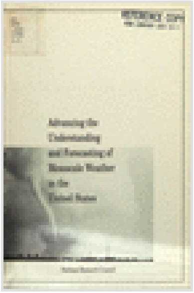

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Board on Atmospheric Sciences and Climate
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Cover: Photograph of an intense tornado that struck Union City, Oklahoma, on May 24, 1973. Observations of this storm on experimental Doppler radar and simultaneously by the Tornado-Intercept Project team of the National Severe Storms Laboratory provided the initial impetus for planning the next-generation weather radar (NEXRAD) system. (Courtesy of Joseph H. Golden of the National Oceanic and Atmospheric Administration.)

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*This report was initiated by the Panel on Mesoscale Research prior to its dissolution in June 1988. Its successor, the Committee on Meteorological Analysis, Prediction, and Research, completed the report.

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Preface

Much of the weather that affects human activity has mesoscale dimensions. In addition, there is growing recognition that atmospheric circulations on this scale (2 to 2000 km) interact importantly with meteorological processes on both larger and smaller spatial scales, including, at the largest scales, global climate. However, mesoscale weather events are often too small and short-lived to be observed by the relatively widely spaced and infrequently reporting radiosonde and surface observing sites that constitute the present operational observing network. Thus an improved mesoscale observational network, along with a research effort that takes advantage of it, should lead to greater understanding of mesoscale weather events and their interactions with processes on other scales and to advances in our understanding of the atmosphere as a whole.

Scientists now recognize that, while there is still much to learn about the dynamics of weather processes, existing limitations in weather predictions and warnings are primarily due to limitations in observations, computers, computer models, data assimilation, and dissemination of forecast information. These limitations are being reduced as new observing systems, improved computer capabilities, advanced models, and communications technologies emerge. These new capabilities will enable us to observe and predict the weather in unprecedented detail and accuracy provided we develop the necessary knowledge and skills to use the new capabilities advantageously.

Taken together, the development of enhanced technological capabilities, the scientific and socioeconomic importance of mesoscale weather events, and the new opportunity to make progress all point to the need for implementing the National Stormscale Operational and Research Meteorology (STORM) Program. This program will capitalize on the new observing systems and will create the knowledge base needed to improve forecasts in all seasons and all sections of the country.

The framework for the National STORM Program grew out of a series of workshops held by the atmospheric sciences community in the early 1980s. An essential aspect of the program is that it has both research and operational components. The need for STORM, and its underlying precepts, was endorsed by the NSF-UCAR Long-Range Planning Committee in their report *The Atmospheric Sciences: A Vision for 1989-1994* (National Science Foundation, Washington, D.C., 1987). This report recommends that the program be carried out as planned.

The reader may ask why another report urging that the planned National STORM Program be implemented is needed at this time. The answer is twofold: (1) Despite much planning effort over the last several years, as indicated in Chapter 1, this very important program has been overshadowed by other programs and has not made the expected progress toward implementation, and (2) the imminent modernization of the National Weather Service, involving bringing sophisticated new observing systems on-line, will not achieve the maximum possible improvement in weather forecast and warning services without a complementary scientific program of research and development. This report restates the need for such a program and argues that the planned STORM program is well designed to fulfill this need.

I am grateful to the Panel on Mesoscale Research and its successor, the Committee on Meteorological Analysis, Prediction, and Research, for their thoughtful and stimulating discussions of the issues and for articulating the needs and opportunities in mesoscale meteorology. We are all indebted to the staff of the Board on Atmospheric Sciences and Climate of the National Research Council for their help and counsel and especially to Kenneth Bergman and Doris Bouadjemi for their assistance in preparing this report.

Peter S. Ray, *Chairman*
Committee on Meteorological Analysis,
Prediction, and Research

Contents

Executive Summary

Significant advances in our understanding of mesoscale[1] atmospheric processes are needed in order to increase the accuracy of predictions and warnings of important weather events that occur on this scale. The opportunity exists to improve the 0- to 48-hour prediction of precipitation and severe weather through an enhanced fundamental understanding of precipitation, the hydrologic cycle, and other mesoscale processes, and through full utilization of the advanced observing systems that will soon be available.

Mesoscale weather systems play a significant role in global atmospheric circulation through transport of heat, moisture, and chemicals. The effects of clouds generated by mesoscale weather systems are the largest variable in the global energy budget. Therefore, improved understanding of mesoscale processes is essential for improved understanding of climate processes and climate change. A recent report, *Meteorological Support for Space Operations: Review and Recommendations* (NRC, 1988), recognizes the importance of mesoscale weather events to the nation's space program; thus enhanced understanding of mesoscale processes should contribute in this arena as well.

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[1] Mesoscale processes are those that occur on scales of 2 to 2000 km, such as thunderstorms, tornado outbreaks, local heavy rain and snowstorms, flash floods, windstorms, downslope winds, and significant air pollution events.

In order to achieve the goals of improved understanding and prediction of mesoscale weather processes, we need to fully exploit new observing systems, such as the Demonstration Wind Profiler Network, the next-generation weather radar (NEXRAD) Doppler radars, instrumented commercial aircraft, and the GOES NEXT satellite; new data-processing methods, such as the Advanced Weather Interactive Processing System for the 1990s (AWIPS-90) and four-dimensional data-assimilation techniques; and a new generation of computers and numerical prediction models. These improved capabilities must be used as an integrated system in order to gain the maximum benefits from each component.

The new mesoscale observing systems that will soon be deployed as part of the National Weather Service's modernization have been chosen to greatly enhance the present national weather observing capability. The new systems will be critical for understanding and predicting precipitation and severe weather and for understanding interactions of meteorological processes on different spatial scales. The new observations will also contribute to improvement of numerical weather prediction models through use in initialization and verification of the models.

In order to advance understanding and improve weather forecasts, this report recommends that

- The planned development and deployment of the new weather observing systems and technologies should continue and be kept on schedule.
- The capabilities of new instruments should be systematically assessed in order to maximize their utility for short-term forecasting and warning and for initializing and testing numerical prediction models.
- Investigation into possible additional applications of the new data streams should be undertaken in order to realize the full benefits of new observational technologies.
- The data from the new observing systems should be processed, archived, and made available to a wide range of users in an efficient, timely, cost-effective, and easy-to-use manner.
- Data-assimilation techniques should be developed to combine the many kinds of data into coherent, gridded data sets suitable for a wide range of weather forecast and research tasks.
- Numerical prediction models should be improved to more accurately account for physical and chemical processes, including those involved in the hydrologic cycle; sensible, radiative, and latent heating throughout the troposphere; and energy exchange at the earth's surface.
- Large observing programs, timed to take advantage of the newly deployed observing systems, should be conducted. These programs should make use of the new observing systems to look at the multiscale interactions arising from mesoscale weather events. Additionally, observing

programs that cover smaller regions and specific weather phenomena and that complement the larger-scale programs should also be planned and carried out.

- Forecasters should be retrained and, where necessary, university curricula in the atmospheric sciences should be revised, updated, and expanded to produce a sufficient supply of new meteorologists capable of using the new observing systems and scientific concepts to best advantage.

The necessary actions to fulfill these recommendations are embodied in the National Stormscale Operational and Research Meteorology (STORM) Program (*STORM Program Plan* [NCAR, 1990]).

> **Therefore this report recommends that the National STORM Program be implemented as soon as possible.**

By building on the large investment already committed to new observational technology and capabilities, the National STORM Program will provide the focus for important advances in basic understanding of mesoscale weather processes and in the country's operational abilities to forecast weather events.

1
Introduction

THE PROBLEM

Each season reminds us of our vulnerability to destructive or incapacitating weather events such as tornado outbreaks, windstorms, hailstorms, heavy snowstorms, and flash floods. Our society relies increasingly on technology that is vulnerable to the weather, thereby increasing the need for improved weather predictions and warnings. There is, for example, heightened awareness of the crucial role played by weather in major air and space transportation accidents, such as the Dallas-Ft. Worth airliner crash, the Centaur Atlas launch lightning accident, and the Challenger space shuttle disaster. The costs of inadequate warnings of tornadoes, floods, and other severe weather can be very large.

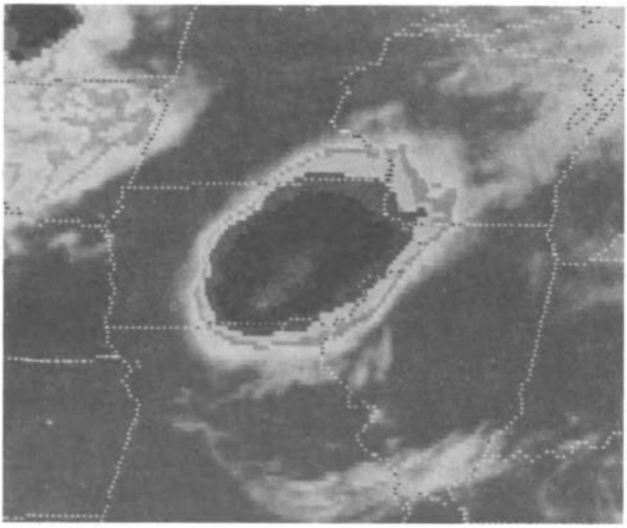
Events of 1989 alone dramatically reminded many Americans of their vulnerability to severe weather events. In addition to Hurricane Hugo's costly (21 U.S. mainland deaths and about $7 billion in damage) strike into South Carolina, the nation reported a near-record 845 tornadoes that caused 48 deaths and much property damage. The outbreaks that caused the most deaths occurred on November 15 near Huntsville, Alabama, (21 deaths) and on November 16 in New York State (9 deaths), the latter tornado activity being very atypical in terms of location and time of year. Heavy rains brought flash floods to parts of Kentucky in February, Pennsylvania in May, Louisiana in both June and November, and northern Florida in October, when up to 40 cm (16 in.) of rain fell in one day. Fargo, North Dakota, recorded a record snowfall of 62 cm (24.4 in.) from a local snowburst embedded within a severe blizzard-producing storm in January. Similar severe weather events, many of them mesoscale, occur every year, have similar impacts, and typically cause some billions of dollars in economic losses as well as significant loss of lives.

A singular characteristic of heavy precipitation and severe weather is that they are often highly localized events that occur over small areas and for limited times. These mesoscale weather events are the ones that most directly affect humans, yet many elude detection by the present upper-air weather observing network, which is built around 12-hourly balloon soundings at sites some 500 km apart, and even by the surface observing network, which has typical site spacings of 100 to 200 km. Moreover, these events cannot at present be reliably predicted with numerical models.

