Current Mesoscale Meteorological Research in the United States (1981)

Pages
41

Size
5 x 9

ISBN
0309292395

Ad Hoc Panel on Mesoscale Processes; Committee on Atmospheric Sciences; Assembly of Mathematical and Physical Sciences; National Research Council

Assembly of Mathematical and
Physical Sciences (U.S.).
Current mesoscale
meteorological research in

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Ad Hoc Panel on Mesoscale Processes
Committee on Atmospheric Sciences
Assembly of Mathematical and Physical Sciences
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1981

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This material is based on work supported jointly by the National Science Foundation and the National Oceanic and Atmospheric Administration under Grant Number ATM-8024257.

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Summary

A brief summary is presented of the current status of mesoscale meteorological research in the United States. In strong agreement with recent studies, it is concluded that the time is ripe for important scientific and technological advances in this subject that would be of significant benefit to the nation. Progress would be greatly accelerated through strong coordination of research efforts. It is recommended that a National Mesoscale Program be established in order to focus and enhance research into the mesoscale aspects of extratropical cyclones and severe local storms. The principal practical goals of this research would be significant improvements in short-range weather forecasts of precipitation and the occurrence of severe weather including hurricanes, thunderstorms, and tornadoes.

1

Introduction

In September 1980, in response to a need expressed by the Associate Administrator of the National Oceanic and Atmospheric Administration, an Ad Hoc Panel on Mesoscale Processes was appointed by the Committee on Atmospheric Sciences of the National Research Council. The charge to the panel was to "conduct a brief survey of the current mesoscale meteorological research being conducted throughout the federal government and to develop a preliminary assessment of the adequacy of this research in terms of the important opportunities that exist in this area of scientific endeavor." The panel met twice, once in Princeton, New Jersey, on October 2, 1980, and a second time in Boulder, Colorado, on January 15-16, 1981, and heard extensive presentations by representatives of various federal agencies (Appendix A) concerning ongoing and planned mesoscale research.

The panel decided to summarize the activities in mesoscale meteorology by agency and by general topic (Chapter 2) to make an assessment of the adequacy of current research, emphasizing the areas that stand out as especially important for more concentrated efforts in the 1980's (Chapter 3) and to make recommendations for the organization of future efforts in this field (Chapter 4). These assessments and recommendations are based on the presentations to the panel during its two meetings and on recent reports of workshops and panels, especially the following:

— NR Oct 80 pp 1-3

The Atmospheric Sciences: National Objectives for the 1980's, NRC Committee on Atmospheric Sciences (National Academy of Sciences, Washington, D.C., 1980), 130 pp.

Atmospheric Precipitation: Prediction and Research Problems, NRC Commit-

L NR Feb 81 pp 27-31

tee on Atmospheric Sciences (National Academy of Sciences, Washington, D.C., 1980), 63 pp.

Extratropical Cyclones: Progress and Research Needs (Report of a Workshop on Extratropical Cyclones held in Seattle, Washington, September 10-12, 1979).

Technological and Scientific Opportunities for Improved Weather and Hydrological Services in the Coming Decade, Select Committee on the National Weather Service (National Academy of Sciences, Washington, D.C., 1980), 87 pp.

An important recommendation from the first report concerned short-range prediction of precipitation and severe weather:

> Recent technological developments provide opportunities to improve both special and general local weather forecasts, from less than an hour to 12 hours in advance, which are of particular value during periods of weather that threaten life and property or disrupt normal commerce and transportation. These developments include higher-resolution satellite imagery, Doppler radar, acoustical probes, and other remote sensing devices; improved methods of communicating and analyzing these observations; and emerging techniques for the rapid dissemination of forecasts and warnings to special users and the general public.
>
> This new technology can and should be used simultaneously for intensive study of fundamental meteorological processes occurring on the local scale and for the development of kinematic, dynamic, and statistical methods for local forecasting that can lead to additional benefits to the public. *A well-focused, coordinated program, involving research, development, and pilot operations, should be conducted by government operational and research groups and those university groups that are involved in research in this area.*
>
> Prediction of wind and temperature fields up to 48 hours over the United States have steadily improved over the past two decades. There has been some improvement in predicting the areas in which precipitation will occur during the next 24 hours; this improvement has come most recently from development and use of high-resolution numerical models over limited geographical regions. However, there has been less success in predicting amounts of precipitation or the times of onset and cessation. *Research should now be concentrated on (a) theoretical and modeling studies*, using existing observing capabilities and special field programs to investigate the mesoscale structure and dynamics of midlatitude winter cyclones and to determine the extent to which prediction of amounts of rain or snow can be improved, and (b) *major field experiments, with special observing networks of finer scale than are routinely provided by the National Weather Service*, to identify the factors that force the outbreak and control the intensity of severe convective storms and

storm systems that occur most often in spring and summer. These two research areas will require expanded computing and graphical display capabilities.

In support of the above assessment, the second report concluded:

> WE RECOMMEND A MAJOR, COORDINATED NATIONAL MESOSCALE RESEARCH PROJECT TO STUDY MECHANISMS INVOLVED IN THE FORMATION OF PRECIPITATION IN BOTH SUMMER AND WINTER STORMS IN VARIOUS REGIONS OF THE NATION.
> Many of the problems involved in the understanding and forecasting of precipitation that are highlighted in this report are concerned with mesoscale processes. The frequency of occurrence and relative importance of various physical mechanisms that produce mesoscale precipitation phenomena vary over the United States and with the seasons. A central feature of a national mesoscale research project should be comprehensive field observational studies to take place periodically at selected sites. While emphasis should be placed on the mesoscale, associated synoptic and microscale studies will be necessary. We envision the national mesoscale research project to be a closely coordinated research endeavor involving federal agencies, universities, and other research establishments and carried out over the next decade.

