Extratropical Cyclones Progress and Research Needs

Report of a Workshop on Extratropical Cyclones held in Seattle, Washington September 10-12, 1979

FRONTISPIECE: *A satellite view of a cyclonic storm (right of center) approaching the west coast of the United States. The occluded front trails off to the southwest for a distance of about 3000 km. Behind the main cyclone, in the polar air mass, is a smaller comma-shaped cloud (or "polar-low").*

"Certain it is that, although our conclusions may be incorrect, our judgment erroneous, the laws of nature and the signs afforded to men are invariably true. Accurate interpretation is the real deficiency—What is needed is more and better observations."

Robert Fitzroy

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Preface

In response to a request from the Division of Atmospheric Sciences of the National Science Foundation, a Workshop was convened in Seattle, Washington, from September 10-12, 1979, to review our current understanding of extratropical cyclones, to identify the principal gaps in our knowledge of these large weather systems, and to propose means by which these gaps might be bridged through future research efforts. In view of the importance of forecasting (and the possibility of eventually controlling to some degree) precipitation in extratropical cyclones, this aspect of the total problem received particular attention.

The Workshop consisted of twenty-seven invited experts who were divided into three working groups covering the principal scales of phenomenon involved in cyclones: macroscale, mesoscale, and microscale. In addition, a fourth group of representatives from federal agencies provided guidance on organizational and administrative matters for the proposed future research efforts.

The Workshop itself produced a large quantity of written material which, through progressive refinements, was reduced to manageable proportions. The final iteration of these efforts is contained in this Report.

We wish to thank all the members of the Workshop who contributed to this task. We are also grateful to the National Science Foundation for support of this effort under Grant ATM79-19409.

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Richard J. Reed

Co-Chairmen
Workshop on Extratropical Cyclones

I Summary and Conclusions

Cyclones dominate the weather throughout the mid-latitudes of the world. More accurate forecasts of the weather associated with extratropical cyclones would provide important economic and human benefits. Thus, improvements in agricultural production, the management of water resources, energy production and conservation, flood control and disaster prevention would accrue from better weather forecasts. In addition, improved understanding of cyclones would aid the development, evaluation and utilization of space-derived meteorological observations, climate predictions and weather modification, and increase our understanding of the meteorological-chemical interactions involved in air pollution and atmospheric chemistry and of the effects of weather on microwave communications and the control and performance of airborne and space vehicles.

The objectives of the Workshop on Extratropical Cyclones, held in Seattle in September 1979, were to review our current understanding of these large weather systems, to identify the gaps in our knowledge that appear to be hindering progress in the understanding and forecasting of the weather associated with cyclones, and to propose a program of research for the 1980's to remove these gaps.

The processes involved in extratropical cyclones span almost the entire range of scales of phenomena involved in the atmosphere, from the macroscopic events ($\sim 10^3$ km) responsible for the formation and propagation of baroclinic waves, through the mesoscale processes ($\sim 1 - 10^3$ km) that lead to appreciable precipitation and severe weather, down to the smallest microscale events ($\sim 10^{-2}$ μm) associated with the nucleation of cloud particles. During the past decade, good progress has been made in our understanding of phenomena that occur on all of these scales. For example, on the macroscale there has been progress in delineating the roles of ageostrophic motions in determining the structures of cyclones and fronts, the energy budgets of extratropical cyclones, and the role of cyclones in exchanging air and trace chemical constituents across the tropopause. The mesoscale organization and microphysical structures of the various types of rainbands that occur in extratropical cyclones have been established in at least one location in the past few years and numerical models for the phenomena that occur on these scales have been developed.

Despite well documented improvements over that past two decades in synoptic-scale forecasts of temperature, winds and moisture fields, quantitative forecasts of precipitation have not improved significantly. One reason for this is that the spatial resolution of the numerical forecasting models currently in use are not adequate to resolve the moderate to heavy rainfalls that occur on the mesoscale and in convective clouds. This has led to a resurgence of interest in mesoscale and convective phenomena and in the detailed microphysical processes that lead to precipitation. Significant advances in these subjects have been possible in the past few years due to new technological resources available for mesoscale and microscale studies (e.g. satellites, Doppler radars, instrumented aircraft) and the increase in the capacity and speed of computers that permit detailed meso- and micro-scale models to be run in reasonable time periods. Recent experimental forecasts with mesoscale numerical models have demonstrated their ability to reproduce some of the mesoscale features that are observed in cyclones and to improve short-range precipitation forecasts. These studies have indicated that one of the most important processes in the development of mesoscale and microscale structure is the feedback between moist convection and large-scale processes. Boundary layer processes which transport heat, moisture and momentum in the vertical, are also important in the development of mesoscale features within extratropical cyclones. Additionally, recent field studies have indicated important links between micro- and mesoscale processes in cyclones; for example, the precipitation efficiencies of mesoscale rainbands may be enhanced if they are "fed" from above by ice crystals falling from higher level clouds.

In view of the range of problems hindering progress in our understanding and prediction of the weather (particularly precipitation) associated with extratropical cyclones, the workshop recommended the establishment of a National Cyclone Project to extend over a period of ten years. Encouragement that a national program dedicated to the cyclone problem would be profitable in terms of improved understanding and better weather forecasts stems from several considerations. Firstly, there are powerful observational techniques that could be more effectively directed toward the mesoscale prediction problem. Secondly, the progress that has been made in recent years in mesoscale and microscale studies and in fine-mesh numerical modeling is such that a more concentrated and coordinated effort in these areas is likely to produce impressive results. Thirdly, the availability of faster communication systems and more adequate displays of information permit more detailed information to be assimilated, utilized and passed on to the public, than ever before.

Central to the proposed National Cyclone Project is a series of field programs aimed at providing sufficiently detailed data on all scales to resolve many of the outstanding questions relevant to basic understanding and for testing analytical and prognostic models of extratropical cyclones. In order to obtain various types of data and to test specific hypotheses, it is proposed that the field programs be carried out in different regions of the country in different years.

Analytical and diagnostic studies of the field data would improve understanding of current weather prediction techniques by demonstrating how often they work and for how long in the future. More importantly, the field programs would provide the data to determine what was occurring in the atmosphere when various types of numerical predictions were either successful or failed. We anticipate that a National Cyclone Project on the scale proposed in this report would lead to economically significant improvements in the prediction of the weather (particularly precipitation) associated with cyclones.

The National Cyclone Project should involve the federal, university, and private sectors of the meteorological community and the National Center for Atmospheric Research. It should be assured of consistent support on a level commensurate with the tasks it would undertake. One federal agency must take the leadership in developing and organizing the overall project. Given the magnitude and scope of the problem, and the relevance of the project to weather prediction, the appropriate federal agency would appear to be the National Oceanic and Atmospheric Administration (NOAA). However, additional support should be forthcoming from other federal agencies, as well as state and local organizations, with interests in the various benefits and applications that would accrue from a National Cyclone Project.

In view of NOAA's policy to increase significantly its cooperative research with universities, and the interest of the University Corporation for Atmospheric Research (UCAR) in broadening its scope of scientific and administrative activities, it is proposed that the National Cyclone Project be adopted as a UCAR Cooperative University Program, and that UCAR seek support for the core program from NOAA and for support of selected aspects of the program from other agencies.

II Report of the Workshop

1. Importance of Problem and Historical Perspective

1.1. Importance of the Problem

Extratropical cyclones dominate the weather throughout mid-latitudes. These regions encompass the most highly industrialized and agriculturally productive areas of the world. The need for improved and more detailed weather forecasts of these large weather systems has increased as human activities have become more complex, particularly as the mid-latitudes of the world are the regions of densest population. One has only to consider the enormity of the disruptions caused almost annually by heavy snowfalls in the Northeastern region of the United States, or the magnitude of the dislocations and economic loss produced by flooding in Southern California during the winter of 1977–78, to appreciate the vulnerability of modern society to the vagaries of cyclones. Agriculture is critically dependent upon the weather; adverse weather conditions in any of the so-called "bread basket" regions of the world, all of which lie in mid-latitudes, now have worldwide ramifications. Water supply is of growing concern for energy needs, irrigation, and fisheries. Profligate use of water resources is a thing of the past. The most efficient use of available water depends upon actions taken for its retention or release in reservoirs, the need for which is dictated both by energy demands and downstream requirements (both of which are weather dependent) and by the risk, in flash flood situations, of overflow and, in some regions, by dispatching of water between basins. The alerting of the public to unusual weather events is also important for disaster prevention.

These public needs, and many others, depend for their solution in part upon accurate and timely weather forecasts and perhaps, in the future, upon weather modification. In turn, since many significant weather events are associated with cyclones, improvement of our knowledge of these weather systems is important for the welfare of the nation and the world.

In addition to improved weather forecasts, the data and improvements in understanding of extratropical cyclones that would result from increased research efforts would have many applications, ranging from the effects of cyclones on world climate to their effects on stratospheric chemistry, communications systems, remote sensing from satellites, air quality and acid rain.

The importance of cyclones, as outlined above, is not in itself sufficient justification for an enhanced research effort toward solution of the cyclone problem. Rather, we need to examine whether with the resources at hand it appears feasible to improve our understanding of the physical processes that take place in extratropical cyclones and whether this improved understanding would lead to significant improvements in the forecasting of the weather elements associated with cyclones.

1.2 Historical Perspective

Extratropical cyclones have been an object of serious scientific study since the early Nineteenth Century, and practical analyses with a view to forecasting their associated weather patterns have been carried out since soon after the invention of the telegraph. Due to a lack of knowledge of the physical processes involved, and also of description other than that afforded by sparse surface observations, weather forecasting for most of the first century after its initiation consisted of synoptic analysis followed by extrapolation of cloud and precipitation patterns. Introduction by the Bergen School, of the polar-front cyclone model, around 1920, afforded a scheme for organizing the observations into a systematic model of cyclone structure, and at the same time brought out the fact that cyclones generally go through a regular process of evolution in their circulations and the associated weather. Thus, from sometimes rather subtle indications in the surface observations, it became possible to extrapolate not just the existing weather systems but to predict weather systems likely to develop in the near future. Attempts to explore the three-dimensional structures of cyclones, first by the analysis of observed cloud motions, then by balloon soundings, were sporadic up until the late 1930's; systematic studies of cyclones and anticyclones as parts of the global atmospheric circulation were not possible until after World War II, when hemispheric-scale upper-air networks and large-scale synoptic observations came into being. Thus, in a practical sense, our knowledge of cyclones in their large-scale environmental setting has been developed only during the past three or four decades.

With the development of high-speed digital computers, weather forecasts based upon the numerical solution of the hydrodynamic equations describing the behavior of the atmosphere became possible. The first simple model of this type was developed in the 1950's and showed some skills in making one-day forecasts. Present numerical forecasting models, which contain more detailed representations of the physical processes described by the primitive equations, are capable of forecasting certain aspects of the atmospheric circulation (e.g. winds and temperature) with considerable skill for several days ahead. These advances, however, have not been accompanied by corresponding improvements in the quantitative forecasting of precipitation. As we will see later, one of the principal reasons for this disparity is that the present numerical models predict large-scale circulations, while significant precipitation occurs on much smaller scales.

Encouragement that enhanced research efforts might improve the forecasting of precipitation in extratropical cyclones stems from several considerations. Firstly, we know that there is much observational material that is relevant to the problem which is not now incorporated into forecasts. Secondly, it is only recently that substantial effort has been put into studies of the mesoscale and microscale structures and organization of clouds and precipitation in extratropical cyclones and into finer-grid numerical modeling. It is reasonable to anticipate that these efforts will lead to improvements in forecasting, just as large-scale modeling has done over the past three decades. Thirdly, the introduction of faster communications and more adequate display of information will permit more detailed forecasting to find its way to the user. Lastly, there are some phenomena, not yet fully understood, which when included in numerical prediction models may lead to improved forecasts. Notable among these is the dissipation of kinetic energy by clear-air turbulence. Also, even fine-grid numerical models do not yet include fully detailed resolution of upper-level frontal layers, which may influence the development of the macroscale structures in which they are embedded.

In the following chapters, we review the present state of scientific knowledge of extratropical cyclones, the principal gaps in our knowledge of cyclones are identified, the research needed to remove these gaps is described, and an administrative structure for mounting the required new research programs is suggested.

2. Review of Current Knowledge of Extratropical Cyclones

The phenomena involved in extratropical cyclones span almost the entire size range of atmospheric processes, from the nucleation phenomena involved in the formation of cloud particles to baroclinic waves (Fig. 1). In terms of spatial scale, fifteen orders of magnitude are involved*! This broad range of scales can be conveniently broken into three principal parts: the *macroscale*, which represents horizontal scales greater than 1000 km and corresponding time scales on the order of a week, the *mesoscale*, which represents horizontal scales ranging from a few to ~1000 km and time scales of hours to a day, and the *microscale*, which represents horizontal scales ranging from a few hundredths of a micrometer to a few kilometers and time scales of seconds to an hour. To provide further refinement, the macroscale can be divided into two sub-divisions (α and β), the mesoscale into three sub-divisions (α, β, γ), and the microscale into six sub-divisions (α, β, γ, δ, ε, and ζ). Shown in appropriate portions of the body of Fig. 1 are a number of important atmospheric phenomena. It can be seen that, for the most part, each phenomenon falls into just one of the spatial scales defined above.