Mesoscale events result from complicated, nonlinear processes that themselves occur across a wide spectrum of spatial and temporal scales extending from variations in the global atmospheric circulation pattern to microscale physical processes in individual clouds. In addition, mesoscale systems, once initiated, affect the larger-scale atmospheric circulations in which they are embedded. For example, Figure 1.1a shows an enhanced infrared image of a mesoscale weather system as seen from a satellite vantage point over Iowa at 0730 UTC on July 16, 1982. Although the cloud cover depicted in this image suggests a single weather entity with a scale of about 300 to 400 km, radar observations of this system made at approximately the same time (Figure 1.1b) and subsequent visible satellite imagery (Figure 1.1c) indicate that the system was composed of several clearly distinguishable elements of distinctly different scales, that is,

1. a broad, roughly circular zone of stratiform precipitation with a diameter of about 200 km,
2. cyclonically curved bands of heavier precipitation (≈50 km wide and about 200 to 300 km long), and
3. individual thunderstorms, each on the order of 2 to 20 km in scale.

In addition to displaying these directly evident multiscale features, this system substantially altered the flow field of its larger-scale environment and produced a large anticyclonic wind perturbation that spanned nearly 1000 km (Figure 1.1d). At smaller scales, high-resolution aircraft observations of such systems suggest that microphysical processes such as freezing, melting, drag, and evaporation of hydrometeors significantly affect the circulations of such systems. These inherently complex systems have so far defied complete scientific understanding, largely because it has not been possible to simultaneously measure how the many different scale components of such systems interact with each other and with their large-scale environment. As a consequence, consistent and accurate prediction of these systems has remained elusive, as in the present example (see Figure 1.1), where over



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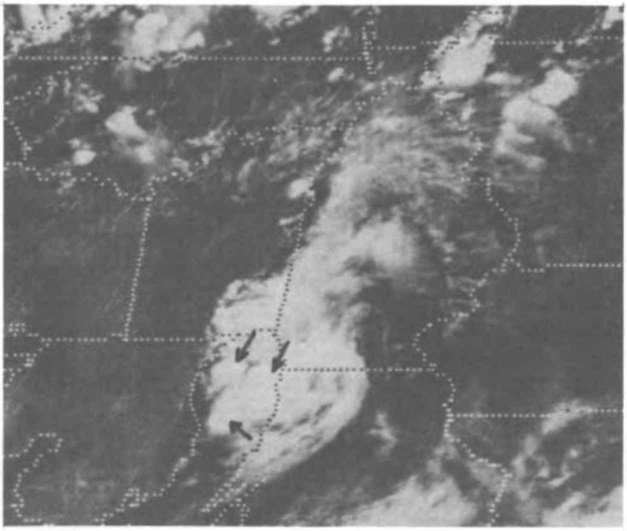

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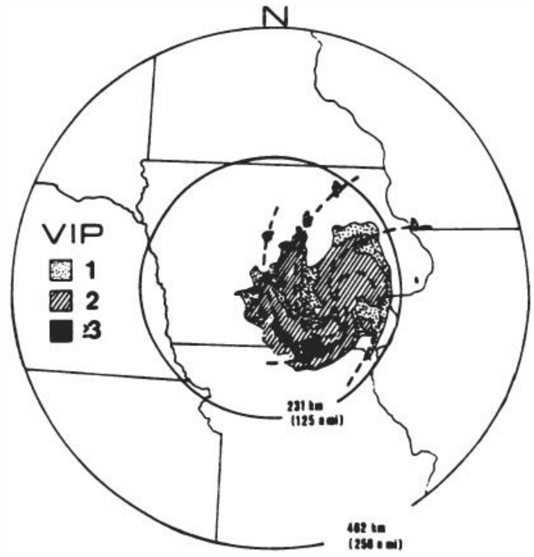
FIGURE 1.1 (a) Enhanced infrared satellite image for 0730 UTC, July 16, 1982. (b) Des Moines, Iowa, radar horizontal display for 0700 UTC, July 16, 1982. Levels of precipitation intensity (VIP) are shown along with axes (dashed) of maximum precipitation, suggesting rotation. (c) Visible satellite image for 2130 UTC, July 16, 1982. Arrows indicate individual



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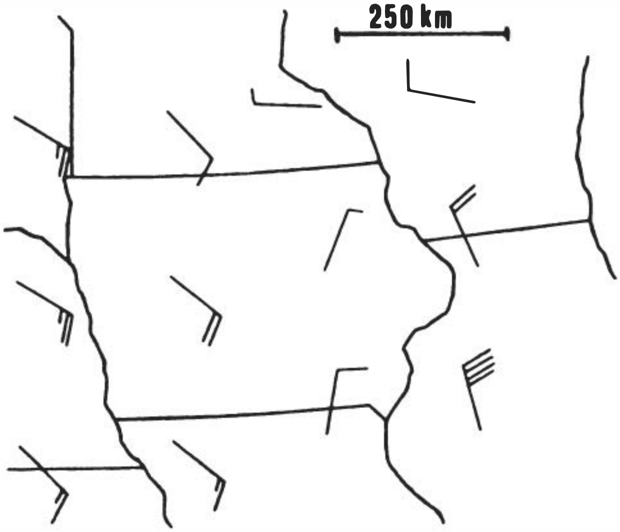

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thunderstorms developing within the vortex. (d) 200-mb perturbation wind field produced by the mesoscale convective complex shown in (a); valid time, 1200 UTC, July 16, 1982. Full barb = 5 m/s. (Reprinted, with permission, from Murphy and Fritsch, 1989. © 1989 by the American Meteorological Society.)

10 in. of rain with attendant flash floods occurred as the system moved into southern Michigan. This example is just one of many such occurrences of complex mesoscale systems that have resulted in unpredicted severe weather.

A massive capital investment in technology now under way as part of the National Weather Service's modernization will permit weather observations of increased detail in space and time. These observations should greatly enhance our ability to observe small-scale weather systems such as the one discussed above. However, as with all new observing systems, research on how they can best be used is required to realize the systems' full potential and bring about improved understanding and prediction of mesoscale weather.

Mesoscale systems also significantly affect the exchange of water between the earth and the atmosphere and form a critical link in the hydrologic cycle. The improved basic understanding of the hydrologic cycle resulting from a mesoscale research program will support improved water resource policies and contribute to our understanding of global climate change.

HISTORICAL PERSPECTIVE

Meteorological observations form the basis of our understanding of the weather. The improvement of numerical weather prediction and the illumination of physical processes depend on the frequency, accuracy, and spacing of available observations. Significant weather events can form on scales as small as 2 km, much smaller than the existing operational networks can resolve, and hence their origins are often not detected. Mesoscale weather events also tend to be episodic rather than periodic, which further decreases the chances of their detection. Furthermore, mesoscale weather phenomena interact importantly with larger-scale weather systems, but the exact nature of these interactions is not well understood.

As early as 1969, scientists recognized the need for special programs to observe and study mesoscale weather phenomena and their interactions with larger weather systems. As an outgrowth of this recognition, scientists in 1973 proposed a multiscale program, the Severe Environmental Storms and Mesoscale Experiment (SESAME; NOAA, 1976), which was designed to specifically address the vital scale-interaction problem mentioned above. However, a lack of sufficient resources and observational capability prohibited carrying out a multiscale field experiment. Instead, the program was separated into two phases: the first phase concentrated on the larger synoptic and meso-α scales (200 to 2000 km), while the second focused on the smaller meso-β (20 to 200 km) and meso-γ (2 to 20 km) scales. Also in 1973, the Cyclonic Extratropical Storms (CYCLES) Project attempted to examine meso-α- and meso-β-scale disturbances embedded in winter cyclones. These projects were followed in 1975 through 1980 by the High Plains Experiment (HIPLEX) series of field studies and in 1981 by the Cooperative Convective Precipitation Experiment (CCOPE), both of which recognized the importance of mesoscale processes and scale interactions in their plans. However, resources and observational capabilities remained inadequate for detailed study of scale interactions. Over the years, the scientific community has nonetheless remained steadfast in its call for a multiscale, scale-interaction experiment that focuses on understanding and predicting mesoscale weather processes.

About a decade ago, the associate administrator of the National Oceanic and Atmospheric Administration (NOAA) requested the National Research Council (NRC) 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 ensuing NRC report, *Current Mesoscale Meteorological Research in the United States* (NRC, 1981), recommended the establishment of a national mesoscale program of basic and applied research directed toward better understanding and improved prediction of mesoscale weather events.

In 1982, a group of atmospheric scientists met at the National Center for Atmospheric Research (NCAR). They concluded that significant improvements could be achieved in local weather forecasts and warnings of severe weather as a result of then recent and planned developments in space- and ground-based observing systems. In addition to enhancing early warning capabilities, these new observing systems were considered to have the potential for greatly improving physical understanding of small-scale weather processes. Advances in computer technology, by enhancing the ability to numerically model weather processes, would enable the new observations and improved understanding to be translated into better local weather forecasts and warnings. The scientists recognized that in order to realize the potential for improved understanding and prediction of weather, a coordinated, national effort was needed. The proposed effort was named the National Stormscale Operational and Research Meteorology Program, or simply the National STORM Program (UCAR, 1982).

The technical opportunities and scientific basis for a national effort centered on mesoscale meteorology were discussed in detail in *The National STORM Program: Scientific and Technological Bases and Major Objectives* (UCAR, 1983a). It was recognized that the proposed national program required two parallel efforts: one centered on improved understanding of the physical processes involved, and the other on applying this knowledge to improving weather services. *The National STORM Program: A Call to Action* (UCAR, 1983b) supported the recommendations of the previous two documents, urged the community to capitalize on the emerging observational technology, and called for implementation of the two components of the National STORM Program.

In 1986, the National Science Foundation's Division of Atmospheric Sciences (ATM) and the University Corporation for Atmospheric Research (UCAR) were advised by a specially appointed committee on the important priorities for atmospheric research over the next decade or so. In the committee's report, *The Atmospheric Sciences: A Vision for 1989-1994* (NSF, 1987), progress in mesoscale meteorology was highlighted as one of the top two research priorities. Also, in 1988, the UCAR, in conjunction with the Council of the American Meteorological Society, identified the protection of life and property through improved weather prediction as one of two top priorities for the United States to pursue in the immediate future (AMS, 1988).