Finally, the workshop on extratropical cyclones recommended a long-term effort consisting of coordinated basic and applied research to achieve the above objectives:

> In view of the range of problems hindering progress in our understanding and prediction of the weather (particularly precipitation) associated with extratropical cyclones, the workshop recommended the establishment of a NATIONAL CYCLONE PROJECT to extend over a period of ten years. Encouragement that a national program dedicated to the cyclone problem would be profitable in terms of improved understanding and better weather forecasts stems from several considerations. Firstly, there are powerful observational techniques that could be more effectively directed toward the mesoscale prediction problem. Secondly, the progress that has been made in recent years in mesoscale and microscale studies and in fine-mesh numerical modeling is such that a more concentrated and coordinated effort in these areas is likely to produce impressive results. Thirdly, the availability of faster communication systems and more adequate displays of information permit more detailed information to be assimilated, utilized and passed on to the public, than ever before.
>
> The NATIONAL CYCLONE PROJECT should involve the federal, university, and private sectors of the meteorological community and the National Center for Atmospheric Research. It should be assured of consistent support on a level commensurate with the tasks it would undertake.

These reports provide details of important mesoscale meteorological problems, with scientific justification that the time is ripe for significant progress in areas that will provide important economic and safety benefits to the United States in the near future. In general, we endorse their recommendations and urge the relevant government agencies and the other sections of the scientific community to work together in an efficient way to solve the important problems.

An overriding property of the atmosphere is its indivisibility, which leads to difficulties in subdividing atmospheric research. Thus, an attempt to separate mesoscale meteorology from other parts of atmospheric science cannot be fully justified, since many of the processes that control mesoscale events also affect larger- and smaller-scale processes. In addition, atmospheric scientists are inclined to separate themselves more by the techniques that they have mastered than by the phenomena to which they apply the techniques. Finally, there is the usual dichotomy, especially strong in the geophysical sciences, between those who divide a problem into conquerable bits and those who approach it holistically. However, no field of science progresses uniformly, and we believe that some current trends can be defined fairly unambiguously.

The next chapter summarizes the types of mesoscale meteorological research that are necessary to mount a coordinated effort to solve the complicated scientific and technological problems that stand in the way of providing the public with information they can effectively use to save life and property when severe weather threatens or make economically profitable decisions in the more common situations of daily weather events. Current, major research efforts in mesoscale meteorology are summarized according to the organization supporting or conducting the research and also by the type of research.

2

Survey of Current Research in Mesoscale Meteorology

In recent years, there has been much research on mesoscale meteorological processes. In this report we classify this research into four basic types: (1) observational studies and field programs, (2) theoretical studies, (3) numerical modeling simulations and laboratory simulations, and (4) technological advances in measurement systems. Although some research overlaps two or more of these categories, most projects tend to belong predominantly in one of them.

Most progress in meteorological understanding has begun from observations made possible by technological advances in observing systems. Once a phenomenon is identified, case-study analyses help to define the phenomenon and suggest hypotheses in terms of fundamental processes. Theoretical studies seek to explain the phenomenon in terms of the evolution of the structure from an initial or basic state as a function of the boundary conditions and internal forcing mechanisms. A technique of growing importance in mesoscale meteorology is numerical simulation by computer models, used as a form of theory and as a partial replacement for laboratory experiments. Ultimately the numerical models may be applied for practical prediction problems.

In complicated meteorological problems, there is often feedback and interaction between different areas of research. Thus theories suggest how to model or parameterize physical processes in numerical models. Numerical models may show behavior requiring theoretical explanation, provide hypotheses for observational verification, or demand certain kinds of observations that only new technology can provide. New observing systems provide different viewpoints of phenomena that help to elucidate physical principles and suggest hypotheses for further study.

Much past and recent theoretical work has helped to clarify our understanding of the fundamental processes in mesoscale meteorology. The basic mechanisms and sequences of buoyant and shearing instability and of stable wave dynamics are understood. It is dangerous to make predictions about fundamental research, however, and entirely new concepts may emerge that will change our basic approach to what were thought to be fairly well-understood phenomena. Some important areas of current research (see also Section 2.4) include the evolution and maintenance of rotating convective storms and intense vortices, the role of moisture and planetary boundary-layer processes in fronts, entrainment into the tops of stratiform and cumuliform clouds, and the interaction of gravity waves with turbulence and mean flows.

Case-study analyses tend to respond rapidly to the existence of new observational and analysis techniques, such as increasing availability of quantified satellite and Doppler radar data as well as continued improvement of computational facilities. Various medium-sized field projects, summarized below, are specifically aimed at providing data sources for such research. If adequately supported, these and other programs should provide the scientific basis for improvements in forecast capability.

In addition to the importance and value of small- and medium-sized projects, there is increasing realization among scientists that occasional major, coordinated research efforts involving scientists from all four areas of research are necessary to make major progress in understanding important atmospheric phenomena and to apply the knowledge gained to national needs. Such projects involve large computer simulation studies to help design the project; tightly organized field projects utilizing modern remote-sensing techniques as well as conventional data sources; and extensive data processing, analysis, and numerical modeling efforts after the field program to extract maximum information from the data. Some scientists, especially at universities, are reluctant to participate strongly in such work, expressing doubt as to the efficiency of "big-science" projects in comparison with the more traditional modes of individual and small-group research. However, there is a growing recognition that, in many cases, there is no alternative to occasional big projects if we are to make scientific headway in the complex problems that continue to confront operational meteorologists. For example, tropical meteorologists participated in the GARP Atlantic Tropical Experiment (GATE) project, and probably much of their best work is yet to come. The same process is starting to occur around the Severe Environmental Storms and Mesoscale Experiment (SESAME).

Once mesoscale meteorological phenomena are understood and a predictive or simulative capability has been demonstrated, it is important to make this capability available to those who can benefit from it—so-called technology transfer. Often this transfer is as big or a bigger problem than the original scientific one, but its solution is vital if the promised economic and safety benefits are to accrue.