Until recently, meteorologists have tended to concentrate on the study of macroscale atmospheric phenomena (such as weather patterns associated with baroclinic and ultra-long waves) and upon microscale phenomena (e.g. atmospheric turbulence and the growth of cloud and precipitation particles). However, as a result of the recent development of new measuring systems, good progress is now being made toward an understanding of the crucial mesoscale processes which so often provide the organization for daily weather events.

In this chapter, we organize our review of current knowledge of extratropical cyclones according to the three principal spatial scales involved. It should be noted however, that while a particular phenomenon might be confined primarily to one scale, interactions between scales are undoubtedly important and must receive particular attention in future studies.

2.1 Macroscale Processes

The wide variety of atmospheric structures associated with precipitation include isolated cumulus convection, squall lines, widespread cyclonic precipitation and monsoons. In all cases, precipitation results from upward air motion, adiabatic cooling and a change of phase of the water substance. The latent energy released through phase changes accelerates the vertical branches of the circulations that are linked to the quasi-horizontal transport of water vapor that feeds the convection. These essential factors are common to all the scales on which precipitation is realized. In most other respects, the structure and dy-

* To appreciate the enormous extent of this spatial scale, it might be noted that the ratio of the linear dimensions of the Milky Way to that of the earth is also about 10^{15}.

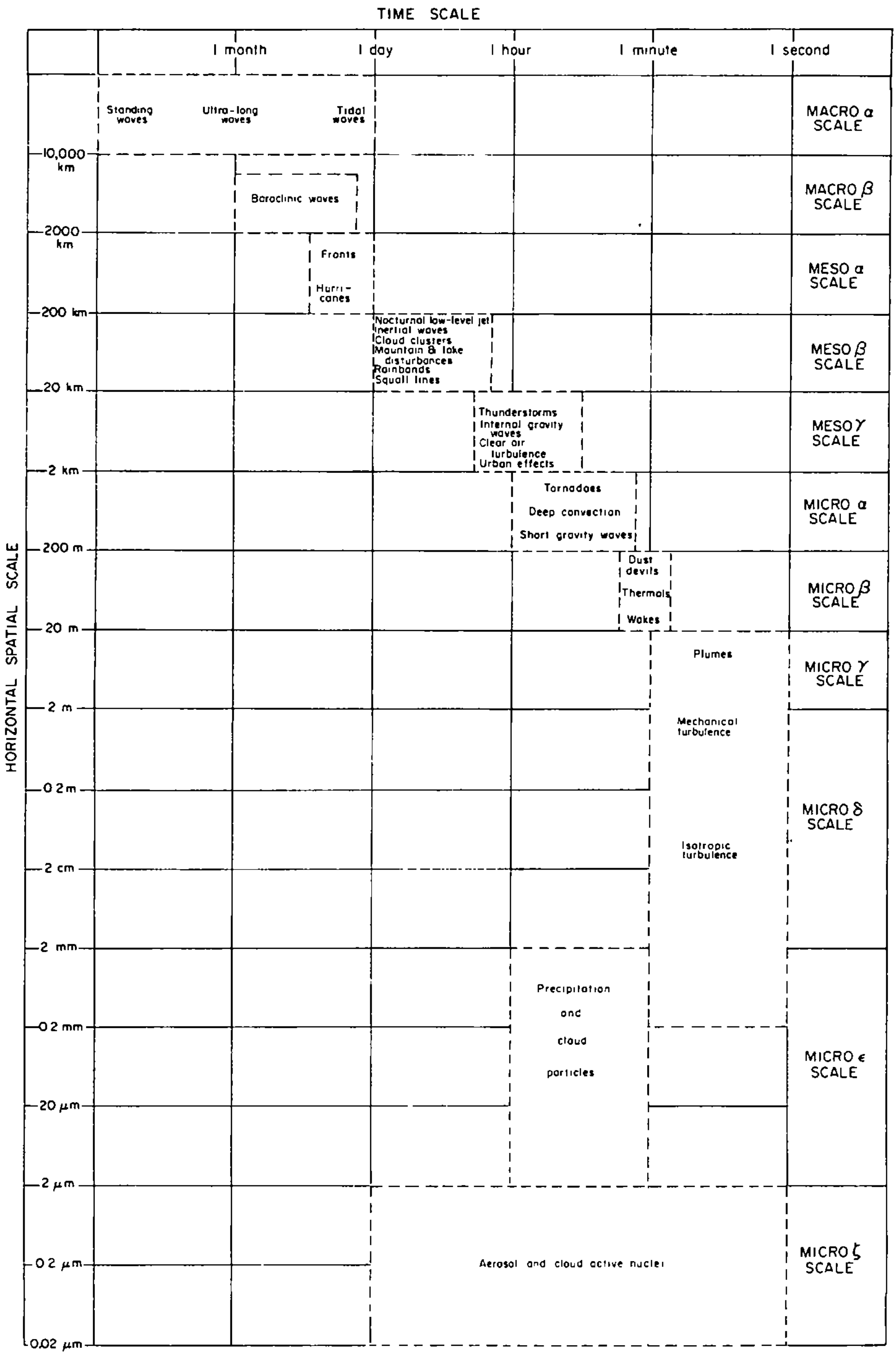

Figure 1. Scales and processes involved in the atmosphere. (Adapted from Bulletin Amer. Meteor. Soc., **56**, *528, 1975.)*

namics of the forcing of circulations within which precipitation occurs vary from scale to scale. In this section we summarize our current understanding of the macroscale processes associated with the development of precipitation in extratropical cyclones, the current status of precipitation forecasting, and the role of cyclones in transport processes across the tropopause.

Dynamic and Thermodynamic Aspects

Precipitation develops through the excitation of instabilities or forcing by larger scales in regions of weak static and dynamic stability. The stability of the atmosphere is determined by horizontal and vertical density contrasts, velocity shears, boundary conditions and the vertical distribution of moisture.

For precipitation to occur, a link has to be established between the sources of water vapor in the environment and the smaller scales over which clouds and precipitation form. In extratropical cyclones, these links can involve the large-scale transport of water from oceans to continents, jet-like structures feeding the cyclonic circulation, or simply gentle inflow within the low troposphere and/or the planetary boundary layer. The most intense precipitation occurs where the dynamic and thermodynamic instabilities within atmospheric structures combine in supplying the water vapor through transport processes and in forcing deep embedded convection.

Frontal Zone—Jet Stream Systems

Extratropical cyclones may be viewed as cyclonic circulations embedded within baroclinic waves in the westerlies. Periods of baroclinic wave amplification and extratropical cyclone development nearly always accompany each other; exceptions are some shallow cyclone circulations that appear as relatively stable waves on frontal structures during cyclone development. The formation and/or intensification of narrow hyperbaroclinic zones embedded within cyclone circulations are also observed. These narrow hyperbaroclinic zones, usually referred to as fronts, are also associated with upper-level jet streams. Frontal zones contain the largest gradients of temperature, wind velocity and moisture within cyclonic disturbances. Fronts exhibit both macroscale and mesoscale aspects; their length is macroscale while their width is characteristically mesoscale. Since both observational and theoretical studies show that the primary mechanism for initiating the development of frontal zones is forcing by the large-scale deformation or shear flows associated with an extratropical cyclone, we will consider fronts as a macroscale phenomena; however, the substructure of fronts (e.g. rainbands) are mesoscale phenomena and will be considered in the following section.

Fronts near the earth's surface form primarily in response to quasi-horizontal advective processes; in the middle- and upper-troposphere fronts are associated with jet streams and they evolve in response to both horizontal and vertical motions associated with imbalances in the distribution of mass and momentum. Smaller scale processes, such as latent heat release within frontal precipitation, turbulent heat and momentum flux within the planetary boundary layer and clear-air turbulence (CAT), are intrinsic physical processes that are frequently excited within cyclones and contribute to the evolution of frontal systems.

The vertical mass circulations across frontal zones are typically an order of magnitude stronger than those averaged over the parent cyclone. The most intense cloud and precipitation systems are coupled with transverse mesoscale circulations of frontal systems that develop in the presence of cyclonic intensification. The understanding of this frontal-precipitation coupling with cyclogenesis is of primary importance in improving the predictability of the distribution of moderate and intense precipitation within extratropical cyclones.

Recent observations have revealed that the turbulent dissipation of kinetic energy within patches of CAT in upper fronts and above jet streams is a significant process in the energy budget of extratropical cyclones. Very strong kinetic energy dissipation rates in CAT patches, when averaged over entire cyclonic systems, are comparable to those found at the earth's surface. These dissipation rates have been measured by research aircraft within frontal structures near the tropopause. Frontal zones and cyclones therefore function as the linkage between the energy-bearing baroclinic waves, precipitation systems, and the energy dissipating motions of turbulent-scale mixing processes.

During the last few years there has been further progress in the understanding of the role of ageostrophic motions and displacements in determining the structure of fronts, cyclones and anticyclones. Recent dynamical models, that go beyond quasi-geostropic (QG) models by describing higher order processes, retain much of the intuitive simplicity of QG theory but give greater resolution to cyclones than to anticyclones.

The most recent developments involve the combining of vertical isentropic coordinates with horizontal geostrophic coordinates to generate a two-dimensional coordinate system through which only geostrophic flow occurs. These recent advances should help in determining the importance of geostrophy in forcing frontogenesis and the mesoscale circulations that lead to precipitation.

Quantitative Precipitation Forecasting

Improvements in synoptic-scale forecasts of temperature, winds and atmospheric moisture have been demonstrated for the past two decades. However, corresponding progress in quantitative precipitation forecasting has been slow and disappointing.

Long-term verification records for precipitation forecasts are comparatively few. Only during the last decade have complete records been available for many stations in the United States. The subjective forecasts of rain archived for Boston, Chicago, and Washington since 1954 show a gradual improvement from inception through the middle 1960's. Comparatively little improvement has occurred during the last decade although some very recent evidence suggests a renewed slow upward trend since 1975 (Fig. 2).

Since 1960 a specialized group of meteorologists at the National Meteorological Center (NMC) has been preparing quantitative precipitation forecasts for the United States. These forecasts are subjectively prepared one to two days in advance from numerical forecast guidance and current surface weather, radar and satellite information. Forecasts of 24-hour accumulated precipitation are routinely prepared for 12.5 mm and 25 mm for the first and second 24-hour periods after forecast issuance. Despite improvement in NMC's forecasts of the details of synoptic-scale circulation features, the day 1 skill scores for precipitation have remained nearly constant. There is some suggestion, however, of an improvement at the 12.5 mm threshold beginning about 1971. Day 2 skill scores for precipitation have shown some slow improvement since records were kept, especially for the 12.5 mm threshold. This improvement likely reflects the success of the NMC Limited Fine Mesh model (LFM) in providing experienced forecasters better 24-48 hour circulation forecasts in more recent years. However, it still remains true that skill in predicting the region to be covered by a heavy rainfall event 24 hours in advance is little improved from 20 years ago (Fig. 3).

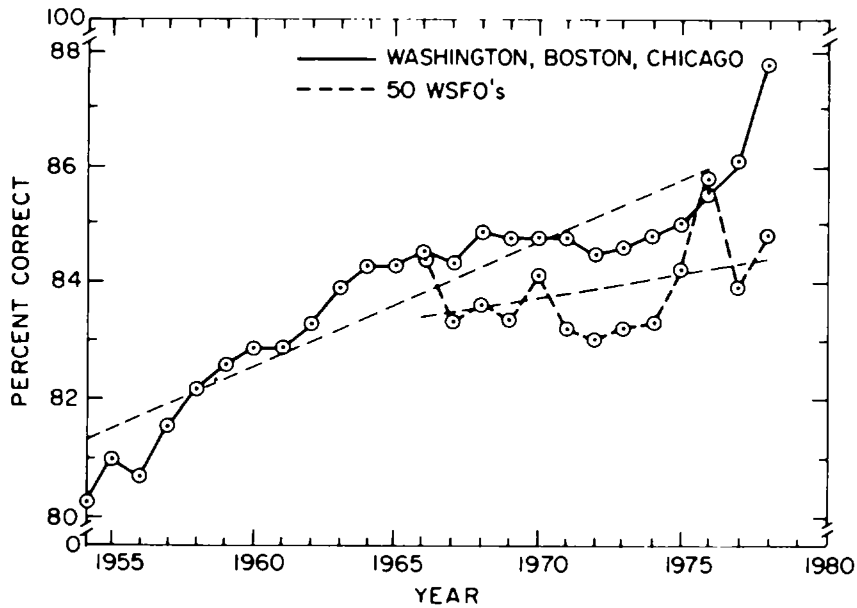

Figure 2. The percentage of occasions on which forecasts of precipitation (i.e. precipitation or no precipitation) were correct for Washington, Boston and Chicago and for fifty National Weather Service Forecast Offices (WSFO's). The annual scores for the three cities are for the calendar year plotted, whereas the annual scores for the WSFO's are for the twelve months beginning in April of the year plotted and ending in March of the following year. The annual scores for the three cities were smoothed with a five-point weighted average operator (except that four and three points were used for 1977 and 1978, respectively). The dashed lines are linear regression trend lines. (Charba and Klein, 1980, personal communication.)

