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Scientific Approaches for Very Short-Range Forecasting of Severe Convective Storms in the United States of America

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SUMMARY

A review of severe convective storm forecasting is given, with the emphasis on scientific approaches using mesoscale and storm-scale conceptual models. By concentrating on the ingredients for particular severe weather events, a focus is provided for the forecasting process. Such a focus is needed as diagnostic and prognostic products proliferate with the advent of new observing technology and powerful workstation approaches in the forecasting workplace. Training and education of forecasters is discussed also, as a necessary component in a balanced approach to weather forecasting in the future.

In a companion paper (Doswell 1993, hereinafter D93), a review is given of severe convective storms in North America, describing the convective weather events having disaster potential. Also provided in D93 is a broad description of the processes by which those events arise, at least as those processes currently are understood. It is assumed in this paper that the understanding of those processes leading to the weather events should form the basis for any *scientific* approaches to forecasting those events. Doswell (1986) has provided an overview of short-range forecasting in general and recent papers (Johns and Doswell 1992; Doswell et al. 1993; hereinafter JD92 and DWJ93, respectively) have reviewed severe thunderstorm and tornado forecasting, as practiced in the United States of America, in detail. Both Schaefer (1986) and Galway (1992) have reviewed the history of severe storm forecasting in the United States. This paper will summarize that material in the context of dealing with the problem of the disaster potential associated with the weather events.

As in the aforementioned works, I must distinguish between very-short range *forecasting* and *detection* of severe convective storms. This paper is not about detection and warning; rather, it is about anticipating the events in time for appropriate public responses to be made.

As noted in D93, different ingredients (and processes) are associated with each of the severe weather events, so the forecasting concepts developed herein will be keyed to the particular phenomena. For official purposes, severe weather in the United States is defined as one or more of the following: a tornado, a hailfall with maximum stone diameter $\geq$ 1.9 cm, a damaging surface wind gust (associated with convection) ≥ 25 m s^{-1}. In this paper, the definition of severe weather includes the official definitions, but is broadened to include any convective weather event capable of having a deleterious impact on humans and their activities.

In the United States, severe convective weather forecasting is currently structured so that forecast guidance is produced centrally and distributed to the local offices. There is a multi-tiered series of centralized guidance products coming from the National Severe Storms Forecast Center (NSSFC), described by Ostby (1993), with the products (ideally) becoming increasingly focused on particular convective storms as the time of the event approaches.

Since local offices experience extreme convective weather only relatively infrequently, having centralized guidance provides the forecasters at NSSFC with considerably more day-to-day experience in dealing with severe convection. The same can be said for the forecasters at the National Meteorological Center (NMC) who provide centralized guidance for flash floods. The guidance products are (ideally) true forecast products, issued in advance of severe convective weather events, albeit with short lead times on occasion (see Anthony and Leftwich 1992) and, realistically, there are times when the guidance products are not perfect.

The local offices issue warnings once the severe convective storms develop and are detected. Of course, no system works perfectly in practice, even when the system itself approaches some abstract ideal. To the extent that severe convective weather is not correctly anticipated by forecasters at the local offices, warnings may be neither timely nor accurate. It is a fact of life that if severe weather is not *forecast* well, it is not *detected* well and severe weather can indeed strike without warning. Every forecaster in the severe convective weather-prone parts of the United States (a large

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fraction of the total area) needs to be concerned about being able to anticipate severe convection.

2. Tornadoes

Tornado forecasting, as discussed in D93, is aimed primarily at supercell-related tornadoes, simply because much more is known about such events than non-supercell tornadoes. It appears that local topographic features can play a large role in the development of non-supercell tornadoes (see Wakimoto and Wilson 1989, or Brady and Szoke, 1989), but the whole topic is relatively new and there is not yet much evidence about the mechanisms by which non-supercell thunderstorms produce tornadoes, at least outside of the plains in the immediate lee of the Rocky Mountains near Denver, Colorado.

