

U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NATIONAL WEATHER SERVICE
OFFICE OF SYSTEMS DEVELOPMENT
TECHNIQUES DEVELOPMENT LABORATORY

TDL OFFICE NOTE 86-1

REMOTE SENSING - UPSCALE FORECASTING:
A TECHNICAL STRATEGY FOR CONTRIBUTING TO IMPROVED
MESOSCALE FORECASTING

Wayne E. McGovern

February 1986

REMOTE SENSING - UPSCALE FORECASTING:
A TECHNICAL STRATEGY FOR CONTRIBUTING TO IMPROVED
MESOSCALE FORECASTING

Wayne E. McGovern

ABSTRACT

Over the past several decades, substantial progress has been made in defining general areas of potential severe weather through the application of increasingly sophisticated large scale numerical models. This present large scale numerical modeling approach is frequently able to outline broad areas likely to experience severe storms 1/2 to 2 days in advance. We define this approach as "downscale" forecasting in that the data base to initialize the numerical models comes basically from the large scale rawinsonde and satellite sounding networks which are generally much coarser in resolution than the local severe weather events of interest. In contrast, short-range (0-4 hours) numerical models capable of being more specific in forecasting the onset, duration, areal extent, and specific nature of the weather associated with individual storms have yet to be developed operationally. While research is proceeding in this area, the very complex problem of modeling many physical and dynamical processes simultaneously, some of which are not fully understood, combined with the lack of the necessary fine mesh data to initialize such models, makes the operational implementation of a full range of severe storm models unlikely in the near future. Another obstacle to the implementation of high-resolution models lies in the fact that future small scale meteorological observing systems will be primarily remote sensing in nature and will not always provide information directly compatible with the numerical models.

In contrast, high resolution mesogamma scale data (2-20 km resolution) from a variety of relatively economical remote sensors can potentially be used in an "upscale" mode to diagnose and forecast larger mesobeta scale (20-200 km resolution) severe weather events. For example, classical statistical methods, in particular multiple regression procedures, can effectively be used to provide short-range forecasting guidance. Specifically, quantitative radar reflectivity data, similar to that which will be found in the future NEXRAD system, when used in conjunction with multiple regression procedures, have dramatically improved our short-range forecasting of severe local thunderstorms. Alternatively, non-modeling techniques, such as the analog approach, have provided only limited success in local forecasting applications since such alternate approaches are best suited to forecasting situations that are not associated with extreme events. In general, the forecasting of extreme weather events is difficult when dealing with highly non-linear or unstable systems (i.e., storms) which rely on initial forecasting data from well before the onset of the growth or mature stage of the storms. In such circumstances, very small changes in the initial data set can often produce significantly different forecasts. Contributing to this problem is the strong possibility that the critical data necessary to differentiate the evolution of severe from non-severe events may be contained within atmospheric scales smaller than normally observed by our present networks.

In contrast, high resolution remote sensors are primarily activated and often most applicable during disturbed atmospheric conditions. Under these circumstances, selected remote sensing parameters, obtained during such meteorologically active periods, can potentially provide the necessary critical data for determining which particular local weather situation may evolve into an extreme event. At present, as a class, classical statistical procedures appear to be the most compatible technique with remote sensing information. Procedures such as multiple linear screening regression can ingest information from a variety of sensors in an assortment of data formats. In addition to their flexibility in assimilating dissimilar types of sensor data, multiple regression procedures can readily incorporate climatological parameters to delineate regional and seasonal differences. Like almost all other forecasting procedures, regression has some difficulty in differentiating between extreme and non-extreme events or the ability to forecast the unusual situation. Yet this problem is less severe than with other forecasting procedures if in selecting predictors from remote sensors, care is used in selecting those predictors that are strongly linked to the evolution of local severe storms. For example, from experience gained over the past several years, the vertically integrated liquid water (VIL) appears to be such a predictor in that various VIL properties are very useful in isolating thunderstorms that are likely to produce severe weather. There is some evidence that VIL is also an excellent indicator of possible hailstorms. Another possible example is provided by columnar wind shear measurements from the NEXRAD system, which has been shown to be an excellent predictor in spotting potential mesocyclones likely to spawn tornadoes. In short, classical statistical procedures appear to be an optimum process for maximizing the "upscale" mesoscale forecasting capabilities associated with emerging remote sensors, one which would naturally complement our present "downscale" numerical modeling efforts.

