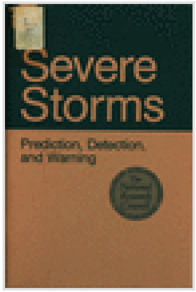

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Severe Storms:

Prediction, Detection, and Warning

A Report of the
Panel on Short-Range Prediction
and the
Panel on Severe Storms
to the
Committee on Atmospheric Sciences
Assembly of Mathematical and Physical Sciences
National Research Council

NATIONAL ACADEMY OF SCIENCES
Washington, D.C. 1977

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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PREFACE

During the summer of 1973, the Committee on Atmospheric Sciences established two panels to look into the problems of the short-range prediction of general weather and violent storms. The Committee had earlier identified in its report, *The Atmospheric Sciences and Man's Needs: Priorities for the Future* (National Academy of Sciences, Washington, D.C., 1971), that activities in the atmospheric sciences addressed to weather dangers and disasters should have as a major objective the substantial reduction of "...human casualties, economic losses, and social dislocations caused by weather." Severe weather, however, covers a number of phenomena that have a wide range of time and space scales, namely, pollution episodes, blizzards, hurricanes, and severe drought and floods. In light of the general distribution of frequency of damage and loss of life inflicted throughout the United States, and to present to the panels problems of a specific and more manageable scope, their attention was directed to those severe weather phenomena of a convective origin that generally strike the heart of the nation, namely the thunderstorm and its many allied phenomena--wind, hail, flash floods, lightning, and tornadoes.

The Panel on Short-Range Prediction was to concentrate on needs, problems, and techniques related to the development of an improved capability to predict important weather variables over time periods up to 12 hours in advance, with particular attention to the use of modern computer techniques. The Panel on Severe Storms was to concentrate on the observational problems of detecting and tracking violent storms and the communication problems of providing adequate warnings.

Although the initial meetings of these two panels were held independent of each other, apropos their separate and distinct charges, the many overlapping interests of the two panels resulted in several of their meetings being held jointly at locations where activities of immediate relevance to both panels were being conducted.

As a consequence, the two panels, separately or together, visited such centers as the National Severe Storms Forecast Center, Kansas City, Missouri; the National Severe Storms Laboratory, Norman, Oklahoma; the Techniques Development Laboratory and the Integrated Systems Laboratory of the National Weather Service, Washington, D.C.; the National Environmental Satellite Service, Suitland, Maryland; the Space Science and Engineering Center at the University of Wisconsin, Madison, Wisconsin; the Global Weather Central of the U.S. Air Force, Omaha, Nebraska; and the Environmental Research Laboratories, Boulder, Colorado; where attention was devoted primarily to recent developments in remote sensing by infrared, radar, and acoustic techniques, and to the role of the proposed SESAME Project in providing information needed for the improvement of skill in short-range predictions. In addition, some of the work in this field in progress at the National Center for Atmospheric Research was reviewed by both panels.

Subsequently, the two panels organized and drafted the reports, which, because of their relevance to the general problem of severe storms, are presented here as Parts I and II of a single document.

Cecil E. Leith, Jr., *Chairman*
Panel on Short-Range Prediction

C. Gordon Little, *Chairman*
Panel on Severe Storms

I
Report of the Panel on Short-Range Prediction

1 SHORT-RANGE PREDICTION OF LARGE MESOSCALE FORCING OF SEVERE STORMS

Early in its deliberations, the Panel on Short-Range Prediction considered a wide variety of short-range prediction problems covering such diverse kinds of forecasts as airport visibility, damaging frost, flash floods, weather conditions for planting and harvesting, wind storms, and thunderstorms. The Panel recognized that there was a similarly wide range in the methods used for the prediction of these different phenomena. To make its task manageable, the Panel agreed to limit it to consideration of the prediction of the large mesoscale developments that apparently control the outbreak of the severe convective storms, such as those of April 3-4, 1974, that have spawned hundreds of tornadoes throughout the central United States (see map inside back cover). This limitation in the task of the Panel complemented in a natural way the task of the Panel on Severe Storms, which was to concentrate on the observational problems of detecting and tracking severe storms and on the communication problems of providing adequate warning.

In examining examples of severe convective storm outbreaks, it is clear that, although individual convective elements are far too small to be resolved in the present observing and computing grids, the large mesoscale region within which such storms occur is hundreds of kilometers in size and is near the present limit of resolution of the continental radiosonde network and of numerical prediction models. Therefore, the most important immediate objectives contributing to the improved prediction of severe storms would seem to be (1) better detection and tracking of convective activity, (2) development of better statistical relationships between convective storms and the large mesoscale disturbances that produce them, and

(3) an improvement in the dynamical prediction of these large mesoscale disturbances.

The first of these objectives is a concern of the Panel on Severe Storms; the Panel on Short-Range Prediction has concentrated its attention on the second and third objectives in arriving at its recommendations for a combined numerical and observational program.

As a starting point for discussion of the third objective, Chapter 2 presents a summary of the accomplishments and problems in numerical weather prediction. Of particular interest is the question of the relative importance of analysis errors and various kinds of model errors, especially those that arise from inadequate model resolution. Chapter 3 deals with the statistical regression methods that are currently being used to predict local weather events and that provide a basis for the discussion of the second objective.

Within the constraints of available computing power, the increased resolution required for the third objective must be obtained with regional numerical models. The design of such models is discussed in Chapter 4, with some comments on predictability of smaller scales of motion, the parameterization of unresolved influences, and the treatment of the planetary boundary layer.

The data requirements for short-range prediction are discussed in Chapter 5. These are divided into the requirements for immediate improvement in short-range prediction of mesoscale convective systems and the data requirements for research. The research requirements lead to discussion of a suggested experiment, which is, in fact, a component of the SESAME Project presently being planned by the National Oceanic and Atmospheric Administration (NOAA) and the university research community.

The final chapter is a summary of the aspects of short-range prediction that the Panel regards as important and a listing of the Panel's recommendations.

2 NUMERICAL WEATHER PREDICTION

The major weather services throughout the world base their forecasts on numerical weather-prediction models that simulate as accurately as possible the dynamical and physical processes that govern the evolution of the larger-scale motions of the atmosphere. Recent developments in numerical weather prediction have been surveyed by Leith (1975) and by Haltiner and Williams (1975).

The speed of presently available computers imposes a practical limit on the resolution of numerical models. A gridpoint model of the northern hemisphere, for example, is limited to a definition of variables on about five vertical levels and at horizontal gridpoints separated by about five vertical levels and at horizontal gridpoints separated by about 400 km in order that a three-day forecast can be computed in about an hour. The horizontal resolution can be increased by reducing the geographical area covered in limited-area models, although boundary errors then tend to destroy forecast skill in about two days.

The initial atmospheric state for a forecast model calculation is provided by an analysis and interpolation procedure that converts the measured values of temperature, pressure, moisture, and wind observed at a particular synoptic time at irregularly distributed locations into numerical values of variables at the regular gridpoints of the model. A combination of observing instrument errors, fluctuations of atmospheric variables on a spatial scale too small to be resolved, and interpolation errors leads inevitably to some uncertainty in the proper determination of the initial state. We shall refer to this uncertainty as the analysis error.

There have been many studies in recent years of the theoretical limit to the predictability of the atmosphere imposed by the initial analysis error. These show that, even for a model providing a perfect simulation of the atmosphere, the atmospheric dynamics would cause error to grow with a root-mean-square error doubling time of about 2.5 days or a mean-square error doubling time of 1.25 days. This effect alone for typical present initial analysis errors would provide a theoretical limit of a week or so to the range of skillful forecasts. Actual forecasts presently have a skillful range of about three days; the discrepancy arises presumably from remaining imperfections in the present numerical weather-prediction models. The first objective of the Global Atmospheric Research Program (GARP) being pursued at many research centers around the world is the identification and correction of analysis and model errors in order that the skillful range of forecasts may be extended.

Quantitative error budgets are most naturally computed in terms of mean-square error for which independent contributions are additive. A crude budget of the relative contribution of analysis errors and model errors can be based on an approximate differential equation for error growth:

$$\dot{E} = \alpha E + S, \tag{1}$$

where E is the mean-square error, $\alpha = 0.55\ \text{day}^{-1}$ is an error growth rate parameter that characterizes perfect model behavior, and S is an error source rate arising from model imperfections. Integration of Eq. (1) taking into account an analysis error E_0 of the initial and verification analyses leads to the equation

$$E_f(t) = E(t) + E_0 = 2E_0 + (E_0 + S/\alpha)(e^{\alpha t} - 1) \tag{2}$$

for the perceived mean-square error as a function of the forecast period t.

Equation (2) can be fitted to the observed error of operational forecasts of the northern hemisphere 500-mbar geopotential height field for forecast periods up to two days with the choice of parameters $E_0 = 200\ \text{m}^2$ and $S = 800\ \text{m}^2/\text{day}$. The corresponding error source is $S = 3000\ \text{m}^2/\text{day}$ for persistence forecasts in which it is assumed that no change occurs and therefore no model is used. In Table 1 are listed the root-mean-square geopotential height errors computed from Eq. (2) for several real and hypothetical forecast procedures. It is clear from the

TABLE 1 Forecast Error of the 500-mbar Height Field Computed from Eq. (2) for $\alpha = 0.55\ \text{day}^{-1}$

Forecast Method	E_0 (m^2)	S (m^2/day)	$E_0^{1/2}$ (m)	Computed rms Error $E_f^{1/2}$ (m)			
			0 Day	½ Day	1 Day	1½ Day	2 Day
Persistence	200	3000	14.1	46.8	67.4	87.5	108.3
Operational	200	800	14.1	30.4	40.2	50.2	61.0
Perfect model	200	0	14.1	21.5	23.4	25.6	28.3
Perfect analysis	0	800	0	21.5	32.7	43.2	54.0

table that model errors impose a severe limit on the range of forecast skill, but that analysis errors make an important contribution to forecast errors for the first half-day.

Although root-mean-square errors in prediction of the 500-mbar geopotential height field are commonly used as a measure of forecast skill, a measure that weights small-scale motions more heavily and is perhaps more closely related to important weather events is the root-mean-square vector velocity error. When Eq. (2) is fitted to velocity error variance it is found that $E_0 = 15$ (m/sec)^2 and $S = 15$ (m/sec)^2 day^{-1}. The dimensionless ratio $E_0/(S/\alpha)$, which measures the relative asymptotic importance of analysis and model errors, is thus about 0.55 for velocity variance, whereas it is about 0.14 for geopotential height errors. Velocity forecast accuracy is four times more sensitive to analysis errors relative to model errors than is geopotential height forecast accuracy. This difference arises from the two facts that analysis is relatively poorer for velocity and that relatively large model errors in planetary scales are more important for height forecasts.

The numerical weather-prediction models in common use are based on the so-called primitive equations, which are general enough to describe rapidly moving gravity-wave modes. Although such modes probably do occur in the atmosphere, they do not have amplitudes as large as those induced by analysis errors. The nonlinear nature of the dynamical equations has made it difficult to identify and to remove erroneous gravity-wave modes in the initial analysis, and these produce unrealistic starting transient oscillations, which are normally damped out during the first day of the forecast. These initial errors, which arise from a partial incompatibility of the analysis procedure and the model, are not taken into account in the simple error budget of Eq. (1), but they can be particularly important for forecasts up to 12 hours.

Another effect not taken into account in Eqs. (1) and (2) is the nonlinear bound on error growth, which limits E to a value determined by the natural climatic variance. Equation (2) should therefore not be used for forecast periods beyond about 2 days.

A key problem at the present stage of development of numerical weather-prediction models is the identification of the kinds of error that are contributing to the model error source rate S. These may be either numerical errors introduced by the finite numerical approximations to the continuous dynamical equations or physical errors in which the dynamical equations themselves are incomplete or incorrect in describing atmospheric behavior. Although the distinction between these two kinds of error source cannot be made precise, they seem to be of comparable importance in present models.

Among numerical errors, those arising from limited horizontal resolution seem to be dominant. In second-order gridpoint models with grid interval Δx one finds that advected waves of wavelength λ and wavenumber $k = 2\pi/\lambda$ are erroneously slowed down by a factor $[1 - (k\Delta x)^2/6]$ (Grotjahn and O'Brien, 1976). The resulting numerical dispersion leads to erroneous group velocities for wave energy transfer and to the erroneous breaking up of localized structures. This numerical dispersion error is ameliorated in fourth-order gridpoint models and removed entirely in spectral models in which horizontal fields are represented by an expansion in surface spherical harmonic functions.

Although spectral models are free of linear dispersion errors, there remain nonlinear errors arising from truncation. These have been studied by Puri and Bourke (1974), who analyzed the separation of solutions of barotropic spectral models differing only in truncation. From their experiments, one can estimate that horizontal truncation errors provide an error source rate of $S = 150\ m^2/day$ in a simple barotropic model with a truncation at wavenumber $J = 30$ corresponding roughly to a 200-km grid interval. Their experiments with differing resolutions suggest that this contribution to S is proportional to J^{-2}, as expected from simple scaling arguments for truncation in a -3 power range of the energy spectrum (Meriless, 1977). Their results suggest, therefore, that the horizontal truncation errors of present models with a 400-km grid interval can be making an important contribution to the observed error source rate and that an increase in resolution by a factor of 2 is needed before other error source mechanisms can be easily identified.