Quantitative precipitation forecasting represents a critical challenge to a numerical model. Existing numerical models with grid meshes of approximately 100 km cannot adequately resolve the moderate to heavy rainfalls that occur on the mesoscale. These rainfalls pose a major forecasting problem in that they are often associated with disastrous flash flooding. Efforts aimed at the improvement of small-scale precipitation forecasts through convective parameterization schemes are in early stages of development and are marginally successful.

It should not be concluded at this point that a lack of understanding of convective precipitation processes is the sole remaining stumbling block to a successful quantitative precipitation forecast. Larger-scale rainfall represents a considerable forecast challenge. Over time scales of 12 to 24 hours a typical synoptic-scale weather system may deposit an ellipsodial swath of precipitation with a major axis of 1000 km and a minor axis of 100-200 km. Thus a small phase error in a model forecast of the locus of maximum precipitation can result in a very poor forecast.

A limited study designed to assess the state of the art of quantitative precipitation forecasting by the NMC LFM-II operational model was conducted at MIT during the first part of 1979. Model 12-24 h and 24-36 h quantitative precipitation forecasts were verified on an areal averaged and point basis for southern and central New England. The LFM-II model beat the climatological control forecast by 18.5% on an areal averaged basis for the 12-24 h forecast. However, the LFM-II model lost to the climatological control forecast by 7.4% on an areal averaged basis for the 24-36 h forecasts. Individual point forecasts were uniformly poor. Examination of individual forecasts suggests that much of the loss

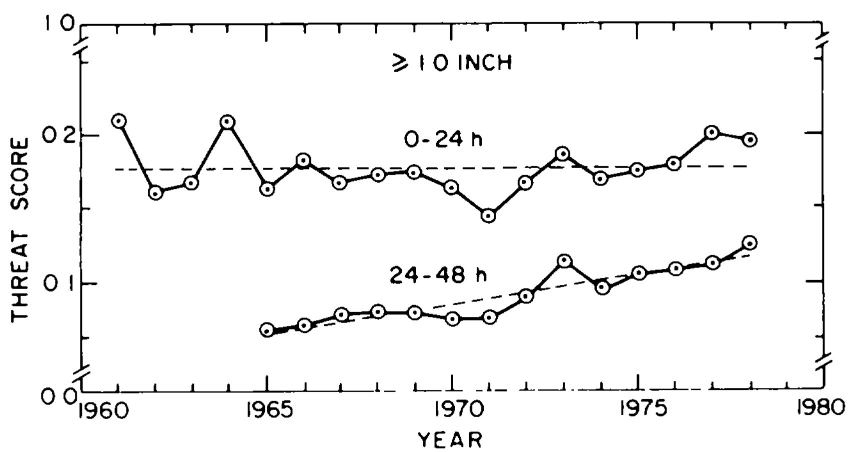

Figure 3. Annual areal threat scores for quantitative precipitation forecasts of ≥ 1.0 inch (25 mm) produced subjectively at the National Meteorological Center. The dashed lines are linear regression trend lines. (Charba and Klein, 1980, personal communication.)

of skill in the model forecasts was due to the overprediction of rainfall accompanying synoptic-scale systems during the cool season even though the synoptic-scale circulation patterns were reasonably well forecast.

It is clear that the present operational, numerical forecasting models have inherent limitations in the prediction of cyclone development and motion, and serious errors in their prediction of precipitation. In the remainder of this section, we mention some possible causes for these problems.

One of the oldest problems in the use of primitive models of the atmosphere for short-range forecasting has been their initialization in ways free of spurious gravity wave-like oscillations. In most operational primitive equation models these spurious oscillations contaminate the 0-12 hour forecast to the degree that the instantaneous forecast fields, including prediction of precipitation, have little utility. Within the last few years this problem appears to have been solved both theoretically and practically for global models through the development of nonlinear, normal-mode initialization procedures.

A linear analysis is carried out to identify, for a particular model, the slow rotational modes and the fast gravitational modes. Any observed field can be decomposed into these two modes. In global models, for example, these modes are the tidal Hough functions. The linear initialization procedure used for some years at NMC consists of retaining the rotational and suppressing the gravitational modes. It has been found, however, that the nonlinear terms in the equation of motion of the forecasting model immediately regenerate gravitational modes from rotational modes. The solution for this difficulty in the nonlinear, normal-mode initialization procedure is to introduce a small gravity wave-like mode, the development of which balances the tendency generated by the nonlinear terms. The nonlinear balance condition is satisfied by a nonlinear iteration process which has been found to be relatively efficient.

Nonlinear initialization has now been applied successfully to hemispherical and global spectral transform and grid-point models, including the operational forecasting models in Canada and at the European Center for Medium Range Weather Forecasting. The gravity wave-like balancing modes generated in this process have associated with them divergence and vertical velocity fields. As such, the procedure becomes a diagnostic tool for the study of these and other ageostrophic components. It has been found that the first iteration of the procedure generates vertical velocity fields satisfying the "ω-equation" of classical QG theory. Thus, the balancing procedure can be considered a refinement of traditional diagnostic techniques. The approach works as well for computing the balanced secondary ageostrophic motions forced by diabatic and nonlinear dynamical processes.

An outstanding problem is the application of the nonlinear balancing procedures to limited area models in order to benefit from application of this diagnostic tool to the cyclone scale in data rich regions. The normal modes of a limited area model are influenced by the specification of lateral boundary conditions for which no completely satisfactory procedure exists. Yet a reasonable constraint on the boundary conditions is that the slow modes of behavior be disturbed as little as possible. Thus, it may be that the two problems, boundary conditions and initialization, may best be solved together.

Perhaps the clearest test of success in solving these two problems would be provided by experiments with a limited area model embedded in a hemispherical model for which the normal mode analysis was computed. The proper imposition of large-scale information on the boundaries of the embedded model should maintain as well as possible the nonlinearly balanced state of the larger scales and avoid the generation of smaller-scale gravitational modes in the domain of the limited model.

Historically, one of the most controversial topics in the development of numerical weather prediction has been the parameterization of subgrid scale processes. Because relationships between grid and subgrid scale events can only be established empirically, one is faced with several uncertainties when small to large-scale feedback influences are important. For this reason, improvements in physics and numerical accuracy through increased resolution do not always lead to an improved final product. In fact, the forecast accuracy may be degraded, because the new degrees of freedom may react unfavorably to data and model errors.

In addition, a parameterization scheme that is suitable for a given numerical model in short range forecasts may not be adequate when the same model is extended to longer periods. Events that can be described with skill during the early stages of integration may not be forecasted well at extended periods due to the damping and aliasing of smaller scales which may invalidate the parameterization scheme. This aggravates the problem by introducing an added set of erroneous events which hastens the time when even the forecast skill of the largest scale features is degraded.

These difficulties have led to a cautious approach in the operational implementation of new parameterization techniques by the NMC. Feedbacks that involve sources of energy have been restricted within rather narrow limits and the algorithms have been constructed with relatively few degrees of freedom.

The introduction of new models, particularly those with reduced truncation errors through increased resolution, has magnified subgrid scale problems. The most serious impact was the treatment of convective processes and the manner in which latent heating was distributed in the vertical.

During the early phases of model development, convective processes were not allowed to produce latent heat release or consume water vapor. When convective instability was indicated by model parameters, overturning was simulated by mixing internal energy between layers. This led to vertical stabilization without permitting an energy source. Physical inconsistency was introduced that allowed precipitation to fall out during the process even though latent energy and vapor supply were ignored.

The approach had the advantage of improving areal coverage and amounts of precipitation in favorable regions, even though the vertical velocities and moisture convergence were inhibited by a large grid increment, but led to problems where precipitation occurred in nonfavorable regions. As experimentation with fine mesh models proceeded, it became evident that the system described above was inadequate to simulate the important vertical redistribution of heat carried out by convective motions in developing storms. With the introduction of finer meshes, a more realistic approach was established. A subgrid scale system was designed to be more closely related to the large-scale environment but which had controls to limit erratic behavior induced by data and model errors.

The possibility of generating convective clouds in either of the two lowest layers of the LFM has been included and the source of moisture for each upward penetration is assumed to be in the layer of origin. In addition, the onset of condensation in an updraft is more carefully regulated by calculation of a lifting condensation level and specification, by tuning, of an initial temperature anomaly to generate updrafts.

The differences in accuracy of various convective schemes are difficult to establish. However, all versions of the approach have shown success in aiding cyclonic development and also in placing a governor on the intensification of cyclones in fine mesh models. This, coupled with the fact that precipitation verification scores are improved, gives reasons for optimism that further research in mesoscale and cloud-scale parameterization will lead to improvements in the forecasting of precipitation.

Chemical Exchange and Transport Processes Across the Tropopause

Results from recent investigations of extratropical cyclones and their associated jet stream-frontal zone regions have provided new evidence that these systems play an important role in exchanging air and chemical trace constituents between the stratosphere and the troposphere (Fig. 4.). These observations are important since the transport of anthropogenic and natural chemical constituents across the tropopause can lead to significant changes in the radiative properties and chemical budget of the earth's atmosphere. For example, the transport of chlorofluoromethanes into the stratosphere results in the depletion of ozone within the ultraviolet radiation absorbing ozone layer. The application of fixed nitrogen fertilizers to the soil produces additional amounts of nitrous oxide which may lead to a significant depletion of ozone when carried into the stratosphere. Water vapor that enters the stratosphere provides a source for the odd hydrogen reactants which play an integral part in the chemistry of the stratosphere. Ozone, which is carried out of the stratosphere into

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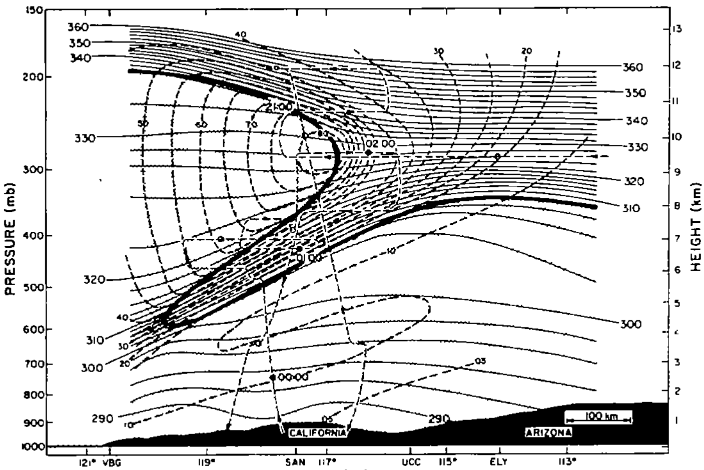
Figure 4. (a) Cross section through a tropopause folding event at 0000 GMT on 13 March 1978. Potential temperature (in °K), thin solid lines; wind speed (in m s^{-1}), heavy dashed lines, aircraft flight track, thin dashed lines; the 100 × 10^{-7} °K mb^{-1} s^{-1} potential vorticity tropopause, heavy solid line, troposphere, stippled area. (b) Concentration of ozone (in parts per hundred million by volume). Analysis for upper flight track data, dotted lines; lower flight track analysis, solid lines; tropopause, interfaces between stippled and clear area. (c) Concentrations of condensation nuclei (in particles per cm^3), thin solid lines; the 12 pphm/vol ozone isopleth from (b), heavy solid line; tropopause, same as (a) and (b). (From J. Atmos. Sci., **37**, *990, 1980).*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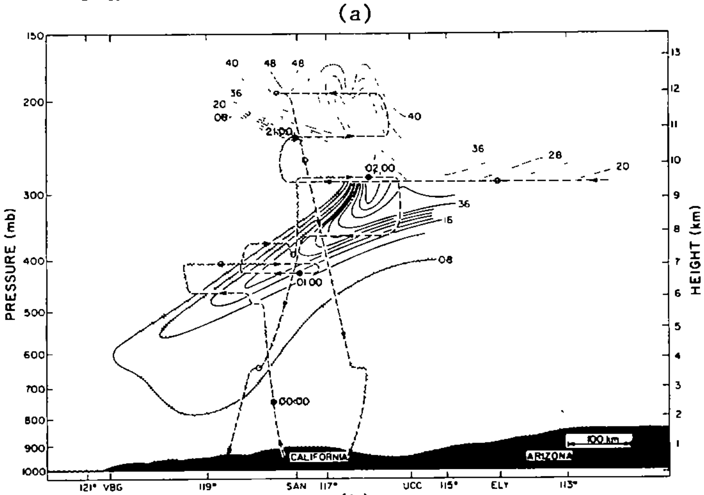
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02:00
01:00
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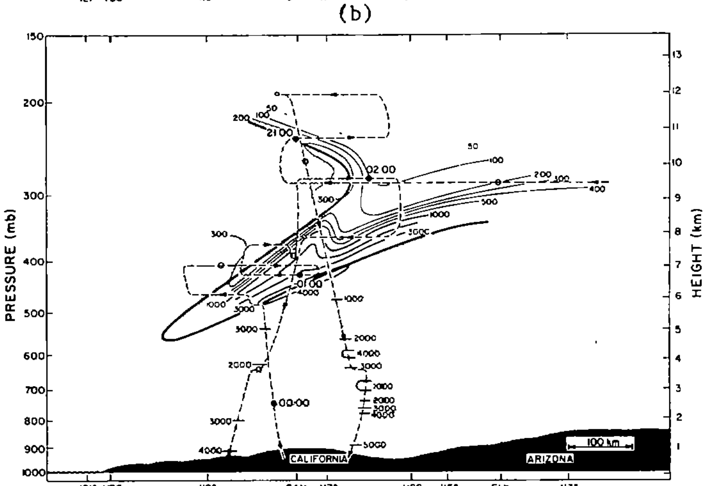
CALIFORNIA
ARIZONA
100 km
121° VBG
119°
SAN
117°
UCC
115°
ELY
113°