1. INTRODUCTION

Atmospheric motions cover a broad range of scales from planetary waves (wavelengths $> 10,000$ km), through synoptic scale waves (2,000-10,000 km), to mesoscale waves (2-2,000 km) and below (Orlanski, 1975). The general thrust of operational weather forecasting is to correctly discern the movement of these "waves" and infer the weather associated with such systems. Efforts in this area over the past three decades have been primarily concerned with numerically simulating the progression of synoptic scale wave systems. The result of these efforts has been such that today, forecasting skill levels associated with the synoptic scale for periods of four days are comparable to those exhibited thirty-five years ago at the end of only one day (Bengtsson, 1985). Nevertheless, while significant improvements have occurred in the forecasting of general synoptic weather patterns, less success has been exhibited in the forecasting of locally severe weather. Severe weather events, such as heavy precipitation bands or squall lines, are frequently embedded in the middle of the mesoscale, often referred to as the mesobeta scale (20-200 km). Forecasting events on the mesobeta scale has, until recently, relied primarily upon a single data source; qualitative radar reflectivity data. However, with the advent of a variety of new and improved remote sensors (e.g., quantitative Doppler and reflectivity radar, profiler and lightning location systems, and newer satellite observing systems) the problem of an insufficient data base in support of an effective mesoscale or local forecasting program appears less formidable than a decade ago.

The expected implementation of the above technologies during the coming years has led many meteorologists to visualize the beginnings of an effective meso-scale data base in support of local severe storm forecasting during the 1990's. How best to use the new systems, both individually and collectively, in support of local forecasting is the key question that meteorologists are increasingly beginning to look at. In this paper, this question is addressed by presenting the outlines of a technical procedure aimed at effectively employing this new technology, in conjunction with past efforts, in order to develop a vastly improved local weather forecasting capability by the turn of the century.

2. FORECASTING SITUATION

In the past, the forecasting of mesoscale events generally began with a synoptic analysis followed by a highly subjective and detailed small scale analysis. The first approach basically employs synoptic scale upper air rawinsonde and satellite sounding data to initialize objective numerical models designed specifically for large scale weather prediction. In this approach, upper air data with an effective resolution of several hundred kilometers (300-400 km over the continental United States) is used in conjunction with numerical models to infer broad areas of potential severe local weather. This approach has the advantage of indicating relatively large areas of severe weather a day or so in advance. However, a major drawback to this approach is that present numerical models can not resolve phenomena smaller than the lower end of the subsynoptic scale (also frequently referred to as the mesoalpha scale--200-2000 km). This effort to resolve in a general way severe weather phenomena which, in the main, are smaller in space and time than the effective input data and model resolution can be classified as the "downscale" mesoscale forecasting approach.

Doubling the resolution of our land based upper air network, i.e., a four-fold increase in the number of sounding systems, or a comparable increase in the spatial resolution and accuracy via satellite sounders or profilers would still not provide sufficient data to permit operational numerical models to effectively function well within the mesobeta scale (20-50 km), the effective scale of many severe weather events. An improvement in the resolution of the upper air network would, however, provide needed data to better delineate areas likely to experience severe weather a half a day or so in advance, as well as possibly providing sufficient data to permit an upgrading of the present 12-h synoptic forecasting cycle to 6 hours.

The short-range forecasting of severe local weather events (0-4 hours) appears to require a second objective approach complimentary to the success obtained in larger scale numerical weather prediction (NWP). In the NWP "downscale" approach, so defined because one proceeds from large scale data to infer smaller scale phenomena, the time associated with centralized collecting, processing, and distribution of the results, for now, prohibits the effective use of such procedures in "nowcasting" (0-1 hours) or very short-range (0-4 hours) forecasting applications. Compounding this problem is the fact that mesoscale events are usually three-dimensional in nature requiring not only very fine mesh models, but models which accurately portray complex physical processes, some of which are only vaguely understood. Even if effective operational meso-scale models existed, and efforts are going forward in the research community to develop improved models of this type, there is the problem of lack of pertinent fine mesh data to initialize such models in an operational framework.