As has already been pointed out, a factor of 2 increase in horizontal resolution is available at a given computing power by the use of limited-area fine-mesh models (LFM). Although boundary errors penetrate the limited area used, the LFM models are useful for forecast periods up to a day or so and can provide a basis for identifying other general model error sources. Use of evolving boundary values obtained from a coarse-mesh hemispheric model, run 12 hours earlier, has recently increased the skillful range of the National Weather Service's LFM model to 48 hours. The introduction at the National Meteorological Center (NMC) of the very fine-mesh (VFM) model with a further factor of 2 increase in horizontal resolution over that of the LFM model is, of course, a step in the right direction. (See Recommendation I.1.)

3 STATISTICAL METHODS

Many weather variables of practical interest such as daily maximum temperature in a city or visibility at an airport are not computed explicitly in a numerical weather-prediction model, and those variables that are computed explicitly may be subject to systematic errors. To the extent, however, that weather variables are found to be significantly correlated with certain model variables, classical statistical linear regression provides an objective method by which weather variables may be predicted using computed forecast model variables as predictors. A recent survey of the application of such model output statistics (MOS) methods to the forecasting of local weather has been provided by Klein and Glahn (1974).

General linear regression provides an estimate $\vec{\hat{y}}$ of a column vector $\vec{y}$ of predictand anomalies as a linear function $\vec{\hat{y}} = \vec{R}\vec{x}$ of a column vector $\vec{x}$ of predictor anomalies. The regression matrix $\vec{R}$ is determined by the requirement that the components of the unpredictable residual $(\vec{y} - \vec{\hat{y}})$ are uncorrelated with the components of $\vec{x}$ so that

$$\vec{O} = \langle (\vec{y} - \vec{\hat{y}})\vec{x}^* \rangle = \langle \vec{y}\vec{x}^* \rangle - \vec{R}\langle \vec{x}\vec{x}^* \rangle$$

and thus that

$$\vec{R} = \langle \vec{y}\vec{x}^* \rangle \langle \vec{x}\vec{x}^* \rangle^{-1}.$$

Here $\vec{x}$ and $\vec{y}$ being anomalies their ensemble means vanish, $\langle \vec{x} \rangle = \langle \vec{y} \rangle = 0$; an asterisk indicates a transpose so that $\vec{x}^*$ is a row vector; and $\langle \vec{y}\vec{x}^* \rangle$ and $\langle \vec{x}\vec{x}^* \rangle$ are covariance matrices of which only $\langle \vec{x}\vec{x}^* \rangle$ need be square.

In practice, the infinite ensemble averages indicated by the brackets $\langle\ \rangle$ are not known but must be estimated from a finite sample of many cases of which N, say, are effectively independent. Theoretical analysis of the effect of sampling errors on the utility of a regression equation is still incomplete, but it indicates that sampling errors increase the fractional variance of estimation of a predictand by an amount $(k + 1)/N$, where k is the number of predictors used. Thus unless a particular predictor leads to a real incremental reduction in fractional variance by an amount $1/N$, it is not worth using. For meteorological time series an effectively independent sample occurs about once every three to eight days, depending on geographical location (Madden, 1976).

The regression equations for MOS methods are developed from a data base of as many past forecasts as are available for a particular numerical model. Sampling errors associated with such a finite data base seem to limit the number of significant predictors for each predictand to be of order ten, and stepwise screening procedures have been developed to select a significant group of predictors. In this screening process, model output predictors must compete with other potential predictors taken from any observations available before the time that the forecast is made. It is important to note that the regression equations provide automatically for at least a partial correction of those systematic model errors that have been revealed empirically in the available past forecasts.

An important aspect of regression methods is that they can provide forecast information in probabilistic terms. Thus forecasts can be given of a best estimate of a meteorological variable together with an associated measure of uncertainly such as the standard or root-mean-square error of the estimate, or they can be given in terms of the probability of occurrence of various weather events. It is this kind of probabilistic information that is of value as input to the decision-making process of users who wish to maximize their expected gain or to minimize their expected loss.

A number of combined dynamical and statistical methods are currently being used by the National Weather Service in the operational forecasts of severe weather up to 24 hours in advance. These utilize a number of different numerical models and choices of predictors.

Forecasters have traditionally associated the occurrence of severe weather with moist hydrostatic instability of the atmosphere, and numerical indices quantifying potential instability are natural choices as predictors. The various indices that have been used operationally have been summarized by Alaka *et al.* (1973). Among these are the Showalter (1953) index, which was supplanted in 1969 by the lifted index (Galway, 1956; Stackpole, 1967), the *K*-index (George *et al.*, 1960), the Alaka-Reap index (Reap and Alaka, 1969), the tornado likelihood index (Willis, 1969), and the total totals and sweat indices (Miller, 1972). A new predictor is suggested by the work of Darkow and Livingston (1975), who have shown that the small-scale variation in the surface static energy field may also bear a relationship to the location and timing of severe storm activity.

Operational forecasting procedures developed in the Techniques Development Laboratory (TDL) of the National Weather Service combine several of these indices with predictors taken from three operational numerical prediction models, namely, the primitive equation (PE) model (Shuman and Hovermale, 1968), the limited-area fine-mesh (LFM) model (Howcraft, 1971), and the trajectory (TJ) model (Reap, 1972). The MOS procedure uses a linear regression prediction equation based on a screening, selection, and weighting of the best of these available predictors (Reap, 1974; Reap and Foster, 1975).

At present, such 24-hour forecasts, which give probabilities of thunderstorms and conditional probabilities of severe thunderstorms, are produced at the NMC in Washington, D.C., and transmitted once daily to the National Severe Storms Forecast Center (NSSFC) in Kansas City. A typical forecast is shown in Figure 1.

Another procedure, developed by Miller and David (1971) and David (1973) at NSSFC, uses multiple screening regression to derive equations for forecasting severe weather up to 30 hours in advance. The predictors in this case are synoptic rawinsonde and surface observations at the initial time and forecast values taken from the PE model.

On a smaller scale, Charba (1974, 1975) has used multiple screening regression to develop an objective method that yields forecasts of severe weather from two to six hours in advance in square areas 150 km on a side. In the most recent version of the method, predictors are derived from observed surface atmospheric variables, manually digitized radar data, local climatic frequencies of severe weather, and basic variables as predicted by the LFM model. Predictor quantities computed from these data are appropriately positioned relative to the predictand areas and are "linearized" to enhance their correlations with the predictand.

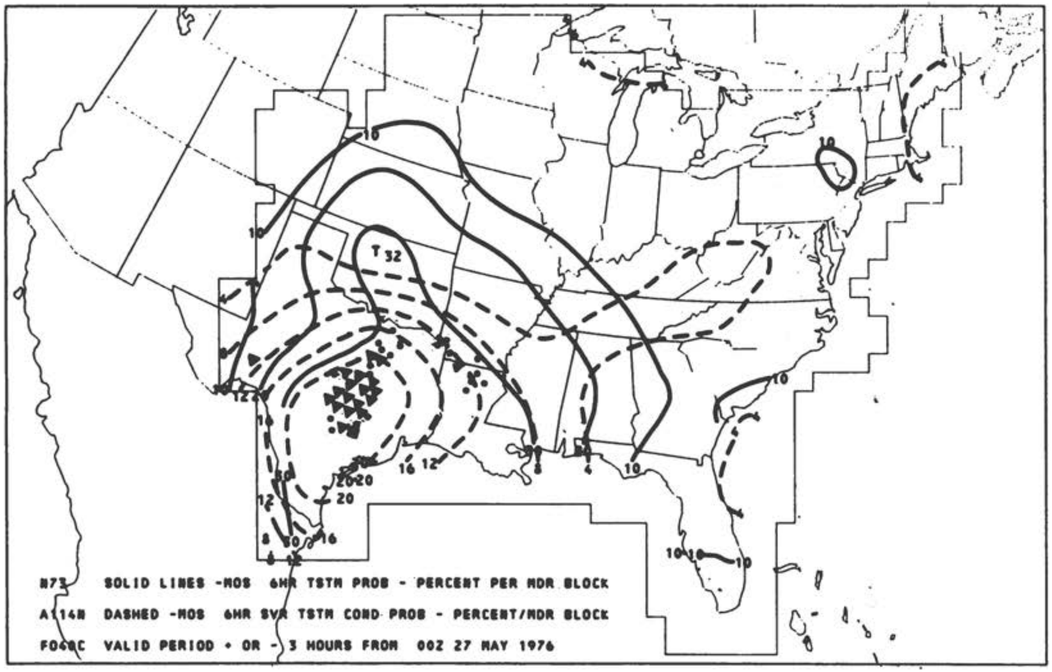

FIGURE 1 Computer-drawn map of thunderstorm probability (solid) and conditional probability of tornadoes, large hail, or damaging winds (dashed). The probabilities are valid for each manually digitized radar (MDR) block during the 21-27 hour interval following 0000 GMT initial time or ± 3 hours from 0000 GMT the next day. Observed tornadoes, ▼; hail, ●; and damaging winds, ■ .

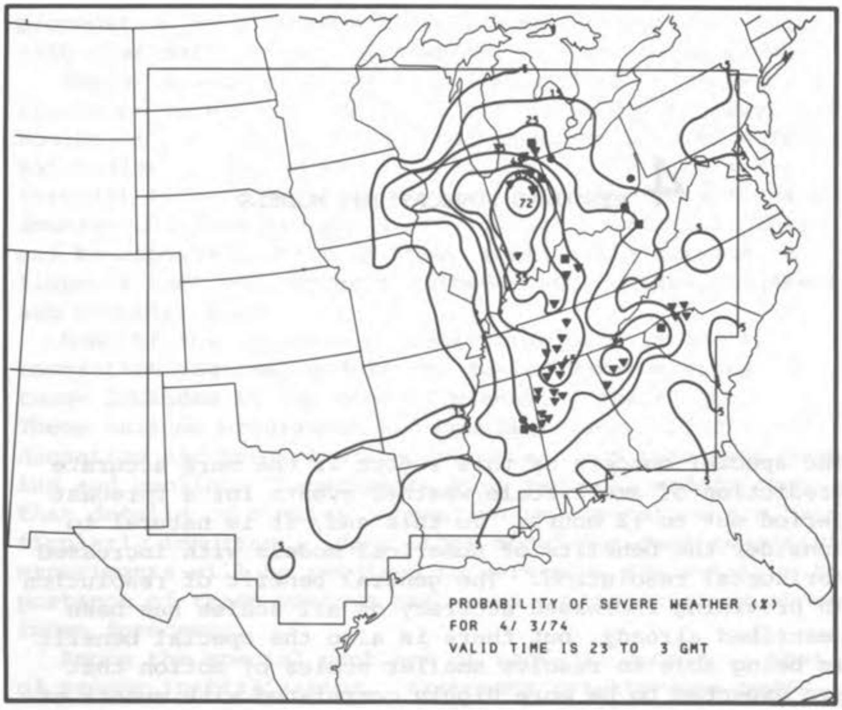

FIGURE 2 Two- to six-hour probability of severe weather. The severe weather reports plotted are valid for the forecast period. The symbols are ▼, tornado; ●, hail ≥ 3/4-in. diameter; and ■, damaging surface wind gusts.

During the spring and summer of 1974, experimental forecasts valid for 17-21 CST, produced by this scheme, were transmitted from NMC to NSSFC. In 1975, forecasts were transmitted three times daily; these were valid at 11-15 CST, 14-18 CST, and 17-21 CST. The sample forecast shown in Figure 2 is for the extensive tornado outbreak of April 3, 1974. In 1976, forecasts were prepared by an improved scheme based on predictors obtained from manually digitized radar reports, LFM forecasts, and objectively analyzed surface data. (See Recommendation I.2.)

4 REGIONAL FORECASTING MODELS

The special concern of this report is the more accurate prediction of small-scale weather events for a forecast period out to 12 hours. To this end, it is natural to consider the benefits of numerical models with increased horizontal resolution. The general benefit of resolution in providing increased accuracy on all scales has been described already, but there is also the special benefit in being able to resolve smaller scales of motion that are expected to be more highly correlated with events of interest. The benefit can be measured by the greater value of the predictors provided by the model to the regression process leading specifically to more sharply defined probabilities of occurrence of small-scale events.

For this improved skill to be realized, it is necessary, of course, that the finer resolution regional models describe the detailed behavior of the atmosphere more accurately. As with coarser models, this capability depends on the accuracy of the observation and analysis of the initial state and on the accuracy of the model in simulating the behavior of the atmosphere.

The relative importance of an accurate initial analysis depends on the characteristic lifetimes of smaller-scale structures in the atmosphere. According to theoretical scaling arguments based on a -3 power energy spectrum and on direct observations, the characteristic lifetime of disturbances in a Lagrangian sense is of the order of a day and is not strongly scale-dependent for scales down to about 50 km. At a fixed observing station or model gridpoint, however, the Eulerian lifetime of a disturbance is determined by advection processes and is shorter in proportion to its scale. For short-range prediction models, the principal requirement is for the advection and propagation of disturbances to be computed with an accuracy that matches that with which they can be observed.

There is some evidence from the studies of the sensitivity of forecasting skill to model resolution (Puri and Bourke, 1974) that the nonlinear coupling between different scales of motion can lead in the course of a model forecast to more skill in the description of small-scale details that was present in the initial analysis. This may be especially true if known small-scale surface influences such as orography, albedo, and surface roughness are properly modeled.

Most of the physical processes included in the finer resolution regional models are scaled-down versions of those included in the coarser planetary scale models. These include orographic and boundary-layer effects, condensation and precipitation processes, and radiative heating and cooling. Experiments with regional models show that details of cumulus convective precipitation are particularly important. Many other model forecast sensitivity experiments will be required to determine the relative importance of these various processes to the skill of short-range forecasts.