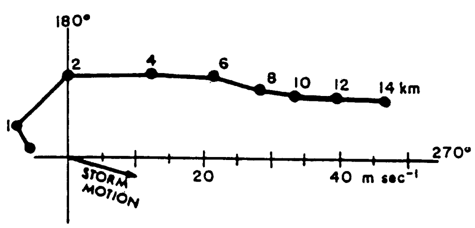

Fig. 1. A schematic, typical hodograph associated with supercell storms (from Chisolm and Renick 1972).

Therefore, the emphasis in tornado forecasting is on where conditions for supercells are likely to develop. As noted in JD92, this involves the conditions for deep, moist convection (moisture, conditional instability, and lift) in the presence of a favorable vertical wind profile in the storm environment. In the United States, such a profile typically resembles Fig. 1, having a clockwise turning hodograph in the lower troposphere and a deep layer of more or less unidirectional shear above that.

These ingredients are most likely to be brought together in United States during the spring, when the mid-latitude baroclinic zone is intense, leading to cyclone development in the central plains of the United States as upper-level disturbances move over the low-level baroclinic zone. The development of cyclones frequently takes place in the lee of the Rockies, where the low-level flow can tap the moisture flowing inland from the Gulf of Mexico, the mid-level flow brings across the dry, high lapse rate air that develops over the elevated terrain to the west, and the baroclinic zone's vertical wind shear (basically associated with the thermal wind) is generally similar to that shown in Fig. 1. The structure in such a situation is that of a "classical" tornado outbreak (e.g., Fig. 2), and the tornadoes are virtually always associated with supercells.

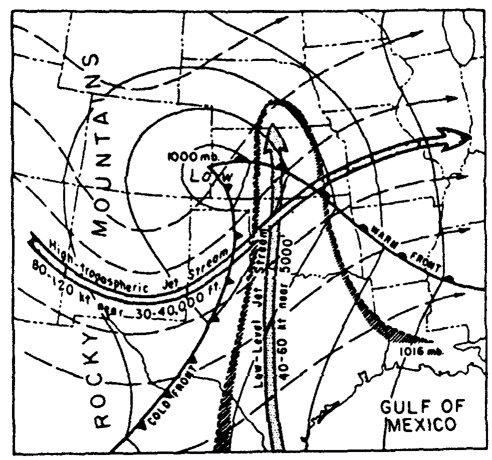

Fig. 2. A schematic, typical synoptic weather pattern associated with "synoptically evident" tornado outbreaks (from Newton 1967).

Not all supercells arise in such classic settings; in fact, most days with tornadoes don't fit this pattern all that well (see DWJ93 or Maddox and Doswell 1982). The number of days per year that are as "synoptically evident" as that depicted in Fig. 2 is small; perhaps as few as two or three per year. Most tornado days are characterized by synoptic patterns that are much more subtle, and the tornadoes are more localized. That is, the supercell-favorable environment is not a direct consequence of synoptic scale processes, but is mediated by mesoscale events. Such factors as pre-existing convective outflow boundaries, topographic influences, and diurnal circulations (i.e., sea breezes, mountain-valley flows, etc.) provide the final concatenation of ingredients.

Such events occasionally can be quite difficult to detect, even after the event occurs. Wind profile changes, in particular, can be quite challenging to forecast, and they often are critical in determining the nature of the convection (see Burgess and Curran 1985), which can change rapidly on small space and time scales, due to mesoscale environment variations.

It is interesting to note that there is an asymmetry between the spring and fall. Tornadoes are much less likely during the fall transition, in spite of the return of the low-level baroclinic zone. There is not a clear explanation of this observation, but I offer the following speculation. In the spring,

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the upper atmosphere is relatively cool, while the surface is being heated slowly by the lengthening day and increasing solar zenith angle. Since deep convection has been suppressed during the stable winter months, the result is relatively large instability, especially when moisture is adequate. High lapse rates can develop above the warm, moist low-level air flowing into the warm sector of extratropical cyclones, in the presence of significant shear. At times, the moisture fails to come into coincidence with the other ingredients, but intense convection and supercells can result even with only marginal low-level moisture.