In the near future, the majority of high resolution meteorological data (on a scale of a few kilometers or less) will be derived primarily from remote sensors (e.g., satellite sensors, radar, profilers, or lightning location systems). The general nature of these data (e.g., radiance, reflectivity, and lightning locations) is such that they are not readily assimilated by experimental small scale models which are not presently structured to accept data from this diverse set of high resolution remote sensors. Under these circumstances, a new outlook is needed in utilizing mesogamma scale data (2-20 km) to forecast mesobeta scale (20-200 km) events. This approach, which we will shortly elaborate upon, will be termed the "upscale" approach since it uses high resolution mesogamma scale meteorological data to forecast upscale larger mesobeta scale phenomena.

3. UPSCALE FORECASTING

The basic thrust of the "upscale" mesoscale forecasting approach is the effective use of data collected on the mesogamma scale (2-20 km resolution) to diagnose and/or subsequently forecast mesobeta scale (20-200 km) weather events. Due to the relatively high unit areal costs of mesoscale data from direct sensors, much of the meteorological mesogamma scale information will be forthcoming from remote sensors. Potential remote data sources for this "upscale" approach are NEXRAD (NEXT Generation RADar--both Doppler and reflectivity information), lightning detectors, profilers, and satellite observations, both visible and infrared imagery. While being cost effective, these systems are also more sensitive in measuring disturbed compared with undisturbed atmospheric conditions, or those conditions which are instrumental in creating local severe weather events.

However, a major drawback is encountered in that information from remote sensing systems is generally not directly assimilable into numerical models since these sensors measure electromagnetic (EM) energy which often has to be converted into state variables (i.e., temperature, pressure, wind speed and direction, and moisture) before they are capable of being used in a direct meteorological context. The associated error in converting the EM information to a state variable is balanced in part by the fact that remote sensors sample a larger and more representative volume of the atmosphere than direct, in-situ instrumental measurements of state variables.

In addition to the above qualities, small-scale remote sensing meteorological information has, as the name implies, a relatively short characteristic meteorological lifetime. Under these circumstances, much of the data can be used only in a short-range forecasting context. This disadvantage is partly compensated for by the precision possible in forecasting the local position and/or timing of the pertinent phenomena.

If centralized numerical models do not presently appear to be an ideal medium for responding to short-range weather events and for exploiting, in this context, high resolution remote sensing technology, the question then arises: How best to use the emerging remote sensing capabilities in an "upscale" meteorological context? In the next section, we will examine this question and in particular explore various technical procedures, including statistical techniques, which can effectively complement present "downscale" numerical modeling efforts.

4. SHORT-RANGE FORECASTING PROCEDURES

Before the introduction of NWP models now commonly in use to forecast large scale meteorological conditions, the major objective forecasting procedures for the synoptic scale were classical statistical methods. With the advent of NWP models, this method fell into minimum use and new statistical procedures were developed which were strongly dependent upon the new model output. In the forecasting of local weather events, particularly individual severe storms, effective operational models do not presently exist. Under such circumstances, the meteorologist must examine past successful procedures, including the analog method, armed in the near future with a new battery of remote sensing observations.

The analog method tries to match a given, usually current, event in its essential characteristics with a well documented past weather pattern. Documentation of past weather events is normally developed as a result of an in-depth study of historical data of a large number of cases. These studies give, as their name implies, a thorough analysis of the typical characteristics of a specific weather event. If known, the processes leading to the extreme nature of the event are often described. A catalog of such studies gives the forecaster or operational meteorologist the principal conditions preceding the severe weather situation. Additional case studies may refine the forecaster's insight, but at some point the increasing number of individual studies become difficult to assimilate. This point of "diminishing returns" depends upon the pattern recognition capabilities of the individual forecaster in recalling specific historical cases as well as the procedure for classifying a current event with past studies. For the most part, the analog approach has had limited value in effectively forecasting severe synoptic scale events.

Application of the analog approach on the mesoscale, while the mainstay of local forecasting for many years, has likewise provided only very limited success. In many situations, the forecaster may recognize the potential danger of a given set of synoptic conditions, but not have sufficient information and/or techniques on hand to forecast the specific onset of a local severe event. The best that can be done in these situations is to note the possibility of a storm by issuing a "watch" statement. Often, during the initial stages of a severe weather event, the forecaster may be effectively limited to monitoring the severity, position, and direction of the system. Warnings of the actual occurrence of a local severe weather event are often issued after the fact, particularly with respect to tornadoes, hail, high wind gusts, heavy rains associated with thunderstorms, and, to a lesser extent, heavy snows.