Among the special problems of regional models is that of proper initialization. Erroneous gravity-wave modes with associated vertical motion can trigger erroneous convective-scale disturbances. This is an especially delicate problem, since there is some evidence that real gravity-wave modes may do just that, and one must try to remove a false effect without removing a real one.

Another special problem of regional models is that of embedding them in a larger-scale flow. This has been done by choosing boundary values for a regional model from a concurrent forecast carried out with a coarser model. Some mathematical and numerical problems remain in the proper specification of such boundary conditions. It is theoretically desirable to permit the regional model results to influence, in turn, the coarser model, and such two-way interaction schemes are being investigated. Although spectral models permit in many ways a more natural separation of scales, little work has been done on the problem of embedding a regional spectral model into one treating larger scales. (See Recommendation I.3.)

PARAMETERIZATION AND EMPIRICAL CORRECTION

In addition to the explicitly computed variables in an atmospheric model, the real atmosphere is influenced by many subgrid-scale variables that describe scales of motion or physical processes that are too small to be resolved. Even the explicit variables may be influencing the atmosphere through processes that are not properly described in the model. A central problem in model development has been the devising of parameterization procedures to estimate the average influence of hidden variable and processes on the evolution of the explicitly computed variables. Most efforts to solve this problem have examined separately different physical processes such as convection, boundary-layer turbulence, or radiative heat transfer. An alternate approach is to seek an empirically determined modification of the dynamical equations of the model in order to account for all the hidden effects that are causing model forecast errors.

The first-order modification involves the addition of forcing terms to the model dynamical equations in order to counteract any tendency for the mean field of an ensemble of forecasts to drift away from the observed climate mean field. Such forcing terms preserve the first moment properties of the atmosphere in the forecast model and can be interpreted as a parameterization of the many fixed or slowly changing surface-forcing influences that determine the mean climate. In this way, for example, the surface temperature averaged over many forecasts would reproduce the observed mean diurnal temperature cycle.

The second-order modification involves the addition of terms linear in the model variables, which are the regression estimates of the discrepancies between the observed and computed rates of change. Such linear terms can be shown theoretically to preserve in the forecast model the zero-time-lag second-moment properties of the atmosphere such as the distribution of variance over different scales. They can be interpreted as the best empirical linear fit to the parameterization of hidden effects in terms of model variables. The practical determination of a second-order modification is subject to the sampling error limitations of any regression estimate that were described in Chapter 3. It is necessary to find by a judicious screening process the few most significant predictors for each predictand, and it is not yet clear how effectively this can be done for existing forecasting models. It seems likely, however, that since correlations are local the choice of predictors will be more effective in a gridpoint rather than in a spectral representation of model variables. Higher-order modification is probably not feasible with present models, but it is not so important for short-range as for extended-range forecasts.

BOUNDARY-LAYER MODELS

Processes in the planetary boundary layer are known to have an important effect on the occurrence and severity of convective storms. And, of course, the values of meteorological variables in the boundary layer are those that affect the most people. The planetary boundary layer is characterized by its turbulent behavior, which is produced by thermal convection and mechanical shearing processes. It undergoes the most pronounced diurnal variation of any region of the lower atmosphere.

The special problems of devising numerical models of the planetary boundary layer include the detailed balancing of solar and terrestrial radiative heating and cooling effects; the estimation of the divergence of vertical turbulent fluxes of heat, moisture, and momentum; and the proper specification of large-scale forcing influences. Much progress has been made in recent years in the development of such models that have succeeded in simulating the diurnal change in boundary-layer properties in agreement with data from a number of experiments carried out in selected areas.

The most complex of the boundary-layer models (e.g., Deardorff, 1972) compute rather detailed three-dimensional flow, temperature, and moisture fields and would be far too computationally expensive to cover the domain of interest for regional forecasts. The complex models are being used to test simpler schemes for making boundary-layer forecasts that can be included in regional forecasting models. Such schemes produce predictions of the mean value of wind, temperature, and humidity in the boundary layer within the context of a regional-scale model. A boundary-layer model, which will contain 10 levels, is being developed by the National Weather Service's Techniques Development Laboratory for operational implementation at the National Meteorological Center. Predictions from the model should be valuable in their own right and as input to MOS forecasts of thunderstorm probability.

5 DATA REQUIREMENTS

In stating data requirements for short-range prediction, it is necessary to take account of the size and nature of the phenomena to be predicted, the technological and economic feasibility of the required observing systems, and the purpose for which the data are gathered, whether for operational use or research. Ideally, one would like to observe all pertinent atmospheric variables with sufficient density, frequency, and accuracy to resolve completely the phenomena under consideration. For many of the mesoscale systems of importance in short-range prediction, observations with a horizontal spacing of 10 km or less are required to achieve this objective. Even if the technological means could be found to obtain meaningful descriptions of atmospheric fields on such a small scale, the costs of maintaining a suitable network of regular observations covering a substantial geographic area would be prohibitive. Clearly, any practical statement of data requirements for short-range prediction must recognize the severe technological and economic constraints involved and must differentiate between operational and research goals.

This report focuses on the mesoscale patterns connected with convective activity and severe storms, which may generate thunderstorms, tornadoes, hail, strong winds, and heavy rains. The basic purpose of this report is to suggest means for improved prediction of the mesoscale systems, in both the short term, through application of presently available technology, and in the long term, through research that will increase knowledge and understanding of the mesoscale systems and their interactions with larger- and smaller-scale systems. It thus seems appropriate to consider observational requirements from the point of view of both short- and long-term objectives.

A. DATA REQUIREMENTS FOR IMMEDIATE IMPROVEMENT IN SHORT-RANGE PREDICTION OF MESOSCALE CONVECTIVE SYSTEMS

Short-term advances in prediction can be pursued by following three promising routes: (1) better identification and tracking of the mesoscale features, (2) development of better statistical relationships between severe-storm occurrence and synoptic-scale fields, and (3) development of improved limited-area, fine-mesh numerical prediction models for more accurate prediction of the larger-scale environmental changes that determine and control the convective activity. The associated data requirements are as follows.

1. Identification and Tracking of the Mesoscale Features

Weather surveillance radars (10 cm) and geostationary satellites offer the best tools for monitoring convective activity. (See Recommendation I.4.) Radar display should indicate echo depth and intensity, and a search should be continued for even better radar indicators of severe-storm activity. Surveillance should be continuous during periods of severe weather. Geostationary satellite digitized images, both visible and infrared, should be provided at half-hourly intervals, with resolution of about one mile for the visible and five miles for the infrared. Infrared data should give equivalent blackbody or cloud-top temperatures. (See Recommendation I.5.)

2. Statistical Prediction

The development of short-range forecast schemes based on regression equations requires large samples of data covering more than one storm season. Currently available data that are useful in such schemes are (1) conventional hourly surface observations, (2) fields computed from numerical prediction models, (3) manually digitized radar (MDR) data, and (4) reported occurrences of severe weather. Required data that are not currently available with complete coverage of the severe storm belt of the United States are (1) automatically digitized radar data; (2) digitized satellite data (visual imagery and cloud-top temperatures from one- to five-mile resolutions and three-hour time intervals; and (3) any wind, temperature, and moisture data in the middle and lower troposphere that could be used to derive diagnostic meteorological fields accurately with a three-hour frequency and corresponding spatial resolution. Quantitative satellite and aircraft measurements are potential sources of such data.

For operational purposes, most of the listed data would be needed within two hours or less of the observation time.

3. Limited-Area Fine-Mesh Prediction Models (LFM)

Conventional surface and upper-air observations are the current sources of data for fine-mesh models. Since the existing upper-air network was established with the purpose of delineating larger, synoptic-scale features, it is too coarse for detecting the large mesoscale systems that may influence severe-storm development. Consequently, it may be presumed that a denser grid network would lead to more accurate and useful predictions of the conditions that spawn convective outbreaks. However, it would seem premature to recommend additions to the upper-air observing network until more is known about the performance of the LFM's in convective situations and also until more is known of how the performance is affected by the grid spacing. Simply put, no sound guidelines exist at this time for recommending a finer observational grid for routine use. Until suitable experiments are run to yield the required information on the effect of grid spacing on forecast accuracy, it seems advisable to maintain the networks in their present form.

Plans are currently under way at the Technique Development Laboratory of the National Weather Service to run an operational boundary-layer model in conjunction with the National Meteorological Center's LFM, the latter being used to provide lateral and upper boundary conditions for the former. Data requirements are similar to those of the larger model, except that more horizontal resolution is needed. Horizontal resolution may be aided by using output from the previous forecast. Initialization requires fairly detailed profiles of temperature, wind, and humidity from the surface to 2 km. Approximately 10 levels of data with conventional accuracy will suffice. Additional desirable initial data include (1) rainfall from the previous day; (2) soil temperature; (3) cloud analysis, including not only clouds within the lowest several kilometers but also cloud cover (high, middle, and low fraction) above the boundary layer; (4) geostrophic winds; and

(5) tendencies of the wind vector, temperature, and moisture for use in a variational initialization technique. Remote sensing of clouds and water vapor from satellites should provide much of this information.

Since much of the severe weather in the central United States occurs between 21Z and 03Z, it is probable that upper-air data at 18Z would greatly benefit short-range forecasting. Therefore, consideration should be given to the addition of routine rawinsonde observations at 18Z in the central United States during the severe storm season. Dynamical and statistical techniques would have to be developed to utilize these data, and at least two seasons' data will be needed to develop and test the techniques. This data collection would cost about $100,000 per month (22 sites, 30 soundings, $150 per sounding). These data could be used for

1. A last-minute update for statistical prediction schemes valid in the 21Z-06Z time interval.
2. An up-to-date three-dimensional synoptic-scale data base on which the midday and afternoon satellite and radar data can be superimposed for more complete interpolation and as ground truth for calibration of operational satellite data.
3. A test of the benefits of reinitializing the LFM and boundary-layer models with midday observations.
4. An improved synoptic-scale data base for use in analysis of severe storm field experiments of NOAA and NASA.

B. DATA REQUIREMENTS FOR RESEARCH IN SHORT-RANGE PREDICTION OF MESOSCALE PATTERNS

The following data requirements are stated with specific research objectives in mind. These objectives are (1) to describe more clearly the mesoscale thermodynamic and kinematic structures associated with organized intense convective systems that produce severe weather including tornadoes; (2) to define the key atmospheric phenomena or processes responsible for organizing these mesoscale structures and determine their relationship to the larger scales; and (3) to develop an improved capability for forecasting where and when these mesoscale convective patterns will form and the movement and structural changes of already existing patterns.

To carry out these objectives requires the establishment of special data-gathering networks and the use of the most sophisticated instrumentation available. To keep costs within bounds, the data gathering must be limited both in time and space. A region of about 1 million km^2 in which severe storms have a high probability of occurrence, and in which special observational facilities already exist, and a time period of two or three months during the season of greatest activity would seem desirable for an initial experiment. It is expected that the data obtained would be used to test and improve fine-mesh numerical prediction models and to develop models of smaller convective features whose structure cannot be resolved with the fine-mesh grids but whose behavior can be related to resolvable larger-scale features.

The data requirements are as follows.

1. Surface Observations

Wind, temperature, humidity, pressure and precipitation rate, cloud cover, and cloud base height are required with the usual accuracy and frequency at regular synoptic stations. Continuous recordings of the first five elements, with microbarographs used for pressure, are needed in a special network of more closely spaced stations. Some 100 stations spaced about 25 km apart are desirable.

2. Rawinsonde Observations

Supplementary rawinsonde measurements are needed within the roughly 1 million km^2 experimental area. The number added should be sufficient to reduce the spacing between the regular stations by a factor of 2 or more. A mesh size of about 200 km, requiring about 25 additional stations, is desirable. The rawinsondes will measure wind, temperature, pressure, and humidity with the usual accuracy. Releases should be made every three hours during disturbed weather or upon its approach.

3. Indirect Sensors

High-resolution satellite photos, visual and infrared, and surface temperature are required at half-hour intervals. Also required are vertical temperature and moisture soundings and cloud wind measurements at hourly intervals. Effective blackbody or cloud-top temperatures are required in digital form. Geostationary satellites will be capable of providing these data in the near future.

Four types of radar data are required: (1) composite digitized echo maps that give a three-dimensional representation of the echoes, (2) dual Doppler radar measurements of horizontal wind fields, (3) dual-wavelength radar measurements of liquid water, and (4) FM cw radar measurements of the fine structure of precipitation and the structure of gravity waves and other small-scale features of the clear air.

4. Boundary-Layer Observations

The proposed special rawinsonde network would provide valuable boundary-layer data. Within a limited region, these data should be supplemented by acoustic soundings, which will give a record of boundary-layer depth, by measurements of fluxes of heat, moisture, and momentum by gust-probe aircraft and by measurements of ground temperature made radiometrically from aircraft. Flux measurements from a central mast would also be useful. Solar and terrestrial radiation measurements are needed with sufficient accuracy to determine radiative flux divergences.

5. Terrain Description

Data are required on terrain height, large-scale surface roughness length, surface albedo, average soil conductivity, and heat capacity and soil moisture.