2.1 OVERVIEW OF MESOSCALE RESEARCH

During its two meetings, representatives from the federal agencies listed in Appendix A provided the panel with considerable information on current and planned mesoscale meteorological research. Much of the material could not be included in a brief report because of its length and complexity. Therefore, we decided to include only the major areas of current research. A summary of this research, presented in Table 1, reflects the panel's perception of current, major efforts, although it may omit some important activities. Nevertheless, we believe that the summary in Table 1, and the more detailed reviews of the four areas of mesoscale research to follow, provides a representative overview of current mesoscale research activities in the United States.

Two conclusions may be drawn from Table 1. First, a large number of groups, supported by different federal agencies, are working on similar problems; with a few exceptions, this research is conducted without coordination with other groups working on similar problems. As discussed in Chapter 3, we believe that progress could be enhanced by increased cooperation and coordination between various groups. Second, much research is being conducted in the mesoscale aspects of extratropical cyclones and the precipitation processes embedded within the cyclones. This emphasis is in agreement with the conclusions reached in the recent reports listed in Chapter 1 and reflects the importance of precipitation to the nation.

2.2 OBSERVATIONAL STUDIES AND FIELD PROGRAMS

The study of mesoscale meteorological processes has been hampered by lack of observations. Unlike case studies of large-scale meteorological systems, which have benefited greatly by operational data bases and analyses, mesoscale observational studies generally require special measurement programs to obtain the high spatial and temporal resolution data necessary to describe the evolution and structure of the mesoscale phenomena.

Most of the recent mesoscale field programs (Table 2) have been centered around phenomena belonging to the lower end (meso-γ) of the mesoscale spectrum (horizontal scales ranging from 2.5 to 25 km). These studies include cumulus convection, thunderstorms, frontal rainbands, flow around small hills, and urban meteorological processes. Because of their much higher cost and more extensive logistical requirements, observational studies of meso-α

TABLE 1 Summary of Federal Mesoscale Research in the United States as of January 1, 1981

	Research Areas[a]												
Organization	CYC	PCP	CUM	MCS	TDO	HUR	FNT	TER	PBL	AQL	STC	OPL	INST
NSF													
Universities	X	X	X	X	X	X	X	X	X	X			X
NCAR		X	X		X		X	X	X	X			X
NASA													
Universities	X	X											
Goddard	X	X		X	X	X			X				X
Langley	X			X									X
Marshall	X	X		X	X					X			X
NOAA													
ARL										X			
GFDL	X	X	X			X	X		X				
NESS	X	X				X							X
NHC						X					X	X	
NHRL						X							
NMC	X	X				X						X	
NSSFC					X							X	
NSSL			X	X	X								X
OWRM		X	X	X				X					
TDL	X	X							X		X	X	
WPL													X
DOD													
Air Force	X	X		X	X		X						
Army	X	X					X	X	X				
Navy	X					X			X			X	
EPA								X	X	X			
DOE			X					X		X			
DOA (Forest Service)								X	X	X			
DOI (BUREC)	X	X	X				X						

[a] CYC, extratropical cyclones; PCP, precipitation; CUM, cumulus convection; MCS, mesoscale convective systems; TDO, tornadoes; HUR, hurricanes; FNT, fronts; TER, terrain effects; PBL, planetary boundary layer; AQL, air quality/chemistry; STC, statistical methods (e.g., Model Output Statistics); OPL, operational research; INST, instrumentation development.

TABLE 2 Summary of Mesoscale Observational Studies and Field Programs

Project	Objective	Status	Contact Persons[a]	Funding Agencies[a]
(a) Warm Season				
Cooperative Convective Precipitation Experiment (CCOPE)	Oriented toward precipitation evolution and enhancement through measurement of microphysics and dynamics of growing and mature convective clouds	Field observations near Miles City, during May–August 1981	B. Silverman (BUREC) P. Squires (NCAR) A. Super (BUREC)	DOI/BUREC, NASA, NOAA, NSF
Virginia–Illinois NOAA Program (VIN)	To investigate whether low-level convergence precedes convection in midlatitudes, as in Florida	Analysis of data gathered in 1979	R. Holle (NOAA/ERL) M. Garstang (U. Virginia)	NSF, NOAA/ERL, U.S. Army, U.S. Air Force
Joint Airport Wind Study (JAWS)	Development of surveillance for warning aircraft of hazard due to low-level wind shear, especially from downbursts	Observations in spring and summer 1982 at Stapleton Airport, Denver	T. Fujita (U. Chicago) J. McCarthy (NCAR/FOF)	NSF, FAA, NASA, NOAA
Severe Storms and Mesoscale Experiment (SESAME)	Initially oriented toward initiating and organizing mechanisms of severe thunderstorm systems, currently increasing emphasis on heavy precipitation	Analyzing results of 1979 field program in central United States, planning for future field program	F. Sanders (MIT) S. Barnes (NOAA/ERL)	NOAA/ERL, NASA/MSFC, NASA/GLAS, NSF, others
NSSL Spring Program	To elucidate interaction between motion, water, and electrical fields, and	Doppler radar, electrical, rawinsonde, aircraft measure-	E. Kessler (NOAA/NSSL)	NOAA/NSSL, FAA, DOD, NASA

	and to assess associated hazards to aircraft	ments in Oklahoma, April–June 1981		
Hurricane STRIKE Program	To improve short-term prediction of hurricane landfall and intensity	High-resolution data from aircraft, with real-time relay to forecasters at NHC	S. Rosenthal (NHRL)	NOAA/AOML, NOAA/NWS
(b) Cold Season				
Cyclonic Extratropical Storms Project (CYCLES)	Description and understanding of the mesoscale structure of winter cyclones in the Pacific Northwest	Analysis of previous measurements. Next major field program January–February 1982	P. V. Hobbs (U. Washington)	NSF, U.S. Army, U.S. Air Force
Sierra Project	Assessment of potential to enhance winter/spring orographic precipitation in American River Basin, includes mesoscale observations	Analysis of previous measurements. Next field program 1981–1982	B. A. Silverman (BUREC)	DOI/BUREC
Lake Effects Studies	Determine nature and origin of storms over Lake Michigan caused by cold-air outbreaks from Canada	Field program 1980–1981	R. R. Braham, Jr. (U. Chicago)	NSF
Alpine Experiment (ALPEX)	Understanding and predictability of lee cyclogenesis and other large and mesoscale effects of an airflow over large mountain massifs	Field program 1982	J. Kuettner (NCAR)	NSF, NOAA, NASA

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[a] See Appendix B for key to abbreviations to organizations.