In the past, tools and techniques to actually predict, even for very short periods (0-4 hours), the imminent occurrence of severe weather were limited. The analog method, while valuable in delineating possible areas of severe weather, is not generally suited to picking specific extreme situations with any degree of consistency. Under these conditions, in order to provide adequate public protection it has often been necessary to issue "watches," even in cases with a large degree of uncertainty. The net result has been a high severe storm false alarm rate and sometimes an accompanying diminished confidence in the Weather Service's capabilities. The alternate situation of issuing watches only when the forecasters are "sure" would result in a significant increase in the number of severe weather events with no advance warning at all--

an unacceptable alternative. The present operational procedure tries to steer between the "horns" of this dilemma--a dilemma caused largely by our present inability to observe and accurately predict the smaller scale activities of the atmosphere.

As previously noted, the short response time associated with severe local weather forecasting does not for now allow the direct application of complex numerical models to the forecasting of local severe weather events. Presently, in the forecasting of synoptic scale phenomena, statistical techniques are used very effectively in combination with NWP model output. For medium range forecasting the two most frequently used procedures are the Model Output Statistics (MOS) and Perfect Prog methods. Since both methods are model dependent, they too are not specifically applicable in the very short term forecasting of local severe weather.

Before the introduction of numerical models, statistical procedures, by necessity, had to incorporate the time lag associated with the independent variables or predictors. As noted by Glahn (1985), the classical statistical technique does not depend upon NWP models and is applicable to very short-range forecasting situations (0-4 hours). An additional advantage of the classical statistical approach is that the observational data or atmospheric predictors do not have to be in the form of state variable measurements (i.e., temperature, pressure, wind, and moisture). The input data in the classical statistical approach can be a mixture of observations from remote sensors whose measurements are somewhat difficult to assimilate directly in a NWP model.

Like the analog and/or case studies approach, statistical procedures usually are best suited to forecasting events which do not fall far outside the "range of normal events." Almost by definition, severe weather is an abnormal occurrence, and the application of statistical procedures to remote sensor data might be of little value if several remote sensors (radar, lightning detectors, and satellite imagery) did not possess the following common property; namely, remote sensing systems by their nature are often most responsive as sensors under disturbed atmospheric conditions, or those conditions strongly linked with the evolution of local severe storms. Judicious use of just such observed remote sensor parameters as predictors can be instrumental in differentiating the degree of severity of a local weather situation. In Section 5, a brief illustration of this approach is given to support this concept.

Somewhat parallel to the pure downscale numerical modeling efforts has been the continuing development of hybrid statistical/numerical models (Charba, 1979; Glahn, 1980) which in several respects acts to bridge the gap between the so-called downscale and upscale approaches. These hybrid methods use model forecasts and surface observations, including some remote sensing data such as radar data, in conjunction with joint statistical and/or numerical procedures. Respectively, they provide centralized short-range (2-6 h), severe storm forecasts over limited subsynoptic areas or permit hourly local updating of the present 12-h forecasting cycle for comparable areas, out to 20 hours. These methods stem primarily from a modified downscale approach and use hourly surface data over limited areas to provide more frequent updating of the initial NWP forecast. Such methods use statistical procedures, often in conjunction with simplified dynamic methods; it is in this latter aspect that they probably differ most from the upscale remote sensing procedure which at present does not

try to forecast into the region of significant dynamic change. The capability to forecast significant dynamic changes on the local level will probably need to await the development of operational numerical mesoscale models.

5. EXAMPLE OF AN UPSCALE FORECASTING APPROACH: RADAR

Of the various forecasting procedures presently available (NWP models, analog, and statistical methods), it would appear that classical statistical procedures in conjunction with emerging remote sensing data can be an effective approach in immediately improving short-range local severe weather forecasting (0-4 hours). As previously mentioned, remote sensing data are not always directly tractable in a numerical modeling context, and present technological capabilities and meteorological knowledge are still far removed from providing effective numerical operational models capable of discerning where or when specific local weather situations may develop into a severe event. To support the applicability of classical statistical methods and remote sensing data to the severe storm problem, we will describe such an approach using radar reflectivity data.

