrary lower limit, such as 10^4 cm^2 sec^{-1}, in the regions of the model above the surface layer. This lower limit is set on the grounds that phenomena such as breaking gravity waves cause mixing, and that observed variations of wind and temperature can be simulated only if a lower limit on K is set.

3.5.2) The Gaussian formula for plume diffusion contains the wind speed in the denominator. In order to avoid difficulties during light wind conditions, it is recommended that the diffusion formula involving the time rate of change as well as the advection term be used when the wind speed drops too low.

3.4.3) Physical models may profitably be used to model light wind, stable conditions.

3.6 Predictability of Mesoscale Flow

The question of the predictability of the earth's general circulation has received much attention lately. We should also investigate the predictability of mesoscale circulations.

3.6.1) The final answer to this question depends on observations, which have not yet been made. We are still in the beginning stages of the art of mesoscale predicting. An experimental field program is needed.

But this program should not be sold as a panacea for forecasting problems. It should be a tool for developing models.

3.6.2) Current mesoscale models can be divided into two groups: those that predict local details and those that simulate the statistics. The initial data are most important for short range predictions (< 6 hours), while boundary conditions and external forcing functions are most important for forecasting times greater than 6 hours.

3.6.3) There is a question whether the present level of university or specialized meteorological training is adequate for developing people to interpret model results for users. Also, users should better define their problems so that modellers can develop more specific solutions.

3.6.4) It might be helpful in specifying the need for future mesoscale modelling research to formulate the problem in comprehensive terms using an approach like that of the Global Atmospheric Research Program (GARP). In contrast with global modelling, we are further along in mesoscale modelling techniques than in the development of applications.

3.7. Data Base

There always exists the need for field programs. For the mesoscale problem this need is especially acute. This study group reached the following conclusions:

3.7.1) There are now good models that can be made better with data.

3.7.2) Temperature and moisture profiles may be the basic requirements. Wind and radiation measurements are not so important. At the surface, measurements of pressure are important.

3.7.3) Real time data processing is desirable.

3.7.4) The initial field experiment should be a location where the flow is not unduly influenced by a mesoscale surface inhomogeneity In order to take advantage of existing instruments it is recommended that the National Severe Storms Laboratory in Oklahoma be investigated as to suitability as the site for the initial experiment. The terrain is flat and an instrumented grid is already in operation. The horizontal grid spacing should be ten to twenty kilometers, with the total extent of the grid comparable to the NMC grid (250-500 km). A smaller grid system could be imbedded inside one of the ten-kilometer squares.

3.7.5) Weak elements of models (such as mixing coefficient K) should be tested.

3.7.6) The facility should not be operated continuously for mere collection of data, but operated only when there is a specific requirement to satisfy modelling needs.

3.8 Justification for Mesoscale Modelling

There are two different uses for mesoscale models: operational forecasting and decision making. An example of the first is snowstorm prediction over the Great Lakes. An example of the second is the determination of the effects of a several thousand megawatt power plant on the air flow. The following specific points were made:

3.8.1) A study by economists of the economic impact of weather on society is needed before we can determine the top-priority problems.

3.8.2) We should excercise scientific honesty when asked to solve real mesoscale problems, such as diffusion over complicated terrain over distances of hundreds of kilometers.

3.8.3) Before mounting an extensive field program, we should use available data as much as possible. In addition, current mesoscale models serve as valuable research tools in the study of the physics and dynamics of geophysical boundary layers. They make it possible to formulate and test hypotheses concerned with this subject as a purely scientific problem. Therefore, the decades of scientific effort invested in the development of the set of models discussed in this conference should be fully exploited for this purpose also.

3.9 Research Priorities

Our future work plans depend on the problems that the group feels are the most important. The results of this study session are given below:

3.9.1) Better cost-benefit relationships must be established.

3.9.2) A national center for development of physical models would be a good thing at this time.

3.9.3) A program plan similar to the Global Atmospheric Research Program (GARP) should be designed for mesoscale research.

3.9.4) Sensitivity analyses and comparisons of mathematical models with each other and with physical models and data should take place at all stages of model development.

3.9.5) Three-dimensional models should be further developed because of the three-dimensional nature of problems such as the urban heat island.

3.9.6) More specific research topics include: man's effect on and response to environmental problems on urban and regional scales; sea breeze; mesoscale forecasting of precipitation; city design.

3.9.7) A field program is needed, as outlined in section 3.7.

4. Highlights of Recommendations:

1. Mesoscale boundary layer research should be organized into a program similar to the Global Atmospheric Research Program.
2. There should be close cooperation between mathematical and physical modelling and field experiments.
3. Cost-benefit relationships of applications of mesoscale models should be undertaken. The needs of users should be better defined.
4. Three-dimensional models should be further developed.
5. In forecasting or predictive mesoscale models, accurate initial data are very important.
6. Expanding grid systems are useful in mathematical models near regions with discontinuities. However, the possible effects of the coordinate change on the result should be closely watched.
7. The assumption that the fluxes are invariant with height in the model layer immediately above the earth's surface is recommended.
8. One possibility that exists to prevent the development of excessive vertical gradients in model research is to arbitrarily set a minimum mixing coefficient, K, of about 10^4 cm^2 sec^{-1} for stable light wind conditions above the surface layer.
9. In order to satisfactorily model the radiative cooling of aerosol layers, the geometrical, chemical, and radiative properties of these aerosols must be determined.
10. Before mounting a field program, we should use existing data as much as possible.