RECENT DEVELOPMENTS

Many of the recommendations found in the documents referenced above have been or are in the process of being implemented. The deployment of an advanced national weather observing system has received particular emphasis. This system, representing an investment of more than $1 billion, includes the next-generation weather radar (NEXRAD) Doppler network, the Automated Surface Observing System (ASOS), the Demonstration Wind Profiler Network, the next generation of geostationary satellites, and the Advanced Weather Interactive Processing System for the 1990s (AWIPS-90). However, the parallel research and application efforts needed to maximize the benefits to be derived from this impressive array of instruments have largely been lacking. To help address these needs, the National STORM Project Office has recently been established to coordinate improvements in the National Weather Service's (NWS) operational systems with the nation's weather research program and to plan for a national mesoscale program that will further both understanding and predictive capability.

Experts in numerical modeling, in observational research, and in operational forecasting from the government, academia, and the private sector have been involved in planning for the National STORM Program. This process has resulted in a community consensus on goals, objectives, and schedules for the program. The preliminary program plans have been reviewed by this committee and its predecessor, the Panel on Mesoscale Research.

The proposed National STORM Program has two equally important goals:

- Improve the 0- to 48-hour prediction of precipitation and severe weather events.
- Advance fundamental understanding of precipitation and other mesoscale processes and their role in the hydrologic cycle.

As this report makes clear, the atmospheric community is now well positioned to address these goals. The new technologies for observation, data analysis, and information dissemination will soon be operational. An effective administrative framework has been established. The atmospheric sciences community is in agreement on the goals, objectives, and method of attack. Therefore, a well-focused program of basic and applied research directed toward achieving the full potential of the new observing technologies for operational prediction and warning is urgently needed.

PURPOSE AND SCOPE OF THIS REPORT

As noted above, little progress has been made in undertaking a well-focused basic and applied research program that will exploit the full potential of the new observing technologies for improved fundamental understanding of mesoscale interactive processes. Without this fundamental understanding, the full benefits of the new technologies for operational prediction and warning cannot be realized. It is the purpose of this report to make recommendations that will assure that the full potential of new observing technologies is realized in terms of improved understanding and better forecasts. In this report, the committee urges the implementation of a national mesoscale program that will provide both the scientific understanding and the development of the operational techniques required to make the best use of the large investment in instrumentation and technology, leading to improved weather predictions in all parts of the nation.

This report discusses several new technological capabilities relevant to mesoscale meteorology and their relationship to advances in scientific understanding; important relationships between mesoscale meteorology, atmospheric chemistry, and climate are also identified (Chapter 2). The potential implications of the new technologies for improved operational meteorology are summarized (Chapter 3).

The report concludes with statements of needs and recommended actions for capitalizing on the opportunities that now exist (Chapters 4 and 5). The recommended actions should lead to major progress in understanding scale interactions, a virtually unexplored frontier in mesoscale meteorology. This increased understanding should have the direct, positive impact of improving weather forecasts and products delivered to the public. In addition, understanding of the role of mesoscale processes in the global circulation, in the transport of greenhouse gases and other trace constituents, and hence in climate should be much improved.

The message is clear. The community has prepared itself well to undertake a national mesoscale program. There is broad agreement on the goals, objectives, and plan of attack, and the technological components are being put into place. This is the optimum time to begin such an effort. The program should result in a major leap forward in understanding of mesoscale processes and in developing markedly improved weather forecasting services for all segments of our society.

2

Status of Technology and Science in Mesoscale Meteorology

EMERGING OBSERVING SYSTEMS AND NEW TECHNOLOGIES

Since the first plans for the National STORM Program were formulated in the early 1980s, there has been progress in the development of new in situ observing systems as well as ground-based and space-based remote sensors. In addition to those described below, accurate wind reports from commercial jet aircraft and satellites are available for meteorological use, several national ground-based lightning detection networks are in place, and lightning detection from satellites is planned. Great progress has also been made in the ability to integrate and use these and similar observations. The spectacular advance of computer capabilities and digital electronics has dramatically improved the technical capability for processing heterogeneous meteorological data for use in forecasting and research.

A key to progress is the ability to process so-called raw observations, such as radar reflectivity, radar Doppler velocity, and satellite-observed infrared radiance, into meteorological information, such as three-dimensional wind velocity, temperature, and moisture. For example, fields of radial velocity from Doppler radars have been combined with data from multiple wind profilers to derive upper-atmospheric wind fields having much higher horizontal resolution than do those obtainable from traditional wind-observing systems. Similarly, techniques to process satellite infrared soundings have improved, yielding higher horizontal resolution of temperature and moisture fields.

The new wind profiler provides an improved capability to observe winds through the troposphere and lower stratosphere. These wind measurements are normally derived every hour, although for special studies it is possible to increase the temporal resolution to 6 minutes. A demonstration network of such profilers, now being established in the central United States (Figure 2.1), will vastly increase information on the kinematic structure of the atmosphere.

The next-generation weather radar (NEXRAD) system network will shortly become operational and will cover most of the continental United States (Figure 2.2). NEXRAD radars are over 100 times more sensitive than existing network radars and can detect both liquid- and ice-phase precipitation much more effectively. Therefore, the NEXRAD radars will be far more useful than existing systems in defining wintertime snowstorms. The enhanced sensitivity of NEXRAD systems also permits the measurement of air motions in parts of the boundary layer where precipitation is not occurring. Recent research indicates that these measurements will be useful in detecting the initiation of convective storms as much as 2 hours before the first clouds appear. NEXRAD system capabilities are summarized in Appendix Table A.1.

Another area of significant progress has been the development of data-assimilation procedures, which allow the integration of data of differing accuracies and spatial and temporal resolutions into consistent meteorological fields. Workshops on data assimilation have been held, and a national effort is being coordinated to bring together data from both standard synoptic and nonstandard heterogeneous sources. Computerized atmospheric models are planned that will integrate diverse observational data in a physically and dynamically consistent manner, resulting in improved accuracy and predictive capability, but much additional research and development are needed to achieve this goal.

The prospects for rapid technological progress in the observing and processing of mesoscale meteorological data are bright, and new ideas continue to be proposed. The Radio Acoustic Sounding System (RASS) is a simple and inexpensive addition to a radar wind profiler that produces very accurate measurements of temperature in the lower several kilometers of the atmosphere. The Doppler velocity of air motion excited by an acoustic wave is measured by a wind-profiling radar. The measurement gives the speed of sound as a function of height. Since the speed of sound is directly related to air temperature, computations of temperature with accuracies from 0.15 to 0.30°C are possible. Excellent vertical and temporal resolution allows delineation of important lower-tropospheric structures such as temperature inversions and fronts. The Japanese have used a powerful RASS to obtain accurate temperature soundings from the surface to an altitude of over 20 km.

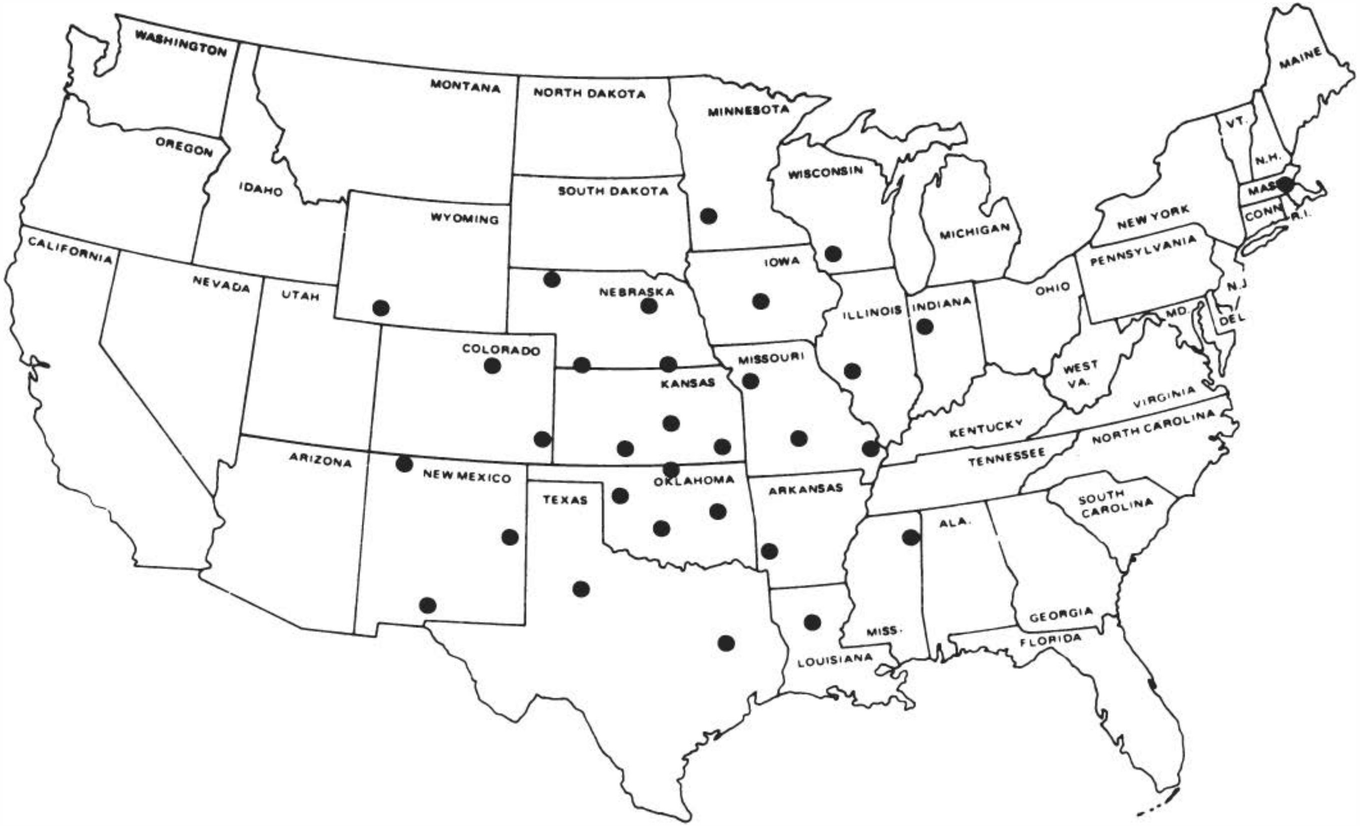

FIGURE 2.1 Site locations of the Demonstration Wind Profiler Network. (Courtesy of the National Weather Service.)

Another promising technique is the use of interferometers to increase the amount of meteorological information that can be derived from infrared radiation measurements. Plans have been proposed that would use the GOES NEXT satellite platform in the late 1990s to sense radiation at infrared wavelengths in over 2000 channels rather than the 20 channels currently used. This 100-fold increase in channels will permit construction of vertical profiles of atmospheric temperature and moisture with much greater resolution than is currently possible. Infrared interferometers may also be very cost-effective as ground-based thermodynamic profilers.