During the 1970's, several technological developments suggested possible significant improvements within the operational National Weather Service (NWS) radar system. The first of these improvements dealt with development of automated digitized radar computer products for the purpose of enhancing the national radar database. A second development was associated with measuring radial wind components at a radar site through the Doppler shift. The Doppler shift is the change in the pulse frequency emitted by and subsequently returned to the radar receiver when there is relative radial motion between the target (winds carrying precipitation particles) and the receiver. By late 1983, 10 digital Radar Data Processors (RADAP II) were installed among the 56 network radars (s-band, 10 cm wavelength) and 71 "local use" radars (c-band, 5 cm) of the NWS operational radar network. For radar sites without RADAP II, radar information is generally qualitative in nature. In contrast, the RADAP II sites can process qualitative radar reflectivity images into quantitative values which in turn are translated into objective hydrometeorological products capable of display on alphanumeric terminals.

Current plans for the modernization of the national radar system calls for the NEXRAD system to combine the digitized reflectivity and Doppler capabilities with a sophisticated color graphics display system. To assist in this transition, a series of operational experiments were held at the NWS Weather Service Forecast Office (WSFO) in Oklahoma City starting in 1983. The purpose of these experiments was to test a statistical severe weather probability (SWP) algorithm, using relatively high resolution radar data (3 x 5 km resolution) as input, to forecast the probability of severe weather from individual thunderstorms up to 1 hour in advance. The specific statistical procedure used to develop the SWP algorithm was a multiple screening regression technique (Miller, 1958) which related various radar parameters to severe weather reports. A more detailed description of the initial development of this algorithm and subsequent modifications can be found in the paper by McGovern et al. (1985).

The results from these experiments are impressive and have been reported on by a number of authors (McGovern and Saffle, 1983; Winston and Ruthi, 1984;

McGovern et al., 1984; Devore et al., 1985). These results, as documented in Appendix A, demonstrated that the quantitative RADAP II information (mesogamma scale) was capable of detecting areas likely to experience severe thunderstorm weather (mesobeta scale) for forecast periods of up to 1 hour.

In a larger context, this experiment showed the importance of quality mesogamma scale data (2-20 km resolution) in forecasting "upscale" severe thunderstorms (mesobeta scale--20-200 km resolution), and, in particular, the importance of the use of radar derived VIL parameters during disturbed conditions as severe storm predictors. This algorithm development, based on classical statistical methods, shows considerable promise for extension to other meteorological parameters as well as for using alternate remote sensing capabilities individually and in various combinations in producing effective short-range forecasting techniques.

Even now, research is underway to develop a new hail algorithm based on similar VIL parameters (Devore, 1985), while Beasley et al. (1985) are likewise investigating the local and seasonal variations of VIL parameters with the seasons for the Oklahoma City region. Those studies are based on 3-dimensional volumetric radar data available in 10-minute intervals. Extensive data sets of this nature will permit further improvements in incorporating both the seasonal and regional aspects of these remote sensing measurements within selected algorithms as well as the development of a mesoscale radar climatology. The latter characteristic, development of a mesogamma scale climatic data base associated with severe events, could be used in a number of ways--for example, in composite studies and/or in developing joint interactive climatic predictors as described by Reap and Foster (1979). Studies along both these lines could be subsequently incorporated directly into the multiple screening regression procedure far more readily than within a numerical modeling context.

In short, the upscale approach using the multiple screening regression procedure appears to offer considerable flexibility in allowing seasonal and regional tailoring and local modification of remote sensing algorithms. However, final tuning of such algorithms for a variety of sites could involve a considerable additional effort. This increased effort in software development could increase significantly as more predictors from a collection of remote sensors are focused upon a single type of severe weather event. A possible remedy to this problem could be the development of "algorithm shells" in which local modifications could be subsequently introduced. With computer capabilities projected to increase significantly at local sites, additional on-site modifications to many of these algorithms would become feasible, thereby involving the local staff in regional developmental efforts.

Finally, as new sensors and additional techniques become available, new procedures will need to be developed to assist the operational meteorologist in deciding which individual techniques or combination of procedures would best describe a particular weather event. At that point, developments in expert systems capabilities may provide a new architecture in designing an effective forecasting system--again, probably best accomplished within a statistical context.

