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Tornado Forecasting: A Review

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1. INTRODUCTION

Present-day operational tornado forecasting can be thought of in two parts: anticipation of tornadic potential in the storm environment, and recognition of tornadic storms once they develop. The former is a *forecasting* issue, while the latter is associated with warnings (or so-called *nowcasting*). This paper focuses on the forecasting aspect of tornadoes[1], by dealing primarily with the relationship between the tornadic storm and its environment. We begin with a short history of tornado forecasting and related research in Section 2, while Section 3 provides an overview of current tornado forecasting procedures within the Severe Local Storms (SELS) Unit at the National Severe Storms Forecast Center (NSSFC). Section 4 gives a short summary of 35 years of SELS tornado and severe thunderstorm forecast verification, while Section 5 describes our current understanding of the connection between tornadoes and their environment. We conclude in Section 6 with our thoughts about the future of tornado forecasting.

2. SHORT HISTORY OF TORNADO FORECASTING

Our historical review necessarily must be brief; interested readers can consult Schaefer (1986) for additional details about the history of severe weather forecasting in general; another review by House (1963) is somewhat dated, but provides excellent background material. Although tornado forecasting has its roots in the 19th century, stemming mostly from the work of J.P. Finley (see Galway 1985 for more on Finley), it wasn't until the early 1950s that serious tornado forecasting began. Before then, the use of the word "tornado" in public forecasts was prohibited, largely because of the perception that tornado forecasts would cause public panic. It is clear that modern tornado forecasters owe a great deal to the pioneering efforts of Ernest Fawbush and Robert Miller (1952, 1954), two Air Force officers who had some early tornado forecasting successes at Tinker Air Force Base in Oklahoma in the late 1940s. On the civilian side, work was proceeding (e.g., Showalter and Fulks 1943, Lloyd 1942), but until 1952 the civilian weather service (then called the Weather Bureau) still was reluctant to use the word "tornado" in any forecast. The successes of Fawbush and Miller clearly paved the way for a civilian tornado forecasting program.

The first civilian tornado forecasts began with the formation of a specialized unit as part of the Weather Bureau Analysis (WBAN) Center in Washington, D.C. during March of 1952 (see Galway 1973, 1989 for more details). This unit became the Severe Local Storms (SELS) Center in early 1953, and moved to Kansas City, MO in August 1954, eventually forming part of the National Severe Storms Forecast Center (NSSFC) in 1966.

[1] Recognition and detection issues will be treated elsewhere in this volume, by Burgess et al. (1992).

When SELS first came into being, the relationship between the synoptic-scale environment and the tornado was not well understood; forecasting was essentially empirical. Various forecasters and researchers observed that certain meteorological elements, detectable within the large-scale data networks (surface and aloft), tended to be present in many tornado events (e.g., Fawbush et al. 1951, Beebe and Bates 1955). These "features" included static instability, significant extratropical cyclones, abundant low-level moisture, jet streams, surface convergence boundaries, and so forth.

Early on, however, it became clear that no *single* set of such features was present with each and every tornado event; rather, particular collections of elements were associated with particular groups of cases. In effect, *pattern recognition* became the basis for forecasting. This approach was applied to synoptic maps and vertical soundings to develop what Schaefer (1986) calls a "forecast rote." The essential reference on this forecasting approach is Miller (1972), which describes map types commonly associated with major severe weather outbreaks. The notion of indicating the location and orientation of the various features of interest on a single map, the so-called *composite chart* (Fig. 1)[2] is the cornerstone of the forecast rote. Another form of this method is the *checklist* (also described in Miller 1972), as shown in Fig. 2.

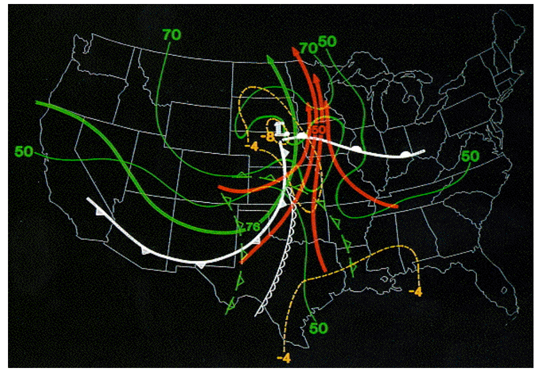

Fig. 1. An example of a composite chart; in this case it is a composite *prognosis*, depicting 12 h forecast positions of surface and upper air features at 0000 UTC 27 April 1991 based on initial data from 1200 UTC 26 April 1991. Black symbols are conventional surface frontal features, green lines denote 50 and 70% mean (surface to 500 mb) relative humidity, red streamlines are at 850 mb with a 50 kt maximum indicated, blue stream line is the 500 mb jet stream axis, with a 76 kt maximum indicated, the blue dashed frontal symbols depict 500 mb thermal trough axes, and the orange lines are isopleths of the forecast lifted index.

SEVERE THUNDERSTORM AND TORNADO PARAMETER WORKSHEET

AREA	ADVISORY NUMBER	DATE	ADVISORY VALID
LA-MS-AL	86	21 FEB 71	21 / 18 Z to 22 / 06 Z

PARAMETER	1200Z ANAL		0000Z PROG		REMARKS/VERIFICATION
	VALUE	RATING	VALUE	RATING	
SWEAT	500-550	S+	500-666	S	MAX PROGGED OVER CNTRL & NRN MS
TOTALS	58	S+	58-60	S	
LIFTED INDEX	-5	S+	-7	S	
PVA	30°	M+	40°	S	
500 MB HT FALLS	-200M	S	-200M	S	
500 MB JET	95K	S−	90K	S	
850 MB MOISTURE	11°	M+	13	S	
850 TEMP RIDGE	W OF MOIST RIDGE	S	W OF MOIST RIDGE	S	
LO-LEVEL JET	45-55K	S	50K	S	
700 MB DRY INTRUSION	——	S	——	S	
700 MB NO-CHANGE TEMP	WINDS CROSS < 20°	W+	WINDS CROSS 20-40°	M	0000Z DATA ACTUALLY STRONG S
WINDS VEER WITH HEIGHT	YES	—	YES	—	
WINDS INCREASE WITH HEIGHT	YES	—	YES	—	
INTERSECTING UP AND LO JETS	YES	—	YES	—	
SFC DEW POINT	62°	M+	66°	S	
SFC PRESSURE THREAT AREA	1008	M+	1002	S	
FALLING PRESSURE	YES	—	YES	—	
INCREASING SFC TEMP	YES	—	YES	—	
INCREASING DEW POINT	YES	—	YES	—	
THICKNESS RIDGE	YES	—	YES	—	
THICKNESS NO-CHANGE	YES	—	YES	—	
MESO OR SYNOP PATTERN	FAVORABLE		FAVORABLE	—	

REMARKS
MARKED DIFLUENCE OVER THREAT AREA AT 1200Z AND PROGGED FOR 0000Z.
NUMEROUS TORNADOES OCCURRED FROM N.E. LA INTO MS AFTN AND EVNG.

Fig. 2. Example of a checklist for severe weather.