Advanced airborne Doppler radars are being developed to observe, over great distances, the evolution of mesoscale systems over both land and oceans. The latest design synthesizes three-dimensional air-motion fields through the use of innovative antenna scanning while the aircraft flies along a straight-line track safely outside of severe storms. A high-altitude, downward-pointing airborne radar design will measure vertical air motions in unprecedented detail. Advanced ground-based radar techniques use polarization diversity for discrimination of the ice and water phases, detection of hail, and better estimation of very heavy rainfall.

Other remote sensing techniques being investigated include the measurement of temperature, moisture, and winds from ground-based lasers. Significant advances in laser technology promise much more powerful lasers at greatly reduced cost. A summary of the principal new observing system technologies and their current status is given in Appendix Table A.2.

Clearly, the new observing technologies described above require concomitant advances in data-processing technologies. The increase in computer performance per unit of cost during the 1960s and 1970s has maintained its pace in the 1980s. Industry experts predict that personal computers with power comparable to that of the CRAY-1 will be available before the mid-1990s. Atmospheric analysis and prediction are particularly amenable to parallel processing, in which different parts of a program are run simultaneously on different processors. There are commercially available computers with high-speed performance in the range of several gigaflops (10^9 floating-point operations per second), and prospects are good for computers with processing capability in the teraflops range in the late 1990s.

Important concurrent advances in computer software have been at least as important as improvements in hardware in increasing the speed and utility of computers. Examples include faster routines to solve elliptic boundary value problems, vectorization of computer codes, and algorithms for parallel processing of computer programs.

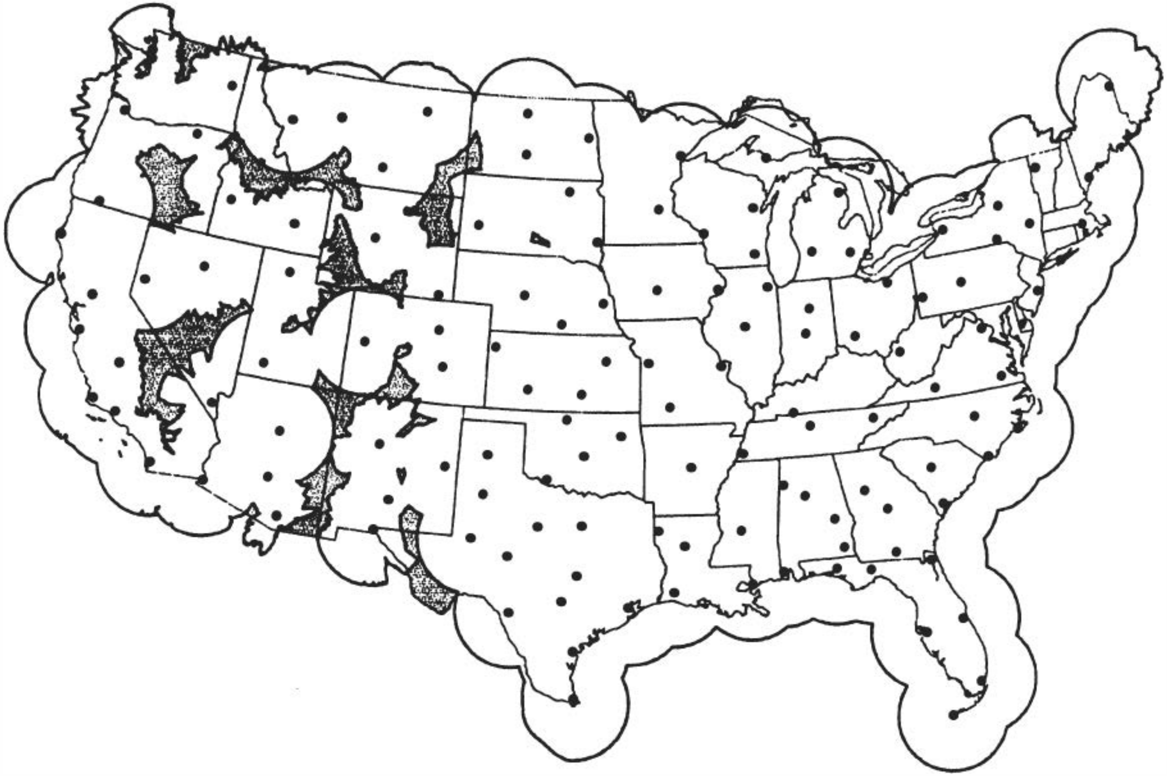

FIGURE 2.2 Site locations and total coverage (at 10,000-ft elevation) of the national NEXRAD network. Shaded areas are gaps, mostly in mountainous areas, in NEXRAD coverage. (Courtesy of the National Weather Service.)

NATIONAL WEATHER SERVICE MODERNIZATION

Beginning in 1990, a next-generation series of geostationary weather satellites will provide improved continuous weather surveillance of North America and its surrounding oceans. This will be supported by an even more advanced polar-orbiting weather satellite system that will begin operations in 1992. On the ground, the National Oceanic and Atmospheric Administration (NOAA) will deploy a network of wind-profiling radars that will provide data in unprecedented detail on the small-scale structure of intense atmospheric phenomena. Combined with temperature and moisture data from satellites and balloons, wind profiler observations will lead to improved forecasts of local weather.

Critically important for the detection of locally violent weather is the NEXRAD system, which is capable of sensing hazardous wind shears, tornadoes, and downbursts—major causes of loss of life and property in the United States. The implementation of the NEXRAD network will begin in 1990 and is to be completed by 1995.

In order to exploit the new observing systems, NOAA will implement a sophisticated data communication, analysis, and product display system in the 1990s. The Advanced Weather Interactive Processing System (AWIPS-90) will enable rapid communication and video display of weather observations and information to forecasters for the timely issuance of storm warnings. Also, to ensure the most effective use of the new technology, an organizational restructuring of the National Weather Service (NWS) is in progress.

A major purpose of NWS modernization is to improve weather warnings. The implementation of AWIPS-90, NEXRAD, and new space-based sensors on the planned GOES NEXT geostationary satellite is amply justified by the much-improved weather warnings these new systems will facilitate. Additionally, these same systems will serve as the basis for improving short-term forecasts, both directly and through their contribution to research studies that lead to improved weather predictions and warnings.

Research results based on these new observing systems will permit trained forecasters to use appropriate conceptual models of mesoscale weather systems. The conceptual models help the forecaster understand and make proper use of weather depictions produced by the AWIPS-90 integrated displays. Additionally, the results of research will allow the new observations to be incorporated properly into a variety of diagnostic and predictive computer models, ranging from comparatively simple algorithms to comprehensive high-resolution mesoscale models. In particular, a new operational mesoscale-α model with a domain that covers most of North America is planned at the National Meteorological Center as part of the overall NWS modernization. This model will have 80-km horizontal resolution, consist of 16 layers, and contain the best available physical and topographical representations. This and other models will provide the basis for significant improvements in weather forecasts and warnings. Thus the full value of the NWS modernization will be realized only by pursuing a vigorous national mesoscale research program directed toward the optimal use of the new systems.

DEVELOPMENT OF NEW MODELS

Along with the huge increase in computer power during the past 3 decades has come a commensurate increase in numerical modeling activity. This increase is particularly evident in mesoscale meteorology, where models have been developed to investigate a multitude of different mesoscale phenomena. Regional models with domains ranging from a single state to the entire United States are able to simulate with fidelity hurricanes, thunderstorm squall lines, and other mesoscale convective systems. They also can simulate mesoscale features such as precipitation bands, sea breezes, regions of stratiform precipitation, frontal zones, orographic systems, polar lows, mountain-valley circulations, lake-induced vortices, internal gravity waves, and areas of heavy precipitation. The large breadth and extent of mesoscale modeling activity are evident from the great number and diversity of mesoscale models active in 1988 (Appendix Table A.3). It is clear that modeling has become an important tool in mesoscale research.

Recently some regional-scale models have been modified to assimilate continuing observational data, such as profiler winds, during a forecast period. These models have provided much-needed guidance for the design of data-assimilation routines and special observing networks. Other recent efforts in mesoscale modeling have focused on the refinement of existing computer models in order to better simulate individual storm systems. In particular, models of cumulus clouds have revealed subtle but complex interactions between gravity waves in the stable troposphere and the organization of clouds in the boundary layer. Such models have also produced realistic simulations of microbursts and low-level wind shear.

Three-dimensional models of cumulonimbus clouds have been used to simulate thunderstorm downdrafts, downbursts, and gust fronts produced by the outflow from downdrafts near the surface. They have also been used to clarify the processes involved in the formation of rotating thunderstorms and to study the effects of thunderstorm rotation on the formation of tornadoes. Some of these models now also include detailed microphysics, for example, the physics of ice-phase changes and hail formation. Electrification processes have been added to some cloud models so that the interaction of cloud-charging processes with storm motions can be examined. Other models include chemical reactions that occur in clouds and precipitation. Explicit simulation of radiative heating and cooling rates associated with clouds has been added to some mesoscale models. These models have revealed that convective circulations are highly sensitive to radiative effects. Cloud models have also been expanded in horizontal scale to allow, for example, simulation of squall-line thunderstorm systems and mesoscale convective systems over the Rocky Mountains. Recent increases in computer speed and capacity have made possible the use of nonhydrostatic models to simulate convection on such mesoscale domains.

A new development in cloud and mesoscale modeling is the use of interactive, grid-nesting techniques. This approach allows larger scales of motion to affect smaller scales, and vice versa, and it permits otherwise impossible model simulations to be made by economically increasing resolution in the principal region of interest. Using this technique, regional models on the scale of the United States are designed to interact with finer-resolution models of motion on the scale of squall lines and mesoscale convective complexes. Because interactive grid-nested models allow smaller scales of motions to affect larger scales, the impact of mesoscale convective systems on larger scales of motion can be examined. Interactive grid-nesting techniques have also been useful in elucidating some of the fundamental physical processes involved in the entrainment of environmental air into individual cumulus clouds.

In recent years global-scale general circulation models (GCMs) have obtained sufficiently high resolution to permit exciting opportunities for studying interactions between global scales of motion and mesoscale weather systems. For example, the European Centre for Medium Range Weather Forecasts (ECMWF) has a global numerical weather prediction model with sufficient resolution for the routine prediction of relatively large mesoscale phenomena, for example, mesoscale convective complexes (MCCs). At the same time, cloud models have been expanded in scale so that they include much of the mesoscale domain. Thus we are entering a period when powerful new modeling approaches can be used to increase our understanding of storms and mesoscale phenomena. Despite these promising developments, much additional research on modeling the mesoscale domain needs to be done in order to translate the new developments into models useful for operational mesoscale weather prediction.