C. SESAME PROGRAM

There is presently being planned within the Environmental Research Laboratories of NOAA the SESAME Scientific Program with the principal aim of "observing, experimentally predicting, and understanding the formation, evolution, and meteorological impact of severe convective storms." The major observational components of the SESAME program are two multiscale experiments planned for the springs of 1980 and 1982. Two preliminary experiments are also planned: the first, a boundary-layer systems test in 1978; the second, a regional-scale experiment in the spring of

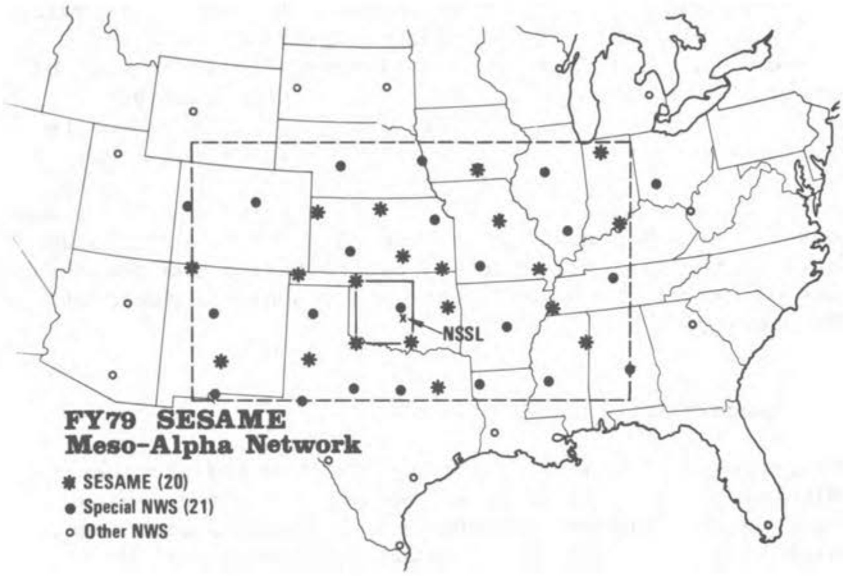

FIGURE 3 SESAME rawinsonde network for 1979 regional-scale experiment [from Figure 3.3 of Project Severe Environmental Storms and Mesocale Experiment (Environmental Research Laboratories, National Oceanic and Atmospheric Administration, 1976)]

1979. In the regional-scale experiment, about 20 rawinsonde stations would be added over the central United States to reduce spacing to about 200 km, as shown in Figure 3. The resulting data set is to be used primarily for the initialization and testing of regional models during periods of anticipated strong convection. The special merit of conducting the regional-scale experiment during 1979 lies in the existence during that time of the enhanced data network over midlatitude oceans provided by the First GARP Global Experiment (FGGE). The SESAME program provides the best opportunity to satisfy the data requirements for research in short-range prediction of mesoscale patterns described in Section B, above. Therefore, the Panel strongly endorses the SESAME program and, in particular, the conduct of the regional rawinsonde experiment in the spring of 1979.

6 SUMMARY AND RECOMMENDATIONS

The most important steps that could be taken immediately to improve prediction of severe storms are (1) better detection and tracking of convective activity, (2) development of better statistical relationships between convective storms and the large mesoscale disturbances that produce them, and (3) an improvement in the dynamical prediction of these large mesoscale disturbances. The Panel on Severe Storms has dealt fully with Item (1) in its report, which constitutes Part II of this document. *This Panel strongly endorses the recommendations of the Panel on Severe Storms relating to the importance of developing and applying the various new sensing schemes to the identification and tracking of convective activity and to the importance of designing an effective warning system.*

An analysis of recent experience with numerical weather-prediction models indicates that horizontal resolution is of great importance to the improvement of forecast skill.

Recommendation I.1. The Panel recommends, in light of the marked improvement in skill of the limited-area fine-mesh model (LFM), that a study by the National Oceanic and Atmospheric Administration be made of the potential benefits in providing greater computing power to the National Meteorological Center for a further increase in model resolution.

The present use of statistical relationships in predicting regional probabilities of severe storm outbreaks has led to a considerable improvement in skill beyond that achievable by purely dynamical methods.

Recommendation I.2. The Panel strongly recommends the continued development of combined statistical-dynamical methods of objective forecasting such as the method of model output statistics.

The use of statistical approaches to the parameterization and empirical correction of dynamical models should be explored further.

Higher-resolution regional models are able to resolve smaller scales of motion. These scales are expected to be more highly correlated with events of interest and thus to provide more valuable predictors for statistical regression and to lead specifically to more sharply defined probabilities of occurrence of small-scale events.

Recommendation I.3. The Panel strongly recommends the continued development of mesoscale regional models by a number of research groups and urges their use for predictability and observing system simulation experiments of the sort that have been carried out with planetary scale models.

Two important data sources that will contribute to the better identification and tracking of mesoscale and convective activity are weather surveillance radars (10 cm) and geostationary satellites.

Recommendation I.4. The Panel recommends that automatically digitized radar data be provided with complete coverage of the areas of the United States susceptible to severe storm development.

Boundary-layer research will contribute in an important way to the development of mesoscale models.

Recommendation I.5. The Panel recommends that geostationary satellite digitized images, both visible and infrared, be provided at half-hourly intervals, with the highest possible resolution.

Much of the severe weather in the central United States occurs between 21Z and 03Z, and it is probable that upper-air data at 18Z would greatly benefit short-range forecasting if utilized with proper dynamical and statistical techniques.

Recommendation I.6. The Panel recommends that consideration be given to the addition of routine rawinsonde observations at 18Z in the central United States during the severe storm season.

An early experiment in the SESAME Scientific Program is a regional-scale experiment with a doubling of the density of rawinsonde stations over the central United States.

This experiment contributes directly to the understanding of the statistical relationships between convective storms and the large mesoscale disturbances that produce them. *The Panel strongly endorses the SESAME Program and, in particular, the conduct of the regional rawinsonde experiment in the spring of 1979.*

II
Report of the Panel on Severe Storms

7 INTRODUCTION

The Panel on Severe Storms of the Committee on Atmospheric Sciences was set up in the summer of 1973 to review the field of severe storms, with particular reference to severe thunderstorms and tornadoes. Recognizing that a related Panel on Short-Range Forecasting was concerning itself (in part) with the forecasting of severe storms, this Panel has concentrated on the other phases most critical to a warning service; namely, severe-storm monitoring and the preparation and dissemination of warnings. Chapter 8 serves as an introduction to the problem, summarizes some of the principal relevant factors of severe thunderstorms, and examines the need for a warning service. Chapter 9 emphasizes the systems approach to the design of the warning system and urges that primary attention be given to the user needs and to the detailed specification of the services required. Only when these warning services have been fully specified does it become practicable to determine the optimum weather observing, data processing, and telecommunication systems. Chapter 10 reviews the environmental monitoring system, with particular reference to the potential benefits of providing NWS and AWS weather radars with Doppler wind-sensing capability, to enable identification of regions possessing unusually high velocities, velocity shear, vorticity, and turbulence. Chapter 11 stresses the role of communication facilities and the warning message characteristics in the delivery of warning services. The final chapter summarizes the issues that have come to the attention of the Panel and presents recommendations for the next steps in resolving these issues.

8 SEVERE STORMS AND THE NEED FOR A WARNING SERVICE

In any one year, some 100,000 thunderstorms occur within the 48 contiguous states of the United States. The vast majority of these cause no damage and, indeed, provide great benefit through their precipitation--it is estimated that approximately 50 percent of the summer precipitation so essential to agriculture comes from thunderstorms. Nevertheless, severe thunderstorms represent one of the greatest of the geophysical hazards. White and Haas (1975) present the available statistics for the 15 principal natural hazards in the United States. Their data show that, if we combine the tornado, hail, and lightning components of the severe-storm hazard, severe storms are first in deaths, second in injuries, and third in property damage. (Addition of the flash flood and strong wind components of thunderstorm hazards would have increased the relative magnitude of the severe-storm losses, but these figures are not separately available, being grouped with losses from other forms of flood or damaging wind, respectively.)

The peak intensities of the lightning, precipitation, winds, and hail associated with a storm vary enormously from storm to storm and with position within the storm. Given this wide range in the intensity of the meteorological phenomena involved, and the fact that thunderstorms are common in many parts of the United States, our society evolves so that the median storm causes very little damage. On the other hand, the most extreme storms are so much more severe and occur so infrequently at any one location that we have little opportunity or economic incentive to develop immunity to them. As a result, such storms are likely to cause considerable local damage. Thus, in a very real sense it is natural that about 10 percent of the thunderstorms are designated by the National Weather Service as "severe" because the winds, hail, or precipitation associated with them are sufficient to cause some damage. Further, roughly 10 percent of these severe storms have embedded in them small regions of extremely high velocity, circulating winds, or vortices (known as tornadoes), which can damage or destroy almost everything in their path.

In considering the severe-storm and tornado warning problem, it is essential to recognize the great variability that exists within the total population of tornadoes. Although approximately 700 to 1200 tornadoes occur within the United States each year, most of them are relatively weak and short-lived. This majority of small tornadoes typically lasts only a minute or two and causes relatively little damage over a track often not more than 100 m wide and less than 2 km in length. Because of their short life and small dimensions, the issuance of a timely warning in these cases is difficult. On the other hand, the vast majority of tornadic deaths, injuries, and property damage are caused by the relatively infrequent, large, and long-enduring tornadoes whose paths may be up to 2 km in width and 160 km or more in length. These destructive tornadoes can last up to three hours and, therefore, are much easier to track and warn against than the more common but, fortunately, much less damaging, short-lived, small tornadoes.

The extreme variability of tornadoes is well brought out in the study by Fujita (1975a) of the major outbreak of tornadoes that occurred on April 3-4, 1974. (See map at end of this report.) This outbreak was the most severe in recorded history in terms of total number of tornadoes, the length of their tracks, the total area affected, and the total damage incurred. Some 315 persons were killed and over 5400 injured; property losses were estimated by the Defense Civil Preparedness Agency at $600 million, and over 27,000 families were affected. Another indicator of the severity of the outbreak is that at one time at least 15 different tornadoes were on the ground simultaneously.

Most of the 148 tornadoes located by Professor Fujita from his aerial and ground observations of this outbreak caused relatively little damage. Thus, taken together, the least destructive half of the tornadoes caused less than 1 percent of the casualties (injured or killed); two thirds of the tornadoes caused no deaths, and almost one half caused neither death nor injury. On the other hand, more than half of the deaths were caused by less than 5 percent of the tornadoes (the worst single tornado struck Xenia, Ohio, killing 34 persons and injuring 1150). The six most destructive tornadoes each had paths longer than 50 km; in two cases, the paths exceeded 160 km.

Although tornadoes are the most dramatic of the severe-storm hazards, major damage can also be caused by flash floods, hail, strong winds, and lightning. The extreme variability in total damage caused by individual tornadoes is paralleled by similar variability in each of the other hazards. Thus, while most thunderstorms cause essentially no damage, the most severe storms can devastate agricultural areas by hail and high winds, and flash floods resulting from intense precipitation can cause major loss of life as well as large agricultural losses. For example, the June 9-10, 1972, flash flood in the Rapid City area of South Dakota resulted in the loss of 237 lives and over 3000 injured; and the recent (July 31, 1976) Big Thompson Canyon flash flood west of Loveland, Colorado, is known to have killed at least 138 persons with another 12 persons still missing and believed to have died. In another example, over $50 million of damage to crops was caused on October 10, 1973, in the Enid area of Oklahoma as a result of thunderstorm precipitation amounting to almost 500 mm in about 12 hours.

Hailstorms in the United States are estimated to do an average of $680 million each year in crop damage alone, with most of it caused by a small percentage of the storms (Boone, 1974). For example, a single hailstorm in southeastern Missouri on July 15, 1971, destroyed or damaged between 50 and 100 percent of field crops over an area of one quarter of a million acres at a cost to the farmers of more than $17 million.

Thus, a severe-thunderstorm warning service must be able to identify those rare and exceptional events that form the extreme tail of the distribution of a common meteorological phenomenon (the thunderstorm), which occurs almost daily somewhere in the United States. Severe storms have occurred in almost every part of the conterminous United States; they have occurred at every time of the day and in each season of the year. The problem is, therefore, one of identifying rare and possibly short-lived events from among the hundreds or thousands of potentially similar storms in time to transmit and receive effective warnings and for the public to take appropriate action.

Although relatively little can yet be done to minimize the damage to crops and property caused by severe storms, experience over many years has shown that accurate and timely warnings disseminated effectively to a well-prepared public can do a great deal to reduce the numbers of persons killed or injured. Following the April 3-4, 1974, tornado outbreak (the worst in historic record), the NOAA Survey team concluded (National Oceanic and Atmospheric Administration, 1974) that "the NWS Warning System, the relay of warnings by the news media, and the protective actions taken at the community level saved thousands of lives." Examples of warnings followed by effective action that minimized or eliminated casualties abound in the reports of the April 3-4, 1974, outbreak; there are also tragic stories of ineffective warnings or warnings that went unheeded.

While the main goal of such a warning system is to save lives and prevent injuries, there are a number of possibilities of preventing or minimizing damage to property, for example, the movement of parked aircraft or vehicles and the diversion of aircraft in flight. Other preventative measures, such as alerting auxiliary power facilities in hospitals in the face of a severe storm, are also important goals of the warning system.

Improved detection techniques and quicker dissemination of messages have beneficial effects, but there is evidence to suggest that there are additional important limitations. Brouillette (1966) observed that in the 1965 Palm Sunday tornadoes, "Many persons who had received an early tornado warning took no steps to seek shelter." Also, the mayor of a small Mississippi town, warned of an impending tornado, was reportedly unsuccessful in his attempts to evacuate people to shelter--17 deaths resulted. These examples indicate that the ultimate effectiveness of a warning system rests upon those factors that determine whether the warning will be heeded.