(b)


PRESSURE (mb)
HEIGHT (km)
21:00
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CALIFORNIA
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100 km
121° VBG
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ELY
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(c)

the troposphere during tropopause folding within extratropical cyclones, photodissociates and becomes a key chemical ingredient in the tropospheric budgets of many gases. Stratospheric ozone may also be involved in the formation of acid precipitation.

Chemical measurements when combined with meteorological observations have been shown to provide additional information with regard to three-dimensional air motion trajectories within extratropical cyclones. Ozone acts as a tracer for stratospheric air, whereas water vapor, condensation nuclei, and industrial pollutants can be used to trace tropospheric air motions. Simultaneous aircraft measurements of the vertical turbulent fluxes of heat, momentum, ozone and condensation nuclei within patches of clear air turbulence near the tropopause in the vicinity of extratropical cyclones have provided a new insight into the importance of turbulent mixing processes in transtropopause exchange.

2.2 Mesoscale Processes

We have seen in the previous section that present numerical forecasting models have some serious inherent limitations, particularly in the forecasting of precipitation. As a consequence, there has been a resurgence of interest in the past few years in the mesoscale structure of cyclones and the detailed physical processes that lead to precipitation. Advances in these areas have been possible due to progress in the technological resources available for mesoscale observations (e.g. satellites, radars, instrumented aircraft) and the increase in the capacity and speed of computers that permit detailed mesoscale models to be run in reasonable time periods.

In this section we identify some of the important mesoscale phenomena that are embedded in and affect the circulation, release of latent heat, and distribution of precipitation within extratropical cyclones and some of the physical processes that are thought to be responsible for their existence.

Phenomena

Surface and mid-tropospheric fronts are characterized by a large cross-stream horizontal gradient of potential temperature which is in geostrophic balance with a frontal jet. Associated with this geostrophic flow is a mesoscale (~200 km in dimension) ageostrophic cross-stream circulation. The dynamics of large-scale fronts depend strongly on this ageostrophic circulation, which can enhance or diminish the intensity of a front. It is believed that this circulation sharpens the front against frictional dissipation in the boundary layer and that this balance maintains and preserves the front as it is advected over large distances. Figure 5 shows the ageostrophic flow across a cold front as predicted by a numerical model that contains boundary layer processes. The predicted flow shows many similarities to the observed air motions at cold fronts (see for example, Fig. 8 in this report).

Precipitation in extratropical cyclones is often produced on scales much smaller than those of the cyclonic and frontal circulations. A hierarchial precipitation pattern typically occurs in which smaller more intense precipitation entities are embedded in successively larger features, up to the size of the total precipitation region of the cyclone and its associated fronts. The larger mesoscale features are often band-shaped and oriented parallel to one of the fronts. Observational studies by the University of Washington in the CYCLES Project carried out off the Pacific Coast of Washington, have shown that these rainbands may be classified as follows (see Fig. 6).

TYPE 1: WARM-FRONTAL RAINBANDS. Type 1a occurs ahead of and parallel to the surface warm front, while Type 1b coincides with the surface warm front.

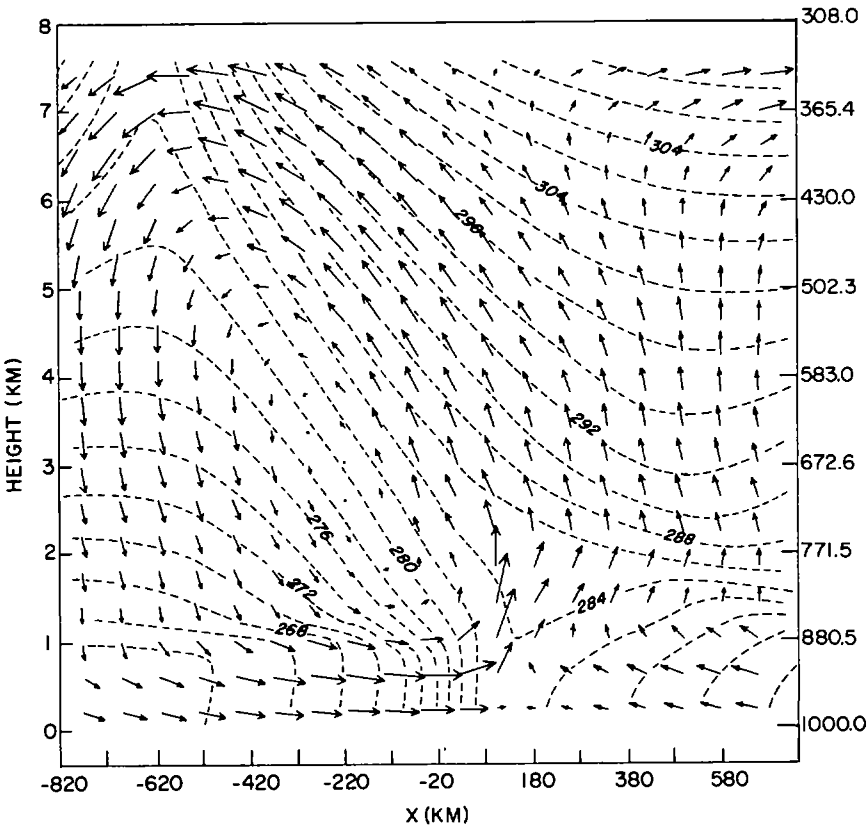

Figure 5. A vertical cross section perpendicular to a cold front showing the absolute *ageostrophic circulation (arrows) and potential temperature (°K) (dashed lines) as predicted by a numerical model containing high-resolution planetary boundary layer physics. The simulation is at 84 hours. The initial conditions were obtained from the analytic frontal solution of Hoskins and Bretherton at 60 hours. (Keyser and Anthes, 1980, personal communication.)*

TYPE 2: WARM-SECTOR RAINBANDS These occur parallel to and ahead of the surface cold front.

TYPE 3: COLD-FRONTAL RAINBANDS Type 3a is very narrow and coincides with the cold front at the surface, while Type 3b is wider and may straddle the narrow cold-frontal rainband or lag behind it. On the small mesoscale, the heaviest precipitation in cold-frontal rainbands is organized into ellipsodial-shaped areas oriented at an angle to the cold front.

TYPE 4: SURGE RAINBANDS Type 4a coincides with the leading edge of a surge of cold air aloft, ahead of the main cold front in the occluded portion of the cyclone. A field of convection, frequently organized in small rainbands, Type 4b, may occur behind the surge rainband.

TYPE 5: POSTFRONTAL RAINBANDS These occur in the cold airmass behind the cold front and usually to the rear of the large cirrus shield associated with the cyclone. They are oriented approximately parallel to the cold front.

This general pattern of rainbands has been observed in extratropical cyclones in various regions of the world (e.g. the west coast, east coast and midwest regions of the United States, the British Isles and Japan). These features are not produced by topographical features, rather they are intrinsic to the cyclone itself. The rainbands are associated with substructure within the cyclones, and they contain embedded convection.

One of the most active of the mesoscale rainbands associated with cyclonic systems is the prefrontal squall line. It is an organized convective system in the warm sector of a cyclone which is usually parallel to the front. It may be viewed as an intense case of the warm-sector rainband defined above in which severe thunderstorms are organized into a line.

Prefrontal squall lines are composed of strong, deep convective elements that transport significant amounts of heat, moisture and momentum vertically. Through downdraft transports they are able to sustain low-level convergence ahead of the squall line and to detach themselves from frontal influence; they are then able to propagate away from the front. Through vertical transports they may influence other mesoscale developments.

Almost any disturbance in the stably stratified atmosphere will excite internal gravity waves. An example is the penetrative convection organized by the frontal cross-stream circulation. If this convection penetrates deep into the stable atmosphere it can produce internal gravity waves parallel to the convective line. Recent satellite observations show that such gravity waves are fairly common. These internal waves propagate away from the source of generation. In special environmental conditions they may trigger the formation of rainbands that then propagate with the speed of the gravity wave. The waves are well simulated by numerical models.

Internal gravity waves of a different scale can be generated by Kelvin-Helmholtz instability. In the frontal jet they may produce cloud bands in the form of billow-clouds, but perhaps the most important effect upon the frontal system is the dissipation of momentum and temperature gradients.

During the warm season over the central and eastern United States, the mesoscale organization of the convective elements is often blobular or circular; these appear to be the most important weather systems to affect the country east of the Rockies in summer; they attend the weaker cyclonic disturbances characteristic of summer.

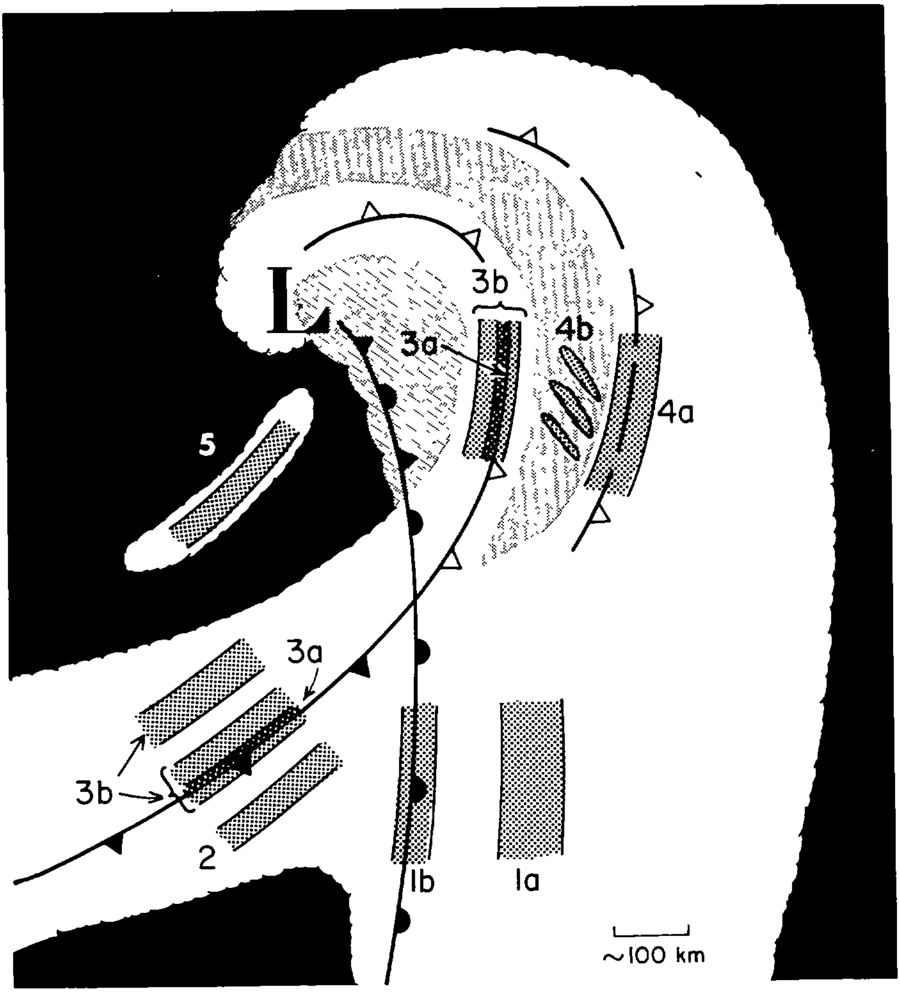

Figure 6. Schematic depiction of the types of mesoscale rainbands (darkly stippled areas) observed in extratropical cyclones just off the coast of Washington in the CYCLES PROJECT. The upper-level cloud shield of the cyclone is shown as white; lower cloud decks are shaded light gray. Type 1: *Warm-frontal rainbands.* Type 2: *Warm-sector rainbands.* Type 3: *Cold-frontal rainbands.* Type 4: *The surge rainband.* Type 5 *Postfrontal rainbands. (From* Quart. J. Roy. Meteor. Soc., **106,** *29, 1980.)*

Physical Processes

The following physical processes are thought to be important in modifying cyclones and modulating the distribution of precipitation on the mesoscale.