6. SUMMARY AND CONCLUSIONS

Modern meteorology is considered by many as beginning with the introduction of numerical modeling in the 1950's. In the intervening decades, considerable

progress has been made in numerically simulating synoptic scale waves and the general weather patterns associated with such waves. With increasing computer power (factor of approximately 10^4 in 25-30 years) and new numerical techniques, the resolution of models has continually increased so that today models can span meteorological scales ranging from planetary scales to the subsynoptic. Parallel to developments in numerics has been improved insights into the physical and dynamical processes associated with larger scale events. The net result has been that, on the average, the quality of synoptic forecasts has increased roughly one day per decade. In other words, the skill in forecasting synoptic patterns has, on the average, through each 10 years of research and development, been extended approximately an additional day.

Comparable progress, however, has not been matched in the forecasting of local or mesoscale severe weather events. In the early 1980's, the forecasting skill levels associated with local weather events such as precipitation had been modest (Charba and Klein, 1980) compared to the progress of synoptic numerical weather prediction. This situation is the result of several factors including the lack of effective mesoscale operational models, pertinent data bases to initialize such models, and a communication/dissemination system to process and distribute the model results. For the next couple of decades, these problems will probably continue to exist, thereby preventing the implementation of a centralized mesoscale forecasting system similar to that developed with respect to the synoptic scale.

With the introduction of a series of local remote sensors, a new procedure needs to be called upon to assist in local severe storm short-range forecasting. This procedure, termed here the "upscale" approach will digest remote sensor mesogamma data, with a corresponding resolution of a few kilometers, process the data locally, and infer severe storm conditions for areas as small as 20 km. By their nature, classical statistical methods appear to be an effective technical procedure for forecasting mesobeta scale (20-200 km) events based on remote sensing data, provided some care is exhibited in the selection of remote sensing predictors.

This "upscale" approach may be very effective in discriminating between "routine" and more extreme thunderstorms as well as, in general, differentiating between other severe and non-severe weather events. Such a procedure could most readily account for regional and seasonal differences. In doing so, the upscale approach would act as a natural complement to downscale forecasts from both numerical models and hybrid offshoots. The latter efforts, in which numerical model output is used in a statistical context, can increasingly serve as a bridge between the upscale and downscale approaches. In short, no single forecasting procedure will cover all daily operational meteorological scales. It has been suggested that the optimum span of scales for numerical models is near two octaves, and, therefore, a variety of techniques and/or models will be necessary to cover the spectrum of operational meteorological problems. In this paper, we have outlined such a range of approaches which as a unit appear capable of providing operational forecasts from 1 hour through 1 day to 1 to 2 weeks in duration. With this concept of downscale, hybrid, and upscale processes serving as an overall meteorological-technical strategy, we believe that a real improvement in weather forecasting can occur by the turn of the century.

APPENDIX A

The National Weather Service Forecast Office (WSFO) at Oklahoma City has been operationally testing digital radar reflectivity data or RADAP II since 1983. In 1984, during the spring storm season, and for the spring of 1985, Doppler radar data from the National Severe Storms Laboratory in Norman, Oklahoma were also made available to forecasters at WSFO Oklahoma City. The combination of these data sets, similar to the type of information associated with NEXRAD, had a positive impact upon severe storm forecasting at the WSFO.

Specifically, the verification scores for WSFO Oklahoma City for the period between 1977 and 1985 for the months of March through June are exhibited in Table 1. The abbreviations POD, FAR, and CSI stand for the probability of detection, false alarm ratio, and critical success index, respectively. The POD is defined as the number of forecasted severe weather events which occurred in the specified period (i.e., hits) divided by the total number of severe weather events (i.e., hits plus misses). A forecasted severe storm which did not verify is classified as a false alarm. The FAR is then defined as the number of false alarms divided by the total number of forecasted severe weather events (i.e., hits plus false alarms). The CSI, or critical success index, is defined as number of hits divided by the total number of hits, misses, and false alarms. A more complete description of these terms is given by Donaldson et al. (1975). In short, improved forecast skill in Table 1 is represented by a higher POD and CSI and a lower FAR. As indicated in Table 1, with the installation of the RADAP II/ICRAD system at WSFO Oklahoma City at the beginning of 1983, the verification scores, as tabulated by the Techniques Development Unit (TDU) at the National Severe Storms Forecast Center, showed a significant improvement.