ADVANCES IN FUNDAMENTAL UNDERSTANDING

Using sophisticated new observing tools, advanced high-speed computers, and complex computer models, meteorologists have advanced our understanding of storm structure and dynamics and the physical processes leading to precipitation and severe weather. (See Appendix Table A.4, which summarizes the principal U.S. mesoscale observational studies and field programs that have led to these advances.)

A greater understanding has been obtained about the processes involved in the formation and evolution of mesoscale convective storms. Synoptic features such as jet streaks, short waves in the global circulation pattern, low-level jets, surface fronts, and dry lines have been shown to play an important role in storm initiation. At the same time, processes of storm initiation and evolution, such as the growth of convective cloud systems by individual cloud mergers, the behavior of intersecting gust fronts and gravity waves emitted by neighboring clouds, the development of large cold pools by evaporation of precipitation in downdrafts, the systematic release of latent heat in the upper troposphere by anvil clouds, and the role of topographic features such as mountains and land-water thermal contrasts, are all now better understood.

Much has been learned about the structure of individual convective storms and the processes governing storm intensity. The importance of nonhydrostatic vertical pressure gradients in driving convective updrafts and downdrafts is now recognized. Likewise, the contribution of vertical wind shear (change in horizontal wind speed and direction with height) to the development of nonhydrostatic vertical pressure gradients in storms and in establishing rotating storms has been clarified. Recent research has shown that boundary layer forcing is frequently the dominant mechanism for convective storm initiation. Progress has been made in understanding the genesis of tornadoes and strong surface winds, the formation of hailstones, and the relationship between thunderstorm dynamics and cloud electrification processes.

Significant advances have also been made in understanding the structure of mesoscale convective storm systems. Observational analysis and numerical simulation of squall lines have revealed that lines in the tropics and midlatitudes exhibit many common features. Both consist of a line of vigorous convective cells and showers along with widespread regions of steady rainfall. However, in the midlatitudes, where winds usually increase in speed and change direction with height, some squall lines exhibit features distinctly different from those of squall lines in the tropics. In the midlatitudes, a line of convective cells may consist of one or more persistent, severe, rotating cells along with more transient ordinary cells typical of those found in the tropics. The presence of persistent, rotating cells alters the kinematics of a squall line and increases the likelihood of severe weather such as tornadoes, large hail, and strong straight-line winds occurring with it.

A better understanding of the organization and structure of MCCs has also been achieved in recent years. An MCC is a comparatively large mesoscale weather system composed of both convective cloud regions and stratiform cloud zones. Seen from satellites, the MCC is characterized by a large, circular high (cold) cloud shield that may be several hundred kilometers in diameter (see Figure 1.1) and may persist at this size for 6 hours or more. The system frequently includes one or more squall lines and often exhibits a warm core vortex structure in the stratiform cloud region. In some instances, the vortex grows large enough and persists long enough to become inertially stable and is instrumental in initiating several new mesoscale convective systems over a period of several days. MCCs typically produce heavy rains and prolific lightning, and occasionally tornadoes and hail. Some 25 percent or more of the MCCs produce severe straight-line winds in swaths that may be 50 to 100 km in width and several hundred kilometers in length.

Progress has been made in understanding the role of radiative cooling at the tops of clouds in the formation and intensification of mesoscale convective systems. Also, the effects of gravity waves, excited by deep convective clouds penetrating the relatively stable middle and upper troposphere, on mesoscale convective systems are better understood. Interactions of gravity waves generated by neighboring clouds are now believed to be important in the growth of convective systems.

In general, mesoscale wind, cloud, and precipitation features are initiated by two mechanisms: (1) instabilities in the larger-scale environment and (2) forcing by inhomogeneities at the surface (such as terrain features). Recent observations and model simulations have revealed a great deal about mesoscale instabilities in the larger-scale environment. For example, mesoscale precipitation bands, associated with locally intense precipitation, form in both extratropical and tropical cyclones, and evidence has accumulated that many of the bands are manifestations of gravity waves or conditional symmetric instability (CSI). It is now recognized that CSI is capable of generating strong vertical motions of several meters per second. Such motions can account for the anomalously heavy snow bands associated with extratropical cyclones.

Terrain-forced phenomena, such as cold air damming, are also better understood. For example, subcloud-layer evaporational cooling not only enhances the thermodynamic conditions favorable for damming but also helps to establish a "wedge ridge" in the cold air. Rotationally trapped Kelvin waves can be instrumental in initiating cold surges that result in cold air damming.

Sometimes the two general mechanisms for producing mesoscale features are combined. This is the case with amplifying mountain waves that produce severe downslope windstorms. Recent studies have shown that, in addition to atmospheric thermal and wind stratifications, vertical moisture stratification is also important in the formation of mountain waves.

Progress has also been made toward understanding the processes involved in the genesis of intense cyclonic storms along coastal areas and in the lee of major mountain barriers. These storms often result in excessive snowfall and rainfall. In recent years field research programs along both the east and west coasts of the United States have revealed the potential importance of scale-interaction processes in the explosive development of extratropical cyclones that produce severe winter storms. Besides confirming the role of large-scale, upper-level waves in intensification of surface cyclones, such studies have shown the important contribution of mesoscale processes to the strength of a storm. Intensification of coastal winter storms has been related to energy transfers from the warm ocean surface, latent heat liberated in convective and stratiform clouds, and dynamic instabilities associated with both lower- and upper-tropospheric wind maxima. Scale-interactive mesoscale processes can cause severe winter storms to develop in a surprisingly short period of time.

Although considerable progress has been made in the scientific understanding of mesoscale weather processes and in their simulation by numerical models, there are many areas where additional study is required to gain sufficient understanding and simulation capability that, in conjunction with the new observing capabilities, should lead to significantly improved forecasts and warnings. The step from understanding to accurate prediction is large and will require a focused national effort, involving both research and operations, if it is to be achieved.

RELATIONSHIPS TO CLIMATE AND ATMOSPHERIC CHEMISTRY

The scientific challenges of mesoscale meteorology are linked to a wide range of other underlying problems in climate and atmospheric chemistry. Mesoscale weather systems transfer momentum, energy, and water vapor horizontally and vertically; thus they are important components of the global atmospheric circulation. The latent heat realized through moist convection is an important source of energy in the maintenance of the global circulation. Moreover, mesoscale weather systems are the dominant precipitation-producing systems in the tropics and much of the summer midlatitudes; thus they are major components in the global hydrological cycle. They are a link between tropical sea-surface temperature anomalies and anomalies in the global atmospheric circulation.

A key factor for predicting global climate is the impact of cloudiness on the radiation budget of the earth-atmosphere system. Mesoscale weather systems often produce extensive layers of clouds that can persist for days, long after the systems themselves decay. Such residual clouds, along with clouds produced by active weather systems, greatly alter the radiative properties of the troposphere and, consequently, the global energy budget. Together with the release of latent heat, the radiative heating of layered clouds in the upper tropical troposphere is a significant source of energy for driving the global circulation. Moreover, changes in the global composition of atmospheric aerosol particles can alter the concentration of cloud droplets and ice particles, which in turn affect the radiative budget of the atmosphere.

A detailed understanding of the behavior of mesoscale weather systems will contribute substantially to better formulations of the physical processes in general circulation models and to a better understanding of past, present, and future climates, including the influence of human activities on climate.

Convective systems also transport large amounts of trace chemical species, such as sulfur dioxide, nitrogen oxides, ozone, methane, and chlorofluorocarbons, from the earth's boundary layer to the free atmosphere above. In the process of transporting boundary layer air upward, the convective systems bring water, ice, and lightning into proximity with trace chemicals and act as atmospheric chemical reactors to process and transform the chemicals. High in the atmosphere, the chemical species and reactants disperse and may be transported over great distances by jet streams. The large amounts of residual pollutants in the middle and upper troposphere that are dispersed around the globe significantly alter the global chemistry of the troposphere. In the polar stratosphere, reactions involving the chlorine that derives from chlorofluorocarbons take place in the presence of ice crystals, thereby reducing the concentration of the earth's protective ozone.

The deposition of acidic precipitation over a region is frequently dominated by a few major mesoscale events. Organized mesoscale circulations, such as clusters of individual mesoscale convective clouds within extratropical cyclones, can sweep large volumes of polluted air into regions of moist convection, where the pollutants are transported aloft and scavenged through precipitation. One such system can scavenge enough acidic contaminants to dominate the annual average chemistry of a given watershed or local ecological system.

Lightning is also an important contributor to the production of certain chemical species such as nitrates and ozone. An assessment of the global chemical budget of these species requires a knowledge of the frequency of lightning events associated with different weather systems. Recent research has revealed that, for some areas, a single large mesoscale convective complex can account for as much as 25 percent of the total annual lightning occurrences in the area.

A detailed description of mesoscale weather systems will aid in the diagnosis and prediction of chemical distributions and reactions and of acidic precipitation. Conversely, detailed atmospheric measurement of trace chemical species can provide information on air motions within and around mesoscale storm systems.

3

Implications for Operational Meteorology

Operational meteorologists will have exciting new opportunities to improve weather forecasts and warnings in the 1990s as the National Weather Service (1) inaugurates its Advanced Weather Interactive Processing System (AWIPS-90), (2) begins to take advantage of radically new observing systems such as NEXRAD and the Demonstration Wind Profiler Network, and (3) modernizes and restructures its field offices in support of more detailed and timely forecasts. These improvements will permit more detailed weather information to be obtained in real time, with easy accessibility and display in a variety of formats including color and animation, and will permit more frequent analyses of surface and tropospheric conditions based on intensive use of new data sources.

Provided that these opportunities are matched by parallel research efforts and significant upgrading in the educational and training requirements for NWS personnel, they should lead to more detailed and accurate "nowcasts" and short-range weather forecasts.

This chapter describes briefly the potential impacts of increased capabilities in mesoscale meteorology.

OPERATIONAL DATA BASES

Data bases of the future will contain much more detailed information than they do now. The extremely high volume of data that is anticipated will force regular purging of most data after immediate use, yet facilities must be developed to archive data for selected weather situations either because they affected the general populace adversely (and thus the data may have use in legal actions) or because they have other research and training value. Forecasters newly arrived at a station will have the opportunity to learn the local peculiarities of the weather if they have the capability to reexamine events in the same sequence as they originally unfolded.