The importance and benefits of warnings and tornado drills at schools have been brought out repeatedly in the past. The April 3-4, 1974, outbreak produced at least two more examples, quoted in the Natural Disaster Survey Report (National Oceanic and Atmospheric Administration, 1974): "In Hanover, Indiana, a high school physics teacher spent the last 25 minutes of his class on April 2 discussing tornado safety. The discussion included the danger of being hit by a tornado while in a vehicle and advocated leaving the car for a ditch or ravine. The next day a Hanover school bus was on a collision course with an approaching tornado. One of the students who'd been in that physics class convinced the driver to stop and everyone headed for a ditch. The bus was demolished but none of the passengers was injured." Or again: "Many Indiana schools were damaged. At Monroe Central High

School (10 miles east of Muncie) students were dismissed early when a watch was issued for their area. The teachers who remained posted a lookout and when a tornado was spotted they went to a predetermined interior hallway. The school was destroyed but the interior hallway remained intact and no one was injured." The absence of a similar emergency plan in Xenia makes it even more fortunate that the tornadoes that struck that city came after school hours.

9 SEVERE-STORM WARNINGS AS A SYSTEM DESIGN PROBLEM

The design or improvement of a severe-storm warning service is best undertaken using a systems engineering approach. In this method, attention is first focused on the overall objectives of the total system. Once the overall system objectives are well understood, the necessary subsystems are identified. These are then designed and carefully evaluated to ensure that each subsystem is contributing optimally to the performance of the total system. Repeated iterations of the specifications of the desired overall system performance and the design of the necessary subsystems help ensure creation of a balanced total program, in which each subsystem contributes strongly and efficiently to the performance of the whole.

Using this approach, we recognize that the overall purpose of a severe-storm warning service is to stimulate an appropriate response by the intended recipient of the warning to the occurrence of a local severe-storm hazard. It is *not* adequate to limit the overall system design to the mere dissemination of a warning to some population of users. Only when the warnings result in appropriate adaptive behavior on the part of recipients can the service be said to have been performed successfully.

This accounts for the emphasis of the National Weather Service on campaigns to enhance the ability of communities and individuals to respond to warnings. This focus on the creation of an appropriate adaptive response is critical to the design of a warning system. It ensures maximum attention to the needs of the users and requires that high priority be given to optimize the timing, nature, wording, and method of delivery of the warning messages.

It is important to recognize that the design of a warning service should proceed in a manner opposite to its operation. In designing the system, one must start with the users and identify with considerable care the specific needs for warning services. From this information, one can then identify the warning messages that are needed, helping to define the telecommunication system requirements as well as the necessary atmospheric observing system and its associated data processing and interpretation. The operation sequence, however, starts at the opposite end with observations, collation, and interpretation triggering the warning preparation and dissemination, followed then by response on the part of the user.

Mileti (1974), in an exhaustive analysis of response to flash-flood warnings in Rapid City, South Dakota, makes it clear that adaptive response to a received warning message rests on a host of determinants, most of which have yet to be explored in connection with tornado warnings (Mileti, 1975). A comprehensive review of the literature of warnings of all types revealed that there are at least 25 identified variables that directly or indirectly determine response to a hazard warning (Mileti *et al.*, 1975). The extent to which these variables and hypothesized relationships apply to all types of hazard warnings is unknown. Mileti (1975, p. 19) concludes that:

> ...little is known about: (1) whether these factors really make a difference for *all* types of natural hazards; (2) if some factors are more important than others; and (3) which factors are most important.
>
> Furthermore, several areas of concern which could be policy-relevant and central to warning system effectiveness have not been studied sufficiently in reference to natural hazards: (1) the efficacy of sirens in upgrading response; and (2) formulation of the content of the warning message to increase belief in danger but not cause fear.

Given the lack of knowledge about the receipt of tornado warning information and response to it, it is difficult to know what steps should be taken to optimize response to the tornado warnings that are released by the National Weather Service. Even with a perfect detection system, lives can be saved and injuries avoided *only if* the potential recipients actually get the warning messages. At present, what proportion of the potential recipients in an area being warned actually receive one or more warning messages? Does that proportion differ by time of day or night? Does it differ by region of the country? There are only limited documented answers to these critical questions. In the absence of such answers, policy decisions must of necessity be made on a subjective basis. This unsatisfactory situation should be changed as soon as possible by the conduct of studies designed to permit development of improved policies and practices by providing answers to such questions.

An effective warning delivery system has been defined (National Advisory Committee on Oceans and Atmosphere, 1973) as one that:

> ...must be capable of detecting an impending disaster, determining its scope, deciding on the type of warning to be issued, and disseminating the warning. On its part, the community thus warned must be prepared to take appropriate action. All of these components must function properly and quickly if lives and property are to be saved. The response time from detection to public action must be made short. While the Weather Service does not have the responsibility for public response, it shares responsibility with other agencies for final delivery to the public, and it does have the responsibility of assessing how successful to the whole is its part of the effort.

A clear, quantitative, definition of the warning service requirements, including numerical performance specifications such as indicated below, is critical to the creation of such a warning system. The definition, because it is quantitative, can be used both to guide the design and to evaluate the performance of the system. The definition of the required warning service must be established on the basis of user needs and should not be determined solely by the capabilities of present technology. This quantitative definition provides the long-range goals to guide the development of the warning service. It also must provide the framework within which different alternative technologies are evaluated and selected.

As indicated earlier, a considerable amount is now known about temporal and spatial characteristics of severe storms. This is based on observations over many years, and as a result we may state that the general nature of the hazard is well understood. What is much less understood, however, is the nature of the response of individuals to disaster warnings. Relatively little research has been conducted in this area, and, as stressed later in this report, it undoubtedly will be desirable to increase our knowledge of this aspect of the warning service as time progresses. Nevertheless, enough is known of the characteristics of the total system to warrant setting up quantitative objectives for the accuracy of the services along the lines of the following examples, which deal with the accuracy of the geographic delineation of the warned area and the timing of the messages. Obviously, the specific criteria proposed here are offered *only as examples* and should be replaced by totally new sets based on careful studies of user needs and responses.

Example 1 Possible quantitative requirements for geographical accuracy of watch, alert, and warning areas.

Total geographical area affected to be defined accurately with no errors of omission and with the outer false-alarm area to be as follows:

(a) Watch: within 50 miles of the affected area boundary for 90 percent of the events.

(b) Alert: within 20 miles of the affected area boundary for 90 percent of the events.

(c) Warning: within 5 miles of the affected area boundary for 90 percent of the events.

Example 2 Possible quantitative requirements for temporal accuracy of watch, alert, and warning periods.

If hazardous weather conditions commence in a particular area at time t_1 and cease at time t_2, 90 percent of the time watch, alert, and warning messages are issued and received by the public within the time limits specified below:

(a) Watch

Issuance of watch message: Not later than $t_1 = 4$ h

Onset of watch period: $t_1 = 2$ h to $t_1 = 1$ h

Termination of watch period: Not earlier than t_2 and not later than $t_2 + 2$ h

(b) Alert

Issurance of alert message: $t_1 = 2$ h to $t_1 = 1$ h

Onset of alert period: t_1 = 1 h to
t_1 = 0.5 h

Termination of alert period: Not earlier than t_2 and not later than t_2 + 1 h

(c) Warning
Onset of warning: t_1 = 30 min to
t_1 = 10 min

Termination of warning: Not earlier than t_2 and not later than t_2 + 30 min

Similar quantitative requirements would, of course, be required to cover the accuracy of identification of the hazard and the percentage of the populace who receive the warning.

Obviously, substantial effort will be necessary to provide quantitative definition of the required or desired warning services. All important severe-storm phenomena should be included, and quantitative parameters such as time, position, and intensity should be utilized to the maximum possible extent. Clearly, to be effective the warnings must, above all, be credible. The system must provide a high probability of detection and warning of the hazard and a minimum of false alarms. Excessive false alarms and unduly large warning areas and durations may well be among the major causes for the lack of effective response on the part of the public to the present system of warnings.

10 MONITORING SEVERE STORMS

A severe-storm warning service can be no better than the meteorological information on which it is based. Without accurate, timely observations of the relevant storm conditions, the warnings of necessity will be less specific and less valuable than they otherwise could be.

Major progress has been made since World War II in the ability to locate and monitor thunderstorms. Geostationary satellites are able to watch the developing cloud patterns even before precipitation commences and to infer a great deal as to their nature. Weather radars are able to record the position and intensity of precipitation, hence, to track the storms once they have developed. The operational problem is not only to know where the storm systems are located but to identify the location, motion, and development of any hazardous regions embedded within them. Current observational methods do not provide adequate information to permit routine, quantitative identification of such hazards. For example, the best identification of the presence of tornadoes is from the reports of human observers. However, this method is subject to many difficulties, especially at nighttime or in regions of heavy precipitation or in sparsely populated areas. Under such conditions, the tornado may go unreported for many minutes. There is, therefore, a continuing need for reliable methods that can, under all weather conditions, accurately and routinely identify the nature and location of severe-storm hazards.

In considering the design of the severe-storm monitoring system, once again it will be appropriate to use the systems approach. In this case, the end product desired from the monitoring subsystem clearly is concerned with the ability to define in essentially real time the location, nature, and intensity of severe-storm hazards. The key parameters that need to be observed are undoubtedly wind, precipitation, and lightning, although further study is necessary to define the required accuracy of measurement in time and space and the particular characteristics of these parameters that are most closely related to hazards. It is possible that, on further consideration, some of these parameters should be subdivided. Thus, wind might well require subdivision into straight-line winds; circulatory, tornadolike winds; and turbulence. Similarly, precipitation might appropriately warrant subdivision into rain and hail. Because of the relatively small size and rapid motion of tornadoes, it would appear that spatial resolutions of the order 1 km and time resolutions of the order 1 min will *eventually* be desirable. Further study will also be required to identify precursors of such key events and their associated hazards in order to provide the earliest possible identification of the potential hazard.

During recent years, there has been a major effort to identify improved methods for locating, measuring, and tracking severe-storm hazards. We turn now to a discussion of the current status and perceived potential of these methods and include recommendations pertaining to their further development and application.

SATELLITE MONITORING OF SEVERE STORMS

As indicated above, geostationary satellites are readily able to monitor the location and development of the cloud patterns associated with thunderstorms. Particularly in the early phases, the satellite pictures may give the only indication of the presence of developing storms. Viewing the storm from above, however, means that much of the internal structure of the storm is hidden from view. At this time, it does not appear likely that the infrared and optical images will permit direct identification of tornadoes or regions of heavy precipitation. However, as shown by Fujita (1975b), the heights of the tops of the clouds can undergo fluctuations indicative of changes in the intensity of updrafts within the storm. These updrafts are an indication of the intensity of the storm and often are associated with regions of high vorticity. It is likely that further progress can be made in learning how to use satellite images to locate and monitor hazardous regions. Such investigations have been initiated and should be accelerated. The possibility of using satelliteborne radars to probe thunderstorm conditions is being studied, although at this time the problems of achieving adequate temporal or spatial resolution or both seem severe.

CONVENTIONAL WEATHER RADAR

Convention (i.e., non-Doppler) weather radar has proven to be the most valuable single tool for the monitoring of severe storms. Its ability to map, in three dimensions, regions of precipitation out to some 200 km from the radar site provides the observer with excellent information on the location and evolution of storms and quantitative estimates of rainfalls that cause flash floods. Radar data find immediate use in systems for air traffic control, pilot briefing, and public warning.

Modern methods for processing and displaying radar data, including digitized echo strengths presented in color, can provide visually dramatic indications of precipitation areas, including automatic synthesis of radar information with data from self-reporting rain gauges. Calibration of the radar data with rain-gauge measurements is important because the radar echo strength is a function of several radar parameters, as well as the raindrop number density and size distribution. As such new capabilities are introduced into routine operation, the accuracy and timeliness of warnings will increase and radar use will extend to general hydrologic purposes.

Several techniques have been used successfully in attempts to distinguish between hail and rain. With a single 10-cm radar, an echo strength implying a radar reflectivity factor greater than about 10^5 mm^6/m^3 at a 3-km height has been found to be a suitable criterion for identification of regions of hail. In the research mode, a two-wavelength (10 cm/3 cm) pair of radars with matched antennas has been used successfully in the National Hail Research Experiment to identify regions of hail (Carbone *et al.*, 1973; Eccles, 1976; Jameson, 1976). In Canada, the use of circularly polarized radars permits the measurement of the cancellation (or depolarization) ratio, and a parameter referred to as "percent orientation" shows promise of being useful in distinguishing hail from rain (Barge, 1974). These methods all require further research to determine their reliability and operational feasibility.

There has been limited though significant success in the use of operational weather radars for the identification of a unique tornado signature. Here, the appearance of a particular type of curved echo pattern, known as a "hook echo," is currently the best operational radar indicator of the probable existence of a tornado. However, less than half of all tornadoes are associated with recognizable hook echo patterns, and tornadoes do not always occur even when a clear hook echo is observed. Attempts to identify regions of nontornadic severe winds and turbulence from the echo patterns have been much less successful.