[2] It is noteworthy that the composite chart, as employed in severe weather forecasting, specifically attempts to establish the interaction between features aloft and at the surface. Thus, it is a product with a long history of addressing what Mass (1991) considers a common deficiency in synoptic analysis; namely, the failure to depict 3-dimensional relationships among features at different levels.

Unfortunately, there was little information in this approach that allowed forecasters to make a direct connection between what they saw in their analyzed weather data and the storms responsible for producing the tornadoes. On the scale of a weather map, a tornado is a microscopic dot. There is no information on a weather map distinguishing a tornadic from a non-tornadic storm, except insofar as there is some association between the storm and its environment.

What weather map typing gives one is an association, but it does little to explain cause and effect. What was the basis for making the operational distinction between tornadic and non-tornadic situations? For forecasting purposes, the connection between the storm and its environment has been and largely remains by means of a synoptic climatology, generally derived quite subjectively.

When the techniques of the 1950s were being developed, there was little comprehension of the structure and evolution of tornadic storms and what relationship existed between the tornadic storm and the tornado. Weather radars were a brand-new technology, and no scientific basis existed to use a radar for understanding tornadic storms, much less detecting them when present. Real-time radar in a national tornado forecasting unit was a distant dream, as were real-time satellite views of storms and computer-based analysis and forecasting.

The radar observations of the 1950s created a great deal of interest in learning more about tornadic storm structure and evolution. Research surface mesonetworks had been established in the early 1950s to pursue some ideas about tornadoes (e.g., Tepper 1950, 1959), but radar rapidly became the primary means for observing tornadic storms. Thus, while forecasters concentrated on empirical methods based on synoptic scale surface and upper air data, the focus of tornado-related research dealt with storm-scale processes as revealed by radar. This schism between research and operational goals grew with time; by the early 1960s, an institutionalized fission of the tornado research and forecasting communities was created with the establishment of the National Severe Storms Laboratory from the Weather Bureau National Severe Storms Project (see Staff, NSSP 1963) in 1964.

The research produced a picture of the tornadic storm as a "supercell" (as detailed in Browning and Fujita 1965), a type of convective storm which differed significantly from other, non-tornadic storms in its radar structure and evolution. While it became apparent that not all supercells produced tornadoes, and not all tornadoes came from supercells (see Doswell and Burgess 1992), supercells clearly were prolific tornado producers in comparison to other convective storms.

In these pioneering studies, it also was found that supercells favored certain environments, although the reason for this association remained somewhat unclear. In spite of these gains, the knowledge of tornadic storms developed during this research was not readily incorporated in the operational environment;[3] research and operations seemed unable to communicate effectively. By concentrating on different scales and data streams, most forecasters and researchers no longer spoke the same language.

By the mid-1970s, numerical cloud modelling had become capable of fully 3-dimensional, time-dependent storm simulations. We think the flowering of these models has signaled the beginning of the end to the barrier separating basic storm-scale research from operational forecasting, although this was not widely recognized at the time. We believe this because the cloud models can be used to explore how the characteristic features of a simulated storm depend on the larger environment in which it develops. Subsequent cloud model-based research indeed has been quite successful in developing the storm-environment con-

[3] Some of the research results have had an impact in *some* operational detection and warning programs, although even there, progress has been slow.

nection for the first time (e.g., Weisman and Klemp 1982, 1984).

Another critical source of insight into convective storms has been research Doppler radar observations. While Browning's work (e.g., Browning 1964) made innovative use of reflectivity information to infer storm flow, the detailed velocity field information has confirmed the basic supercell storm structures deduced from non-Doppler radar studies (e.g., Brandes 1977), and has been quite important in validating concepts developed from numerical cloud models (see, e.g., Weisman and Klemp 1984).

A third important research development of relevance has been the deployment of "storm chase" teams: groups of meteorologists attempting to observe tornadoes and tornadic storms firsthand. This has produced an unprecedented number of detailed visual observations, including many storms of the non-tornadic variety. For the first time, scientists have been able to relate events (tornadic and non-tornadic) observed directly in the field to structures seen in large-scale weather maps. It should be obvious that tornado forecasting is an essential part of a storm chase; thus, storm chasers have become contributors to forecasting research (e.g., Weaver and Doesken 1991, Davies and Johns 1992, Brady and Szoke 1988)

In spite of the proliferation of new technologies in the workplace and the burgeoning research developments, the decades following the 1950s have not seen much change in operational tornado forecasting techniques. Rather than supporting qualitative changes in the way tornado forecasting is done, new observing and analysis tools have been used to increase the precision and timeliness of the forecasting approaches primarily developed in the 1950s. The new observations most often have been used to identify new ways to detect severe storms (e.g., the satellite-observed "enhanced-V" signature noted by McCann 1983; see Fig. 3) as well as to enhance recognition of previously-known elements (e.g., intersecting thunderstorm-generated outflow boundaries, as in Purdom 1982). Although severe storm recognition and detection has been improved by the new observations, their value as forecasting tools often has been compromised by a lack of exploration of the times the features were present and yet nothing happened (see, e.g., Stensrud and Maddox 1988).

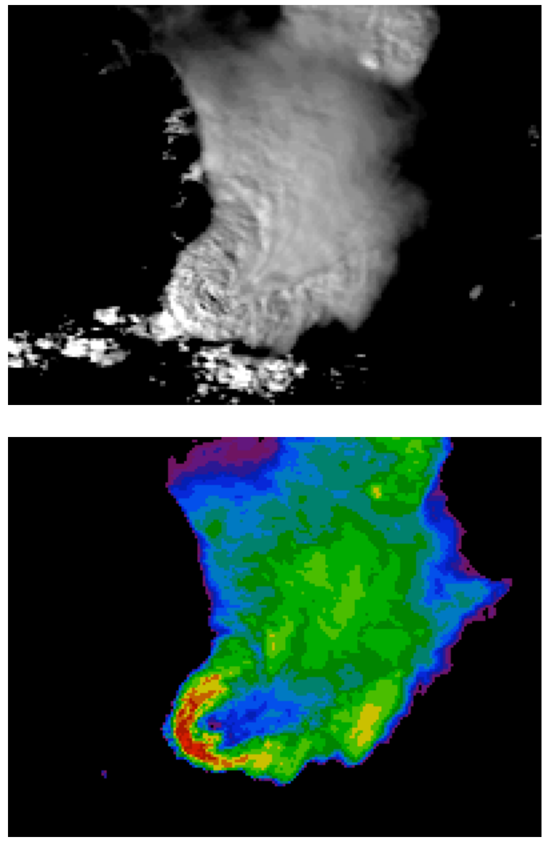

Fig. 3. Example of an "enhanced-V" signature from a satellite image (from Setvák and Doswell 1991), showing the visible appearance (top) and the enhanced thermal infrared appearance (bottom), the latter of which emphasizes the signature.

Moreover, computers have been used mostly to speed and enhance subjective analysis techniques developed decades earlier (mostly by automated data plotting), rather than to create new techniques. In effect, for operational forecasting, the computer often has been asked to duplicate electronically what used to be done manually.

In recent years, the research and operational sides of tornado forecasting have begun to collaborate once again. For example, recent research into streamwise vorticity (Davies-Jones 1984) is being applied directly in assessing tornado potential (e.g., see Johns et al. 1990, Davies-Jones et al. 1990, and Davies and Johns 1992) operationally.