Beginning in 1983, significant improvements in the CSI were related to increased skill in determining which storms were likely to be severe (hits) combined with a far lower false alarm ratio. Through the severe weather probability (SWP) algorithm modified with VIL values, and the two-dimensional display of the storm structure on the Interactive Color Radar Display (ICRAD) system, the forecasters were far better able to determine which thunderstorms were unlikely to produce severe weather. This dual set of both quantitative (SWP) and qualitative (2-D display) information provided a key technical factor in achieving the striking reductions in the FAR.

Devore et al., (1985) verified separately severe thunderstorms and tornadoes from March through May for WSFO Oklahoma City. Their results, tabulated both by warning and county, are shown below.

By Warning

	1983	1984	1985
POD	.79	.79	.76
FAR	.29	.21	.13
CSI	.60	.66	.68

By County

	1983	1984	1985
POD	.84	.86	.82
FAR	.52	.40	.29
CSI	.44	.54	.61

The lowering of the POD scores between 1984 and 1985 was due in large part to hardware problems, while the FAR improvement was credited to the increase in confidence and experience gained by the staff in the use of RADAP II system.

For tornadoes with a positive lead time, the skill levels for Oklahoma City were:

By Warning

	1983	1984	1985
POD	.57	.62	.70
FAR	.66	.61	.59
CSI	.25	.31	.35

By County

	1983	1984	1985
POD	.60	.62	.70
FAR	.77	.76	.73
CSI	.20	.21	.24

In a separate verification study for Oklahoma City, Winston and Ruthi (1984) subdivided the temporal domain into 30- and 60-minute intervals and the spatial domain into warning boxes ranging in size from 10 by 20 n mi to 25 by 40 n mi. The specific warning box size varied with the size and speed of particular storms in addition to the length of the warning period. As defined in the overlap mode, a new independent warning, valid for 30 or 60 minutes, could be issued with each new volumetric scan (i.e., new SWP and VIL values) or every 10 minutes. In the 30-minute mutually exclusive mode, once a warning was issued in this simulation exercise, no new warnings were issued until the initial warning expired. For further details, the reader is referred to the above reference. The results of this effort are summarized in Table 2.

Winston and Ruthi (1984) concluded that:

- o Frequently-updated output from the RADAP II algorithm is an important guidance tool for operational forecasters which can significantly enhance their performance.
- o The ability of such automated systems to continually monitor and diagnose the state of the atmosphere is a valuable attribute in a limited time environment; therefore, either this or a similar system can play a significant role in diagnostic nowcasting.
- o The demonstrated ability of the RADAP II system to detect areas likely to experience severe weather illustrates the importance of digitized volumetric radar data as a warning tool.

We concur with these conclusions and would add:

- o Skill scores are dependent upon both the area and time span used in the verification process. Therefore, for comparison purposes, a standard unit of area and time should be established in contrast to the present county by county warning verification procedure. If, as suggested, skill predicting which storms are likely to be severe is more advanced than where and when a particular storm is likely to proceed, then a separate severity and positioning verification procedure may be more applicable for smaller scale storms.
- o Based upon these experiments, we believe that selected radar algorithms (e.g., SWP based on VIL values, heavy precipitation monitoring, and hail size) may be both regionally and seasonally dependent. In association with the NEXRAD program, efforts have begun to investigate these possibilities.

ACKNOWLEDGMENTS

These radar experiments at Oklahoma City would not have been possible without the active participation of many individuals, in particular, Robert E. Saffle and Robert C. Elvander, who respectively developed the ICRAD display and SWP algorithm capabilities, as well as the staff at WSFO Oklahoma City. In addition, I would like to acknowledge Mr. Preston Leftwich for the verification information in Table 1, Mr. Ronald M. Reap for his review of the manuscript, and Mrs. Belinda Howard for typing it.

REFERENCES

Beasley, R. A., D. R. Devore, and L. J. Ruthi, 1985: A preliminary analysis of operational RADAP II information, corresponding thermodynamic variables, and concurrent severe weather events in Oklahoma. Preprints Fourteenth Conference on Severe Local Storms, Indianapolis, Amer. Meteor. Soc., 135-138.