The presence of rainbands in extratropical cyclones, even over the oceans, in which local forcing effects such as orography are not present, indicate a release of convective instability and possible subsequent growth, maintenance and propagation through non-linear processes. The evolution of layers of convective instability may come from macroscale processes such as differential horizontal advection, while the convective instability is released when the layer is lifted by the cyclonic circulation. Although it may prove impossible to predict the evolution of a particular rainband, the development of a suitable environment for the growth of rainbands may be predictable by numerical models of mesoscale processes.

Recent experimental forecasts with numerical models having a nominal horizontal resolution of 50 km and covering domains approximately 2,500 km on a side have shown a potential for simulating mesoscale precipitation features and improving short-range (0-4h) precipitation forecasts. However, the finer mesh size admits more degrees of freedom and permits more unrealistic development, as well as improved simulation of mesoscale features. Causes of erroneous small-scale cyclogenesis and mesoscale features have been documented. Such numerical "disasters" result from an incomplete understanding and treatment of mesoscale processes as well as inaccurate specification of initial conditions, notably the specifications of static stability and moisture distribution. It appears, from a limited number of studies, that one of the most important physical processes in the development of mesoscale and microscale structure is the feedback between moist convection (in a saturated environment) and larger-scale processes. Moist convective systems, which are subgrid-scale in present numerical forecasting models, transport heat, moisture and momentum through the entire troposphere in short periods of time. These vertical transports cause rapid adjustments in the larger-scale mass and inertial momentum fields through rapid dispersion of inertial gravity waves. If the larger-scale fields are adjusted so that convection is enhanced (through mesoscale moisture convergence, for example) a positive feedback occurs and rapid amplification of the mesoscale precipitation system can result.

Important to the evolution of extratropical cyclones are the vertical fluxes of heat, moisture and momentum in the boundary layer. Differential heating affects the static stability of the lower troposphere and often determines whether or not moist convection can occur at all by influencing the depth of the mixed layer. Evaporation probably contributes significantly to the water budget and precipitation of a region 20° × 20° of latitude over periods as short as 24-48 h. Momentum extraction by the earth's surface creates ageostrophic motions in the boundary layer. The resulting secondary vertical circulation can modify the flow throughout the entire troposphere.

Boundary layer processes are related to the development of mesoscale features within cyclones. They provide the energy which drives the mesoscale circulations and other convective features of cyclones. These processes embrace circulations and other convective features of cyclones. They also embrace a wide range of spatial scales, and the energy transfers similarly vary widely in magnitude. Within the surface or constant turbulent flux layer, vertical transfer depends largely on vertical gradients of windspeed, temperature, and humidity, and on the roughness of the surface. Vertical transfer in the surface layer can be represented using bulk transfer equations containing bulk turbulent transfer coefficients. These transfer coefficients are much larger for statically unstable surface layers than for stable layers. Within stable layers the required conditions of horizontal homogeneity and steady state are seldom realized, so that the aerodynamic theory on which the bulk transfer equations are based is questionable. However, vertical fluxes are so small under stable conditions that this consideration is not dominant. In the mixed layer or planetary boundary layer, extending from the surface layer to the top of the boundary layer, vertical turbulent fluxes are usually characterized as decreasing with height, reaching zero at the top of the boundary layer. As discussed below, this restriction is too severe to be acceptable in discussing mesoscale features. Analytical models of the mixed layer have been developed which account for growth of the boundary layer and transformation of airmasses as they flow from one homogeneous surface to a contrasting homogeneous surface. A parallel and independent endeavor has shown that the planetary boundary layer is often unstable to small perturbations, with the result that secondary helical circulations develop. We know, also, that convective cells often develop having their roots within the planetary boundary layer.

The top of the boundary layer is often characterized by an inversion layer. In some cases a cloud layer is present at this level. Although the inversion may tend to provide for separation of boundary layer processes from free atmosphere processes, the large shears that are typical of this region may result in phenomena such as the breaking of Kelvin-Helmholtz waves. More generally, entrainment processes on a variety of scales result in vertical transfer, and the secondary flows of the planetary boundary layer often result in penetration of the inversion.

Accurate modeling of planetary boundary layer processes is essential for successful simulation of frontal structures, circulations and precipitation. Recent modeling results have illustrated that the intensity of Ekman inflow and horizontal mass convergence are particularly important physical processes for accurate simulation of the evolution of fronts and cyclones. Besides momentum and sensible energy, water vapor is also transported to mesoscale regions of precipitation through Ekman inflow where latent energy generates buoyancy and forces convection. Thus the timing and intensity of convection and precipitation is intrinsically coupled to boundary layer processes.

Different levels of complexities for the modeling of viscous processes in the boundary layer, based on a hierarchy of closures for the parameterization of turbulence, are now being utilized by different research groups. Recent results from several groups indicate that for both intermediate and small scales the form and intensity of atmospheric circulation is sensitive to latent and sensible energy sources under strong baroclinic conditions when the Richardson number is small enough that the atmosphere is either inertially unstable or close to this condition. With relatively small variations in the structure, either closed cyclonic or frontal circulations with different patterns of mesoscale precipitation evolve. Both numerical simulation and synoptic evidence indicate that at times the planetary boundary layer of the cyclone links with the disturbance and intense precipitation develops in conjunction with the formation of low tropospheric fronts. Good simulation of these events is important for accurate precipitation forecasts.

A related problem is the modeling of irregular topography on the mesoscale. At large scales, topography is recognized to play an important role in the momentum balance and formation of extratropical cyclones. Undoubtedly, this problem will be even more complicated in mesoscale models which attempt to forecast weather elements and processes over topography with strong relief. Topography becomes closely related to the distribution of precipitation through its effects on vertical air motions; even very small hills can have appreciable effects on the distribution of clouds and precipitation.

In a stable atmosphere, flow over irregular terrain may produce internal standing waves which propagate to heights of at least several times the height of the hills. In an unstable atmosphere, ascent may trigger the release of potential instability through deep cumulus convection. Because of the fixed nature of orographic forcing, this aspect of the mesoscale precipitation problem may well yield to a combination of observational, theoretical and numerical studies.

Although little work has been done to study the effects of differential radiative heating/cooling on mesoscale precipitation patterns, there is recent observational evidence that precipitation has a strong diurnal variation even in parts of the world, such as the tropical oceans, where diurnal influences might be thought to be small. This variation provides circumstantial evidence that differential radiative heating, both at the surface and in the free atmosphere, is influenced by variations in cloud cover and modulates the convergence/divergence profiles to a degree that important variations in precipitation are produced.

2.3 Microscale Processes

Knowledge of microphysical phenomena and processes associated with extratropical cyclones is necessary to understand the chain of events leading to precipitation, to develop appropriate parameterization of precipitation mechanisms for larger-scale prognostic models, to investigate means for possible artificial modification by cloud seeding, and to understand how the organization and structures of clouds and precipitation affect the radiation balance of the earth (and therefore climate), microwave communications, remote sensing of the atmosphere, and the performance of rockets and missiles during launch and reentry. Insofar as understanding the larger-scale aspects of cyclones is concerned, conventional wisdom has been that details of phenomena on the microscale are of minor importance. However, condensation and precipitation represent major mechanisms for vertical heat transport, and boundary layer fluxes of momentum, water vapor, heat and turbulent diffusion, which are intimately involved in the "workings" of extratropical cyclones, all involve time and length scales that fall within the microscale region. It is generally argued that these processes operate in a reasonably regular and consistent manner from day to day which allows one to ignore them when considering much larger-scale features (much the same way as students of human anatomy ignore the details of metabolism within individual human cells). In spite of these preconceived ideas, recent studies have shown several direct links between mesoscale and microscale processes, especially those involving buoyant updrafts, cold downdrafts and the natural "seeding" of supercooled water clouds by ice crystals falling from higher-level clouds. One may anticipate that many additional links exist between the microscale and mesoscale. It is therefore important that future studies of cyclonic storms contain a strong microphysical component.

In this section we summarize what is known about the microphysical processes involved in the growth of precipitation in cyclonic storms. It should be noted at the outset that, unlike summer convective storms, where quite a lot is known about the microphysical processes leading to precipitation, studies of the microphysics of cyclonic storms are in their infancy. Only in the CYCLES Project, conducted by the University of Washington in the Pacific Northwest, have the cloud and precipitation microphysics of extratropical cyclones been studied in detail and in a mesoscale context. Consequently, much of the following discussion is based on findings from the CYCLES Project. It should be kept in mind that the microphysics of cyclones in other locales might differ from those studied in the CYCLES Project.

Airflows, Microstructures and Precipitation Efficiencies of Rainbands

As discussed in §2.2, the regions of heavy precipitation in cyclones are generally organized into mesoscale rainbands. CYCLES studies have shown that the various types of rainbands (see Fig. 6) are characterized by distinct microphysical structures and precipitation producing mechanisms. The results of these studies are summarized below.

Warm-frontal rainbands (Type 1 in Fig. 6) arise when precipitation is enhanced in a mesoscale region embedded within the widespread area of lighter precipitation associated with warm-frontal lifting (Fig. 7). Natural "seeding" of the cloud layers below the warm front by ice particles from shallow convective cells located above the warm front is an important mechanism in the production of precipitation in these rainbands (the so-called "seeder-feeder" process). The high concentrations of ice particles ($10\ L^{-1}$) produced in the lower regions of warm-frontal rainbands by the "seed" crystals from above results in effective growth of precipitation particles by aggregation. Consequently, precipitation efficiencies (i.e. the ratio of the precipitation rate on the ground to the total condensation rate) for these rainbands approach 100%.

Some warm-sector rainbands (Type 2 in Fig. 6) in extratropical cyclones resemble squall lines. Even the more benign warm-sector rainbands appear to be dynamically similar to squall lines, with younger more active convective elements, containing relatively large amounts of liquid water, being followed by older glaciated clouds. Both the "seeder-feeder" process and deep convection can play important roles in the production of precipitation in warm-sector rainbands. In the convective regions, where liquid water is relatively abundant, precipitation efficiencies are ~50%. In the regions that are "seeded" from above, the precipitation efficiencies are much higher.

The young clouds that form in the strong updrafts associated with narrow cold-frontal rainbands (Type 3a in Fig. 6) have relatively high liquid water contents (~1 g m^{-3}) and low concentrations of small ice particles (Fig. 8). Rimed ice particles, graupel and aggregates are common in these clouds. Alongside the updraft is a downdraft in which are found much higher ice particle concentrations and less liquid water than in the updraft. The heaviest precipitation in the narrow cold-frontal rainband (and generally in the whole cyclone) is contained in this downdraft. However, precipitation efficiencies are only ~50%.