3. CURRENT SELS TORNADO FORECASTING PROCEDURES

Present-day SELS tornado forecasting comprises three steps: the "Second Day Severe Thunderstorm Outlook (hereafter, the DY2 AC), the "First Day Convective Outlook" (hereafter, the DY1 AC), and severe thunderstorm/tornado watches. This suite of SELS products has evolved over time; they are partially described in Weiss et al. (1980), but for a full description the interested reader should consult the National Weather Service Operations Manual, Chapter C-40.

The Outlooks (or ACs) are regularly-issued (and updated) general forecasts of relatively large areas of severe thunderstorm[4] potential. Watches, on the other hand, are issued only as needed (in the judgment of the SELS lead forecaster) and are more specific in terms of timing, location, and expected types of severe weather. The basic premise is that as the time of the event approaches, it is possible to refine the forecasts of severe thunderstorm type, timing, and location. While this premise seems logical, it is not necessarily valid; the relevant scales decrease as the event develops, first shrinking from synoptic scale to mesoscale and then on to the convective storm scale. However, the amount of data available to the forecaster does not undergo an increase commensurate with this scale decrease. It is not uncommon for forecasting to become more difficult as the time of the event approaches (as discussed in Doswell et al. 1986). Generally, it is during the watch phase that SELS attempts to distinguish between tornadic and non-tornadic storms.

3.1. Forecasting Procedures: Convective Outlooks

Operational SELS tornado forecasting employs three general approaches: synoptic pattern recognition, meteorological parameter assessment (checklists), and climatology. These are the tools that developed historically as noted in Section 1. Special synoptic pattern-specific or geographically-specific situations have been used to develop specialized forecasting techniques (for some examples, see Doswell 1980, Hales 1985, Johns 1984, Weiss 1985, Hirt 1985, Weiss 1987) that contribute to the ACs.

As more is learned about the physical processes resulting in tornadoes and/or severe thunderstorms, parameters considered operationally relevant have been changing to reflect that new understanding. Thus, for example, vorticity advection, emphasized in Miller (1972) and questioned by Maddox and Doswell (1982), is giving way to helicity-related parameters, as discussed in Davies-Jones et al. (1990). Continuing efforts to refine the climatological information about tornadoes (Kelly et al. 1979) and non-tornadic severe thunderstorms (Kelly et al. 1985) are aimed, in part, at improving operational forecasting; recall that climatology, modified by knowledge of the synoptic pattern, is a traditional basis for distinguishing tornadic from non-tornadic situations.

For the long lead times of the ACs (up to 52 h in the case of the DY2 AC), the primary input to these products is the

[4] For *official* purposes, a severe thunderstorm is defined as one which produces one or more of the following: hail $\geq$ 3/4 in (2 cm) in diameter, measured winds $\geq$ 50 kt (25 m s^{-1}), "damaging" winds (involving some subjective judgment of effects required to meet the threshold), a tornado. Heavy rain, large quantities of sub-threshold hail, funnel clouds, frequent lightning, etc. are not considered to meet the official criteria (see discussion in Doswell 1985).

numerical weather prediction model guidance from the National Meteorological Center (NMC), of which NSSFC (and, hence, SELS) is a part. With diminishing lead times, and especially with regard to the watches, diagnostic evaluation of surface and upper-air data becomes dominant over model prognosis. In conjunction with the analysis of surface and sounding data, the remotely sensed data (such as satellite, radar, and lightning ground strike location) that have become available in ever-growing amounts are increasingly important. These data, especially satellite imagery, are useful in assessing the numerical model initial conditions (e.g., Hales 1979) and in data voids (most oceanic regions and some sparsely populated land areas, as well as when conventional data are missing or contaminated with convection).

SELS continues to employ many parameters designed to summarize information contained in the data; such parameters often are called "indices" (see e.g., Miller 1972, Galway 1956, Showalter 1953 for some of the myriad thermodynamic indices measuring static instability). Recently, a more comprehensive parameter than the traditional indices for static instability is coming into use in SELS: the Potential Buoyant Energy (PBE, also called the Convective Available Potential Energy, or CAPE; see Moncrieff and Miller 1976) is the "positive" area on a sounding associated with the buoyant part of a lifted parcel ascent between the Level of Free Convection (LFC) and the Equilibrium Level (see Doswell et al. 1982).

Nearly all the parameters (past and present) used on composite charts and/or checklists can be shown to be associated with:

1. Synoptic and mesoscale upward motion
2. Sufficient moisture and lapse rate for a parcel to be positively buoyant
3. Vertical wind shear structure

Therefore, the scientific connection between the parameters used and the physical processes can be made, even if forecasters have not always recognized that connection.

A key notion employed in tornado forecasting is that of "limiting factors". Once a preliminary general threat area has been defined, it is refined by considering what factors make it unlikely that some parts of the original threat area actually will experience severe weather. Obviously, anything precluding thunderstorms will preclude tornadoes.[5] In to rnado forecasting, vertical wind shear structure is becoming the key factor in distinguishing tornadic from non-tornadic events, so this becomes a critical limiting factor in delineating tornado threat areas.

In a few cases (typically fewer than ten days per year), tornado *outbreaks* are forecast in the ACs. Such forecasts began in the mid-1970s, following the 3-4 April 1974 outbreak. A separate public version of the AC is issued in such situations. Although it is impossible to be completely general regarding tornado outbreak conditions that might result in such an AC, they typically are associated with what we call *synoptically evident* patterns. Tornadoes may be mentioned in the outlooks when moderate or greater thermal instability is likely to be coupled with favorable vertical wind shear structures (Davies-Jones et al. 1990, Johns et al. 1990, Leftwich 1990).

3.2. Forecasting Procedures: Watches

The foremost SELS public forecast products are the tornado and severe thunderstorm *watches* (an example of which is shown in Fig. 4). These forecasts usually take the form of quadrilaterals covering on the order of 20,000 mi^2 (about 52,000 km^2), and are valid for time periods of several hours. Some statistical information about watches in 1990 is shown in Table 1.

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[5] As noted in Doswell and Burgess (1992), some atmospheric vortices are not associated with deep, moist convection. These are not considered to be tornadoes.

Table 1. Some facts about SELS watches in 1990.

# tornado watches	249
# severe thunderstorm watches	496
Average watch duration	4.86 h
Average watch area	76,519 km^2 = 29,544 stat. mi^2
Median lead time	31 min

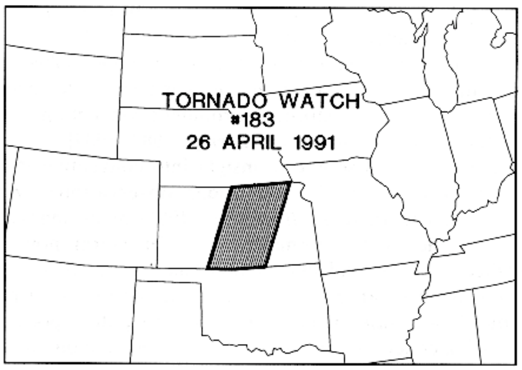

Fig. 4. Plot of tornado watch #183 on 26 April 1991 (cf. Fig. 5).