Bengtsson, L., 1985: Medium-range forecasting--the experience of ECMWF. Bull. Amer. Meteor. Soc., 66, 1133-1146.

Charba, J. P., 1979: Two to six hour severe local storm probabilities: an operational forecasting system. Mon. Wea. Rev., 107, 268-282.

_____, and W. H. Klein, 1980: Skill in precipitation forecasting in the National Weather Service. Bull Amer. Meteor. Soc., 12, 1546-1555.

Devore, D. R., K. L. Gallant, and C. E. Davis, 1985: The operational use of RADAP II and Doppler data: a pre-NEXRAD environment. Preprints Fourteenth Conference on Severe Local Storms, Indianapolis, Amer. Meteor. Soc., 232-235.

Donaldson, R. J., Jr., R. M. Dyer, and M. J. Kraus, 1975: An objective evaluator of techniques for predicting severe weather elements. Preprints Ninth Conference on Severe Local Storms, Norman, Amer. Meteor. Soc., 321-326.

Glahn, H. R., 1980: Plans for the development of a Local AFOS MOS Program (LAMP). Preprints Eighth Conference on Weather Forecasting and Analysis, Denver, Amer. Meteor. Soc., 302-305.

_____, 1985: Statistical weather forecasting. Probability, Statistics, and Decision Making in the Atmospheric Sciences. (A. H. Murphy, and R. W. Katz, Ed.), Westview Press, Boulder, Co., and London, 289-335.

McGovern, W. E., and R. E. Saffle, 1983: Results of the 1982-83 RADAP/ICRAD operational experiments. Workshop on Very Short-Range Forecasting Systems Research Aspect (Boulder, 15-17 August 1983), World Meteorological Organization, 53-58.

_____, R. E. Saffle, and K. C. Crawford, 1984: Verification results from 1982-1984 operational radar reflectivity experiment. Preprints Twenty-second Conference on Radar Meteorology, Zurich, Switzerland, Amer. Meteor. Soc., 188-191.

_____, R. E. Saffle, and R. C. Elvander, 1985: Mesobeta scale thunderstorm forecasting with mesogamma scale data base. Preprints Ninth Conference on Probability and Statistics in Atmospheric Sciences, Virginia Beach, Amer. Meteor. Soc., 11-15.

Miller, R. G., 1958: The screening procedure. Studies in statistical weather prediction. Final Report, Contract No. AF19(604)-1590. The Traveler's Research Center, Inc., Hartford, Conn. 86-95.

Orlanski, I., 1975: A rational subdivision of scales for atmospheric processes. Bull. Amer. Meteor. Soc., 56, 529-530.

Pearson, A., and C. L. David, 1979: Tornado and severe thunderstorm warning verification. Preprints Eleventh Conference on Severe Local Storms, Kansas City, Amer. Meteor. Soc., 567-568.

Reap, R. M., and D. S. Foster, 1979: Automated 12-36 hour probability forecasts of thunderstorms and severe local storms. J. Appl. Meteor., 18, 1304-1315.

Winston, H. A., and L. J. Ruthi, 1984: A study on the issuance of severe storm warnings utilizing RADAP II. Preprints Tenth Conference on Weather Forecasting and Analysis, Clearwater Beach, Amer. Meteor. Soc., 496-499.

Table 1. Verification scores (county by county basis) for period March through June.

Year	Oklahoma City			NWS Southern Region		
	POD	FAR	CSI	POD	FAR	CSI
1977	.38	.86	.11	.36	.93	.06
1978	.44	.86	.12	.38	.91	.08
1979	.43	.83	.14	.50	.90	.09
1980	.61	.82	.16	.61	.88	.11
1981	.67	.82	.17	.47	.86	.12
1982	.54	.81	.16	.48	.83	.14
1983	.76	.52	.42	.55	.78	.19
1984	.82	.44	.50	.67	.72	.24
1985	.82	.35	.57	.64	.63	.30

Table 2. Skill Scores for Reduced Warning Areas.

Score	30 min Overlap	60 min Overlap	30 min. Mutually Exclusive	National Average ¹
POD	0.66	0.55	0.68	0.25
FAR	0.44	0.37	0.48	0.94
CSI	0.43	0.41	0.42	0.04
No. of Storms	671	929	293	--
No. of Warnings	802	815	396	--

¹Pearson and David, 1979