Quantitative measurements of radar reflectivity using modern, economical data-processing systems have demonstrated an encouraging capability for estimating total rainfall, hence, for identifying the flash-flood potential of both hurricanes and severe local storms. While there are limitations to the accuracy with which such measurements can be made, there is little doubt that present methods can be improved sufficiently to detect potentially hazardous flash-flood conditions. There is already an ongoing experiment within the National Weather Service, but progress has been disappointingly slow. A major program is nearing the field evaluation stage in England (Taylor and Browning, 1974; Harold *et al.*, 1974). Such radar methods should be supplemented by more widespread use of river flow gauges and warning devices. The latter instruments reflect the total amount of rainfall that has previously been collected by the drainage basin upstream of the gauge. In this respect, they serve both to verify the earlier indications obtained by the radar and as a warning of imminent dangers.

Thus, we may summarize the role of operational weather radar by indicating that the echo strength, which is directly related to the precipitation size and density, can be used to distinguish hail from rain and to obtain quantitative information on the distribution and intensity of rainfall. The latter are especially valuable for purposes of flash-flood warning. It should be pointed out that the echo strength is not directly related to the wind velocity, and attempts to use the echo patterns as a basis for deductions as to the location of tornadoes or damaging winds have not been satisfactory.

MICROWAVE ATTENUATION

Recent analyses suggest the feasibility of deriving path-averaged rainfall rates from measurements of the attenuation of short-wavelength microwave radio beams. Although such an approach had been attempted with only moderate success more than a decade ago, recent studies by Atlas and Ulbrich (1974) indicate that there is a narrow wavelength band near 1 cm at which the attenuation is directly proportional to rainfall rate and is independent of dropsize distribution and atmospheric temperature. This linear dependence of attenuation on rainfall rate should, therefore, make it possible to measure the average rainfall along a path between transmitter and receiver (or between a 1-cm radar and a retroreflector) regardless of the rainfall rate or its distribution along the path. (Previously unexplained measurement errors are now explainable in terms of differential absorption as a function of radio-wave polarization relative to the orientation of the distorted raindrops.) Monitoring of the rainfall over a drainage basin thus appears feasible, using any of a variety of approaches employing a distribution of retroreflectors.

DOPPLER WEATHER RADAR

Severe-storm hazards are primarily associated with winds and secondarily with precipitation. Therefore, any technique that permits monitoring both the velocity and precipitation fields in all three spatial dimensions is of great potential significance to severe-storm warnings. Doppler radar is such a technique.

Basically, Doppler radar makes use of the change in frequency (the Doppler effect) that occurs when a radar signal is scattered by a moving target. This Doppler shift is proportional to the velocity of the target toward or away from the radar. Any velocity transverse to the line of sight is not detected. (If required, this transverse component could be derived using a second Doppler radar to interrogate the target from a different direction.)

The Doppler effect has been used in meteorological research for a number of years. Recent advances in data processing and display have greatly enhanced its usefulness, and it is now appropriate to recommend the eventual operational use of Doppler weather radars to monitor and display, in essentially real time, the radial component of velocity of the precipitation relative to the radar and the breadth of the Doppler spectrum.

Analysis of five years of research data obtained with the new 10-cm Doppler radars at the National Severe Storms Laboratory (NSSL) has revealed two different characteristics of the velocity field under tornadic conditions. These are a tornadic vortex signature and a mesoscale cyclonic circulation signature. The tornadic vortex signature is typified by strong wind shear, in which the radial component of velocity is found to show very strong shear between neighboring azimuths, e.g., 50 m/sec difference in radial velocity between two sampling cells displaced laterally by 1 km. In one case (the Union City storm of May 24, 1973), very strong wind shear was observed at storm midlevels 25 minutes before the tornado touched the ground. The region of strong shear descended to progressively lower levels, reaching cloud base coincident with funnel cloud appearance. Observed azimuth deviation of maximum shear taken at a radar beam elevation of 0° coincided with the surface track of the tornado. Nine tornadic vortex signatures had been detected, of which seven were associated with either tornado or funnel aloft reports.

Good statistical success was obtained in identifying the mesocyclone vortex signature as registered on a single Doppler radar. The mesocyclone signature usually is found throughout the lowest 10 km of a severe storm. Thirty-seven mesocyclones were identified within 165 km of the NSSL, of which 23 were associated with reported tornadoes. Damaging wind or hail was reported with 12 of the nontornadic signatures, leaving only 2 signatures out of the 37 that produced no reports of severe weather. At no time during data collection did a verified tornado occur unless preceded by a vortex signature; the average lead time before tornado occurrences was 36 minutes. In several cases, either no hook-echo signature was apparent from the storm or it was only apparent for a short period of time, whereas the mesoscale vortex signatures retained good time and space continuity.

In two instances (both at NSSL and at Air Force Cambridge Research Laboratories), the position of a tornado vortex has been marked by an unusually broad Doppler spectrum and large Doppler variance. This is to be expected when both large approaching and receding velocities are found within the same radar pulse volume. Thus, the combination of a mesoscale vortex, large azimuthal beam-to-beam shear, and large Doppler variance appear to be clear signatures of existing or potential tornadoes.

These preliminary results of the use of Doppler radars for tornado detection are extremely encouraging. They indicate that, at least in the research mode, it is possible to identify and track the mesoscale low that is parent of the tornadoes, and, on occasion, the position of the tornado itself is tracked. These studies should be pressed, not only because of their enormous value in *post facto* studies of severe storms but because it is also important that their implications to severe-storm monitoring and warnings be rapidly assessed. It is technically feasible to produce the Doppler signature information on a time scale short enough to be useful as warning information. This will require some expansion of manpower and dollars to conduct the many analytical and experimental studies required before operational exploitation of these dramatic new research results can be achieved.

While we must reserve final judgment whether Doppler radar will provide unequivocal signatures of tornadoes and a sufficiently low false-alarm rate until its capabilities and limitations have been more fully investigated, the potential value of Doppler radar in severe-storm detection and warning is already undeniable. Its other uses, such as the measurement of winds, shear, and turbulence and its ability to distinguish weather targets from ground clutter, add greatly to its potential operational value. Moreover, the importance of Doppler observations of hurricane winds at coastal stations must not be underestimated. Certainly, the striking successes achieved to date warrant a major expansion of the research efforts in order to ascertain the proper role of Doppler radar in severe-storm detection and warning. Indeed, many of those who have worked with Doppler radar are already convinced that it is ready for operational deployment (Donaldson *et al.*, 1975). The USAF Air Weather Service is now moving vigorously in this direction.

Although it would ultimately be desirable to have fully coherent Doppler radars in all regions prone to severe storms, it is possible that existing radars could be retrofitted at reasonable cost to permit Doppler measurements. Also, some of the desirable measurements can be made with relatively simple modifications of existing incoherent radars. These are referred to as "pseudo-Doppler techniques." For example, the azimuthal beam-to-beam shear mentioned previously as a tornado signature may be measured by conventional radar with a dual beam; and velocity differences between neighboring range gates of the same beam, which are indicative of turbulence, have already been measured both at the University of Chicago and in the Soviet Union. Such modifications of incoherent radars would deserve serious consideration should the procurement of new Doppler radars be seriously delayed.

While we have not given attention to the geographical distribution or spacing of the monitoring and detection system, this subject will have to be addressed as part of the system design. Should the system be based upon either Doppler or pseudo-Doppler radar, complete coverage is likely to require station spacing of about 300 km, i.e., a useful detection range of about 150 km at which the normal radar horizon is 1.3 km above the ground. This is to ensure that severe-storm signatures recorded aloft are representative of events at the surface. Of course, the range limit of reliable severe-storm warnings should be the subject of further research.

Whatever the useful range of a ground-based radar, serious consideration should be given to the use of aircraft monitoring systems that can be deployed quickly to areas of severe-storm watches. It is likely that no more than 10 such aircraft systems would be required to cover the severe-storm outbreaks within the contiguous United States. (They could also serve well for hurricane reconnaissance.) While some complexities would be introduced in the Doppler radar processing methods, no technological difficulties are foreseen. Indeed, with far fewer systems, each aircraft could be fitted with the most sophisticated radars and data-processing facilities envisaged. They would also have the advantages of a greater radar horizon and the ability to approach suspect regions for close-in verification and could employ both visual and electrooptical observations. In the latter category, we are thinking of the possibility of using infrared lidar systems, which are capable of measuring the exceedingly large rotational speeds of the cloud particles of the tornado vortex. Such particles are not detectable by microwave radar, nor can microwave radar measure the large tornado velocities without ambiguity. Clearly, the many advantages of airborne severe-storm monitoring systems suggest their serious consideration.

In summary, and repeating the point made at the beginning of this section: In measuring the wind velocity, we are measuring *the* parameter most critical to severe-storm hazards. The striking successes to date of velocity-measuring Doppler radars fully warrant rapid expansion of the effort in order to ascertain their proper role in severe-storm monitoring and warning.

ATMOSPHERICS

It has been known for many years that nearby lightning creates interference, or "static," on radio sets. These radio-frequency emissions from lightning are colloquially known as "atmospherics" or, more briefly, as "sferics" to distinguish their atmospheric origin from the man-made "static" produced by electrical machinery, switchgear, and other apparatus. Over the years, there have been a number of efforts to identify tornadic storms on the basis of possible differences in the atmospherics they radiate. The advantage of such a method (if it were to succeed) is that it relies purely on the passive reception of signals radiated by the storm and does not require construction and operation of sophisticated radar systems.

This technique has been investigated in considerable detail by W. Taylor and colleagues of NOAA's Wave Propagation Laboratory. It has been found that, in general, the burst rate (the frequency of occurrence of short burst of atmospherics at frequencies in the range 3 to 80 MHz) is an indicator of the severity of the storm. Thus, the typical tornadic storm registers over 20 bursts per minute, a typical severe storm (with funnels, hail, or damaging winds but no tornadoes) averages about 10 bursts per minute, and the normal thunderstorm about 1 burst per minute. A careful study, involving between 200 and 300 station months over a four-year period, has confirmed these statistical results but also indicates that a significant fraction of the tornadic storms (especially those with small, short-lived tornadoes) cannot be identified this way. Apparently the electrical activity of a thunderstorm is positively correlated with its severity, but the degree of correlation found so far is not yet adequate to permit unique identification of those storms that are tornadic.

The present conclusion is, therefore, that the failure-to-alarm rate and the false-alarm rate, in relation to tornadoes, of these passive receiving systems are sufficiently high that they must be regarded as secondary, rather than as primary, observing tools. Nevertheless, measurements of sferics are useful indicators of lightning hazards.

INFRASOUND

For some years, it has been known that severe thunderstorms radiate infrasound (acoustic waves of subaudible frequency), which can propagate over long distances with very little attenuation. The azimuth of arrival can be ascertained, using spatial arrays of microphones. If this is done from several well-separated sites, the apparent source of the infrasound can be located by triangulation. While the source mechanism for the infrasound is not clear, there is evidence that it is a product of the turbulent instabilities in rotating flows within the storm and, as such, is a reasonably direct manifestation of the severity of the dynamical effects of the storm. One intriguing result of these studies is that the infrasound appears to be first emitted at detectable intensities about one hour before the occurrence of a tornado (Georges and Green, 1975). The potential value of this result, however, is reduced by the propagation delays, which amount to almost one hour for distances of 1000 km. At close ranges, skip-zone effects, as well as the possibility of enhanced noise at the receiving microphones due to winds from local storms, make the system less useful.

Although the eventual usefulness of infrasound to a severe-storm monitoring and warning service is not clear, it appears at this time that its disadvantages of low propagation velocity and high susceptibility to local noise levels reduce its operational value to, at best, a secondary monitoring role.

11 COMMUNICATIONS AND WARNING DISSEMINATION

The monitoring activities discussed in the preceding chapter are a necessary prelude to the primary function of a severe-storm warning service, namely, the dissemination to the total family of users of timely and accurate warnings of storm hazards. We turn now to some of the social and technological problems and opportunities in this area of warning dissemination.

Warning services must begin with the collection of observations, for example, using surface, balloonborne, or satelliteborne sensors. After analysis of the observations, forecasts and warning messages must be prepared and disseminated by appropriate National Weather Service (NWS) offices. It is important to note that the warning service is a continuous activity, which may require access to the internal office-to-office communication facilities during the entire severe-storm period. Because the storms must be monitored and new messages prepared, it is not possible to dedicate these facilities totally to the warning dissemination function, although during severe-storm periods such messages pertaining have highest priority.

The present warning service provides advisory messages about severe thunderstorm events (tornadoes, hail, rain, wind, and lightning) and flash floods. Two types of advisory statement are issued: the watch and the warning. In both cases, the same message is distributed to all users. The present policy is to use multiple-warning communication facilities to reach the public and the officials who must decide on, and then direct, responsive activities leading to adaptive behavior patterns.

WARNING MESSAGES

The *watch* is a forecast, usually issued some hours before the storm matures. The geographical area covered by a severe thunderstorm or tornado watch typically covers about 60,000 square kilometers (e.g., an area 300 km by 200 km).

The *warning* is a message about a severe-storm event that has been detected and confirmed. The confirmation is usually visual, although more recently radar indications based on echo characteristics and indications of powerline breaks have been used.

Specific inadequacies of this warning service that have been cited during meetings of this Panel, and elsewhere, include the following:

1. The severe-storm watch message covers too large an area. Often the area actually affected by severe weather is two or three (or more) orders of magnitude smaller than the watch area. As a result, many more people are alerted than actually need the message. This leads to a credibility problem for future watch messages.

2. The warning message, if issued, often comes many hours after the watch message and provides little time for reaction. The likelihood of a missed detection and, consequently, no warning message, is believed to be too high at present.