In order to convey information about SELS forecaster interpretations to the forecasting community (*not* to the public), SELS *Mesoscale Discussions* (MDs) are issued as needed. The MDs provide a narrative of probable weather developments and possible forthcoming watch issuance; MDs began in 1986. Another information-conveying, non-public product is the watch-related *Status Report*, begun in the 1950s, which has several aims: to keep the field offices informed about severe weather conditions in and near an issued watch area, to clear those parts of the watch where the severe weather threat has ended, and to provide information about additional, follow-on watches.

In general, SELS forecasters must deduce the character of the subsynoptic scale processes relevant to severe weather watches from limited operational data: hourly surface observations, satellite images, and radar displays. These current sources provide the highest operationally-available space and time resolution for the task at hand. Subjective surface analyses locate and track features believed relevant (see Miller 1972, Doswell 1982) to tornado and severe thunderstorm forecasting. These features then are related to the satellite imagery using the advanced interactive computer system called NSSFC's VAS Data Utilization Center (VDUC, see Browning 1991). Recently, lightning ground strike data have become available (Mosher and Lewis 1990) and are used in SELS for defining, locating, and monitoring convection, as a supplement to satellite and radar data.

In the past, it was common to differentiate tornadic from non-tornadic situations using parameters related to the strength of the winds aloft (as in Miller 1972). This created a seasonal bias to the frequency of issuing tornado watches, with increased likelihood of a tornado watch in the winter and spring (and to a lesser extent, in the fall) when strongly baroclinic disturbances are present in severe weather situations. During the summer, with weaker synoptic scale disturbances, the tendency was toward severe thunderstorm (instead of tornado) watches. Although this method matches climatology reasonably well (see Kelly et al 1979), there was no understanding of the processes relevant to tornadogenesis being employed, largely because that understanding was not available. It was not easy to justify the choice in any given situation, except by experience and climatology.

It is only within the last several years that this situation has begun to change. At present, recognition of the supercell environment is becoming the cornerstone of SELS tornadic vs. non-tornadic decision-making. This philosophy also reflects a lack of knowledge about non-supercell tornadoes at present, at least compared to supercell tornadoes; as noted in Doswell and Burgess (1992), the study of the non-supercell tornado has only just begun.

On the other hand, the high degree of association between supercells and

BULLETIN - IMMEDIATE BROADCAST REQUESTED
TORNADO WATCH NUMBER 183
NATIONAL WEATHER SERVICE KANSAS CITY MO
1210 PM CDT FRI APR 26 1991

A..THE NATIONAL SEVERE STORMS FORECAST CENTER HAS ISSUED A TORNADO WATCH FOR

PARTS OF CENTRAL AND EASTERN KANSAS

EFFECTIVE THIS FRIDAY AFTERNOON AND EVENING UNTIL 800 PM CDT.

THIS IS A PARTICULARLY DANGEROUS SITUATION WITH THE POSSIBILITY OF VERY DAMAGING TORNADOES. ALSO..LARGE HAIL...DANGEROUS LIGHTNING AND DAMAGING THUNDERSTORM WINDS CAN BE EXPECTED.

THE TORNADO WATCH AREA IS ALONG AND 65 STATUTE MILES EAST AND WEST OF A LINE FROM 45 MILES EAST SOUTHEAST OF MEDICINE LODGE KANSAS TO 45 MILES NORTHEAST OF CONCORDIA KANSAS.

REMEMBER...A TORNADO WATCH MEANS CONDITIONS ARE FAVORABLE FOR TORNADOES AND SEVERE THUNDERSTORMS IN AND CLOSE TO THE WATCH AREA. PERSONS IN THESE AREAS SHOULD BE ON THE LOOKOUT FOR THREATENING WEATHER CONDITIONS AND LISTEN FOR LATER STATEMENTS AND POSSIBLE WARNINGS.

B..OTHER WATCH INFORMATION..THIS TORNADO WATCH REPLACES SEVERE THUNDERSTORM WATCH NUMBER 181. WATCH NUMBER 181 WILL NOT BE IN EFFECT AFTER 100 PM CDT.

C...TORNADOES AND A FEW SVR TSTMS WITH HAIL SFC AND ALF TO 3 IN. EXTRM TURBC AND SFC WND GUSTS TO 75 KNOTS. A FEW CBS WITH MAX TOPS TO 600. MEAN WIND VECTOR 23040.

D...LN TCU DVLPG FM SW OF CNK TO BTWN RSL AND SLN ATTM. EXPCT RAPID TSTM DVLPMT WITHIN NEXT HR ALG DRYLN/CDFNT WITH SUPERCELLS AND TORNADO DVLPMT LKLY.

E...OTR TSTMS...CONT WW NR 182. WW LKLY TO BE RQRD WITHIN NEXT HR OR TWO OVR PTNS WRN AND CNTRL OK. WW LKLY TO BE RQRD LATER THIS AFTN OVR PTNS ERN KS AND WRN MO.

...JOHNS

Fig. 5. Tornado watch message #183, issued on 26 April 1991, using the "enhanced" wording. Parts A and B are transmitted to the public and so are in plain text, whereas part C-E are not made public and are written in contractions to save characters.

tornadoes has made it possible to identify situations that are likely to produce tornado outbreaks. Outbreak-related tornadoes are usually produced by supercells and the tornadoes that form from supercells are capable of the highest damage potential associated with any tornado. These cases, not surprisingly, are exemplified best by "classical" severe weather patterns: those that we have called synoptically evident[1]. Thus, SELS has had the option (since the early 1980s) to issue tornado watches that have "enhanced wording" to highlight the tornado threat (see Fig. 5).

[1] Note that a situation we label as synoptically "evident" should not be automatically equated with an "easy" forecast. No real-world forecast situation is ever easy, except in retrospect!

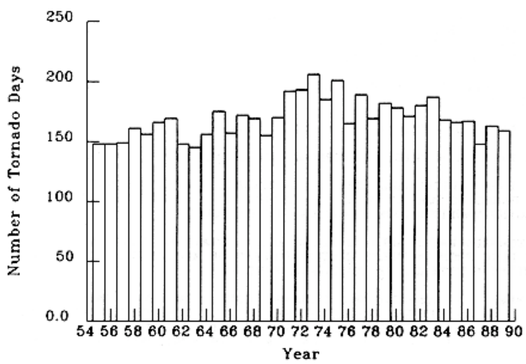

Fig. 6. Plot of yearly totals of tornado days (i.e., days with one or more reported tornadoes).

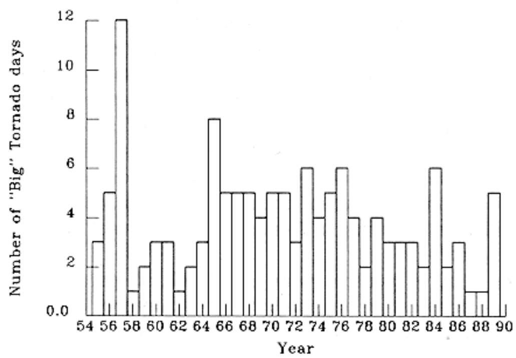

Fig. 7. Plot of yearly totals of "big" tornado days (i.e., those days with at least two or more violent (F4-F5) tornadoes).