HAZARDOUS WEATHER WARNINGS

Most weather forecasters acknowledge that radar data provide the most critical information when severe storms threaten. The NEXRAD radars will bring a new dimension to operational forecasting by depicting low-level winds in clear air during the convective season, as well as winds within storms, at all levels that the NEXRAD radar can survey. Warnings will be more specific regarding the location and size of the threatened area, the length of the critical period for severe weather, and the type and intensity of severe phenomena expected. Warnings are also more likely to be issued farther in advance of severe weather occurrences. Visible and enhanced infrared satellite images, portraying the evolution of clouds and cloud systems, will augment the radar information.

In winter, satellite images together with radar will depict the mesoscale organization of winter storms. Hourly wind profiler data will show, far better than rawinsonde winds, the temporal evolution of these weather systems. As a result, forecasters will be able to specify short-term variations in the intensities and types of storms and to be more accurate in predicting their locations and times of occurrence.

SHORT-TERM WEATHER FORECASTS

More accurate warnings of severe or dangerous weather will save lives and avert property damage, but increased accuracy of routine short-term forecasts will also have tremendous value. Instead of “Twenty percent chance of afternoon showers,” people should expect to hear, “Thundershowers are expected to develop southwest of Chicago this afternoon and move northeast across the south side of the city between 4:00 and 5:00 p.m., causing brief heavy rains, small hail, and gusty winds that may cause some minor damage. The storms should weaken rapidly as they cross the Lake Michigan shoreline.” Instead of “Turning cloudy, windy, and colder tonight with a chance of rain changing to snow,” people should expect to hear, “Mild and breezy prior to midnight, but then turning sharply colder with rapidly falling temperatures. Sprinkles of rain around midnight, changing within an hour to light snow and ending shortly before dawn. An inch of snow on the ground is likely when the rush-hour begins.”

At present, meteorologists are reluctant to make such detailed forecasts because their limited information does not instill great confidence in predicting well in advance either the expected timing or sequence of events. Better information sources and improved communication and display capabilities will encourage all weather forecasters (NWS and private) to be more specific. As a basis for detailed forecasts like those above, the provision of hourly numerical guidance is highly desirable, especially beyond the time when simple extrapolation of the existing weather ceases to be useful.

WEATHER INFORMATION SERVICES

The information industry is burgeoning, and the public demand for weather information is part of the reason. Ten years ago, it was difficult to envision that a 24-hour-a-day television program devoted exclusively to national weather would be a financially rewarding venture. The *Weather Channel* on cable television and its many commercial sponsors are proof of the success of such a concept. Additionally, the weather report is often the most popular segment of television news programs.

Timely collection and dissemination of weather observations and computer-generated weather information are critical. Automated collection and quality control of data have assumed greater importance than ever before. Sophisticated interactive systems must give the data analyst ample opportunity to examine and, if necessary, alter weather information products before dissemination without requiring a large expenditure of the analyst's time.

Forecasters will benefit from having access to a greater variety of analyzed and predicted meteorological fields with higher spatial and temporal resolution. They will be able to translate this information into more specific public forecasts. Private-sector meteorologists will also benefit from an enhanced ability to tailor products to the individual needs of their clients.

Hydrology

A NEXRAD algorithm for the calculation of rainfall rate from radar reflectivity data is under active development. Rainfall rates that are deduced from reflectivity data will be frequently calibrated with automated rain-gauge data. Precipitation runoff models for watersheds can already generate credible estimates of streamflow, given accurate rainfall data. Within reach is the ability to estimate precipitation from a time-history of radar reflectivity over very small areas of a few square kilometers. Such areal estimates, which already agree within a factor of 2 or 3 with point rainfall measurements, will be of great value for flash flood warnings and for water resources management (e.g., deciding whether or not to lower the supply of impounded water in a reservoir).

Agriculture

Many agricultural losses are unavoidable, such as crop destruction by wind-driven hail or lowered yields in a drought year. Yet many important decisions that can limit such losses—whether to spray pesticides, harvest early or late, pump water for irrigation, or protect vulnerable crops from an early or late frost—can be made with more confidence given better weather forecasts. Increased mesoscale information will improve the timeliness and accuracy of weather information on which the agriculture industry depends for many of its critical decisions.

Transportation

Transportation is sensitive to short-term changes in the weather. Rapidly deepening extratropical storms are a sudden hazard to shipping in coastal waters and on the Great Lakes, and hurricanes, the paths of which are often difficult to predict, occasionally menace ships along our Gulf and Atlantic coasts.

Aviation is highly vulnerable to hourly changes in the weather. Minimizing fuel consumption depends on accurate en route winds, favorable weather at both terminals, and careful timing of the departure. The safety of crew and passengers depends on avoidance of thunderstorms, icing, and clear-air turbulence en route, as well as avoidance of poor visibility, heavy precipitation, and wind shear during takeoff and landing. Roughly 1000 fatalities annually in general and commercial aviation are weather-related.

In 1986 the Aviation Weather Forecasting Task Force made these recommendations, among others, to the Federal Aviation Administration and the NWS (AWFTF, 1986):

- Implement an automated aircraft reporting system as one component of a national meteorological observing system.
- Increase the horizontal and vertical resolution of operational weather prediction models so as to permit more detail in the initial conditions on which model predictions depend and, in turn, provide forecasts with greater resolution and accuracy.
- Update weather analyses and forecasts more frequently.
- Provide more precise, timely, and consistent diagnostic and guidance products for aviation users.

The accuracy of analyses and short-term weather forecasts for aviation will improve as higher-resolution satellite images become available and wind profiles, satellite soundings, and automated aircraft reports provide mesoscale detail in the initial conditions for models.

Foul weather associated with mesoscale systems can render road and rail travel hazardous or even impossible within an hour. Accurate and timely forecasts can alert motorists to the risk of sliding on icy highways, hydroplaning in deep puddles, being stranded in a blizzard miles from the nearest shelter, or being swept off the road by a flash flood in a narrow canyon. They can persuade truckers to stay off dangerous or impassable roads for the next 24 hours or to select alternate routes. They can alert snow removal crews in advance of a snowstorm or prevent them from being called out needlessly, and they can alert rail transportation facilities to the need to deice rails and equipment. Hence greater detail and accuracy in predicting the timing and location of significant weather hazards will significantly improve transportation safety and efficiency.

Construction

The building and paving industries are most concerned with the possibilities of precipitation, subfreezing temperatures, and, sometimes, strong winds. Pouring concrete, welding I-beams, excavating for a foundation, painting a house, repairing a roof, and framing exterior walls are all weather-dependent activities. The contractor who sends crews to an outdoor job in unexpectedly bad weather, or who loses a partially constructed house to a windstorm, is likely to blame an inaccurate weather forecast. Therefore, more accurate and detailed forecasts will permit construction industries to cope better with adverse weather conditions.

Outdoor Recreation

A major component of the average person's interest in the weather is connected with outdoor recreation. More accurate forecasts with finer space and time resolution will allow boaters to be warned to return to shore before a squall, swimmers to leave pools, golfers to return to clubhouses, and softball players to vacate playing fields before thunderstorms break. Hunters will be advised in more detail about heavy, early-season snows that could leave them stranded. Skiers who want to avoid travel during heavy snow but be on the slopes as soon as the snow ends will profit from forecasts with better timing of events. All these people will benefit from more accurate and more precise weather information. Furthermore, they will be able to make contingency plans for outdoor activities with greater precision if more accurate forecasts are available.

CONCLUDING REMARKS

Although some improvement in operational meteorology can reasonably be expected just from the availability of new observing systems, the improvement is likely to be very limited unless a systematic scientific program is undertaken to maximize the use of the new observations in increasing understanding of mesoscale weather processes. The resulting increased understanding should, in turn, result in a larger incremental improvement in mesoscale weather predictions and warnings and hence greater benefits to the nation than can be expected from the new observing systems alone.

4
Recommendations

Achieving a better understanding of mesoscale weather events and translating this understanding into improved weather services will depend greatly on the judicious application of resources to a wide range of activities. The following are actions required to complete the task that has been started with the implementation of the new National Weather Service (NWS) observing systems:

> **Recommendation: Continue and keep on schedule the planned development and deployment of the new weather observing systems and technologies.**

Full and timely implementation of the new observational systems that form part of the NWS modernization will allow maximum development and improvement of analytical data bases, numerical prediction models, and operational forecast and warning capabilities. New research-oriented systems and technologies will augment the operational network during shorter-term intensive observing periods. These systems will enhance understanding of fundamental physical processes and permit extensive testing and validation of numerical prediction models.

> **Recommendation: Systematically assess the capabilities of new instruments in order to maximize their utility for short-term weather forecasting and warning and for initializing and testing numerical prediction models.**

The instruments that are part of the NWS modernization effort must be systematically evaluated to determine their strengths and weaknesses over a wide range of weather conditions. These assessments will be an important contribution to (1) four-dimensional data-assimilation efforts and (2) forecasters who need to understand the capabilities and limitations of the observing systems on which they base short-range forecasts and warnings.

> **Recommendation: Investigate possible additional applications of the new data streams in order to realize the full benefits of new observational technologies.**

Unforeseen opportunities often arise to use new observing systems to solve problems that the systems were not originally intended to address. For example, satellite observations originally designed to measure sea-surface temperatures are now also being used to determine indices of vegetation and soil moisture. Many of the new observing systems discussed in this report may similarly be used profitably in new, unforeseen applications.

> **Recommendation: Process and archive data from the new weather observing systems, and make the data available to a wide range of users in an efficient, timely, cost-effective, and easy-to-use manner.**

Advanced technology must be applied to the problem of archiving the massive data sets that will be produced by the new observing systems and to the subsequent distribution in standardized formats of these data to meteorological forecast and research centers, universities, and communication media throughout the country.

> **Recommendation: Develop data-assimilation techniques to combine the many kinds of data into coherent, gridded data sets suitable for a wide range of weather forecast and research tasks.**

Data assimilation will allow improvement of existing numerical prediction models and development of new ones that explicitly simulate circulation features that range from global to cloud scales and that exert control over the development of severe storms.

> **Recommendation: Improve numerical weather prediction models to more accurately account for physical and chemical processes, including those involved in the hydrologic cycle, sensible, radiative, and latent heating throughout the troposphere, and energy exchange at the earth's surface.**

The improved models will serve as a basis for data analysis, numerical simulation, weather forecasting, and diagnostic research efforts necessary to provide better weather forecasts.

> **Recommendation: Conduct large observing programs of mesoscale weather, timed to take advantage of the newly deployed observing systems and designed to examine multiscale interactions associated with mesoscale weather. Additionally, plan and carry out observing programs that cover smaller regions and specific weather phenomena and that complement the larger-scale programs.**

Field programs in different parts of the country, involving enhancement of the operational data systems for a limited period of time, are needed to (1) document and understand the interactive processes that lead to severe storms, (2) design, develop, and verify new models capable of simulating stormscale systems, (3) establish independent data sets required to conduct the instrument evaluations noted above, and (4) address the geographic diversity of weather.