3. Large storm systems involving many simultaneous events require the issuance of multiple watches and warnings. In such case, the public may have difficulty in keeping track of the messages, especially when some of the tornadoes may be traveling at up to 95 km per hour. No information exists at present to assess whether the public is able to understand the severe-storm location data as given in present watch and warning messages. No information exists at present to determine that the watch and warning messages, and their time sequence of delivery, are consistent with public needs.

4. Current warning messages are inadequate in their description of the future positions of a detected severe storm. The counties and states likely to be involved are identified, the present location (and time) are given, and the direction of movement and speed are stated. No information about the specific municipalities along the most probable path, and the expected severe-storm arrival time, is given. The relationship of an individual message to other watch and warning messages should always be cited.

A need exists for an overall review of public needs and message types, based in part on random surveys of possible message recipients. The review could include the addition of a new level of warning message, intermediate between the watch and the warning. We suggest the name "Alert" for such an intermediate message. The hierarchy of three messages--watch, alert, and warning--should be easily understood in the context of "ready, set, go." We think of the alert message as being disseminated one to two hours before the expected arrival of potentially hazardous thunderstorms, at a time when the magnitude and speed of development and motion of the storm is well identified. Such a message would serve many purposes, especially those of refining and making more precise the earlier watch messages and of giving considerably more notice than the warning messages. However, prior to implementation, this concept should be carefully evaluated and tested to determine if it is consistent with the public's warning-service needs.

A need also exists for an overall review of the delivery media, the communications technology, and the listening (or viewing) habits of the public to be considered in delivering the hazard messages to the public. Serious consideration should be given to the use of television as a primary means for warning dissemination and to expanding the NOAA VHF-FM Weather Radio Stations by the addition of UHF TV stations. Some evidence exists to support the concept that the information content of the violent storm situation requires pictorial display, disseminated in nearly real time. In this way, much more information on the present status and probable course and time rate of change of the storm could be disseminated rapidly and effectively. Each viewer would have access to the full range of information selected on the basis of studies of optimum methods for the effective transfer of hazard information. The viewer would, therefore, be in a position to filter the information, to extract from it what he requires for his own specific locale or situation. It may be expected that the amount of information offered, and its manner of presentation, would increase the credibility of the message and, therefore, the likelihood of creating the appropriate adaptive response. Research on warning response has shown that a normal first response to the receipt of a warning message is to seek confirmation of it. Thus, the timely and quantitative nature of the video "nowcasts" may offer a major opportunity for the recipient continuously to confirm their validity for his specific location.

The contrast between such a service and the present oral messages is very large. Such a capability, of course, would have maximum usefulness under rapidly changing severe-storm conditions but could also be available to enhance the normal dissemination of weather information, by routinely providing maps of such parameters as wind, temperature, humidity, cloud, and precipitation. This "nowcasting" is a concept that has been identified as technologically feasible and desirable by other groups. We believe that its potential role in the future of weather services in the United States, and especially in the effective dissemination of severe-storm warnings, should be carefully evaluated.

NATIONAL WEATHER SERVICE COMMUNICATIONS

The principal communication facilities used by the National Weather Service (NWS) are the following.

National Teletypewriter Circuits [NOAA Weather Wire Service, Radar Report Warning Coordination System (RAWARC), FAA circuits]: These include internal NWS communications, plus communications to specialized users, and commercial radio and TV broadcasting stations (typically slow-speed data communications at 75 and 100 words per minute). These circuits require message relays in many cases. During peak loads, circuit delays are unacceptable when relays are involved. On one RAWARC circuit during the April 3-4, 1974, outbreak, 26 of 62 warnings were relayed after their period of validity had expired. Generally speaking, station and network operating protocols create excessive delays during severe-storm peak loads.

National Facsimile Circuits: These internal NWS circuits transmit graphical and map information, including digitized satellite photos, composite radar charts, and graphic severe-thunderstorm outlooks. Generally, these circuits operate too slowly to be of timely value during severe-storm peak loads.

Satellite Circuits: Earth-space communications are maintained with weather monitoring geostationary (GOES) and polar-orbiting satellites (ITOS). These internal circuits are limited to communications between the National Environmental Satellite Service (NESS) and the satellites. NESS relays information to the National Meteorological Center (NMC) for internal distribution on national teletypewriter and facsimile circuits. The GOES satellite also incorporates a message relay capability for digital photos to designated, small earth stations within the United States.

NOAA VHF-FM Radio Broadcast of Weather Information on Frequencies near 162 MHz: In an important policy statement, the Office of Telecommunications Policy has designated this system as the only federally sponsored method for the transmission of natural disaster warning information to receivers optionally available to the general public. A total of 331 transmitters will complete the system and provide the service to some 95 percent of the nation's citizens. As of early 1975, 77 NOAA Weather Radio Stations were operational, and others are being rapidly installed. An important feature of this service is the tone-alarm, which will automatically demute special receivers located in schools, hospitals, disaster action agencies, and local government offices. These stations, however, have a radio coverage of about 40 miles' radius over flat terrain. Hence, only metropolitan areas will be served. (More than 750 stations would be needed to cover 99 percent of the population in the continental United States.)

Defense Civil Preparedness Agency (DCPA) National Warning System: This provides audio communications channels for two-way communications with official agencies (private line, leased voice circuits to county sheriff or equivalent political level). These channels provide for important communication to the NWS of spotter visual detections and an outlet for warnings to local authorities.

Local Telephone Networks: These involve manually implemented, selected telephone calls. These are severely limited in number by available manpower resources, which are in heavy demand during severe weather. Automatic telephone answering systems are operated in certain areas for confirmation of warning messages.

In addition, efforts are presently under way by the NWS, DCPA, Federal Communications Commission (FCC), and the National Industry Advisory Committee (NIAC, representing the broadcasting industry) to develop state and local disaster-warning dissemination procedures, using the Emergency Broadcast System (EBS). The EBS is presently designed for the President to reach the public during a national emergency.

Heavy reliance is placed on commercial radio and TV stations for final dissemination of messages, although many radio and TV stations do not participate in the NOAA Weather Wire Service, principally because of the cost to the station and the need to monitor and select the warning message from the normal weather message.

The Automation of Field Operations and Services (AFOS) is a major step in the right direction. The program will result in automation of 280 Weather Service facilities, including all 52 Weather Service Forecast Offices (WSFO) and 136 Weather Service Offices. The WSFO's will be interconnected with a national communications network called the National Distribution Circuit (NDC), planned to operate in a store-and-forward mode.

A need exists for the completion of an integrated communication system plan for all NWS and National Environmental Satellite Service (NESS) communication facilities, including documentation of existing facilities. The plan should be part of the long-range system design plan mentioned earlier. The AFOS Program Development Plan (National Weather Service, 1976) provides a good beginning, but it does not deal with the communication performance aspects of AFOS. Considering the importance of communications to the warning service, the Panel found the lack of thorough documentation of present communication facilities, and their performance, inconsistent with the communications role. Even the development of long-range plans is inhibited, or degraded, by lack of knowledge of present capabilities. The absence of regular, systematic monitoring of the delivery performance of the current warning system further obscures the identification of areas requiring upgrading.

In addition, an overall review of the planned AFOS network is needed to establish that long-range warning-system requirements will be satisfied for severe-storm peak loads. The AFOS computer-communication terminal is planned to perform the communications and the station data-processing function with two minicomputers and priority protocols. As noted earlier, the data-processing and communication functions must continue simultaneously. Further, the communication relay must be performed by this terminal, both with other WSFO's on the NDC and with intrastate WSO's within the state served by the WSFO. However, no quantitative design constraints have been used for the maximum warning message time delay in the AFOS communication system. Without such design objectives, it is not clear how AFOS will contribute to reducing warning message delays that now exist in the NWS office-to-office communication networks.

As initially planned, the use of a single, national, loop network as a NDC to interconnect the AFOS stations with its inherent message-delay characteristics is not consistent with the rapid dissemination requirements of a warning service. Other network topologies and operating procedures (network control protocols) would improve the potential utility of AFOS in the timely delivery of warning messages and environmental data. Nonloop network topology using digital switching without store-and-forward protocol should be considered as one possible alternative. Once the network has been established and computer software developed, it will not be a simple matter to improve on message delivery delays. (The use of nonstandard TV signal and display formats within AFOS limits the development of real-time video transmission to commercial TV stations without the use of expensive signal and display converters.) Again, system requirements should be used as a basis for design and network plans developed accordingly.

Some immediate attention must be given to improvement of communication between WSO's within each state and across state boundaries, rather than waiting for the AFOS system to be completely installed (planned for early 1981). The communication delays experienced in the April 3-4, 1974, tornado outbreak are unacceptable in the present state of the art.

ADVANCED COMMUNICATIONS TECHNOLOGY FOR DELIVERY

A disaster-warning satellite for warning-message dissemination directly to small, portable, voluntarily owned receivers within the home is an application of advanced technology.

Recent measurements of building attenuation of satellite signals (Wells and Tryon, 1976), using ATS-6 at 860, 1550, and 2569 MHz, outline some design constraints to be overcome. Higher frequencies are not feasible because of rain attenuation. Based on 50 percent of the locations within the average midwestern home, the building increased the signal attenuation by 4.6 dB at 860 MHz, 6.7 dB at 1550 MHz, and 7.5 dB at 2569 MHz. Standard deviations were about ±2.6 dB. Signals within mobile homes were attenuated 21 dB at 860 MHz and by more than 21 dB at 1550

MHz. Even greater attenuation could be expected at 2569 MHz. If the home is located among large trees, an additional attenuation of about 15 dB was observed at 1550 MHz. These attenuations would require very large voice-channel transmitter powers to achieve reliable transmissions to receivers with low-gain antennas within nonmobile homes. These satellite power requirements would be achievable only with major satellite capability developments. The mobile home appears to require an external receiver antenna in the present state of the art.

Advanced technology permits the use of digital address codes to selectively alert and warn small geographical areas, in contrast to the large areas covered by conventional broadcast stations. These code alert techniques require a small computer system to select the appropriate addresses for each warning situation, given that useful decision criteria can be established with the present watch-and-warning message terminology. The crucial problem here is to obtain sufficiently low false-alarm rates and high reliability at reasonable costs. It is expected that high digital transmission rates, perhaps at megabits/second, would be needed to avoid excessive warning delays. A system design study of the application of advanced communication technology to the warning message delivery problem should, therefore, be conducted after establishment of system design requirements.

The system application of TV warning-message dissemination requires careful study. The potential of advanced technology exists now to consider satellite communications for TV distribution from the NWS to commercial radio and TV stations, public officials, schools, hospitals, and large commercial buildings, as well as NOAA VHF-FM radio stations and other NWS facilities. Voluntary public purchase of small (perhaps 4.5-m-diameter antennas) receive-only earth terminals could be offered. The NOAA UHF-TV stations could be developed to cover areas that commercial or public broadcast TV stations could not cover under a contract management instead of the present voluntary method.

The present policy of using multiple communication facilities is believed important. Hence, both NOAA VHF-FM Weather Radio Stations and UHF-TV Weather Stations should be considered, along with satellite audio broadcasts to cover remote areas and areas with low population density. Radio tone-alarm (coded tones) system concepts, the equivalent of sirens, should be considered for small, low-cost, portable receivers to cover rural areas, lakes, rivers, and vehicles in transit. These alternative receiver techniques must be evaluated in terms of public expression of the type of receiver facilities desired. Primary emphasis should be placed on the UHF-TV stations in the study. Tone-and-code selective addressing techniques should be considered for any warning delivery transmission system, since they can be applied to the NOAA VHF-FM, UHF-TV, commercial radio (AM and FM) and TV, and satellite transmissions. Suitable receivers or receiver modifications may be necessary.

The participation of commercial radio and TV stations must be continued. The use of the Public Broadcast System TV stations should be encouraged. A satellite/terrestrial warning-message delivery system appears to be the most reasonable comprise between cost, coverage, and timeliness of the warning delivery.

12 ISSUES AND RECOMMENDATIONS

Although relatively little can yet be done to minimize the damage to crops and property caused by severe storms, experience over many years suggests that accurate and timely warnings, disseminated effectively to a well-prepared public, can do a great deal to reduce the number of persons killed or injured. This argument is bolstered by an overall sharp reduction in tornado deaths over the last two decades, coincident with the growth of efforts to detect and warn of impending tornadoes and to provide public information programs on severe storms.

The occasional catastrophe, such as the April 3-4, 1974, tornadic outbreak is, however, a reminder that there is much yet to be accomplished. This chapter, therefore, summarizes the severe-storm-related issues identified by the Panel and presents recommendations designed to help to resolve them.

NEED FOR A WARNING SERVICE

The Panel is convinced that a need exists for improved severe-storm warning services. At issue is the performance of the present warning service and the question of how the present investment of manpower and facilities can be augmented to give the maximum increase in system performance with the minimum of increased investments. In this, it is important to look both at objectives for the immediate future and also at the long-range goals to be achieved ultimately. The Panel has worked to identify and define issues, and present recommendations, with this in mind.

THE SYSTEMS APPROACH, USER NEEDS, AND QUANTITATIVE SPECIFICATIONS OF LONG-TERM SERVICE GOALS

The first issue to be addressed in any attempt to improve the present services is how to proceed. The Panel believes that a systems engineering approach, designed to stimulate intended recipients of warnings to appropriate adaptive behavior in the presence of local severe-storm hazards, is required.