Let us define a *tornado day* as a day with one or more tornadoes and a ***big*** *tornado day* as a day with two or more violent (F4-F5) tornadoes. The interannual variation in tornado days is rather small, averaging about 175 days per year (see Fig. 6), whereas big tornado days fluctuate considerably from year to year (Fig. 7), with an average frequency of about 10 such days per year. Enhanced wording is used when tornado outbreaks are expected, and outbreaks typically have two or more violent tornadoes, meeting our criterion for a big tornado day. Thus, the enhanced wording in tornado watches is not commonly employed.

The role of vertical wind shear-related parameters in tornado forecasting has made the development and operational availability of additional sources for vertical wind structure quite critical. Therefore, the demonstration network of vertical wind profilers (Gage and Balsley 1978) presently being implemented (National Weather Service 1987) is of great interest to operational forecasters. Also, the wind profiling capability (see Rabin and Zrnic' 1980) of the WSR-88D (NEXRAD) Doppler radars in the pre-storm, clear air environment may be extremely valuable.

4. 35 YEARS OF TORNADO FORECAST VERIFICATION

Since the essential aspect of tornado forecasting is to distinguish between tornadic and non-tornadic situations, this will be the primary issue discussed here. There are numerous other aspects of tornado and severe thunderstorm watch verification that we cannot dwell on here; some will be presented in a future publication. Our data consist of the final SELS log of severe weather reports and records of tornado and severe thunderstorm watches, covering the 35 year period 1955-1989, inclusive.

It should be noted that a tornado watch/event is, in a sense, also a severe thunderstorm watch/event. That is, a tornado-producing storm is, by definition, a severe thunderstorm. Therefore, a tornado in a severe thunderstorm watch verifies that watch, but a non-tornadic event does not verify a tornado watch. However, for the purposes of this paper, we have not accounted for this fact in the verification; that work is not yet complete, but it will be reported upon in the aforementioned future publication.

Another important aspect of tornado forecast verification is that tornado watches are *area* forecasts that typically cover several tens of thousands of square kilometers, whereas tornadoes affect only a few square kilometers even in major events. This disparity in coverage means that successful tornado watches (i.e., those with tornadoes in them) are mostly "false alarms" in the sense that the vast majority of the forecast area is unaffected. The original watch verification schemes considered them as area forecasts, so that a single tornado effectively verified the entire area of the watch. Recently, as described in Weiss et al. (1980), watch verification has been changed such that a single report only verifies a portion of the total watch area/time. However, this new scheme still does not incorporate information about areas outside the watch.

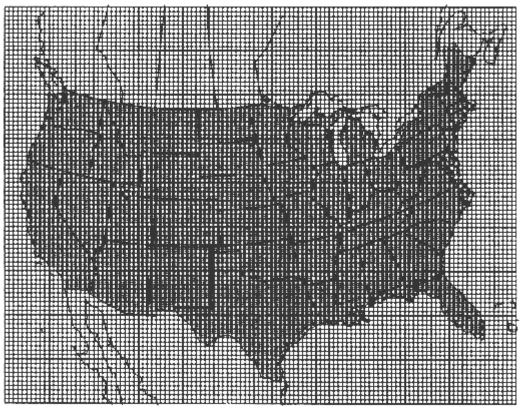

Fig. 8. Illustrating the Manually-Digitized Radar (MDR) grid with those blocks considered in the verification shaded gray.

The verification scheme used herein (first described in Doswell et al. 1990b) is based on the so-called Manually Digitized Radar (MDR) grid shown in Fig. 8. Each MDR box is roughly[2] a square 40 km (25 n mi) on a side. Every watch has been broken down into MDR grid boxes, using the convention that if the *centroid* of an MDR box is within the watch, that MDR box is considered to be within the watch. The valid time of the watch is broken down by hours; if a watch begins on the hour or within the first 29 minutes of the hour the watch is considered valid for the whole hour, whereas watches beginning 30 minutes or more after the hour apply to the next whole hour. The *MDR box-hour* is the basic unit of the verification, and it naturally gives a somewhat "grainy" picture. We have tested the effect of increasing the resolution both in space and time and found that for our verification purposes, it is detectable but does not affect the overall patterns. There are 4533 MDR boxes over the United States (boxes over water are not counted), and each non-leap year has 39,709,080 MDR box-hours.

For verification purposes, a severe weather report is considered to verify an entire MDR box-hour if it occurs anytime within that hour. Reports other than the first in that MDR box-hour are ignored unless they are of a different type (the two types of reports are "tornado" and "non-tornadic severe thunderstorm"). If one or more tornadoes occur within a given box-hour, it is counted as a "tornado hit" irrespective of any concurrent non-tornadic severe thunderstorm reports. If one or more non-tornadic severe events occur within a given box-hour, it is counted as a "severe thunderstorm hit".

Our basic tool for verification is the 3x3 contingency table shown in Table 2, derived via the above process for every MDR box. From the information contained within this basic table, a wide variety of summary measures, histograms, maps, etc. can be constructed, of which we obviously have room for only a small fraction. Although a single number cannot express all of the content implied in Table 2, we shall use the Heidke skill score as a summary measure of skill (see Doswell et al. 1990a,b for details). As shown in Table 3, skill scores have increased by nearly an order of magnitude over the 35 years. If we compare the first decade (1955-1964) with the last decade (1980-1989) of our record (Fig. 9), it can be seen that the primary "tornado alley" skill maximum has persisted, but additional centers of relative skill have developed in North Carolina, New York state, Montana, and Idaho. It is at present difficult to know how to interpret these results; however, spatial distribution of verification scores clearly is influenced by the distribution of severe

[2] Since the grid is defined on a polar stereographic map projection, the grid boxes vary in size across the map by as much as about 10%. The nominal size applies only at 60° N latitude, where the map scale factor is unity.

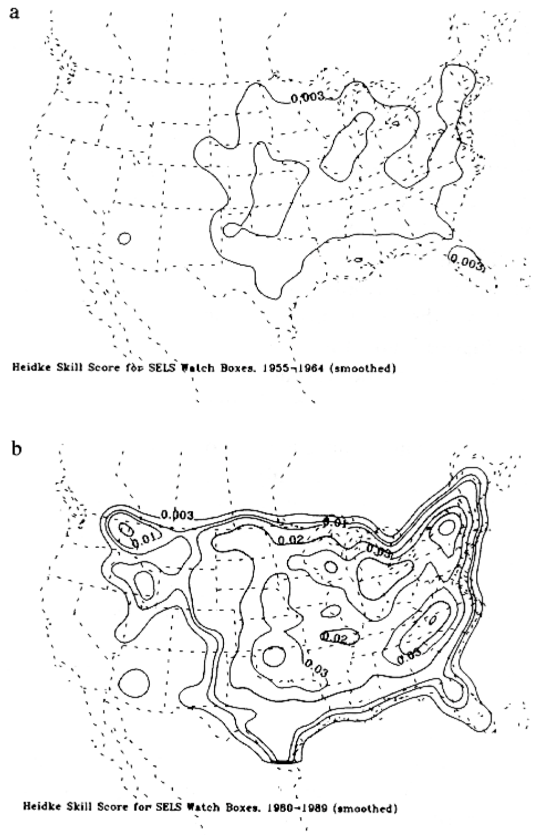

Fig. 9. Maps of smoothed Heidke skill score for (a) 1955-1964 and (b) 1980-1989.

weather reports (compare Fig. 9 with Fig. 10).