(horizontal scales 250 to 2500 km) and meso-β (horizontal scales 25 to 250 km) phenomena, such as tropical cyclones, fronts, organized systems of convection, and the environment of severe local storms, have been less frequent. Project SESAME, which is beginning to provide important results, is an example of a larger field program involving many groups in a coordinated, cooperative study. Additional studies of this magnitude are necessary to fill in the gaps in observations (and our understanding) of these scales of motion that link the synoptic scale to the cloud scale.

2.3 MESOSCALE COMPUTER SIMULATION MODELS

An extremely important area of research is the field of numerical simulation, and a large fraction of the theoretical talent in meteorology works in that field. Much progress is being made in developing and applying new approaches to the problem of artificial lateral and upper-boundary constraints (an aspect of atmospheric indivisibility) and the closely related problem of grid-nesting. Most modelers are becoming sensitive to the need to test a model's sensitivity to uncertainties in the physics and numerical formulations, so that simulation is becoming a more fully respected tool of theoretical analysis.

There is a tremendous variety of so-called mesoscale models, partly because the term mesoscale covers such a wide range of scales and partly because so many different meteorological phenomena belong, at least in part, in the mesoscale. Here we will arbitrarily classify mesoscale models into two basic types: (1) those that deal with the detailed cloud physics and dynamics of individual clouds, and hence explicitly resolve scales of motion less than the meso-γ scale ($2.5 \text{ km} < L < 25 \text{ km}$), which we will call "cloud-scale models," and (2) those that resolve scales of motion larger than those associated with individual clouds and therefore have typical horizontal grid sizes of 2.5 to 100 km. In these models, the effects of clouds are usually not explicitly represented but are parameterized in terms of resolvable-scale variables. For simplicity we will call these "regional-scale models."

2.3.1 Cloud-Scale Models

Cloud models involve many physical processes that take place on scales smaller than the meso-γ scale but that influence the precipitation and dynamic processes on the γ scale. In addition, some of the models treat electrical, chemical, and radiative processes that may influence processes on the mesoscale, such as thunderstorms, acid rain, and radiative cooling of stratus-filled atmospheric layers.

As opposed to regional-scale models, cloud-scale models attempt to simulate the details of precipitation evolution and air motion over grid intervals of a few hundred meters (or less) to one kilometer, and over domains a few kilometers on a side to several 10's of kilometers on a side. Atmospheric depths up to 20 km are often modeled, and the models are generally nonhydrostatic. Cloud models in one, two and three space dimensions and either time dependent or steady state are being used in various aspects of cloud-physics research and operations. The simpler one-dimensional cloud models are coupled with some mesoscale models to yield predictions of precipitation over the mesoscale. The more dynamically complex three-dimensional cloud models simulate many of the characteristics of severe local storms.

Cloud-scale models vary in their microphysical complexity as well as in their dynamic complexity. Simpler, highly parameterized microphysical models require one tenth or less of the computer resources (time and core storage) needed by the detailed particle spectra modeling methods. More microphysical complexity is added as cloud electrification, cloud chemistry, and cloud radiative processes are included in the models. In addition, the treatment of both ice and liquid phases in clouds, necessary for snow and hail predictions (and rain also in highly convective situations), makes the cloud models more complicated and requires more computer power for their solution. The two-dimensional cloud models are being used most often to attack these cloud-physics problems.

The various types of cloud models are summarized in Table 3.

2.3.2 Regional-Scale Models

Regional-scale models as defined here include models with horizontal resolutions (Δs) ranging from about 2.5 to 100 km. Since typical horizontal grids consist of 40 × 40 points, the domains of these models range from 100 km × 100 km to 4000 km × 4000 km. Because regional-scale models simulate phenomena in which the horizontal scales are much greater than the vertical scales, they are usually hydrostatic. In principle, the basic dynamical framework of these models is very general. By altering the parameterization of the physical processes (e.g., shortwave and long-wave radiation, change of phase of water vapor, sensible and latent heat fluxes from the surface, turbulent mixing, cumulus convection, and terrain effects) and by varying the initial conditions, an amazing variety of mesoscale phenomena can be simulated and predicted. For example, models with rather similar basic characteristics have been used to simulate the following:

- Flow around individual hills

TABLE 3 Summary of Cloud-Scale Models Active in 1980

Model Identification[a]	Domain	Emphasis	Contact	Remarks
One-Dimensional Steady-State Models				
BUREC	20 km (vertical)	Cloud top, vertical motion, seeding potential	Matthews	
SDSMT	20 km (vertical)	Cloud top, vertical motion, seeding potential, plume transport	Hirsch, Orville	Used for maximum hailstone size prediction
NOAA/ERL	20 km (vertical)	Cloud top, vertical motion, seeding potential	Woodley	Used to predict covariates in weather modification project
CSU/1D	20 km (vertical)	Cloud top, vertical motion, seeding potential	Cotton	
One-Dimensional Time-Dependent Models				
SDSMT	20 km (vertical)	Cloud microphysics, hail prediction	Farley, Orville	
Two-Dimensional Models				
U. Ill./2D	48 km × 14 km	Single clouds, severe storms	Soong, Wilhelmson	Axisymmetric and slab symmetric models
U. Wisc./2D	~50 km × 15 km	Severe storms	Schlesinger	Liquid bulk water microphysics, slab symmetry
CSU/2D	35 km × 17 km	Tropical Cu, mountain Cu	Cotton	Slab symmetry