On the other hand, in the fall, although moisture on the warm side of the baroclinic zone can be abundant, the effect of convection over the spring and summer has been to warm the middle and upper troposphere, reducing the overall lapse rates. Thus, it is harder to develop large instabilities in the fall as the polar airmasses plunge equatorward; often, the greatest lapse rates are found above the cold air mass at low levels, rather than in the warm sector. It appears that it is *possible* to form supercells with abundant moisture and only marginal lapse rates (see, e.g., Johns et al. 1993) but observations suggest that tornadoes are much less likely from this fall mixture than from the spring mixture of high lapse rates and (possibly) marginal moisture. A detailed explanation for this asymmetry is not yet available.

3. Hail events

Forecasting hailstone size and amount is a difficult task. As noted in JD92, there are several factors to consider in the forecast, including many that are difficult to forecast. Techniques of the past (e.g., Fawbush and Miller 1953) have been shown to have relatively little skill (see Doswell et al. 1982) and are now not being used. There are at least two reasons why such approaches would fail to show much skill. First, they are based on a pure parcel theory estimate of the updraft speed, and there are many complications associated with hail forecasting that are not accounted for in parcel theory. Second, the sounding used as input to the technique may not be very representative of the actual storm environment. While sophisticated numerical cloud models could deal with the physical complexities of hail formation in thunderstorms (at least in principle), the challenge of obtaining a representative environmental sounding before a hail event occurs will continue to be problem for some time to come.

Further, little or no attention has yet been put to the quantitative forecasting of hail amount. As noted in D93, large quantities of officially non-severe (< 1.9 cm in diameter) hail can be quite damaging to crops, but since hailstone *size* rather than the *amount* of hail is what is considered "severe," forecast methods to predict the amount have not been developed at all.

Many supercell storms are prolific hail producers, but hail is not common to all supercells. Those developing in relatively weak convective available potential energy (or CAPE) environments appear to be less likely to produce large hail than those occurring in high CAPE situations. Generally speaking, our detailed understanding of the factors that govern hail production in convective storms is not advanced enough to be of much use to operational forecasters. We know the general issues, but there are many unanswered questions; e.g., do microphysical processes within deep convection have an important role in determining hailfall at the surface (all other factors being equal)? If so, we are a long way at present from having the needed observations relevant to microphysics in thunderstorms.

At either the national or the local level, hailstone size forecasting is not verified; the task is simply to determine whether or not hail meeting the official criterion to be considered "severe." A maximum hailstone size estimate is included in severe thunderstorm and tornado watches (not warnings), but the estimates never have been verified.

Many local warnings for hailstorms are reactions to observed hailfalls rather than forecasts of impending severe hailstorms. Once hailstorms meeting the severe criterion are detected, warnings based on radar can be quite successful, but my experience suggests that many times the first of such storms often occurs without a true forecast and, hence, without a warning. This is especially true for *marginally* severe events (just barely meeting the 1.9 cm diameter threshold). As noted in JD92, NSSFC guidance does not attempt to have every single event occur within a valid watch; this is an impractical goal.

4. Convective wind events

In contrast to the potentially complex issues associated with hail formation and deposition, strong convective wind events are driven almost completely by downdrafts and their associated outflows. Although some supercell inflow winds can attain damaging proportions, the contribution of such events to non-tornadic wind damage from convection is virtually negligible.

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Again, older techniques (e.g., Fawbush and Miller 1954) have been shown to have relatively low skill (Doswell et al. 1982), essentially for the same reasons as the hailstone size forecasting methods. As with the hailstone size estimates, maximum convective wind gust estimates are included in the severe thunderstorm and tornado watches, but have not been verified. Also consistent with hail events is the significant chance that the *first* marginally severe event will not be forecast well.

The physics of downdrafts is simpler than that of hailstones, so downdraft formation is relatively well-understood, and the principles exist whereby success in forecasting convective wind gusts is possible. As noted in D93, however, downdraft instability is not necessarily equivalent to updraft instability. Therefore, indices and forecasting techniques keyed to forecasting severe weather produced by strong updrafts are not necessarily appropriate for forecasting severe weather produced by strong downdrafts.

This change in forecaster thinking was triggered by the problem posed by downbursts (first identified by Fujita and Byers 1977). The human significance of the microburst events as they interacted with aviation seemed disproportionately high in relation to the actual severity of the meteorological event. In short, some microburst-producing storms simply did not appear to be severe storms, at least within the existing official perception of severe storms. Although research has suggested a number of different paths to follow in attempting to forecast downbursts (and microbursts, a small-scale version of a downburst), as seen in, say, Wakimoto (1985), no clear path to operational implementation of these ideas has been found.