> **Recommendation: Retrain weather forecasters and, where necessary, revise, update, and expand university curricula in the atmospheric sciences to produce a sufficient supply of new meteorologists capable of using the new observing systems and scientific concepts to best advantage.**

Educational and forecast training activities must be revised and modernized to ensure that the nation reaps the maximum benefits of advances in observational technology and meteorological understanding. Students, forecasters, and experienced meteorological researchers must work together more closely than in the past to ensure a mutual transfer of knowledge between the meteorological research and operational weather forecast communities.

Sufficient numbers of meteorologists must be trained or retrained through special programs such as that planned at the Cooperative Operational Meteorology, Education, and Training (COMET) Center at Boulder, Colorado, through raising the scientific and technical education requirements for forecasters, and through other such means. The future availability of highly trained professional meteorologists is a critical factor in realizing gains in understanding and prediction capability as a result of NWS modernization.

As Chapter 5 indicates, the necessary actions to fulfill these recommendations are embodied in the National Stormscale Operational and Research Meteorology (STORM) Program plan (NCAR, 1990).

> **This report therefore recommends that the National STORM Program be implemented as soon as possible.**

5

Actions to Fulfill Recommendations

Planned actions that will ensure fulfilling all the recommendations listed in Chapter 4 are contained in the National STORM Program Plan (NCAR, 1990).[1] Designed over a number of years by a broad segment of the research and operational meteorological community, this program has been reviewed by this committee, which endorses its goals and the means proposed for achieving them.

Therefore the committee reiterates its primary recommendation that highest priority be given to implementing the National STORM Program in order to fulfill the recommendations made in Chapter 4. The goals of STORM are

- To advance the fundamental understanding of precipitation and other mesoscale meteorological processes and of their role in the hydrological cycle, and
- To improve the 0- to 48-hour prediction of precipitation and severe weather events.

The National Weather Service's (NWS) modernization, with its new

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[1] After this report was completed, the authoring committee learned that a new mesoscale research initiative was under consideration by the Interagency Committee on Earth Sciences of the Federal Coordinating Council on Science, Engineering, and Technology. This new initiative was still being defined, but the committee understands that the initiative will likely include the goals and objectives of STORM, although it may have additional goals as well. Therefore, the committee expects that this report will be as relevant to goals of the new initiative as it is to those of STORM.

observing systems and improved processing and communications capabilities, will provide an opportunity for significant improvements in operational mesoscale weather prediction and warning services. However, maximum gains will *not* be realized from the modernization *unless* a complementary research program designed to take advantage of the modernization is carried out. The National STORM Program is designed to meet precisely this need. Compared to the cost (estimated to exceed $1 billion) of the NWS modernization itself, the estimated cost of STORM ($240 million over 10 years) is relatively modest but will support an essential incremental effort to ensure the successful outcome of the modernization.

The National STORM Program has several action components, some of the more important of which are described briefly below. The reader is referred to the *STORM Program Plan* (NCAR, 1990) for more detailed information.

- *Basic research*. STORM calls for an integrated program of basic research designed to increase fundamental understanding of the structure and evolution of the mesoscale phenomena that produce severe storms and precipitation. To achieve this, a series of *intensive field projects* are proposed for various parts of the country and in different seasons. The principal purpose of these studies is to gather the data necessary to understand how various scales of meteorological phenomena interact to produce severe weather.
- *Numerical models for weather forecasting*. STORM proposes that a *national numerical weather prediction test facility* be established at the National Meteorological Center. The principal purpose of this facility will be to test, in an operational environment, the most promising numerical weather prediction models developed by the research community. The STORM field projects will provide data needed to initialize, test, and improve these models. Out of these efforts should emerge mesoscale models for use in operational weather forecasting as well as a much better understanding of the theoretical and practical limits of predictability of mesoscale weather systems.
- *Assessment of new observing systems*. Another key activity of STORM is to test, validate, and assess the new NWS observing systems. The close cooperation between engineers and scientists that will be required to achieve these goals will be fostered by the STORM program. For example, the special data sets collected in the STORM field projects can be used for this purpose. Also, the STORM data management system (see below) will provide the framework within which proper assessment of the data can be carried out.
- *Data assimilation, access, and management*. The new meteorological observing systems will provide high volumes of diverse data that must

be assimilated into comprehensible and useful products. At present, no complete mesoscale data assimilation system exists. The *STORM Data Assimilation Working Group* will be responsible for developing such a system. STORM will also develop a *data management system* for the efficient collection, processing, storage, cataloging, retrieval, and distribution of mesoscale data.

- *Education and training*. If the data from the new meteorological observing systems are to be properly utilized to improve basic understanding and weather forecasts, there must be substantial programs of education and training in the universities, the federal government, and the private sector. STORM provides the natural framework in which to carry out this multifaceted task. For example, the STORM program includes the concept of *experimental forecast centers*, where operational meteorologists, researchers, and students can work together to develop strategies for effective operational uses of the new technologies.

This committee is convinced that STORM will provide an unparalleled opportunity to significantly increase our understanding of many atmospheric processes and phenomena. For the first time, it will be possible to observe and understand mesoscale processes on a multiplicity of scales that interact with one another. This new understanding will result in improved weather warnings and forecasts for industry, government, agriculture, national defense, transportation, and the general public. These benefits are large and will exceed greatly the estimated cost of the National STORM Program. For example, the potential savings in reducing property damage alone are estimated to be at least $1 billion a year. When savings from improvements in efficiency in agriculture, industry, national defense, and transportation are considered, the potential annual benefits from STORM increase by several billion dollars.

While the economic benefits promised by a successful STORM program are substantial, the potential benefits of increased protection of human life are even more impressive. Currently, the combination of flash floods, lightning, tornadoes, and weather-related transportation accidents accounts for much needless loss of life and personal injury each year. Timely warnings and better forecasts will substantially reduce these losses.

The National STORM Program is clearly in the best interests of the nation. This program provides an effective mechanism for addressing the challenges and opportunities in mesoscale meteorological research and operations in the next decade. Virtually all segments of our society will benefit, and at a cost estimated to be far less than the value of the expected gains. The program is scientifically feasible, much of the planning has been done, and the atmospheric science community is ready to begin. All that remains is to do it.

The time to act is now. If full advantage is to be taken of the new observational capabilities and the mounting scientific expertise, and if this advantage is to be successfully translated into improved operational forecast and warning capabilities and into improved understanding of mesoscale processes important in global and regional climate, then the National STORM Program, first proposed in 1983, should be put into action without further delay.

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Appendix

TABLE A.1 Summary of NEXRAD System Capabilities and Data Products

Capability	Data Products
Automated severe weather analysis	Vertically integrated liquid water and severe weather probability information
	Storm track information
	Storm structure information
	Mail index
	Mesocyclone and tornado vortex signature
Automated precipitation analysis	1-hour surface rainfall accumulation
	3-hour surface rainfall accumulation
	Storm total rainfall accumulation
	Supplemental precipitation data
Automated momentum analysis	Velocity azimuth display (VAD) winds

TABLE A.2 Advances in Observing System Technology and Capability

New Measurement System	Features	Current Status	Funding Agencies[a]
Airborne Doppler radar	Measurement of three-dimensional kinematic fields within storms and precipitating systems; mobility of aircraft allows wide-area coverage over very large geographical areas	Operational on two NOAA P-3 aircraft in 1989; Next-generation airborne Doppler radar under construction at NCAR for operation on the NCAR Electra in 1992; down-looking Doppler radar being designed for the NASA ER-2 aircraft	NOAA, NSF, NASA
Cross-chain LORAN atmospheric sounding system (CLASS)	High-resolution radiosonde measurements using new LORAN navigational technology; operationally very simple to use; simplified balloon releases	Nine operational systems as of 1985	NSF, ONR
Automated shipboard aerological program (ASAP)	Automatic balloon releases from shipboard systems for radiosonde measurements	Operational	NOAA, NSF, AES-Canada
Next-generation dropwindsonde	Light weight, reduced cost, simplified operation, higher resolution, utilizing advanced navigational systems; can be safely dropped over land	Operational in 1989	ONR, NSF

Radio acoustic sounding system (RASS)	High-resolution remote sensing profiles of atmospheric temperature using combined radio and acoustic wave interactions	Research and development in 1989	NOAA
Raman Lidar	High-resolution water vapor profiling of the lower troposphere using Raman Lidar backscatter	Research and development	NASA
Multiple parameter radar	Combined use of Doppler polarization diversity and wavelength diversity provide for more quantitative assessment of the internal properties of hydrometeors in clouds; examples include being able to distinguish hail from rain and ice from cloud water	Research and development in 1989	NSF, NOAA
New airborne air-motion sensing	Aircraft radome hole gust probe; greatly simplifies high-frequency airborne air-motion measurements; probe less susceptible to icing in clouds, more easily maintained, and permits simultaneous operation with forward-looking navigational radars	Operational on NCAR aircraft in 1988; operational on NRL P-3 aircraft	NSF, NRL

TABLE A.2 continued

New Measurement System	Features	Current Status	Funding Agencies[a]
Lower tropospheric wind profiling	Relatively small UHF antenna systems permit profiling of tropospheric winds to altitudes of approximately 5 km; combined with other new remote sensing devices (e.g., RASS, Raman Lidar), permits complete profiling of the lower troposphere at relatively modest cost for use in augmenting surface network observations	Research and development	NOAA, NSF
Millimeter wave radar	For observations of newly developing clouds, for studies of liquid water distribution in clouds and marine stratus, and for studies of entrainment at cloud boundaries	Research and development	ARO, NOAA, NSF
Multichannel radiometry	High-resolution passive profiling of temperature and moisture	Research and development	NASA, NOAA

[a] Acronym Key—AES-Canada: Atmospheric Environment Service-Canada; ARO: Army Research Office; NASA: National Aeronautics and Space Administration; NOAA: National Oceanic and Atmospheric Administration; NSF: National Science Foundation; ONR: Office of Naval Research.

