KS1.1

MESOSCALE METEOROLOGY: THE LAST TWENTY YEARS AND THE NEXT

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1. INTRODUCTION

In this brief presentation, I will attempt to review the major findings in the field of mesoscale meteorology over the last two decades, and offer some thoughts on where the field may go over the next two, with the requisite allowance made for the very great uncertainties inherent in this kind of forecast.

The definition of *mesoscale* has never been fully agreed on, but a glance at the papers in this volume suggests an operative definition that includes moist convective systems (but not individual clouds), substructure of tropical and extratropical cyclones, including fronts and cloud and precipitation bands, inertia-gravity waves, and topographically and thermally forced circulations on scales at or smaller than the deformation radius. It is attempting to categorize these myriad phenomena as those having Rossby numbers that are neither large nor small, but such a definition does not adequately encompass the abovementioned processes. For example, classical fronts are almost always thought of as mesoscale phenomena, but have Lagrangian Rossby numbers that are small and are in many respects quasi-balanced, obeying, to a good approximation, the semi-geostrophic equations. It is also tempting to offer a completely pragmatic definition: mesoscale phenomena are those that are not properly resolved by today's global models but which are not so small in scale that their statistical properties are well defined within a single grid box. As tempting as these proposed definitions may or may not be, I will fall back on the operative definition described at the beginning of this paragraph.

2. TWENTY YEARS OF PROGRESS

The first Conference on Mesoscale Meteorology took place twenty years ago, in Norman, Oklahoma. At that time, semi-geostrophic theory was only about 10 years old, Doppler radar was a novelty confined to a few labs, universities and TV stations, the mesoscale structure of extratropical cyclones was just beginning to be properly delineated, and anyone with a background in atmospheric dynamics was chronically hydrophobic (one gifted researcher proclaimed that "friction + heating = 0"). The Klemp-Wilhelmson model was five years old; the great-great grandfather of the MM5 model, the LAMPS-NCAR model, was the mesoscale model of the day, and T-bones were then considered a cut of meat. On the operational side, the U.S. regional model was the "limited-area, fine-mesh" model, or "LFM", and we thought that 190 km was a "fine-mesh"; it was run on a supercomputer that was less powerful than the desktop computer you might be using to read or print this paper. Real live human beings made official weather observations, and would have become apoplectic at the gems of today's automated observations, such as freezing rain at a temperature of 36F. Those of us who were outside the NOAA organization received weather data over Western Union teletype and Alden facsimile machines, the chemical odor of whose special paper inspired ecstasy in the weather nut. We scientists wrote each other letters and talked quite a bit on the telephone.

A look back at the abstract volume for the first mesoscale conference shows a reassuring similarity between the topics covered then and now. The first two sessions and a poster session were devoted to fronts and substructure of cyclonic storms, and had papers on frontogenesis, coastal fronts and cold air damming, observations of precipitation bands, and conditional symmetric instability. Sessions

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Corresponding author address: KERRY EMANUEL, Rm. 54-1620 MIT, 77 Mass. Ave., Cambridge, MA 02139; e-mail: emanuel@texmex.mit.edu on mesoscale aspects of moist convection included papers on tropical and extratropical squall lines, MCCs, gravity waves, cumulus parameterization, and the problem of initializing mesoscale models. In sessions on topographically induced circulations, the effect of latent heat release on flow over mountains was discussed, as were the propagation of density currents in mountainous terrain, mesoscale aspects of coastal climate, including sea- and land-breezes, and terrain-induced mesocyclones. The results of some of the very first three-dimensional simulations of flow over mountains were presented, and the effects of high mountains on baroclinic systems such as cyclones and fronts were just beginning to be explored. Other papers concerned such phenomena as undular bores and polar lows. The great debate about the origins of the mesoscale energy spectrum was just beginning in 1983, and continues to this day.

It would be difficult to overstate the degree of change that has occurred since that time. There has been progress on four fronts: mesoscale observation tools and analysis techniques, physical understanding, numerical modeling and data assimilation, and archiving and communication of meteorological data.