The reporting of non-tornadic severe weather has increased markedly with time (Fig. 11), whereas tornado reporting has remained more nearly constant. While the skill has climbed more or less steadily during the 35 years under consideration, how much of this skill is attributable to enhanced reporting? To attempt to account for this "inflation" we did the following. If one does not distinguish for the moment between tornadoes and non-tornadic severe thunderstorms, then the contingency table (Table 2) reduces to the 2x2 table shown in Table 4.

Table 2. Contingency table for severe thunderstorm and tornado watch box-hours, as described in the text.

	Observed			
Forecast	Tornado	Severe Thunderstorm	Nothing	Total
Tornado	n_{11}	n_{12}	n_{13}	$n_{1\bullet}$
Severe Thunderstorm	n_{21}	n_{22}	n_{23}	$n_{2\bullet}$
Nothing	n_{31}	n_{32}	n_{33}	$n_{3\bullet}$
Total	$n_{\bullet 1}$	$n_{\bullet 2}$	$n_{\bullet 3}$	$n_{\bullet\bullet}$

Table 3. Actual 3 x 3 contingency tables for (a) 1955 and (b) 1989, showing the number of watch-box hours as described in the text.

	Observed			
Forecast	Tornado	Severe Thunderstorm	Nothing	Total
		(a) 1955		
Tornado	85	62	39,696	39,843
Severe Thunderstorm	40	56	78,580	78,676
Nothing	420	604	39,589,357	39,590,561
Total	545	722	39,707,813	39,709,080
		(b) 1989		
Tornado	237	1372	61,036	62,645
Severe Thunderstorm	102	1965	96,325	98,392
Nothing	393	4255	39,543,395	39,548,043
Total	732	7592	39,700,756	39,709,080

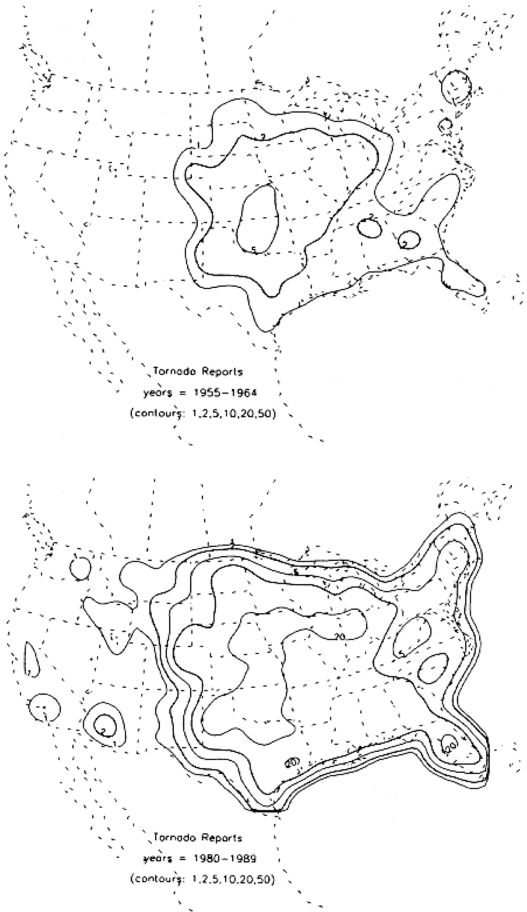

Fig. 10. Maps of smoothed tornado occurrence for (a) 1955-1964 and (b) 1980-1989.

We take the number of severe reports in 1955 as the standard[1], denoted by $(x+y)_{55}$. Subtract this from the number of severe reports in the ith year, $(x+y)_i$, to obtain the difference, d_i. This difference is an estimate of the number of events for the ith year that would have gone unreported in 1955, so these are all put into the z-box (refer to Table 4) in the contingency table. We assume that the ratio of the x-box to the y-box remains the same, and re-do the skill score verification on the revised table. Of

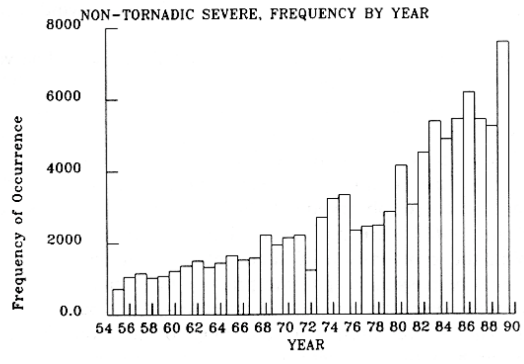

Fig. 11. Plot of yearly totals of non-tornadic severe weather.

course, some of the d_i might actually belong in the w-box, but since w is typically much larger than the other entries in the table, ignoring this creates only a negligible error. While we temporarily have lumped tornadoes and non-tornadic severe thunderstorm events together for this purpose, the Heidke skill scores for the 2x2 and 3x3 versions of the table are not markedly different (see Doswell et al. 1990). The results of this procedure (Fig. 12) show that overall, the skill of severe weather watches has improved by about 50% when report "inflation" has been accounted for, rather than the order of magnitude increase without correcting for this inflation.

Table 4. As in Table 2, with no distinction between tornadoes and severe thunderstorms ($N = x+y+z+w$)

		Observed	
Forecast	Severe	Nothing	Total
Severe	x	y	$x+y$
Nothing	z	w	$z+w$
Total	$x+z$	$y+w$	N

Turning to the specific issue of tornado vs. severe thunderstorm forecasts, the asymmetry of the forecasts is important. That is, as long as one or more tornadoes occur in a tornado watch, there is no problem with having many reports of non-tornadic severe thunderstorm events in that tornado watch (element n_{12} in Table 2). On the other hand, having tornadoes occur in severe thun-

[1] As is the case in accounting for currency inflation, this does not imply that there is anything special about 1955. It simply represents a base, or reference state. We could just as easily have adjusted toward a 1989 standard, with no material difference in our conclusions.

derstorm watches is an undesirable event (element n_{21} in Table 2). Of course, there is an easy way to prevent this from ever occurring: always issue only tornado watches. Doing so would represent

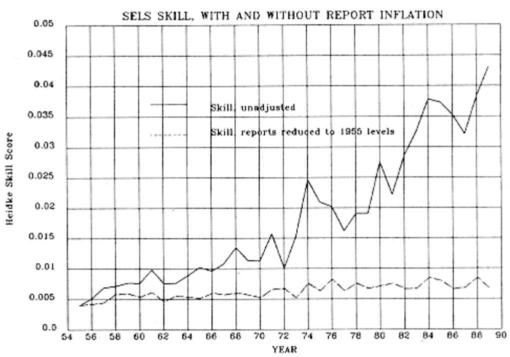

Fig. 12. Plot of yearly values in Heidke skill score, both unadjusted and adjusted (as described in the text) for "inflation" of non-tornadic severe weather reports.

no attempt to discriminate between tornadic and non-tornadic severe thunderstorms and this clearly is not desirable, nor does it reflect what has been done. As can be seen in Table 3, the occurrence of tornadoes in severe thunderstorm watches has increased with time, but only by about a factor of two. This relatively small increase appears to be, in part, a consequence of the relatively modest rate of increase in tornado reporting overall. However, the number of correctly forecast tornado events has increased by about a factor of three, suggesting some increase in the skill of discrimination. The occurrence of tornadoes without any watch of either type actually decreased during the period, although such total misses still constitute the majority of observed tornadic events. Since the majority of *all* tornadoes are weak, and because the probability of detection for tornadoes in watches is lowest for weak tornadoes (Leftwich and Anthony 1991), most of these missed events are weak tornadoes and probably are not associated with supercells. Galway (1975) has observed that the majority of tornado deaths occur in watches, which remains true to this day, suggesting that watches capture most of the significant tornadoes.