TABLE A.3 Summary of Mesoscale Three-dimensional Models Active in 1988

Model	Domain	Approximate Horizontal Resolution (km)	No. of Vertical Layers	Emphasis	References	Users: Government, Universities, and Corporations[a]
NGM	Hemispheric (3 nested grids)	320, 160, 80	16	General*	Phillips, 1979; Tuccillo, 1988	NOAA: NMC, ERL
MASS	North America (3 nested grids)	156, 48, 12	20	General	Kaplan et al., 1982; Kocin et al., 1985; Koch, 1985; Zack et al., 1988; Uccellini et al., 1987	MESO, Inc., NASA (Goddard), ST. Systems Corp., General Sciences Corp., Florida State Univ.
MM4	Nested grids, variable from 30 x 30 to 109 x 109	Variable 1 to >200	Variable 10 to 30	General	Anthes and Warner, 1978; Hsie, 1987; Anthes et al., 1987; Zhang and Fritsch, 1986	Over 50 users
P3DM	60 x 50	Variable 2.5 to 20+	17	Sea breeze, lake vortices, lake snow bands	Pielke, 1984; Lyons et al., 1988; Pease et al., 1988	R* SCAN Corp., ASTER, Inc., San Francisco State Univ.
Pielke	32 x 29	15	26	Sea breeze, thermally forced flows	Pielke, 1974; Abbs and Pielke, 1986	Colorado State Univ.
Ross-Lipps	80 x 80 nested within 50 x 60	20, 5	15 to 30	Squall lines, fronts	Ross, 1987; Lipps and Hemler, 1986	GFDL

TABLE A.3 continued

Model	Domain	Approximate Horizontal Resolution (km)	No. of Vertical Layers	Emphasis	References	Users: Government, Universities, and Corporations[a]
Dudek-Molinari	North America (2 nested grids)	120, 40	15	Convective complexes	Dudek and Molinari 1988; Dudek, 1988	SUNYA
Soong-Ogura-Tao	96 x 96	1 to 3	29	Convective systems	Soong and Ogura, 1980; Tao and Soong, 1986; Tao et al., 1988	NASA (Goddard), General Sciences Corp., Univ. of Illinois (Urbana)
LAMPS	32 x 35	70	15	General	Perkey, 1976; Kalb, 1987	Drexel Univ., Florida State Univ., NASA (Marshall), USRA
NORAPS (ATCM)	109 x 82	80	10	Tropical cyclones	Hodur, 1987, 1988	NEPRF
MFM	51 x 51	Variable, usually 60	10	Hurricanes	Gerrity et al., 1988	NMC
OK	Nested grids, 49 x 27 coarse 72 x 50 fine	111, 35	9	Extra-tropical cyclones	Orlanski and Katzfey, 1987, 1988	GFDL
FSUGSM	7.5-41.25 N 120-86.25 W	100 (63 wave spectral)	12	Extra-tropical cyclones	Daley et al., 1976; Manobianco, 1988	Florida State Univ.
NRL	Arakawa C grid	50	10	Extra-tropical cyclones	Madala et al., 1987; Sashegyi and Madala, 1988	NRL, Science Applications International Corp.

Nickerson	26 x 26	10	15	Orographic clouds and precipitation	Nickerson et al., 1986	NOAA/ARL AFGL
Mudrick	38 x 14 50 x 26	100, 50	10	Polar lows, extra-tropical cyclones	Mudrick, 1982, 1987	Univ. of Missouri
NTCM	30 x 30 nested within 31 x 23	205, 41	3	Tropical cyclones	Harrison, 1973; Chan et al., 1987; Harrison and Fiorino, 1982	Naval Postgraduate School
CMM	40 x 50	100	12	Terrain effects, cyclo-genesis	Sasaki and Goerss, 1982; McGinley and Goerss, 1986	CIMMS
UW	75 x 75	7.5	1	Surface winds	Mass and Dempsey, 1985	Univ. of Washington
MVWM	17 x 18	8	22	Mountain-valley winds	Moore et al., 1987; Liu et al., 1979	Systems Application, Inc.
Klemp-Wilhelmson	90 x 60	2	25	Squall lines	Klemp and Wilhelmson, 1978; Weisman et al., 1988	NCAR
Hsu	17 x 25	30	18	Lake-effect snowstorms	Hsu, 1987	NCAR, Woods Hole Oceanographic Institution
Kurihara-Tuleya	144 x 120	25 to 30	11	Tropical storms	Kurihara and Tuleya, 1981; Tuleya, 1988	GFDL

TABLE A.3 continued

Model	Domain	Approximate Horizontal Resolution (km)	No. of Vertical Layers	Emphasis	References	Users: Government, Universities, and Corporations[a]
RAMS	Nested grids, 40 x 40 per grid	2, 70	17, 28	General	Tripoli and Cotton, 1989a,b	Over 10 users
SIGMET	Nested grids, 20 x 20	5, 50	Variable, usually 15	Terrain-forced circulations	Patniak and Freeman, 1983; Williams et al., 1986	U.S. Army/ASL
AFGL	26 x 26	20	16	Clouds, precipitation	Modica, 1987	U.S. Air Force/AFGL
ETA	Subhemispheric	30 to 80	16	General, orography, rapid development	Mesinger et al., 1988	NOAA (next operational regional model)

NOTE: Includes only primitive equation models covering domains $\geq 10^4$ km^2 with resolution of $\leq$100 km.
*Broad usage, e.g., convective systems, terrain effects, extratropical cyclones, and so on.

[a] Acronym Key--AFGL: Air Force Geophysics Laboratory; ARL: Air Resources Laboratory; ASL: Atmospheric Science Laboratory (White Sands, New Mexico); CIMMS: Cooperative Institute for Mesoscale Meteorological Studies; ERL: Environmental Research Laboratories; GFDL: Geophysical Fluid Dynamics Laboratory; NASA: National Aeronautics and Space Administration; NCAR: National Center for Atmospheric Research; NEPRF: Naval Environmental Prediction Research Facility; NMC: National Meteorological Center; NOAA: National Oceanic and Atmospheric Administration; NRL: Naval Research Laboratory; SUNYA: State University of New York at Albany; USRA: Universities Space Research Association.

TABLE A.4 Summary of Mesoscale Observational Studies and Field Programs in the United States

Project	Objective	Location and Period	Funding Agencies[a]
Warm Season			
High Plains Experiment (HIPLEX)	To study feasibility and environmental impacts of summer cumulus cloud seeding	Mesoscale data collected at three high plains locations, 1975-1980. Cloud seeding experiment in Montana, 1979-1980	DOI/BUREC
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, Montana, during May to August 1981	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	NSF, NOAA/ERL, U.S. Army, U.S. Air Force
Joint Airport Wind Study (JAWS)	To develop 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	NSF, FAA, NASA, NOAA

TABLE A.4 continued

Project	Objective	Location and Period	Funding Agencies[a]
Warm Season continued			
Severe Storms and Mesoscale Experiment (SESAME)	Initially oriented toward initiating and organizing mechanisms of severe thunderstorm systems; currently, increasing emphasis on heavy precipitation	Analysis of results of 1979 field program in central United States	NOAA/ERL, NASA/MSFC, NASA/GLAS, NSF, others
NSSL Spring Program	To elucidate interactions between motion, water, and electrical fields and to assess associated hazards to aircraft	Doppler radar, electrical rawinsonde, aircraft measurements in Oklahoma, April to June 1981 and subsequent years	NOAA/NSSL, FAA, DOD, NASA
Airborne Investigations of Mesoscale Convective Systems (AIMCS), 1984	To conduct preliminary investigations of nocturnal MCSs utilizing research aircraft	Central United States, May to June 1984; some analyses continuing in conjunction with Pre-STORM research	NOAA/ERL, NSF
Oklahoma/Kansas Preliminary Regional Experiment for STORM, Pre-STORM, 1985	To investigate the structure and dynamics of MCSs and help sharpen the scientific objectives of the STORM-Central Program	South-central Plains, May to June 1985; analyses continuing; results being used to define the central U.S. STORM-I Program	NOAA/ERL, NSF

Cooperative Huntsville Meteorological Experiment (COHMEX), 1986	A three-phase program to (1) understand precipitation processes associated with mesoscale and convective-scale systems to help define space-borne remote sensing, (2) investigate the structure of microbursts in humid regions, and (3) develop and test algorithms for wind shear detection	Southeastern United States, June to July 1986	NASA, NSF, FAA
Convection Initiation and Downburst Experiment (CINDE), 1987	A three-phase program to (1) improve understanding of boundary layer processes, particularly along convergence lines, leading to convection, (2) investigate, refine scale-dynamics of the downdraft, and (3) investigate the generation of non-supercell tornadoes	Denver area, summer 1987	FAA, NSF, NOAA
<u>Cold Season</u>			
Cyclonic Extratropical Storms Project (CYCLES)	To describe and understand the mesoscale structure of winter cyclones in the Pacific Northwest	Washington State coastal area, 1973 to 1986; major field program in 1982	NSF, U.S. Army, U.S. Air Force
Sierra Project	To assess potential to enhance winter-spring orographic precipitation in American River Basin; included mesoscale observations and seeding experiments	American River Basin in central Sierras, Calif.; multiyear project: 1976 through early 1987	DOI/BUREC
Lake Effects Studies, 1983/1984	To investigate the structure of the convective boundary layer in lake-effect snow situations	Analyses continuing	NSF

TABLE A.4 continued

Project	Objective	Location and Period	Funding Agencies[a]
Cold Season continued			
Gulf of Mexico Experiment (GULFMEX), 1988	To investigate the structure and character of the return flow of modified continental air from the Gulf of Mexico into the central United States in the winter and early spring	Data archive complete; analyses of data under way, Gulf of Mexico area, winter-early spring 1988	NOAA
Experiment on Rapidly Intensifying Cyclones over the Atlantic (ERICA), 1988/1989	To understand the mechanism of the rapid intensification of cyclonic storms at sea	Atlantic off east coast of United States and Canada, December 1988 to February 1989	NOAA, NSF, ONR
Genesis of Atlantic Lows Experiment (GALE), 1986	To improve the understanding and prediction of the mesoscale features of East Coast winter storms	Observations made over the coastal and offshore Georgia-Maryland region, January to March 1986; analyses continuing	NSF, NOAA, NASA, ONR, U.S. Army, U.S. Air Force, DOE

[a] Acronym Key--DOD: Department of Defense; DOE: Department of Energy; DOI/BUREC: Department of Interior/Bureau of Reclamation; FAA: Federal Aviation Administration; NASA: National Aeronautics and Space Administration, NASA/GLAS: Goddard Laboratory for Atmospheric Sciences, NASA/MSFC: (George C.) Marshall Space Flight Center; NOAA: National Oceanic and Atmospheric Administration, NOAA/ERL: Environmental Research Laboratories, NOAA/NSSL: National Severe Storms Laboratory; NSF: National Science Foundation; ONR: Office of Naval Research.