Another notion of recent importance to forecasting convective wind events is the derecho, as discussed in D93. Derechos apparently are associated with a variety of storm-scale and mesoscale structures: high-precipitation supercells, bow echoes (Fujita 1978), and mesoscale convective systems. Derecho environments (Johns et al. 1990) are characterized by high CAPE and, at least during the mature part of the event, straight-line hodographs (see Fig. 3 and compare with Fig. 2) Understanding of the significance of these observations is not yet complete and, again, operational implementation of this research really needs to await clarification of the proper path to follow in forecasting practice.

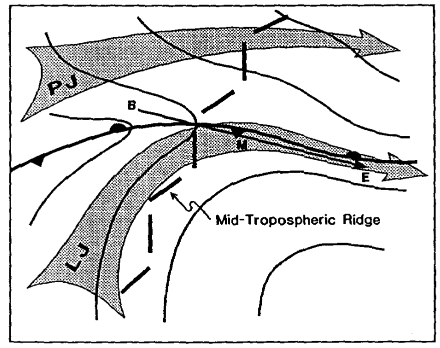

Fig. 3. Schematic synoptic pattern associated with long-lived derechos (from Johns et al. 1990).

5. Heavy rainfall events

As noted in D93, heavy rainfall events become significant in human affairs when they are combined with hydrological elements. However, this paper is not going to address the latter. The problem of forecasting heavy precipitation is especially difficult since it involves making a quantitative precipitation forecast, a problem well-recognized as challenging. Quantitative precipitation forecasting (QPF) in the United States is only now being tentatively explored, at least insofar as convective precipitation is concerned, at the local forecasting offices.

Since heavy rainfall is not considered to be an officially-defined form of severe weather, the system for dealing with it different from the previously-described forms of severe convection. Forecasters at NMC provide field forecasters with various guidance products for QPF. These can be combined with flash flood guidance, produced by hydrologists at the regional River Forecast Centers (RFCs), that indicates how much rainfall is needed in a certain period to create flash floods under the current hydrological conditions.

For heavy precipitation, apart from the guidance provided by NMC and the RFCs, the local offices have most of the heavy rainfall forecast (and all of the warning) responsibility. There is no analog to NSSFC for issuing a range of QPF guidance products for the local offices.

In principle, as noted in D93, most convective heavy precipitation is associated with quasi-stationary rain systems. Although subtle factors like precipitation efficiency certainly deserve some attention, most flash flood events are the result of several individual convective cells, perhaps organized into a mesoscale convective system, passing repeatedly over a given drainage basin.

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Thus, a major question in the heavy precipitation forecast problem in the United States is that of determining *convective system movement*. This is not an easy problem, and often frustrates even the best forecasters. Current observations and the state of scientific understanding simply do not

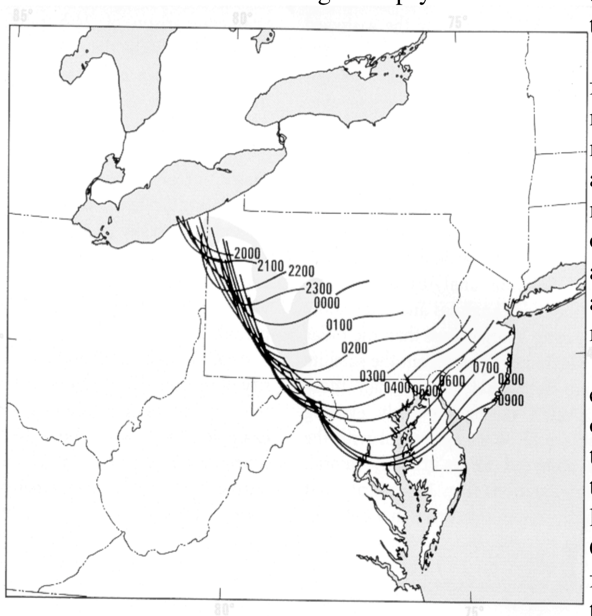

Fig. 4. Successive positions of the outflow boundary associated with a flash flood event at Johnstown, Pennsylvania on 19-20 July 1977 (from Hoxit et al. 1978). Stippling indicates the area receiving excessive rainfall.