On the observational side, the advent of NEXRAD in the late 1980s provided continuous Doppler radar coverage of the almost all of the continental U.S., and it became practical to talk about assimilating Doppler-derived winds into mesoscale forecast models. NOAA and NCAR purchased airborne Doppler radars, which meant that researchers could go to where the weather was and fly past it quickly enough to do dual-Doppler type analysis of the three-dimensional wind field. This led, among other things, to greatly improved analyses of the substructure of tropical and extratropical cyclones, especially as observed during the annual hurricane programs conducted by NOAA’s Hurricane Research Division, and several large field experiments, such as the Genesis of Atlantic Lows Experiment (GALE) in 1986, and the Experiment on Rapidly Intensifying Cyclones over the Atlantic (ERICA) in 1989.

Satellites have continued to improve, to the point of resolving significant mesoscale phenomena in a variety of channels, including traditional visible and infrared as well as water vapor bands and other channels. Only one scatterometer had flown by 1983, and that remained operational for only six months; today, scatterometers provide routine wind information at the ocean surface. Cloud track winds provide almost incredible resolution of mesoscale phenomena, especially near the tropopause. At the same time, measurements taken routinely by commercial aircraft are providing much better information over traditional data voids, such as the oceans.

Unfortunately, this picture is not entirely rosy. Certain valuable measurement systems, especially rawinsondes, continue to decline in number, fueled in part by economic factors in such places as Russia, and in the more developed world by the perception that satellites have rendered them unnecessary. Despite strong appeals from such organizations at the National Academy of Sciences and the U.S. Weather Research Program, we have not yet developed a rational plan for an observing system that takes into account both costs and benefits and which balances the needs of researchers, forecasters and climate monitors.

Along with changes to the observing system have come rapid advances in analysis techniques, especially variational analyses which can smoothly incorporate new data into prior estimates (usually short-term forecasts), with built-in constraints if desired. These techniques provide dynamically consistent initial conditions for models, and means by which measurement/sampling errors can be detected and dealt with. Among the fruit of this development is the advent of global re-analyses, which can be used as boundary and initial conditions for running mesoscale models in cases of historical interest.

Progress in physical understanding has been perhaps more spotty. Theories and reduced models of frontogenesis were well developed by the mid 1980s and various approximations, such as semi-geostrophy, have been compared with primitive equation simulations, but there remain some curious discrepancies between what these models predict and what we observe; I will show an example at the conference. Theories and simulations of mesoscale precipitation bands abound, but it has proven difficult to ascribe with any confidence individual observed cases to any one theory. The development of theories for the generation of inertia-gravity waves through geostrophic adjustment and other non-topographic processes has proven very difficult, and while beautiful examples of such waves have been nicely documented, there is little ability to predict such phenomena. There has been arguably more progress in the understanding of mesoscale convective systems. For example, the RKW (Rotunno-Klemp-Weisman) theory of squall lines, focusing on the interaction of storm-produced density currents with ambient wind shear, has stood the test of time. But while there are intriguing ideas about the origins of mesoscale convective complexes, they have not yet been rigorously tested against observations.

In recent years, there has been accelerated progress in understanding certain mesoscale characteristics of tropical cyclones, after a curious period of dormancy. The role of vortex Rossby waves, considered as early as the 1950s, has been revived to help explain spiral rainbands and the axisymmeterization of vortices, and there is active research on the phenomenon of concentric eyewall replacement cycles, documented so well by radar and other observations published in the last two decades.

One area where theoretical progress has lagged is in understanding the origins of the mesoscale kinetic energy spectrum. There is still no generally accepted theory for this, though attention has focused on stratified turbulence and the possibility that the atmosphere has a saturated spectrum of internal waves, much as the ocean is thought to possess. It would seem that little progress can be made on this problem until and unless we are successful in identifying the particular phenomena that contribute to this spectrum. Doing so may have important ramifications for the degree of predictability of mesoscale phenomena.

Large increases in computer power and reductions in price have made mesoscale modeling much more affordable over the last two decades. As a result, there is a clear trend toward the increasing application of models to mesoscale phenomena. This has enabled the detailed simulation of fine scale processes, from air flow over complex terrain to eddies in the eyewalls of hurricanes. It has also allowed for running ensembles of forecasts, aiding the quest for a better understanding of the degree of predictability of mesoscale phenomena.