NCAR	18 km × 12 km	Detailed cloud microphysics, ice and liquid processes	Hall	Slab symmetry
SDSMT/2D	20 km × 20 km	Hailstorms, cloud electrification, cloud modification	Orville, Farley, Helsdon	Some detailed ice microphysics, slab symmetry
Hawaii/2D	6 km × 6 km	Detailed microphysics, hailstone growth, cloud electrification	Takahashi	Axial symmetry
RAND	10 km × 10 km	Tropical Cb, ice bulk water microphysics	Murray, Koenig	Axial symmetry
U. Wash./2D		Detailed microphysics, particularly ice phase	Hobbs	Axial symmetry
Three-Dimensional Models				
U. Wisc./3D	48 km × 48 km × 14 km	Severe storms	Schlesinger	Liquid bulk water microphysics
CSU/3D	35 km × 35 km × 17 km	Tropical Cb, mountain Cb	Cotton	Some ice bulk water microphysics
NCAR/Ill./3D	48 km × 48 km × 16 km	Severe storms	Klemp, Wilhelmson	Liquid bulk water microphysics
NCAR	50 km × 50 km × 15 km	Hailstorms	Clark	Liquid bulk water microphysics
NCAR	10 km × 10 km × 17 km	Tornado genesis	Rotunno, Klemp	Nested in 3-D cloud model
Hawaii/3D	6 km × 6 km × 4km	Tropical Cu, detailed liquid microphysics	Takahashi	
NOAA/GFDL	3 km × 3 km × 2.5 km	Tropical Cu	Lipps	Liquid bulk water microphysics

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[a] See Appendix B for key to abbreviations.

- Mountain waves
- Orographic precipitation
- Air-quality simulations
- Mountain-valley breezes
- Sea breezes
- Extratropical cyclones (mesoscale structure embedded within)
- Tropical cyclones
- Frontal circulations
- Squall lines
- Mesoscale convective complexes
- Dry lines
- Jet streak circulations
- Coastal effects
- Rainbands
- Urban circulations

The mesoscale models active as of 1980 are summarized in Table 4.

2.4 THEORETICAL STUDIES

Although much of the research involving the numerical simulation models summarized in the previous section can be considered theoretical, the uncertainties in the numerical formulations (such as the finite-difference equations or boundary conditions) set this method of theoretical analysis apart from analytic studies in which closed mathematical solutions are obtained (usually for a physical problem that is greatly simplified compared with the ones investigated with numerical models). In this section we discuss a few of the current theoretical problems that are related to mesoscale meteorology.

2.4.1 Gravity Waves and Wave Interactions

The analysis of small-amplitude gravity waves appears to be rather well established, but much work is proceeding on various large-amplitude nonlinear effects and on the interaction of waves with their mean flow and turbulent environments, from the boundary layer to the upper atmosphere. A recent surge of interest has appeared in three-dimensional mountain wave theory and in the analysis of mountain waves with condensation.

2.4.2 Cloud Dynamics

The three-dimensional simulations of convective clouds and storms noted in Table 3 are leading to much better understanding of the dynamics of convection in an environment with vertical shear. In particular, a sequence of events leading to tornado formation now seems to be definable from the models, a result that should further stimulate observational studies in this area. Another important element of cloud dynamics, the entrainment process, is being reconsidered theoretically on the basis of evidence that much more of it occurs from the top than had been generally assumed. This work may also lead to a useful understanding of the strong downdrafts (downbursts) often observed in thunderstorms.

2.4.3 Nocturnal Boundary Layers

Theoretical understanding of the stable, nocturnal boundary layer has lagged behind understanding of the unstable, convectively driven boundary layer. The nocturnal boundary layer involves strong vertical stratification, strong vertical wind shear, and internal gravity waves. It is affected greatly by complex terrain, with blocking of low-level flow by complex terrain an important process. In addition, low-level jets, which arise from an imbalance of forces during the transition from an unstable to a stable boundary layer, are important phenomena in thunderstorms and squall-line generation. These jets are important for transporting heat and moisture and for producing mesoscale patterns of convergence/divergence.

2.4.4 Frontogenesis and Frontal Circulations

Substantial progress in understanding the dynamics of surface and upper-tropospheric frontal systems has resulted from the use of the semigeostrophic equations in the study of straight frontal zones forming in adiabatic, inviscid flows containing confluence or shear. The semigeostrophic equations have the advantage of possessing the same mathematical form as the analytically tractable quasi-geostrophic equations, but, on account of a transformation of horizontal coordinates, contain the nonlinear physical effects of advection by the divergent, ageostrophic circulation in the cross-frontal, vertical plane. In the case of the surface frontal zones, the analytic model results exhibit realistic slopes, develop from large-scale patterns in a reasonable time period of several days, and are strongest at the ground, as observed in nature. Recent studies into diagnosing the vertical circulations in upper-level frontal-zone jet-stream systems suggest that the thermally indirect circulation associated with upper-tropospheric frontogenesis is a result of the combination of confluence and shearing advection at tropopause level in the absence of curvature. Further progress in the theory of frontogenesis requires explaining the differences in the structure of cold and warm fronts, assessing the influence of curvature on frontal circulations, and including diabatic and viscous effects in an analytic