Wide cold-frontal rainbands (Type 3b in Fig. 6) occur when the lifting of air over the cold front is enhanced by several tens of centimeters per second over horizontal distances of several tens of kilometers in width (Fig. 8). Below the cold front, the clouds associated with wide cold-frontal rainbands contain high concentrations of ice particles, many of which are aggregates. Above the

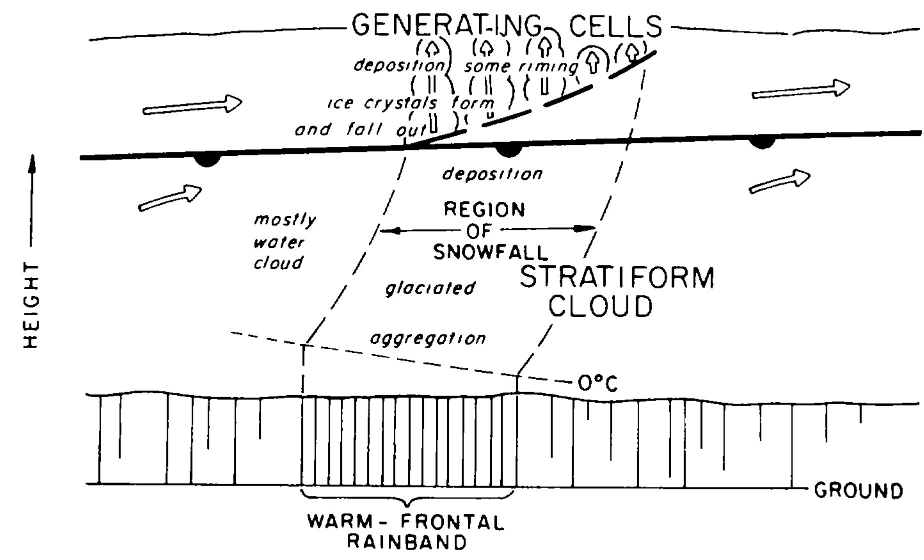

Figure 7. Model of a mesoscale warm-frontal rainband (type 1a) shown in vertical cross-section. The structure of the clouds and the predominant mechanisms for precipitation growth are indicated. Vertical hatching below cloud bases represents precipitation; the density of the hatching corresponds qualitatively to the precipitation rate. Open arrows depict airflow relative *to the warm front and contrast the stable lifting within and above the warm-frontal zone with convective ascent in the generating cells. Ice particle concentrations (ipc) are given in numbers per litre, cloud liquid water contents (lwc) are in g m^{-3}. The motion of the rainband in the figure is from left to right. (From* Quart. J. Roy. Meteor. Soc., **106**, *29, 1980.)*

cold front, the clouds are more turbulent, have more cloud liquid water, and may contain convective generating cells that provide "seed" ice crystals to the clouds below. Precipitation efficiencies can approach 100% in these rainbands.

The clouds associated with prefrontal cold surge rainbands (Type 4 in Fig. 6) are composed of ice particles and liquid water, and precipitable particles grow by riming and aggregation. The wavelike rainbands (Type 4b in Fig. 6) consist of small convective towers that extend upward from the cloud layer associated with the warm front below. The clouds range from young towers, containing mostly supercooled water, to old glaciated clouds with high concentrations of ice particles.

Postfrontal rainbands (Type 5 in Fig. 6) resemble organized convective systems; the clouds in these rainbands have the structures of convective elements in various stages of development.

Stratiform Clouds

In the lower regions of cyclonic storms the clouds between the rainbands are more stratiform, particularly in the regions between warm-frontal rainbands. The stratiform clouds do not appear to be "seeded" by ice particles from

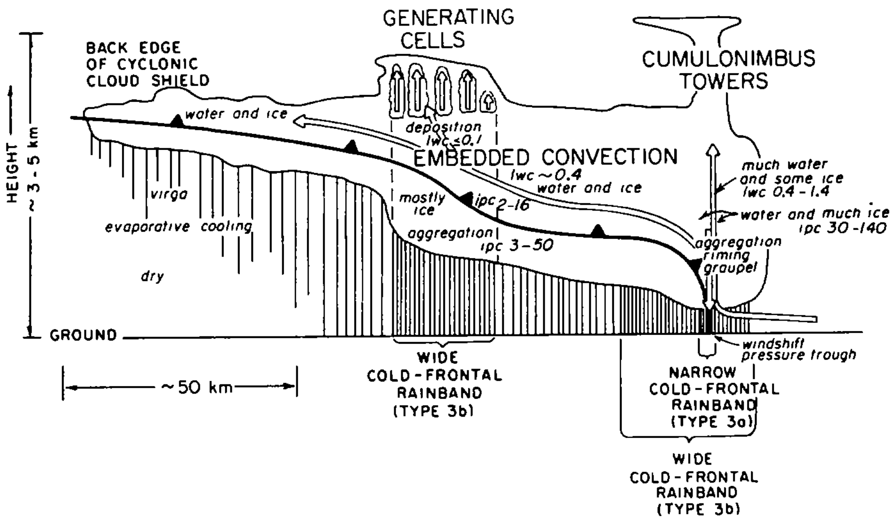

Figure 8. Model of the clouds associated with a cold front showing narrow and wide mesoscale cold-frontal rainbands (types 3a and 3b) in vertical cross-section. The structure of the clouds and the predominant mechanisms for precipitation growth are indicated. Vertical hatching below cloud bases represents precipitation, the density of the hatching corresponds qualitatively to the precipitation rate. Open arrows depict airflow relative to the front: a strong convective updraught and downdraught above the surface front and pressure trough, and broader ascent over the cold front aloft. Ice particle concentrations (ipc) are given in numbers per litre, cloud liquid water contents (lwc) are in g m^{-3}. The motion of the rainband in the figure is from left to right. Horizontal and vertical scales are approximate. (From Quart. J. Roy. Meteor. Soc., **106**, *29, 1980.)*

higher-level clouds; consequently, ice particle concentrations and precipitation rates are much lower than in the rainbands (Fig. 7).

At higher levels, extratropical cyclones are generally covered by cirrus clouds; these clouds produce the characteristic white shield seen on satellite photographs (see Fig. 6). This cloud shield prevents direct observations from satellites of the underlying clouds where most of the precipitation forms and the rainbands are situated. Techniques are being investigated to derive the total mass content of clouds from simultaneous satellite measurements of reflectivity in the visible and infrared.

Modeling

Various components of the microphysical processes responsible for the growth of precipitation in cyclones (e.g. the growth of ice crystals by deposition, riming and aggregation) have been modeled. However, as yet, no attempts have been made to develop combined micro-meso or micro-macro models of extratropical cyclones. In view of the variety of processes that need to be considered in such models, many of the physical processes will have to be parameterized. The recent observations that precipitation particles in certain regions of cyclones follow an exponential size distribution, with the parameters of the distribution varying with temperature, should help in parameterizing some of the microscale phenomena for inclusion in models.

3. Important Gaps in Our Knowledge of Extratropical Cyclones

In the preceding chapter we have summarized current knowledge of extratropical cyclones; implicit in this discussion are many areas of ignorance that are hindering progress. These gaps in our knowledge are highlighted explicitly in this chapter and provide the rationale for the new research efforts proposed in Chapter 4.

3.1 Macroscale

Some major gaps in our understanding of the interactions between frontal-zone jet stream processes and the evolution of extratropical cyclones along with the associated precipitation are:

- The mechanisms of coupling between dynamical processes in the upper-level frontal-zone jet steam and lower-level fronto-cyclogenesis.
- The interactions between dynamically-forced mass circulations and the formation of mesoscale precipitation systems.
- The effects of precipitation processes upon the vertical mass circulations of fronts and cyclones over their lifespan.
- Relation of mesoscale potential vorticity structures near the tropopause, in the vicinity of the cyclonic shear region of the jet stream, and the development of cyclones and precipitation systems.
- The importance of clear air turbulence in the vertical transport of heat and momentum, the changing of potential vorticity, and the dissipation of kinetic energy within extratropical cyclones.

Frontal structures and baroclinic zones that cross the extratropical cyclone vortex play a particularly important role in the vertical exchange of momentum and energy. During the early stages of cyclone development circulation is transferred downward through the baroclinic structure. In the mature and occluding stages, the transfer of circulation is upward, in conjunction with the intensification and evolution of the frontal structure, excitation of latent heat release, and intensification of boundary layer processes. These events, in one form or another, are involved with the vertical exchange of mass, momentum and energy. When viewed individually, they are usually considered mesoscale processes closely linked to the dynamics and structure of the hyperbaroclinic structure that transects the cyclone vortex. However, through their integrated effect on vertical exchange, these mesoscale processes are probably important in forcing macroscale processes. The details of this forcing are unclear and require solution since an understanding of the vertical exchange of momentum and energy by mesoscale features within the cyclone is essential if advances are to be made in forecasting.

As insight into the smaller-scale processes within extratropical cyclones increases, the difficulty of modeling the time evolution of the weather embedded within cyclones is becoming more apparent. Sensitivity studies and intermodel comparisons are needed to determine the effects on simulated cyclones of various changes in the dynamical or physical aspects of the models. Synoptic and mesoscale forecast experiments need to be conducted to study the sensitivity of predicted precipitation patterns to the specification of initial moisture fields. Such experiments should be initiated with a variety of perturbations in the moisture field that are consistent with the streak patterns observed by satellite methods and the stratification and mesoscale structure observed by rawinsondes. Also needed are experiments on the influence of surface friction to study the changing Ekman effects, associated with surface roughness, on the mass and momentum budget of cyclones through the deepening and filling stages.

The sensitivity of predicted cyclone behavior to the manner in which moist convection is parameterized, particularly the vertical distribution of latent heat release, must be studied. Questions regarding the importance of vertical coordinate systems and resolution have yet to be resolved in the modeling of jet streaks and hyperbaroclinic structures. The problem of convective parameterization has additional complications because triggering mechanisms occur at both large and small scales. The onset of convection can only occur in a favorable large-scale environment (unstable lapse rate, sufficient moisture supply, and lifting) in which the convective elements occur individually at much smaller temporal and spatial scales. In attempting to close this gap through field programs and diagnostic studies, experiments must be designed so that the results will be useful for numerical modeling by resolving the relationship between small convective elements and the macroscale environment.

In sensitivity and intercomparison model studies, and in forecast verification, a basic gap remains in the assessment and interpretation of the links between physical and dynamical forcing of cyclone-scale circulations, the interaction of cyclones with larger and smaller scales, and the resulting weather. Most concepts and interpretations of cyclone behavior are based on specific theoretical models with limited degrees of freedom that are restricted by assumptions or by cursory-scale analysis. As a result, the inherent limitation imposed by the assumptions used to achieve tractable theoretical solutions restrict the range of inference and applications in the problem of weather forecasting. For example, it is generally accepted that cyclones are manifestations of baroclinic instability. This fact, however, provides only limited aid to the problem of weather forecasting. Weather forecasting involves predicting subtle differences in the excitation of individual cyclones and mesoscale circulations. The problem of weather forecasting involves predicting small differences in the degrees of freedom that are usually assumed from theoretical considerations to be basic to the forcing of cyclones. Viewed in this context, a principal gap in our knowledge is the lack of a comprehensive understanding of the interrelationships between the many complex processes involved and a means to assess the relative importance of the various processes in forcing the wide variety of observed cyclonic and frontal circulations. Carefully designed model and sensitivity experiments, in conjunction with diagnostics, that bring together the observational results of a comprehensive field research program are needed for fundamental advances in understanding and increased accuracy in the prediction of the weather associated with cyclones.

Additional knowledge of the macro-, meso- and micro-circulations and processes that are responsible for heavy precipitation in extratropical cyclones is needed to improve numerical models for short-range quantitative precipitation forecasting. Once these circulations are resolved, it should be possible to identify signatures in satellite cloud imagery, or other satellite data fields, that can be incorporated into techniques for measuring precipitation via satellites.

Improved observations of the atmospheric moisture distribution associated with cyclones are needed. Present information on the temporal and spatial distribution of precipitation is inadequate. Rainfall measuring networks need to be established to determine relationships between radar, satellite observations and surface rainfall. These relationships would be used in the future to obtain detailed and quantitative measurements of precipitation on the macro- and meso-scales. Results and techniques developed over dense data networks can be used to deduce precipitation amounts in sparse data areas. The results would be combined with available surface and radar observations to be used directly in hydrologic models for flood forecasting, in worldwide agricultural crop assessment programs, and in numerical models for the verification and improvement of quantitative precipitation forecast models.

Sufficient precipitation data must be available to provide proper temporal and areal coverage to verify and modify forecasts based on numerical models. The success of high resolution forecasts cannot be determined from an observational networks that only provide several isolated points of verification within a large region. The density of observations must be expanded through technical advances in the determination of precipitation amounts by radar, satellite, microwave, and other remote sensing techniques.

In order to close some of the gaps described above in our understanding of extratropical cyclones, instrumented research aircraft need to be used extensively to resolve detailed structures and energy exchange within these atmospheric systems. Previous results from aircraft probings of frontal zones, jet streams, and precipitation systems have clearly demonstrated their unique capability for resolving scales of motion ranging from the macroscale down to the microscale.

At present, a gap exists in our knowledge of the contribution made by extratropical cyclones to the total exchange of mass and other atmospheric constituents between the stratosphere and troposphere. The amount of this exchange relative to other mechanisms, such as the Hadley circulation and the penetration of the tropical tropopause by convective clouds, needs to be studied. It is therefore proposed that future field studies of extratropical cyclones include atmospheric chemistry.

3.2 Mesoscale

In discussing some of the outstanding gaps in our knowledge of mesoscale phenomena and processes in extratropical cyclones, we will organize our review under the same two general headings used in §2.2. In addition, sections on modeling and forecasting are included.