In such an approach, attention must first be focused on what is required to produce the desired adaptive behavior on the part of the intended recipients of the service. One must start with the user and document his specific needs. Of necessity, these will be biased by the technology and performance of the current warning system, but their long-range desires of what service would be optimum, should technology continue to advance, should also be ascertained. The Panel notes that adequate information on what is required to produce the desired adaptive behavior does not exist, although evidence does exist that appropriate adaptive behavior cannot be taken for granted, merely because a warning message was delivered in a timely fashion.

In designing a system, current technology is often used as the determining factor in setting system requirements. In the case of severe storms, it is desirable that user needs determine the quantitative objectives for the accuracy of the ultimate service desired. These quantitative definitions will provide the long-range goals to guide the development of the warning service and also the framework within which succeeding generations of technology can be implemented without making existing systems obsolete.

Recommendation II.1. The Panel recommends that the systems engineering approach be used to direct improvements of the current severe-storm warning service. This approach should include a major effort to determine user needs and to set up long-range quantitative goals for system performance. These quantitative goals, to be determined on the basis of improved knowledge of user needs, should be used to guide future developments of the service and to evaluate continuously performance of the system.

MONITORING AND DETECTION

The second issue is the role of Doppler radar in severe-storm monitoring and warning. Here, the Panel concludes that Doppler radar techniques offer the greatest promise of any of the presently available techniques for the monitoring of the development of the mesoscale circulations that precede the formation of the tornado and for remote detection of the tornado itself. The key immediate need is to deploy a few more Doppler radars through the tornado-prone regions of the United States to obtain additional experience with these techniques within a reasonable period of time. Only in this way will we be able to improve our present methods and assess their reliability. Simultaneously, tests should be made of the possibility of retrofitting Doppler capabilities into existing non-Doppler radar as a means of minimizing the cost of a full network of Doppler radars. The feasibility of airborne Doppler radars, to be used in both hurricane and tornado research, should also be vigorously explored, since it is possible that a few such aircraft systems might ultimately provide a more cost-effective solution than a national network of ground-based Doppler radars.

Recommendation II.2. The Panel recommends that high priority be given to a program designed to bring the unique tornado-monitoring capabilities of Doppler radars to full fruition and operational use.

A third issue concerns improvements to the monitoring and detection of flash-flood conditions. Here, area and time-integrated radar measurements of precipitation and a system of river-flow gauges are required. Greater use of self-reporting rain gauges would also be helpful. Experiments of this nature have been conducted for some years, but they need to be accelerated so that the operational applications that they promise may be brought to fruition. Another alternative with considerable promise involves the use of path-integrated microwave attenuation at a wavelength of about 1 cm. This approach is potentially important because (unlike the radar approach) it provides a measure that is directly proportional to rainfall rate and is independent of drop size distribution.

Recommendation II.3. The Panel recommends that the existing programs on time- and area-integrated radar measurements of rainfall for flash-flood warning purposes be accelerated.

Recommendation II.4. The Panel recommends the prompt initiation of studies of the use of microwave attenuation in the 1-cm band for path- and area-integrated rainfall measurements for flash-flood warning purposes.

NATIONAL WEATHER SERVICE INTERNAL COMMUNICATIONS

A fourth issue is that the NWS internal office-to-office communications do not provide reliable and timely warning message distribution. These facilities can, and at times do, become overloaded by the addition of severe-storm monitoring observations and the dissemination of severe-storm forecasts and warning messages that must continue throughout the entire storm period. The technology and relay procedures used limit the performance of these interoffice communication facilities; while the AFOS system is a major step in the right direction, additional immediate improvements in communications between weather offices within a state and between states are needed.

Recommendation II.5. The Panel recommends the development of an integrated communication system plan for all National Weather Service communication facilities, including documentation of existing facilities.

Recommendation II.6. The Panel recommends that the development and implementation of Automation of Field Operations and Services (AFOS) be continued and, if feasible, be accelerated, consistent with long-range warning system requirements. However, an overall review of the planned communication network of AFOS, and its associated hardware, is recommended to establish that warning-system performance will meet long-range requirements for peak severe-storm loads.

Recommendation II.7. The Panel recommends a review of present and planned office-to-office relay network equipment and procedures to ensure adequate performance under peak loads.

WARNING MESSAGES

The following issues in warning dissemination have come to the attention of the Panel:

1. The needs of the public for warning message type, content, delivery media, and delivery communications technology have not been adequately determined.
2. The warning message types (watch, warning) have limitations associated with geographical coverage, delivery time, false alarm, and missed detections.
3. The warning message contents (severe-storm information) and delivery media (tone-alarm, voice, or written message) omit adequate detail about future storm movements.

Almost certainly the recipient of a tornado warning message needs to be reminded what to do. The description of recommended action needs to be kept simple and repeated frequently. It should reinforce the content of any ongoing public education programs. Perhaps most importantly, the "do it now" recommendations should be broadcast only when a confirmed tornado is in the area. If energy is expended in taking emergency actions that are followed by no evidence of a near miss, the call to action in the future will gradually go unheeded.

Recommendation II.8. The Panel recommends an overall review of public needs and message contents, delivery media, and delivery communication technology. This review should include consideration of the addition of a new type of warning message, intermediate between the watch and the warning. The review should give emphasis to the use of television as a primary means for warning dissemination, including the possibility that the NOAA VHF-FM Weather Radio Stations be expanded by the addition of UHF TV stations, and to appropriate training procedures of involved personnel.

ADVANCED COMMUNICATION TECHNOLOGY

Another issue to be raised is that the communication systems (sirens, radio, and television) for delivery of warning messages directly to the public are inadequate and do not make full use of available advanced technology.

Recommendation II.9. The Panel recommends that a system design study of the application of advanced communication technology to the warning message delivery problem be conducted after the system design requirements have been established.

MESSAGE RECEIPT AND RESPONSE

The ultimate payoff for any warning system is in the response generated. Who receives the messages and to what extent are appropriate actions taken as a result? This broad area of concern includes a number of issues that need attention.

One issue concerns what might be called "the social science aspects" of severe-storm warnings. There are instances that suggest that public awareness of an oncoming tornado must be relatively high. In the Omaha tornado of 1975, few persons were killed even though the tornado cut a swath through a densely inhabited area of the city. Whether the low death toll was primarily due to broadcast warnings or to direct observation of the approach of a violent storm, or to some combination of fortuitous factors, is unknown. Other instances suggest that the public has a low level of awareness of the tornado threat combined with a high level of disinterest. It is often asserted that the widespread and repeated use of the tornado "watch" areas produces cynicism and inattention on the part of the public. While the assertion seems reasonable, it has never been checked empirically in any systematic way.

Knowing what to do when one is aware of an impending tornado is obviously important. Public education as to what is appropriate emergency behavior may be decisive in tornado warning response. Toward this end, NOAA, for example, distributes information on tornado safety rules, and both broadcast media and newspapers donate time and space for tornado preparedness announcements.

In the United States, the NWS is responsible for the detection of developing severe storms, for formulating appropriate warning messages, and for making those messages available to all interested broadcast stations and any other would-be recipient. The cost of message transmission, however, must be borne by the recipient. Commercial broadcast stations are encouraged by the NWS to send out the warning messages promptly and without altering the content.

There is no law or related regulation, however, that requires any broadcast station to pay for the equipment to receive warning messages, nor to broadcast messages once received.

Legally, responsibility for tornado warnings ends with the preparation of the messages by the NWS and the broadcast of those messages over its own FM radio stations and the NWS teletype networks. Thereafter, the process is voluntary.

Proposals for in-the-home receiving equipment that can be activated by a government warning source have met with little success.

Many, and perhaps most, local governments have taken no responsibility for participation in the warning process. Apparently it is rare for local government to require that adequate shelters be available for residents of mobile home parks, the most vulnerable of all dwelling areas.

A good case can be made that more responsibility should be taken at the local level for the receipt and further dissemination of warnings. The use of sirens to alert residents within a community, especially at night, seems eminently sensible. Even that idea, however, raises questions of local funding and local control.

There are a number of issues that need to be the focus of research in the immediate future:

1. The time aspect is clearly important. How early are the messages received by the users, and how frequently is the critical information reinforced by subsequent messages?

2. To be useful, messages must be understood. It is important to learn what proportion of citizens in a watch area and in a warning area adequately understand the messages they receive.

3. Perhaps even more important is the answer to the questions, "Of those who receive severe-storm messages, what proportion take action of some type--and what is the nature of that action?"

4. Closely related is the Panel's concern over the impact of "false alarms." To what extent does past experience with "false alarms," as perceived by the citizen, lead to inaction or diminished response in subsequent warning situations?

5. Since the primary objective of a severe-storm warning system is the reduction of death and injury, it is important to examine the association between any action taken, or inaction, and the incidence and location of casualties.

6. At present, only nine states lying within the tornado-prone region of the United States require mandatory tornado drills in public schools. In view of the geographical extent of annual tornado occurrences, there needs to be a careful examination of the role that state, county, and local governments should have in message dissemination and public education regarding response to severe-storm warnings.

7. Finally, to the extent that the issues mentioned above are clarified through research, it will be possible to begin to estimate what changes, if any, are required to make the warning system more closely approximate the range of user needs. Detailed and comprehensive studies of user needs are required in order to design an improved warning system.

The types of research discussed above can be conducted in carefully selected areas of the United States within a few years and at modest cost. The findings are needed for a wide range of policy decisions.

Recommendation II.10. The Panel recommends that research on the receipt of and response to warning messages, such as that discussed above, be conducted in selected areas in the United States.

BUILDING CODES AND PRACTICES

The prevention of deaths and injuries in tornado incidents depends in large part on the structural integrity of buildings. It has been shown that improved structural design and construction can provide internal reinforced shelters (e.g., hallways), where people can be safe from flying and falling debris. Such tornado-safe areas should be readily available and identified in all public buildings.

It also appears important to provide economic incentives to both builders and property owners to encourage the construction of such buildings. These might take the form of lower insurance premiums, tax rebates, or access to federally insured mortgages.

Recommendation II.11. The Panel recommends that recent efforts to provide improved structural designs of buildings be accelerated and that state and local construction codes be modified to require tornado-safe areas, at least in public buildings and schools. Local codes are also needed to require the secure tie-downs of mobile homes. Consideration should also be given to some form of economic incentives to encourage construction of tornado-resistant buildings and shelters.

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STATISTICS OF APRIL 3-4, 1974, TORNADOES

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(See map inside back cover)

This superoutbreak of 148 tornadoes in 16 hours and 10 minutes was the largest number on record. The total path mileage was 2598 miles. Over 300 persons were killed, while 5484 others were injured. 50,000 experienced the twisters' fury, which they will never forget, and many people were "scared to death." Statistics of fatal injuries are: 74% in houses and buildings, 17% in mobile homes, 6% in automobiles, and 3% en route to shelters.

The tornado outbreak began at 1:10 p.m. on April 3 and ended at 5:20 a.m. CDT on April 4. During the height of the tornadoes, 15 twisters were on the ground simultaneously.

Xenia (No. 37), Depauw (No. 40), Sayler Park (No. 43), Brandenburg (No. 47), First Tanner (No. 96), and Guin (No. 101) tornadoes were the six strongest.

Cities hit twice by tornadoes were Etowah, Tenn. (3:00 and 5:30 p.m.); Livingston, Tenn. (7:30 and 11:30 p.m.); Cleveland, Tenn. (3:05 and 5:05 p.m.); Tanner, Ala. (7:00 and 7:30 p.m.); Harvest, Ala. (7:15 and 7:45 p.m.); and Huntsville, Ala. (10:55 and 11:05 p.m.).

Each tornado left behind something unusual. Local residents will remember their awesome experiences for years to come. Following are some noteworthy examples.

Monticello Tornado (No. 13) was the longest-track tornado, which left a 121-mile path in Indiana.

Windsor Tornado (No. 30) crossed the International boundary twice, from the United States to Canada and back to the United States without passport.

Parker Tornado (No. 33) had seven minifunnels inside, the greatest in number.

Xenia Tornado (No. 37) killed 34 persons, the most fatalities by a single twister.

Depauw Tornado (No. 40) deposited a car into the basement, after blowing away the two-story frame house.

Sayler Park Tornado (No. 43) was the only tristate tornado. It originated in Indiana and lifted in Ohio, passing through Kentucky.

Brandenburg Tornado (No. 47) crossed the Ohio River, causing a significant fall and subsequent rise of the water level.

Louisville Tornado (No. 48) uprooted the largest number of trees in urban areas. Cherokee Park was hardest hit.

Frankfort Tornado (No. 54) left the widest path, 5 miles wide near Stamping Ground.

Obey River Tornado (No. 87) descended into a 1000-ft deep canyon with its full strength and then climbed to the top of the cliff on the other side.

First Tanner Tornado (No. 96) killed six persons in one family in a brick house. All were blown into a pine forest, 250 ft away.

Harmony Tornado (No. 97) and Second Tanner Tornado (No. 98) moved over the same house. The house was unroofed by the first one, and the second twister took the whole house away.

Guin Tornado (No. 101) path appeared distinctly in pictures taken by NASA's Earth Resources Technology Satellite, 600 miles above the earth. Path was still visible in October.

Blue Ridge Tornado (No. 120) moved over the 3300-ft Betty Mountain, the highest of all tornado paths.

Murphy Tornado (No. 121) left behind the largest number of debarked, shiny trees. Leaves were completely stripped off.

Meadow Bridge Tornado (No. 137) was the worst predawn tornado in the mountains.