5. CURRENT UNDERSTANDING OF TORNADIC STORMS

Our understanding of tornadic storms and how they interact with their environment is presently in an exciting state of transition. As Doswell and Burgess (1992) have indicated, we have come to realize that tornadoes can occur in many ways, and are not limited to supercell events. Not all tornado reports represent the same meteorological phenomenon and we are just beginning to understand how non-supercell tornadoes might arise (e.g., Wakimoto and Wilson, 1989).

Even for supercell events, however, mesoscale variability in atmospheric structure can be crucial in estimating the chances for tornadoes (see Burgess and Curran, 1985 for a case study example). Mesoscale details, often slipping more or less unnoticed through the present-day observing system, can be the difference between correct and incorrect forecasts. The sorts of events used by Miller (1972) to exemplify tornadic environments are not as difficult to predict, because they are characterized by large-scale environments readily identified as being favorable for supercells with today's data. Such synoptically evident events are not frequent during the tornado season, however (see also Maddox and Doswell 1982).

On some tornado days (typically those with large CAPE but weak to marginal shear) severe storms are likely, but the apparent tornado potential is not high. A notable recent example is 28 August 1990, on which the violent Plainfield, Illinois event occurred. In such environments (many of which produce *no* significant tornadoes), some mesoscale process creates a local environment such that isolated storms become tornadic in ideal conditions, but those conditions are uncharacteristic of a large area. In contrast, major outbreak days (such as the Kansas-Oklahoma outbreak of 26 April 1991 that produced the Andover, Kansas killer tornado, among others), have widespread supercell-favorable environments and many supercells.

Said another way, *more than 90% of the tornado days per year are not synoptically "evident"* ; most tornado events involve mesoscale processes that are difficult to anticipate at present (see Doswell 1987, Rockwood and Maddox 1988). The forecaster must formulate a correct prior assessment of tornado potential, followed by careful monitoring of the observations, watching for crucial developments that might escape notice even when they occur.

Recent research has suggested that the vertical wind shear structure is the most crucial element in supercells. Thus, the source of rotation in supercell-related tornadoes seems to be the vertical wind shear in the environment. Static instability does not seem particularly useful in distinguishing supercell from non-supercell events, since supercells occur within a broad range of instabilities (Johns et al. 1990, 1991), although it may be important in determining other aspects of severe thunderstorm potential.

To the extent that supercells are responsible for most strong and violent tornadoes, the current task of tornado forecasting hinges on predicting environments favorable for supercells. This begins with the requirement that deep, moist convection be possible; in turn, this depends on having sufficient moisture, instability, and lift such that potentially buoyant parcels reach their LFCs. Many of the empirical forecasting "rules of thumb" have physical explanations rooted in the required presence of deep, moist convection. Beyond this, for supercells, it appears that the development of a supercell's deep, persistent mesocyclone takes longer than the 20-40 min lifetime of an ordinary convective cell. Long lifetimes for convective events are the result of propagation, with new convective cells developing in preferred locations relative to existing cells. Preferential convective development is now known to be related to the vertical wind shear (see Weisman and Klemp 1982, 1984). It is also important that the combination of vertical wind shear and storm motion produce enough storm-relative helicity (as in Davies-Jones et al. 1990) to allow the mesocyclone to reach down to the surface (Brooks et al. 1992). Despite some recent progress, the validation of these ideas in forecasting practice has yet to be done, in part owing to a lack of mesoscale detail in the observations.

Although non-supercell events have not yet received the research attention given to supercells, it appears that at least some of them may be related to mesoscale processes associated with terrain features (e.g., Brady and Szoke 1988). To whatever extent non-supercell tornadoes are associated with topography, their prediction may be correspondingly straightforward (see Doswell 1980, Weaver and Doesken 1991). As of this writing, it is not known what fraction of all such tornadoes are terrain-related.

6. FUTURE DIRECTIONS

We have indicated that tornado forecasting is presently in a state of rapid change. We have emphasized how important scientific understanding has become in the tornado prediction problem. It is the new technologies that will make new science possible, but breakthroughs will not arise simply by switching on new systems. Systematic research will be needed to achieve technology's promise, and a commitment to transferring new understanding to operations is required. As new ideas are developed, their forecast value must be verified rigorously and the ideas modified based on the results of the verification.

6.1. Technological Tools

There are several new observing technologies to which the operational weather services in the United States already are committed. The WSR-88D radar network is the keystone for the future health of tornado *warnings*, but what about tornado *forecasting*? With the current emphasis on the importance of vertical wind shear in supercell storms, the clear air wind profiling capability of the WSR-88Ds (e.g., see Fig. 13) becomes potentially valuable. Since this capability is, in general, limited to low levels, it nicely complements the vertical wind profilers, which do not provide low-level winds. An opportunity for increasing our wind observations lies in automated instruments on commercial aircraft, including high resolution data during ascent and descent (in effect creating wind and temperature soundings near major air terminals). All together, these enhancements to observations of the mesoscale flow variations should improve our capacity to diagnose and anticipate the wind shear structure.

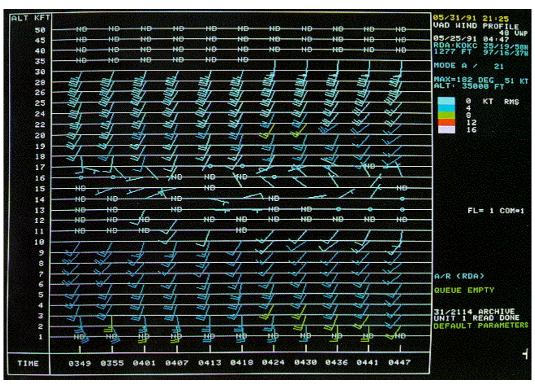

Fig. 13. An example of a time-height cross section of wind from a steerable Doppler radar using the Velocity-Azimuth Display algorithm.

Widespread deployment of automated surface observations should enhance the resolution of our surface data. The new technologies that make automated surface observations feasible have made it realistic to propose the operation of what we now view as research-density mesonetworks over much of the country as we enter the new century. In the past, processes observed with high-resolution networks (see Fujita 1963) were not resolved in operational networks. With the proliferation of such networks in operations, it should be possible to put into practice the concepts derived from the research network observations of the past, as well as to do *new* research on a wider range of situations than the research networks, with their limited area and time of operations, could sample.