Phenomena

The variability of the frontal cross-stream circulation (on which the dynamics of fronts depend) due to orography and water surfaces is not well understood. Also, little is known about interactions between cross-stream circulations, fronts and rainbands. Some observations, as well as numerical simulations, show that after the convective line is generated in the updraft of a frontal system, cooling due to evaporation of precipitation produces a mini-front with an independent cross-stream circulation. This circulation may be important in preserving the convective system regardless of the frontal circulation. The amount of evaporative cooling, which depends on the microphysics of the convection, is unknown.

Although the rainbands in extratropical cyclones have been classified as to their locations in relation to fronts (see Fig. 6), factors that determine when they develop, why they develop in lines and how they are maintained, remain to be investigated. Furthermore, at the present time it is not possible to predict which rainbands will be most intense and produce the heaviest precipitation. The contribution of frontal lifting, the existence of unstable layers, the occurrence of gravity waves, and possibly other instabilities, may be important individually or collectively.

Air motions in the rainbands associated with extratropical cyclones have been documented in detail only in the British Isles and in the CYCLES Project off the Pacific Coast of Washington State. Similar studies are needed in other areas. Such information will provide a better backdrop for discussing precipitation processes and also provide information useful in determining vertical transports by rainbands. Furthermore, if downdraft regions can be clearly identified, this will aid in determining the importance they may have in forcing secondary rainband circulations.

It is not clear how thunderstorms and squall lines interact in the line structures to influence precipitation. It is not known whether outflow from these storms produces additional convergence and latent heat release that further taps low-level moist air (producing strong new cells without competing for existence with the original cells that produced the outflow), or if the generation of new cells ahead of a line due to downdrafts is important in the propagation of lines of convection.

Gravity waves are known to exist in convective and non-convective rain situations and it is possible to argue that they are effective in initiating or organizing rainbands and mesoscale precipitation. How often and under what conditions they serve in this capacity is unknown. Moreover, it is not known where important gravity waves are generated. Methods for measuring the characteristics (e.g. amplitude, scale) of gravity waves and means for determining whether they are sufficient to trigger precipitation development need careful attention.

Physical Processes

Convectively unstable layers can have important effects on precipitation development. Their development needs additional study. Convection produces feedbacks into larger scales but these are not well understood, primarily because of a lack of observations. Studies of tropical precipitation, and recent mesoscale model results, are providing new insights regarding the parameterization of convection. Further study is needed to determine which, if any, of these results are appropriate to extratropical cyclones.

In order to model mesoscale processes properly, an adequate representation of the boundary layer is needed. Processes in the planetary bounday layer transfer heat, moisture and momentum between the surface and the overlying air. Studies are also needed to elucidate the role of rough terrain in forcing vertical transfer in the absence of free convection.

We do not understand in any detail the interaction between radiative heating and clouds and precipitation in extratropical cyclones on either small or large scales.

Modeling

While the capability of simulating specific mesoscale phenomena (e.g. sea breeze circulations, lake-effects and local orographical effects) through numerical modeling has reached rather sophisticated levels, a number of problems limit the simulation and prediction of the complex mesoscale phenomena associated with extratropical cyclones. One of the biggest problems is how to simulate the broad range of interacting eddy scales. In order to simulate mesoscale phenomena with a time scale of 0 to 24 h over a horizontal domain of 4000 km x 4000 km, a grid resolution of 40 km is needed. The model must then have lateral boundary conditions that can freely interact with observed or modeled disturbances on the global scale.

Defining initial conditions for such a model is also of critical importance. The ability to define initial meteorological fields down to a scale of 40 km is not routinely available anywhere over the continental United States. The problem of defining initial fields is most severe in coastal regions where "upstream" data are almost totally lacking on the mesoscale, let alone the scale of resolution of the model. In the interior of the United States, the data-sparse mountainous regions also provide quite a challenge for initializing mesoscale models. The modeler needs numerous real anchor points of data in order to prevent "dynamic initialization" schemes from developing initial wind, thermal, moisture and pressure fields that are erroneous for the meteorological situation under investigation.

The limited resolution of mesoscale models also introduces a number of challenges to the modeler. To represent the role of unresolvable eddies in the transport of heat, moisture and momentum the modeler must develop parameterizations, and the need to parameterize specific processes differs considerably depending upon the meteorology of a given region. For example, on the west coast of the United States parameterization of transports due to deep moist convection may be unimportant. In the southeast, however, convective parameterization would have to form an important part of a mesoscale model. Not only is the mesoscale structure of some cyclones modulated by the presence of deep convection, the entire cyclonic evolution and intensity may be significantly altered by its presence.

The approach to parameterization of boundary layer processes also differs depending on regional influences. Over relatively flat terrain or oceanic regions, use of horizontally-homogeneous boundary layer theory may be appropriate. Over mountainous terrain, the parameterization of boundary layer transport remains a considerable challenge. Little is known about the net transports of heat, moisture and momentum over regions with severe terrain irregularities. The extent to which details of the surface energy budget of the earth modulate the mesoscale structure of extratropical cyclones is also unknown. How important are soil moisture content, snow cover, forests, and urban land-use factors to the generation and intensity of mesoscale features? Likewise the parameterization of radiational processes through the depth of the troposphere represents a major challenge.

Modeling studies using non-hydrostatic models over limited regions (100 km square) are also necessary. Such studies should be geared toward understanding convective transports on small horizontal scales, and for understanding gravity wave influences. The influence of these processes is not well understood in the context of extratropical cyclones.

Viewed in a broad perspective, mesoscale model development is in an early stage. Several key problems need particular emphasis in future studies. These include: model initialization from observed information; investigations into the horizontal and vertical resolution needed to resolve frontal mesoscale structures and circulations accurately; modeling physical processes and associated parameterization of subgrid scale effects; and, modeling the rapidly evolving planetary boundary layer with its diurnal variations and its irregular topography on the mesoscale.

Mesoforecasting and Nowcasting

In the earliest years of forecasting, local information provided the only clues available. As communications improved, macroscale information became available. In this century, improved data networks, faster communications, numerical models of the atmosphere, and digital computers have improved forecast accuracy and timeliness, at least in the 12 to 48 h time span. However, the most recent forecast efforts with the aid of more sophisticated models and faster communications have yielded only marginal improvements in forecasting. Efforts to forecast mesoscale events in time frames of 0-12 h are beginning, but success is spotty. While one of the long-term benefits of further mesoscale studies should be found in more reliable forecasting, immediate returns might be available if existing empirical knowledge were incorporated into nowcasting procedures. To achieve such a goal, effective means must be used to display information in ways that forecasters can assimilate and interpret in terms of their experience and knowledge of local meteorology. This will no doubt involve computer processing of the data and simple modeling procedures, with graphical displays used to arrange the information into usable formats.

Techniques for displaying fields of current data (e.g. from satellites, radars and aircraft) in readily comprehensible form are available. Their incorporation into operational forecasting as in the Automation of Field Operations and Service (AFOS) system, will lead to increases in the accuracy of nowcasting and short-term forecasting.

3.3 Microscale

Studies carried out in western Washington, under the CYCLES Project, have demonstrated the types of detailed information that can be obtained on cloud and precipitation processes through systematic studies of extratropical cyclones. However, many fundamental questions remain unanswered. For example, what is the origin of the ice embryos that lead to precipitation? What ice multiplication mechanisms operate and under what conditions? At what rates do various types of ice particles grow in different environments? What types of size-distribution spectra do ice particles follow in various regions of cyclones and how do these affect measurements of rainfall rate via radars? How do cloud condensation nuclei and liquid-phase microphysical processes affect the formation of precipitation in cyclones? What are the "feedbacks" between micro-, meso- and macro-scale processes in extratropical cyclones?

The second area of ignorance relates to the generality of the picture of extratropical cyclones provided by the CYCLES Project. Whereas there is evidence that the mesoscale structure documented in the CYCLES studies is found in cyclones in other regions of the world, it seems likely that cloud microphysical structures and precipitation-producing mechanisms will vary from region to region. Also, little is known of the effects of orography (both low hills and large mountains) on the microscale structure and the processes leading to precipitation in cyclones.

Finally, as our knowledge of extratropical cyclones increases, proper scientific studies of their artificial modification (both deliberate and inadvertent) become feasible. Weather modification techniques depend, for the most part, on the existence of an excess of supercooled water in clouds that is then artificially nucleated into ice particles by cloud seeding. We now know that the expectations in the 1950's and 1960's of widespread opportunities for precipitation modification by artificial seeding were overly optimistic. However, CYCLES studies have revealed that it is in just those mesoscale features where appreciable quantities of supercooled water exist in extratropical cyclones that precipitation efficiencies are appreciably less than 100% (see §2.3). It has yet to be shown that the artificial seeding of these regions can produce appreciable changes in precipitation on the ground. This is an important subject for exploration.

4. Research Needed to Advance Our Knowledge of Extratropical Cyclones

In this chapter we outline the research programs that are needed in order to tackle in a meaningful way the wide range of problems outlined in the previous chapter. The magnitude and complexities of the required research programs are such that the Workshop recommended that they be carried out under a NATIONAL CYCLONE PROJECT.

The NATIONAL CYCLONE PROJECT would concentrate on the most general aspects of macroscale/mesoscale/microscale phenomena in extratropical cyclones. This should lead to improvements in knowledge and techniques that would benefit all regions of the country. While each region has problems of particular concern, a national project is most efficient at solving general problems. Research on local problems would then be much more effective because, where possible, the general problems would have already been addressed and solved.

4.1 Field Programs

Many of the problems identified in Chapter 3 can only be solved through carefully designed field programs in which simultaneous, high-quality measurements are obtained on all scales. Consequently, field programs must form an important part of the NATIONAL CYCLONE PROJECT.

Scope

A primary consideration in the design of the field programs should be the testing of specific hypotheses and/or seeking answers to specific questions. While the testing of several hypotheses is often possible, it is unlikely that all aspects of extratropical cyclones can be studied with a single field program. It would be desirable to design field experiments that are truly Lagrangian with respect to cyclones. That is, experiments in which measurements were made following cyclones as they undergo cyclogenesis and modulation due to topographical and geographical influences. However, because of our dependence upon surface-bound measurement systems (such as rawinsonde stations, surface meteorological stations and radars) a truly Lagrangian experimental design is not feasible at this time. Another approach is to use mobile observation systems, such as long-range aircraft, to the extent possible, and to set up a series of ground-based networks that are positioned so as to have a high probability of "capturing" cyclones at various stages in their evolution or while they are undergoing differing local modifications (i.e. ocean or lake influences, orographic effects). Unfortunately, the required number of rawinsondes, surface and radar units for, say, three "fine-mesh" observation sites would probably exceed available resources.

As a compromise, it was proposed at the Workshop that the field portion of the NATIONAL CYCLONE PROJECT consist of a series of field experiments, carried out in different locations in the United States and in different years. The selection of the experimental sites and the periods of observation would be based on the probability that data obtained from the various sites would be suitable for testing specific hypotheses and/or answering crucial questions.

For example, we have seen that one of the principal gaps in our quantitative understanding of factors contributing to the variability of precipitation from extratropical cyclones is the role of boundary-layer processes and deep convection on the movement and intensity of extratropical cyclones. Measurements are needed of the boundary-layer and cloud-layer fluxes of heat, moisture and momentum associated with evolving extratropical cyclones. An optimum location for such an experiment might be in the southern and Gulf-coastal region of the United States during late February, March and April when cyclonic activity is vigorous and embedded convection is prevalent. Such an experimental site would also be suitable for investigating coastal and urban effects and the study of cyclogenesis.

Another example is the investigation of the influence of topography or irregular terrain on the evolution of the mesoscale structure of extratropical cyclones. An ideal location for such a study would be over the Pacific Northwest where cyclones impinge upon the Cascade Mountains. Building on previous CYCLES studies of the structure of Pacific cyclones, the experiment site could be moved further east so that the variations in structure could be examined as cyclones moved up and over the Cascade range. The site is also favorable for developing and testing boundary layer parameterizations over irregular terrain and the continued examination of coastal effects.

Another possible observational site would be the Northeast United States, where coastal effects and boundary-layer modifications of extratropical cyclones can be studied with relatively modest terrain influences. Urban influences on the mesoscale structure of cyclones could also be examined in this location.

Consideration should also be given to future oceanic experiments involving ships and buoys to investigate developing cyclones away from the complicating lower boundary conditions over land. In this mode, the NATIONAL CYCLONE PROJECT might well evolve into an international project.

Measurement Systems

To investigate macro-, meso- and micro-scale phenomena in cyclones, rawinsondes, radar, aircraft, surface meso-networks and remote sensors are needed in addition to the conventional observational network. The observational network must be able to resolve the structure and circulation of fronts, hyperbaroclinic zones, deep convection and be able to measure the transport on all scales of properties essential to our understanding of important processes. Specifically, the field program should provide measurements of the distribution and vertical and horizontal exchange of mass, momentum and energies. The distribution of sources and sinks of water vapor and its transport, as well as the clouds and precipitation, must also be measured.