TABLE 4 Summary of Regional-Scale Models Active in 1980

Model Identification[a]	Spatial Dimensions[b]	Typical Horizontal Grid Size; Domain Size	Typical Vertical Grid Size	Emphasis	Contact
GFDL	2, 3	50 km 2500 km × 2500 km	1 km	Tropical cyclones Fronts Meso-α predictions with real data	Kurihara, Orlanski, Ross, Miyakoda
Drexel	2, 3	40 km 2000 km × 2000 km	1 km	Precipitation, meso-α, β predictions with real data	Kreitzberg, Perkey
U. Va.	2, 3	10 km 400 km × 400 km	1 km	Sea breezes, mountain-valley breezes	Pielke
Penn State	2, 3	20–100 km 800 km × 800 km to 4000 km × 4000 km	1 km	Precipitation, meso-α, β predictions with real data, sea breezes, fronts	Anthes, Warner, Seaman

ERL/OWRM	3	20 km 800 km × 800 km	1 km	Mesoscale convective complexes	Fritsch
	3	5 km 200 km × 200 km	500 m	Terrain effects Orographic precipitation	Nickerson
NHRL	2, 3	20 km 3000 km × 3000 km	1 km	Tropical cyclones	Rosenthal, Jones, Willoughby
NMC	3	60 km 3000 km × 3000 km	1 km	Tropical cyclones Mesoscale precipitation	Hovermale Phillips
SUNYA	3	18.5 km 389 km × 426 km	300 m Top 2.5 km	Coastal front	Ballantine
Navy	3	60 km 3000 km × 3000 km	1 km	Tropical cyclones	Madala, Hodur

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[a] See Appendix B for key to abbreviations.

[b] The two-dimensional models predict the variation of the variables in one horizontal dimension and in the vertical. The variation in the other horizontal direction is either neglected or specified.

framework. Spurred by recent observational studies, the theory of rainband formation is now an active area for research.

2.4.5 Small-Scale Convection

Theoretical work on small-scale and moist convection is achieving some success through analytical studies, using limited spectral models, of the transitions between flow regimes. In laboratory experiments, a distinct sequence of flow types involving motionless conduction, steady flows, periodic flows, and turbulence is produced as the intensity of the forcing is increased. The spectral models are designed with limited degrees of freedom but include sufficient nonlinear interactions that make such transitions possible. These models have generated considerable interest in the mathematical community and are now producing physical results (orientation of cloud rolls in a shearing flow) that can be compared to observations of atmospheric convection. Investigators working with these models argue that they reveal the essential physics of the situation, even though it is drastically simplified.

2.5 TECHNOLOGICAL ADVANCES IN MEASUREMENT SYSTEMS

Technologies already demonstrated or at advanced stages of development are beginning to provide practical methods for observing mesoscale weather systems and for collecting, processing, analyzing, interpreting, and disseminating mesoscale data and information products. Continuing rapid progress in these areas is expected.

2.5.1 Observations

The smaller spatial scales and more rapid development and evolution of mesoscale weather systems require substantially greater spatial resolution and more frequent observations than are available from routine synoptic networks. A number of remote-sensing techniques have been developed that address this problem. The geostationary meteorological satellite imaging systems have been available for more than a decade, but fast and convenient methods for processing and interpreting the data have only recently become available at several institutions. The satellite systems provide, about every half-hour, quantitative visible and infrared imagery covering most of the globe with a resolution of a few kilometers. Wind estimates can be derived from cloud motions, and estimates of cloud and surface temperatures can be derived radiometrically. The recent addition of a multichannel atmospheric sounder (VAS) adds the capability to deduce vertical temperature and humidity soundings of a quality similar to those available from polar orbiting satellites in recent years, but much more frequently. Additional improvements to satellite observing systems, including possible wind sounding capabilities using Doppler lidar techniques, are in various stages of planning.

Ground-based remote-sensing technologies also are evolving rapidly. Digital radar techniques have improved the recognition and interpretation of radar echoes from mesoscale structures and the estimation of quantitative precipitation. Doppler radar technology for measuring horizontal and vertical winds has been developed and demonstrated by several institutions. A national program (NEXRAD) to upgrade the nation's weather radar network during the 1980's is under way with the support of NOAA, DOD, and FAA. Specialized radar technologies also are under development for continuous ground-based observation of wind profiles throughout the troposphere and lower stratosphere and for studying cloud formation, structure, and content (8-mm radar).

In connection with the Prototype Regional Observing and Forecasting Service (PROFS) program, NOAA's Wave Propagation Laboratory is developing a continuous, remote-sensing profiler that determines wind profiles using the radars mentioned above and defines temperature and humidity profiles using microwave radiometers similar to those operating on satellites. Total water vapor and liquid-water content are observed using another microwave radiometer. Some components are now in field testing, and a complete system for observing all of these variables should be assembled within the year. Several institutions also have developed optical devices (e.g., lidars) to observe aerosols, clouds, and other constituents, while advanced Doppler lidar instruments are being developed that will be able to measure profiles of winds and possibly temperature.

Automation techniques are being applied increasingly to make and collect observations from mesoscale networks of conventional *in situ* surface instruments. A national program to automate the entire complex of surface synoptic and aviation observations, including ceiling, visibility, and current weather, has been initiated by FAA, DOD, and NOAA. Sophisticated *in situ* and remote-sensing instruments and data-processing systems also have been adapted to research aircraft to allow rapid, high-resolution observations of thermodynamic, cloud physical, and turbulent vertical flux variables, as well as profiles below aircraft. Chemical sampling and analysis instruments for both ground and aircraft also are now available.

Taken together, these technologies provide an impressive and comprehensive array of tools that allow the essential physical and dynamical mesoscale features to be observed.

2.5.2 Data Processing, Analysis, and Interpretation

As noted above, advanced data-processing and display techniques have become an essential and integral part of most remote-sensing observation systems.

This is true both for image processing and manipulation and for quantitative computations (e.g., specifying the location, calibration, and mathematical "inversion" of multispectral radiometric or Doppler radar and lidar data). These techniques are well advanced and are now used routinely to process vast volumes of data in real time.