As of this writing, we are on the verge of having a nationwide network of lightning ground strike detectors and a space-based lightning mapper (Turman and Tettelbach 1980) that will allow observations of intra- and inter-cloud lightning as well as ground strikes. The ultimate value of such information in tornado forecasting remains unknown at present. If such data are to be of value in forecasting, we must integrate the lightning data with the rest of the observations in determining how lightning ground strike information relates to storm severity (see MacGorman 1992).

Multispectral satellite observations of an unprecedented scope are promised for the near future, also. We believe the real value in such observations is not in trying to emulate direct measurement (e.g., rawinsonde) data. Instead, the new data should be used in ways that are consistent with their character; e.g., layer-averaged variables (see Fuelberg and Olson 1991). Given earth- and space-based remote sensing technologies (wind and thermodynamic profilers, Doppler radars), and various direct measurements (rawinsondes, aircraft measurements), the most complete and useful observations will involve the union of all these observing technologies, a task easier said than done.

Another technological tool is the operational meteorological *workstation* . As new observing technologies are about to unleash a torrent of new data on the operational work environment, the same basic technologies also give us the capacity to absorb and integrate it. If a future operational workstation is to have a positive impact on forecasting, it must meet two requirements. First, the workstation hardware must have sufficient data processing resources to deal effectively in real-time with the data transfer rates associated with the new observations. Second, the workstation software must make this torrent of data available in operationally useful ways.

The last technological tool for the future we shall discuss is the numerical prediction model. There can be no doubt that numerical prediction models will continue to assume ever greater roles in the tornado forecast problem. Clearly, the tornado is many orders of magnitude smaller than the environmental processes that give it birth, so scale interaction is a crucial question. However, it will be many years (if ever) before a single numerical prediction model will encompass all these scales explicitly and simultaneously.

The real impact of mesoscale numerical prediction models in operations remains to be seen, but experimental real-time predictions with mesoscale models are underway (see Warner and Seaman 1990). Even numerical cloud models may have a role in operational forecasting (see Fig. 14). See Brooks et al. (1992) for an extended discussion on this topic. The capacity for such modelling can only increase, so such models could come to be viewed as essential diagnostic tools (see Keyser and Uccellini 1987) of the forecaster. The forecaster of the future must be much more than a passive recipient of model "guidance" (see Snellman 1977) – the forecaster would be using numerical models in a way analogous to using pencils and paper weather charts. The computer should *not* be used to do what can be done with a pencil on paper, however. Rather, the numerical models should form the basis for operationally useful exploration of the intricate, nonlinear relationships associated with weather-making processes.

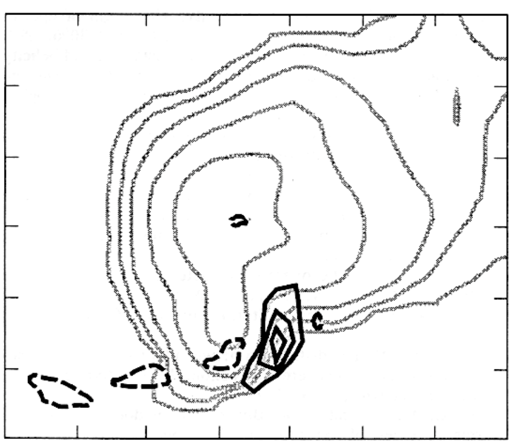

Fig. 14. Output of radar reflectivity (gray contoured at 10 dbz intervals) and vorticity (dark contoured at 0.0025 s^{-1} interval, with the zero contour suppressed) from a numerical cloud model; tic marks are 5.45 km apart. The model began with horizontally homogeneous initial conditions, using a forecast thermodynamic sounding and hodograph on 26 May 1991. The forecast input is valid for northwestern Oklahoma and a supercell tornadic storm developed that afternoon near Woodward, Oklahoma.

6.2. Productive Areas for Research

We believe that tornado forecasting eventually will outgrow its purely associative, empirical roots. The new observing systems mean that forecasters and researchers will be sharing the same data sets in the near future and the application of meteorological science to tornado forecasting probably will be a more natural process than it is now. Such an outcome depends on (a) successful research aimed at increasing understanding of storm-environment relationships, (b) a meaningful education and training program for operational forecasters, and (c) a collective will to overcome a decades-long schism between research and operations.

An issue of considerable concern is the forecasting of the detailed thermodynamic structure of the storm environment, be it tornadic or not. Present models and observations give only a synoptic scale picture that often is inadequate to resolve the important mesoscale details. Of course, on some days, it is possible to do an adequate job with the subjective and objective forecasting tools at hand. The processes by which moisture, momentum, and static stability change are well-known in principle, but those processes are not necessarily well-handled even in research-level modeling, much less in operational practice. Some of this stems from lack of resolution, both in our models and in our observations; some of the inadequacies arise from deficiencies in the physical parameterizations used in numerical models. The parameterization of convection is a crucial issue in the large-scale forecast evolution of static stability; release the convection too soon and the model never develops realistic convective instability, whereas if the parameterized convection is "turned on" too late, the forecast instability can reach unrealistically high levels.

If we continue to depend on physical parameterizations in our numerical models, as we almost certainly shall, it is obvious that improved parameterizations are needed. We believe that research aimed at improving physical understanding is preferable to improving parameterizations in the long run; parameterization is, in effect, a concession made in ignorance, even when it is a necessary concession. Of course, improved physical understanding can have a positive impact on parameterization schemes, as well.

Sensible and latent heat fluxes can have an enormous impact on static stability and moisture availability. The operational model "boundary layer physics" parameterizations leave much to be desired from the viewpoint of a tornado forecaster, especially in data-void areas like the Gulf of Mexico (see Lewis et al. 1989).

In addition to the thermodynamic fields, it is clear that, with the apparent importance of vertical wind structure for supercells, wind forecasting is a key problem in numerical prediction. Owing to their poor resolution using present operational data, mesoscale structures in the wind field depend primarily on the model for their creation, rather than being included initially. Our experience suggests that current operational weather prediction models are rather unsuccessful in predicting those important details reliably. The models have their successes, but there does not seem to be any consistency in them; the predicted details are not reliable, at least for the needs of a tornado forecaster.

As the new, more detailed observations accumulate, we may be able to develop new understanding of these mesoscale processes, heretofore inadequately sampled. This understanding may lead to improvements in mesoscale numerical prediction that will be essential to the tornado forecast problem. However, an additional complication to forecasting details of the wind structure is the impact from convection. Maddox (1983), Ninomiya (1971), and others have shown that persistent deep convection can alter the surrounding environment. This means that new convection developing in the vicinity of pre-existing convection encounters a different wind and thermodynamic environment on the mesoscale than seen by any preceding convection.

Given all of the new technological and associated scientific developments that are likely to take place in the next decade, it is quite plausible to be optimistic about the future of tornado forecasting. There can be no doubt that considerable progress will be made during the next ten years, and we look forward to those developments.

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