To optimize each field program within a region on the order of 100 km^2 it is desirable to provide two or three "nested" grids within this area, each of which should contain at least one conventional radar and a network of surface stations and rawinsondes. Superimposed on each of these nested grids should be a number of well instrumented and well calibrated research aircraft, specialized Doppler, dual-wavelength and zenith-pointing radars, as well as other remote-sensing devices.

Twenty to forty rawinsonde stations capable of releases at 2 to 4 h intervals during cyclonic periods are needed. For maximum benefit these data need to be digitized and transmitted to a centralized facility for computerized data reduction and near real-time data display.

Each of the nested grids should contain a surface network of 20 to 30 stations capable of measuring wind components to ±5%, temperature and dewpoint to ±0.5°C, pressure to ±0.5 mb and precipitation to ±1 mm. The time resolution should be 5 min. These data should be telemetered to a central processing unit (preferably by satellite) for data analysis and real-time display as well as for recording and quality control.

These field programs must include satellite observations of macro- and meso-scale processes. Geostationary satellites are currently able to provide imagery for reseach purposes at time intervals ranging from 3 to 30 min, with a spatial resolution of 1 km for visible data and 8 km for IR data. Cloud imagery in still or animated form can be used for precipitation estimates, sounding interpretation, diagnosing macroscale processes and inferring vertical moisture distributions. Winds can also be computed from cloud motions observed from geostationary satellites. Low-level cloud vectors computed from cumulus fields contribute to better definition of boundary layer conditions in advance of fronts and in unstable cold airmasses. Middle and upper-level cloud vectors can be used to study macro-mesoscale interactions. The east and west GOES satellites can also be operated in stereo mode to provide accurate estimation of cloud top heights and the development of convection. This information is essential to maximize the utility of the cloud motion vectors for research purposes.

In the period 1981 to 1984, one GOES satellite will carry the VISSR Atmospheric Sounder (VAS) instrument. This will provide indirect soundings at 14 km resolution at periods as frequent as 30 min for areas limited to 5° latitude. The VAS will also operate in a multispectral imagery mode and could provide imagery from any of the CO_2 bands or the H_2O bands. These data would have a resolution of 14 km at 30 min frequency. Fields of observed or derived quantities and their evolution could be displayed in real time or from archived information through interactive video computer displays. The information will be particularly useful for describing macroscale moisture and thermal fields and for studying their evolution in the life cycle of cyclones and jet stream circulations.

Polar-orbiting satellites for the NOAA series now make observations approximately 6 hours apart. These satellites provide both visible and IR imagery at 1 km resolution that can be used to augment the GOES data. NOAA satellites also carry the TIROS Operational Vertical Sounder (TOVS). Temperature profiles from the surface to 10 mb are produced routinely from this data by NMC. The TOVS can also provide water vapor information and total ozone content. Satellite soundings from TOVS provide dense, consistent, coherent measurements in both time and space that helps in the location of short waves and mid-tropospheric baroclinic zones.

A number of well instrumented aircraft are already available for making thermodynamic, air motion and microphysical measurements. Using real-time satellite and radar observations, aircraft can be directed to intercept an approaching or developing cyclone and to follow it across a meso-network. A substantial effort is needed to calibrate and intercompare the various airborne data systems. Permission can be obtained from Air Traffic Control for performing the special research maneuvers needed in a program of this type, but the Federal Aviation Administration needs to be involved in the planning at an early stage.

The field program should also be designed to resolve the tropospheric-stratospheric exchange of atmospheric constituents. The observations of atmospheric constituents are not only important to resolve the three-dimensional motion of the atmosphere, but are now needed to resolve some important questions on stratospheric chemistry, the maintenance of the ozone layer and the distribution of CO_2 and other constituents. Atmospheric chemistry observations are best taken in a continuous mode from appropriately instrumented aircraft with supporting observations by rawinsondes, ozonesondes, satellite-derived temperature, wind velocity, moisture and ozone measurements, and other remote sensing techniques.

Hypotheses should be formulated and sharpened during the course of each field program, and observational and operational techniques should be refined. Following each observation period, weaknesses should be identified, needs established, and hypotheses confirmed or refuted. Selected developments would be recommended for implementation in application programs, including weather forecasting services. Another asset that would grow with each field program and with analysis of the data, would be a pool of highly trained and informed scientists who would increase the rate of growth of knowledge and applications.

Communications, Displays and Data Archiving

All measurement systems need to be constituted so that real-time and near real-time data are displayed to the scientists in the field in a form that permits diagnosis of the cyclone, quick response to the diagnosis (by modifying the use of the observational facilities), quality control of the data collected, and initial data analysis during non-operation days. These requirements necessitate computer-directed data recording and display systems and minicomputer systems for data reduction. Evaluation of the success of observational procedures achieved this way in the field can lead to significant upgrading of the field experiment while it is still in progress.

Much general-purpose hardware is available or is easily adaptable from commercial supplies. Also, much processing and interactive software is available, with more to be produced by ongoing projects. Software and hardware are or will be available to accept raw data as well as products from the National Digital Circuit.

Considerable effort will be needed to incorporate unique data sets, processing schemes, and for producing 3-D color presentations. Complete interactive capabilities will be needed to monitor data flow, to manipulate data fields and to assist in model output evaluation.

The data processing system used for the NATIONAL CYCLONE PROJECT should include the GOES Data Collection System (DCS) which has the capability of handling 10,000 transmissions (30-sec average message length) per one-hour period. This system can be used for fixed location sensors which measure temperature, wind, rainfall, river level or for mobile sensors such as balloon and aircraft-borne monitors. DCS data are processed centrally in Suitland, MD and disseminated to users or it can be read out directly, within certain constraints, in real time by the user.

Data archiving and retrieval should be a key element of the system design and should be considered in the project planning stage to ensure that data will be available to other researchers.

4.2 Analytical, Diagnostic and Modeling Studies

The field programs for the NATIONAL CYCLONE PROJECT will provide a wealth of data for analytical and diagnostic studies of the macro-, meso-, and microscale processes involved in extratropical cyclones. Analytical and diagnostic studies of the data will improve our understanding of current weather prediction techniques by showing how often they work and for how long in the future. More importantly, the field programs might provide data that will indicate what was occurring in the atmosphere when the predictions began to fail. We have hypothesized that one reason predictions fail is because of inadequate specification of the initial conditions. Diagnostic studies should show by how much forecasts can be improved with incremental improvements in specifying the initial conditions.

We know that the kinematic depiction of airflow relative to precipitation systems is both complex and critical to understanding precipitation mechanisms. High-quality airflow measurements on a variety of scales will be provided by the NATIONAL CYCLONE PROJECT and they should reveal the types of airflow that recur frequently and those that are crucial to important mechanisms. Many complexities could then be dismissed, and attention directed to the essential features.

We anticipate that our knowledge of mesoscale processes in particular will be advanced by the proposed NATIONAL CYCLONE PROJECT. Analytical studies of the detailed data sets that would be forthcoming from the field programs would provide information on mesoscale circulations, rainbands, and the roles of boundary layer processes and latent heat release in forming ageostrophic motions and precipitation in cyclones under various conditions. Application of this new knowledge should produce small but economically significant improvements in weather forecasts, particularly in the forecasting of precipitation.

A prominent characteristic of the proposed studies is the assimilation of diverse data types into a comprehensive analysis consistent with dynamical relations. Dynamic four-dimensional data assimilation of this type maximizes the information from observations and theory. The result is the best possible depiction of conditions present at each time. These techniques would be used in real-time to guide the conduct of the field programs.

The application of four-dimensional assimilation in real-time results in nowcasting. Nowcasts are the first step in providing users with weather information; the next step is to extrapolate current weather systems into the future. Therefore, at the same time as the NATIONAL CYCLONE PROJECT is developing new information on the behavior of extratropical cyclones, the information could be communicated to diverse users. Many of the assimilation techniques could be applied outside of the research observation periods so that weather forecasts could be improved on the 0 to 6 h time scale. Use of nowcasting in the field programs will expose many operational meteorologists, as well as research scientists, to their strengths and weaknesses so improvements could be made in a broad spectrum of problem areas.

The data collected in the field programs of the NATIONAL CYCLONE PROJECT should provide a "climatology" of the microphysical structures of extratropical cyclones. This, in turn, would provide information on the origins of ice particles and the growth of precipitation in the various regions of cyclones in different geographical locations. The *in situ* microphysical measurements will also provide valuable "ground-truth" data for comparing with various remote-sensing techniques for measuring atmospheric variables.

Analyses of the data should remove the traditional boundaries that have separated macro-, meso-, and micro-scale studies. Analyses and interpretations of any phenomenon are of considerably greater value when the phenomenon is considered as part of a continuum, both affecting and being affected by processes taking place on larger and smaller scales.

Numerical models must form an intrinsic part of the NATIONAL CYCLONE PROJECT, both in the planning and analysis stages. The types of input and verification data required for various models should be paramount in the design of the field programs. Particular emphasis should be placed on parameterization of important physical processes occurring in moist convection and the boundary layers. Diagnostic efforts would be designed to study basic questions important to an understanding of cyclone and mesoscale circulations and to ascertain the strengths and weaknesses of numerical weather simulation efforts. Within the combined realm of diagnostics and modeling, these efforts should include: model sensitivity studies, numerical model intercomparisons, diagnostic model studies, and intercomparison of observed and numerically-simulated cyclone and mesoscale phenomena. As the NATIONAL CYCLONE PROJECT develops improved understandings of atmospheric motions and processes, real-time model outputs and man/model forecasts will need to be compared with forecasts produced by more traditional operational methods.

New insights into phenomena and physical processes provided by the field programs should be incorporated into the models. The ultimate aim of the NATIONAL CYCLONE PROJECT is to produce detailed macro-, meso- and micro-scale conceptual models, and a prognostic numerical model for the complete extratropical cyclone that incorporates the most important features of each of the three scales.

5. A Proposed Administrative Structure for the National Cyclone Project

In view of the central importance of extratropical cyclones in mid-latitude meteorology, and the broad scope of the research efforts that are needed if significant progress is to be made in this subject in a reasonable period of time, it was the recommendation of the Workshop that the research programs described in Chapter 4 of this report be carried out under a NATIONAL CYCLONE PROJECT.

Experience dictates that the NATIONAL CYCLONE PROJECT involve a wide range of talents drawn from all sectors (federal, university and private) of the meteorological community, and that the overall Project extend over a period of ten years with consistent support.

The principal contribution of the NATIONAL CYCLONE PROJECT would be in improved weather prediction. In the broadest national interest, this task is centered in the National Oceanic and Atmospheric Administration (NOAA). However, the wide range of investigations that can be carried out under the Project, and the resulting benefits and applications, make it relevant to the missions of many other federal agencies. For example: the National Aeronautics and Space Administration (remote sensing techniques for monitoring large weather systems; exit and reentry of space vehicles), the Department of Defense (effects of cyclones on communication, command and control systems, forecasting and nowcasting), the Department of Interior (atmospheric resources, artificial weather modification), the Department of Energy (wind and solar energy, effects of weather on energy consumption, production and distribution), the Department of Agriculture (effects of weather and climate on crops), the Department of Transportation (effects of the weather on transportation systems), the Federal Aviation Administration (safety of aircraft operations, nowcasting for optimum flight paths), the Environmental Protection Agency (anthropogenic effects on the weather, effects of weather on air quality), and the National Science Foundation (basic research in the atmospheric sciences). Similarly, the NATIONAL CYCLONE PROJECT is relevant to the needs of many state and local authorities and private organizations and utilities.

The scope of the studies involved in the NATIONAL CYCLONE PROJECT encompasses virtually the complete spectrum of atmospheric research, from measuring systems and observations through to analytical modeling, and from the microscale up to planetary waves. Consequently, the Project should involve representatives from all segments of the University meteorological community and the National Center for Atmospheric Research.

In light of the above considerations, it was the view of the Workshop participants that the NATIONAL CYCLONE PROJECT requires an administrative structure that would permit and encourage the broadest possible support and participation from federal, state, university and private sectors of the community.

However, one federal agency must take the leadership in developing and organizing the overall project. Given the nature, magnitude and scope of the problem, and the relevance to weather prediction, the appropriate agency would seem to be NOAA.

In view of the stated interest on the part of NOAA in conducting cooperative research with universities and the interest on the part of the University Corporation for Atmospheric Research (UCAR) in broadening its scope of scientific and administrative activities, the following structure is proposed for managing and supporting the NATIONAL CYCLONE PROJECT:

- The NATIONAL CYCLONE PROJECT be adopted by UCAR as a Cooperative University Program.
- UCAR seek support for the core program from NOAA.
- The core program be augmented selectively with support from other federal agencies, state, local and private organizations.

These organizational arrangements have the potential for ensuring steady financial support, sound management, and full participation of the relevant scientific community in the NATIONAL CYCLONE PROJECT.

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