At this stage in our conceptual and theoretical understanding of mesoscale weather systems and their structure and dynamics, it is difficult to analyze and interpret completely a comprehensive set of observational data. However, interactive data processing and display tools greatly simplify the task of synthesizing the information content of various meteorological fields and cloud and radar imagery. Reduction to common scales and formats, analysis and contouring of fields, overlay of fields and images (with color enhancements), time-lapse or "animated" displays, three-dimensional perspectives, and other processing techniques facilitate human interpretation of the data. Fast access to a comprehensive data base, coupled with versatile analysis and display software and hardware, allows adaptive exploration of physical hypotheses by interactive analyses.

The capability to assimilate and interpret the massive array of observational data *quickly* is particularly critical to operational applications such as mesoscale weather warnings and forecasts. At present, NWS forecasts at most field offices are unable to extract routinely the mesoscale information content of even the existing data sources, especially satellite and radar data. However, an immediate improvement in warnings and short-range forecasts is possible using existing technologies. These improvements would be enhanced and made widely available by the establishment of reliable conceptual models for mesoscale weather phenomena.

Ultimately, quantitative models of mesoscale weather will be needed if fundamental improvements are to be made in short-range weather forecasting. Extension of numerical-dynamical techniques to the mesoscale has been accomplished in several research models, but this demands rather large computing capacity. The technology exists and is becoming cheaper. Some extension to the larger end of the mesoscale spectrum will be possible with the new operational computers planned for NMC, and statistical models probably can be applied at individual weather stations using the local applications concept of the Automation of Field Operations and Services (AFOS). Additional computing power is needed for research modeling.

2.5.3 Dissemination

For the public or specialized users to take action based on weather information to minimize loss of life or property, or to achieve economies in their activities, weather information must be made available in a timely, understandable, and credible fashion. Mesoscale weather information places an extraordinary demand on dissemination systems because it must be locally detailed and specific and because it is applicable to short-lived, fast-changing phenomena. Fortunately, rapidly evolving technologies are available to address these problems. Fast, reliable communication systems that are capable of providing detailed information, including graphics and imagery, are available. Arrangements to allow selective request-reply services and "targeted" broadcasting are under test by industry. It is up to the meteorological and hydrological communities to develop information products that are suited to these future dissemination systems.

3

Opportunities for Advancing Mesoscale Meteorological Research and Its Applications

The foregoing chapter has documented the extensive efforts being carried on within federal agencies, national laboratories, and universities in the area of mesoscale meteorological research. It is apparent from the survey that impressive advances have been and are being made in developing new techniques for observing mesoscale phenomena; in gathering, analyzing, and interpreting specially acquired data sets; and in constructing theoretical and numerical models of the phenomena. It is also apparent that technological advances in data processing, display, and communications have reached the point where the benefits of research can be put to practical use in making improved warnings and predictions of mesoscale events of great economic significance.

Despite the steady progress that has taken place in recent years, the mesoscale research effort, like many areas of scientific research, has tended to be fragmented, to be guided more by agency missions and the interests of individual investigators than by a common goal of overriding importance. However, in mesoscale meteorology, such a goal is now emerging as a consequence of the advances outlined above, namely, the goal of improved understanding and prediction of mesoscale phenomena by application of dynamical and numerical methods. Improved prediction and warning of severe thunderstorms, tornadoes, flash floods, and a variety of freezing precipitation events associated with winter storms would pay dividends in agriculture, transportation, construction, and other industries as well as reduce the number of injuries and deaths associated with these mesoscale weather phenomena. We do not underestimate the difficulties that stand in the way of achieving this goal. They are indeed more formidable than those that confronted the meteorologists of the 1950's as they embarked on their quest for numerical prediction of large-scale weather. But it is precisely because of the difficulties involved that the establishment of a more vigorous and concerted effort, focused on the goal of improved short-range weather prediction and communication systems, is warranted at this time.

Not all mesoscale research would be included in such an effort. Agencies may well have specialized tasks that are best handled individually. However, for the achievement of the central objective, it is evident that there would be significant advantages to a pooling of resources and talents. Progress would almost surely be accelerated by proceeding according to a well-conceived plan of coordinated research.

Moreover, several federal agencies are now involved in a program (NEXRAD) to upgrade the national weather radar network, which is nearly 40 years old, with modern, quantitative reflectivity and Doppler radars. Similar improvements are under way for satellite and surface measuring systems. A coordinated national mesoscale research effort would provide the scientific basis for these hardware programs and for the interpretation of the vast quantities of data that they will provide, and it would enable the training of the generation of meteorologists and engineers that will be responsible for the operational use of these new systems in the future.

In view of the difficulties that stand in the way of achieving the long-term goal and the urgent need for short-term progress, it is envisaged that a coordinated program of mesoscale research would entail two components: a basic research arm and an applied arm. The basic research arm would be concerned with increasing fundamental knowledge and understanding of mesoscale phenomena and developing an enhanced capability for numerical modeling. The applied component would serve as liaison between the basic research component and the operational branches of the federal agencies. It would be devoted to transferring to operations the scientific and technological advances as they become available and to the development of improved systems of communicating weather information to the public.

An important part of the basic research component, requiring early implementation, would be the conduct of well-chosen field programs designed to provide the data needed for developing a deeper understanding of mesoscale systems and for testing and improving numerical models. Because of the manifold nature of the phenomena embraced by the term mesoscale meteorology, only a limited number of problems could be selected for initial investigation. In establishing priorities among the various possible mesoscale experiments, highest consideration should be given to the depth and breadth of the scientific advances that are likely to stem from the choice of a particular phenomenon and the second highest consideration to the practical or economic importance of the experiment. Among the topics for field experimentation that have been singled out as deserving special attention by participants in recent workshops related to mesoscale meteorology are the following:

- *Mesoscale aspects of extratropical cyclones in all seasons.* Extratropical cyclones dominate day-to-day weather throughout midlatitudes. Although the sizes and lifetimes of extratropical cyclones are synoptic scale, the important weather (clouds, precipitation, squall lines, convective systems, freezing rain areas) belong to the mesoscale. Carefully coordinated theoretical and observational studies of the mesoscale aspects of extratropical cyclones in all seasons and in different regions of the country are required, with particular emphasis on precipitation processes.
- *Convective storms and severe local storms.* Convective storms provide essential, beneficial rain to the United States. However, under special conditions, they produce flash floods, hail, damaging winds, and tornadoes. There is evidence that, far from being random, unpredictable phenomena, the location and timing of these convective systems is determined by a combination of large-scale processes that are predictable several days in advance and smaller-scale physical processes associated with energy sources at the surface. Continued, vigorous investigation of mesoscale convective systems by observational and numerical simulation methods is essential in view of the importance of severe storms.
- *Meteorology over complex terrain.* Because of its relevance to energy development, air quality, water conservation, and agricultural meteorology, the flow of air and precipitation patterns over mountainous terrain and coastal areas is a crucial problem. Comprehensive data sets and model validation studies are required. There is evidence that this problem is technologically solvable, but increased resources and much closer interagency cooperation are needed.

A fourth important area of mesoscale meteorological research is concerned with the understanding and prediction of tropical cyclones. Although the entire circulation of tropical cyclones belongs to the synoptic scale, the high-energy portion of these storms and the rainfall, which has both beneficial and destructive properties, are mesoscale features. In addition, the primary energy source, the release of latent heat of condensation, occurs in mesoscale convection. In contrast to the three areas of mesoscale research emphasized above, tropical cyclone research is well coordinated and is proceeding satisfactorily. In view of the potential for catastrophic destruction and loss of life associated with a major hurricane, continued extensive research efforts are well justified.

For the purpose of facilitating the practical application of scientific and technological advances, it is envisaged that prototype experiments would also be carried out in the applied research area. The Prototype Regional Observation and Forecasting Service (PROFS) being conducted by NOAA is an example of such an experiment.

As stated above, we view an effective national program in mesoscale research to entail both basic and applied components. To the degree possible, these two arms of the program should be mutually reinforcing. When feasible, basic field research programs should have applied components that will take advantage of the special observations to test emerging technologies and methods. By the same token, experiments or pilot studies that are primarily applied or semioperational in nature may also include some basic research elements, particularly in the area of instrument development.

4

Recommendations

In view of the foregoing considerations we recommend the establishment of a National Mesoscale Program. Suggested guidelines for the program are as follows:

- The program should be a cooperative effort involving federal agencies, national laboratories, universities, and private organizations.
- In recognition of the need for both long-term fundamental solutions of the mesoscale prediction problem and short-term practical solutions, the program should have two components: a basic research arm and an applied arm.
- The basic research arm should involve improvement of theoretical and numerical models of mesoscale phenomena, development of new instrumentation, holding of field experiments to gather special data sets, and use of the data in diagnostic and numerical studies of mesoscale phenomena.
- The applied research arm should involve pilot or prototype experiments aimed at testing the utility of the latest technological developments and scientific findings in providing better warning and short-period prediction of important mesoscale phenomena, such as severe convective storms.
- Overlap of basic and applied research should be encouraged when the overlap will assist in the transfer of scientific and technical knowledge to agency operations without compromising scientific objectives.
- The development of the plan for the National Mesoscale Program should be joint responsibility of the federal agencies and the university community, as represented by the University Corporation for Atmospheric Research, and should take advantage of the advisory apparatus of the National Research Council.

- The management of the National Mesoscale Program should be prescribed in a planning document. Past experience would suggest designating the federal agency with the largest commitment—in this case the National Oceanic and Atmospheric Administration—as lead agency, but other possible administrative arrangements could be considered.
- The National Mesoscale Program should be viewed as a long-term project requiring stable funding for a period on the order of a decade.

Appendix A:

Representatives of Federal Agencies* Making Presentations to the Panel

Department of Agriculture
  D. Fox (Forest Service)
Department of Commerce (NOAA)
  W. Togstad (NESS)
  R. McPherson (NMC)
  I. Orlanski (GFDL)
  J. Golden (ERL)
  F. Ostby (NSSFC)
Department of Defense
  T. Cress (Air Force)
  W. Nordquist (Army)
  A. Weinstein (Navy)
Department of Energy
  D. Ballantine
Department of the Interior
  B. Silverman (BUREC)
Environmental Protection Agency
  L. Niemeyer
National Aeronautics and Space Administration (NASA)
  J. Dodge (Headquarters)
  D. Atlas (GLAS)
  W. Vaughan (MSFC)

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*See Appendix B for key to abbreviations used.

National Science Foundation
  R. Dirks
National Center for Atmospheric Research
  D. Lilly
  P. Squires

Appendix B: Abbreviations of Organizations

DOD	Department of Defense
NRL	Naval Research Laboratory
DOE	Department of Energy
DOI	Department of the Interior
BUREC	Bureau of Reclamation
EPA	Environmental Protection Agency
NASA	National Aeronautics and Space Administration
GLAS	Goddard Laboratory for Atmospheric Sciences
MSFC	Marshall Space Flight Center
NSF	National Science Foundation
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
AOML	Atlantic Oceanographic and Meteorological Laboratory
ARL	Air Resources Laboratory
ERL	Environmental Research Laboratory
GFDL	Geophysical Fluid Dynamics Laboratory
NESS	National Earth Satellite Service
NHC	National Hurricane Center
NHRL	National Hurricane Research Laboratory
NMC	National Meteorological Center
NSSFC	National Severe Storms Forecast Center
NSSL	National Severe Storms Laboratory
NWS	National Weather Service
OWRM	Office of Weather Research and Modification
TDL	Technique Developments Laboratory
WPL	Wave Propagation Laboratory

Universities

CSU	Colorado State University
MIT	Massachusetts Institute of Technology
SDSMT	South Dakota School of Mines and Technology
SUNYA	State University of New York, Albany