11. A field program at a site such as National Severe Storms Laboratory should be initiated, with emphasis on vertical distributions of temperature and moisture and surface variations of pressure. Grid distance should be 10 km, with a smaller grid imbedded within one of the 10 km squares. This program should be a tool for developing mesoscale models.

12. To satisfactorily model air flow at scales up to 100 km, physical models of mesoscale flow must be built an order of magnitude larger than current models. A national facility for mesoscale physical modelling could profitably be established.

5. Acknowledgements and List of Attendees

Funds for this meeting were provided by NOAA through its Air Resources Laboratories, and we wish to acknowledge the support and encouragement received from Lester Machta and Donald H. Pack of that organization. Also, a meeting like this would not be possible without careful attention to many details, for which we thank Mrs. Ruth Green, Mrs. Sue Sheffield, and Mrs. Jean Crowe.

A list of meeting attendees is given below:

J. E. Cermak, Col. State Univ.
W. H. Clayton, Texas A&M Univ.
P. R. Coleman, Oak Ridge National Lab.
J. W. Deardorff, National Center Atmos. Res.
M. A. Estoque, Univ. of Miami
J. P. Gerrity, Jr., National Meteorological Center, NOAA
J. H. Gibbons, ORNL
R. P. Hammond, ORNL
W. B. Johnson, Jr., NOAA - Raleigh
R. L. Lavoie, Penn State Univ.
L. L. LeBlanc, U.S. Air Force
J. L. McElroy, NOAA - Raleigh
J. P. Pandolfo, Center for Environment and Man
D. Randerson, NOAA - Las Vegas
F. B. Smith, Met. Office, England
P. A. Taylor, Univ. of Southampton
D. H. Pack, ARL, NOAA
G. A. Briggs, ARATDL, NOAA
F. A. Gifford, ARATDL, NOAA
S. R. Hanna, ARATDL, NOAA

6. Bibliography

The bibliography below contains the more recent work of the meeting participants:

Atwater, M. A., 1971: The radiation budget for polluted layers of the urban environment. *J. Appl. Meteorol.*, 10, 205-214.

Chaudry, F. H. and J. E. Cermak, 1971: Wind Tunnel Modeling of Flow and Diffusion over an Urban Complex. Report prepared by Col. State Univ., Ft. Collins, Col., under contract no. DAAB 07-68-C-0423 for U. S. Army Elect. Com., Ft. Monmouth, N. J., 70 pp.

Davis, L. G., R. L. Lavoie, J. I. Kelley, C. L. Hosler, 1968: Lake Effect Studies. Prepared by Dept. of Meteorol., Penn State Univ., under cont. no. E22-80-67(N) to ESSA-APCL, Boulder, Col., 108 pp.

Deardorff, J. W., 1969: A three-dimensional numerical investigation of the idealized planetary boundary layer. NCAR manuscript 69-160, 32 pp. plus 18 figs.

Delage, I. and P. A. Taylor, 1970: Numerical studies of heat island circulations. *Bound. Lay. Meteorol.*, *1*, 201-226.

Estoque, M. A., 1963: A numerical model of the atmospheric boundary layer. *J. Geophys. Res.*, *68*, 1103-1113.

Estoque, M. A. and C. M. Bhumralkar, 1969: Flow over a localized heat source. *Mon. Wea. Rev.*, *97*, 850-859.

Estoque, M. A. and C. M. Bhumralkar, 1970: A method for solving the planetary boundary layer equations. *Bound. Lay. Meteorol.*, *1*, 169-194.

Gerrity, J. P., Jr., 1967: A physical and numerical model for the prediction of synoptic scale low cloudiness. *Mon. Wea. Rev.*, *95*, 268-282.

Hadeen, K. D. and W. D. Meyer, 1970: The Air Force Global Weather Central Operational Boundary Layer Model. Paper presented at the IUGG-IAMAP-AMS Conference on Planetary Boundary Layers, Boulder, Col., Mar. 18-21, 1970.

Pandolfo, J. P., D. S. Cooley, and M. A. Atwater, 1965: The Development of a Numerical Prediction Model for the Planetary Boundary Layer. Final Rpt. USWB Cont. No. Cwb-10960 by Travelers Res. Center, Hartford, Conn., 88 pp plus appendices.

Pandolfo, J. P., 1969: Motions with inertial and diurnal period in a numerical model of the navifacial boundary layer. *J. Marine Res.*, *27*, 301-317.

Pandolfo, J. P., 1971: Numerical experiments with alternative boundary layer formulations using BOMEX data. Bound. Lay. Meteorol., 1, 277-289.

Taylor, P. A., 1970: A model of airflow above changes in surface heat flux, temperature and roughness for neutral and unstable conditions. Bound. Lay. Meteorol., 1, 5-17.

Taylor, P. A., 1971: Airflow over changes in surface heat flux, temperature, and roughness; an extension to include the stable case. Bound. Lay. Meteorol., 1, 474-497.