The advent of the internet and the enormous increases in the capacity of data storage devices have revolutionized access to environmental data. Twenty years ago, most research centers and university departments were storing paper facsimile charts and teletype output in large racks and file cabinets, and missing information was often obtained through informal networks of synopticians, sometimes by frantic midnight phone calls in advance of conference deadlines. Adding to the technical barriers to efficient archiving and distribution were certain political barriers, as government weather services sought to fend off real or perceived competition from the private sector and/or the weather services of other political entities. Even in the U.S., there were dark hours in the early 1980s when the National Weather Service was poised to implement a new internal data distribution network that would have prevented the flow of real-time weather data to anyone outside the NOAA structure. Only vigorous lobbying prevented that outcome.

Today, students in our field enjoy access to real-time and archived data that would have caused heart palpitations in the students of my time. So, too, have the political barriers to data distribution fallen; today NOAA makes available in near real time virtually everything it produces. The civilized world has seen fit to regard environmental data as a public good; in due course, Europe is sure to follow. The benefits to research and forecasting of the revolution in data storage and communication should not be underestimated.

3. A LOOK AHEAD

"Prediction is difficult, especially about the future." So said Yogi Berra. The safest course is just to extrapolate current trends.

One trend that is sure to continue is the evolution of mesoscale models to ever finer resolution, as computing power continues to increase. This offers the hope that we will no longer have to concern ourselves with the difficult and controversial job of parameterizing moist convection. Already, models with grid spacing of a few kilometers are referred to as "cloud-resolving models", though observations of real clouds show important structure down to a few tens of meters. Experience with the modeling of entrainment into boundary layers, which has shown that extremely fine resolution is necessary to obtain numerical convergence of entrainment, should caution us that processes important in convective physics, such as entrainment and the upward advection of boundary layer turbulence into clouds, may still be badly underresolved even with grid spacings of 100 m. The question of when underresolved explicit clouds are to be preferred to parameterizations is by no means settled.

Questions of mesoscale variability and predictability have long focused on the dynamical variables of temperature, pressure and wind. The variability of water vapor has been somewhat neglected by comparison. Studies of tracer transport show that passive tracers can develop very fine structure even in flows that vary slowly in space an time. The time-evolving, three-dimensional distribution of water vapor in unsaturated air poses a particular challenge for mesoscale meteorology, since the mesoscale structure of clouds and precipitation ultimately depend on it and because it is poorly observed. Though satellite methods can yield high horizontal resolution, they so far have not been able to provide the needed vertical resolution. Here, high-resolution mesoscale models can help by quantifying the kinds of water vapor variability that matter for weather and by defining observational requirements for specifying its distribution.

There is increasing evidence that cloud-radiation interactions can play a significant role in mesoscale weather phenomena. It is already well known that this has a profound effect on MCCs, contributing to their diurnal cycle, among other things. The more general question of how cloud-radiation interaction may affect other kinds of mesoscale systems is still open.

On the more practical side, cheap and powerful computers, the proliferation of mesoscale models, and the easy communication of real-time weather data has made it feasible for small organizations, such as small companies and university departments, to do real time mesoscale NWP and to post forecasts on the web. At the same time, work on ensemble modeling is beginning to show the benefits of multi-model ensembles. In the field of hurricane track prediction, for example, the superiority of multi-model ensembles over single control forecasts and single-model ensembles has been clearly demonstrated. We are witnessing what may prove to be the beginnings of a radical de-centralization of NWP in general. Although the WRF project provides a badly needed framework whereby myriad organizations can contribute to model development, the benefits of model diversity should not be overlooked. In addition to continuing its crucial mission of running large, centralized NWP models, NOAA could also choose to act as a clearinghouse for the dissemination of NWP products generated outside NOAA, thereby helping us reap the benefits of multi-model ensembles.

"All politics is local" quipped Tip O'Neil. In the same vein, we may say that all weather is mesoscale.