permit an easy answer to this question in every case. There are certain synoptic patterns that favor development of such quasi-stationary rain systems; see Chappell (1986) or Maddox et al. (1979) for some examples. In general, the development of nearly stationary rain events involves situations wherein individual cell movement is nearly canceled by the propagation caused by new cell development. This typically involves the convective outflow boundary produced by existing convection. As shown in Fig. 4, part of the outflow boundary can move while another part remains more or less stationary. Under the right conditions, when the low-level moisture impinges on this part of the outflow, new cells develop that then track down roughly the same path. Such events often take the form of mesoscale convective systems.

On some occasions, supercells can become prolific rain producing events. Generally, it appears this is when the middle and upper level storm-relative flow is weak. This results in the mesocyclone becoming enveloped in precipitation. Such storms often move relatively slowly, can achieve a near steady-state structure, and can develop rainfall rates in excess of 50-100 mm hr^{-1}. Overall wind flow (and vertical wind shear) need not be weak for convective storms to be capable of heavy rainfall. Such storms are especially dangerous because they may produce other forms of severe weather, that can distract from the flood threat.

The frequent nocturnal occurrence of flash floods in the United States makes forecasting even more important than it would otherwise be. When most of the public is asleep, even the most accurate and timely warnings can be useless. Forecasters must be especially alert to flash flood threats overnight, in order to offer the greatest possible advance notice. In doing so, it is likely that false alarms might increase. I will discuss this issue more extensively in the next section.

In many parts of the country, terrain is a critical element in precipitation events. This is true not only for the rugged terrain of the western third of the United States, but can be the case in the area of the Appalachian Mountains in the east, and even in locations with relatively modest relief (e.g., see Caracena and Fritsch 1983). In general terms, forecasters must be aware of any synoptic patterns that interact with their local terrain to produce quasistationary convective systems.

While overall storm motion is important, the other factors associated with the potential for heavy convective precipitation deserve attention. Certainly, environments with modest amounts of moisture are far less likely to produce heavy precipitation. Even a slow-moving storm producing limited rainfall is unlikely to be a problem. The relationship between vertical wind shear and precipitation is not yet well-understood; it may be that vertical wind shear is not a reliable or useful predictor of precipitation, or it may be that it must be combined with other, as yet unknown factors to be an effective forecasting tool.

6. Discussion

Maddox (1979) proposed a methodology for forecasters in the United States to use in anticipating heavy precipitation and flash floods. That methodology, suitably generalized, can be applied equally well to all forms of severe convective weather. In essence, the technique involves the following elements (not in any particular order):

1. Careful analysis of all available data
2. An understanding of how numerical model guidance relates to the forecasting questions of concern

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3. An awareness of the necessary ingredients for producing severe convective events
4. An awareness of how the ingredients in #3 are distributed and their likely distributions in the future
5. Knowledge of how synoptic-scale processes interact with local topography
6. Knowledge of the local synoptic climatology of the particular severe weather events

Anticipation of the potential for severe convective weather in a particular synoptic situation is the essential task. It is what forecasters ideally are expected to be able to do with some considerable reliability. However, anticipation of possibilities is not equivalent to issuing a warning to the public. Overwarning is not a good long-term policy, for obvious reasons, in spite of its obvious appeal: overwarning means that a forecaster is likely to be "covered" when something significant happens. Being overly cautious, on the other hand, is a formula for disaster. Uncertainty is the biggest factor in indecision; indecision, in turn, is the biggest factor in situations where timely warnings were not issued. So how does a forecaster deal with uncertainty?

If a forecaster anticipates the potential in a situation, it is far less likely that an unpleasant surprise event will catch that forecaster unprepared. A proper analysis, combined with an understanding of what are the key factors in a weather situation, allows the forecaster to focus on those observations of crucial importance in an uncertain event. Properly anticipated, key observations trigger an appropriate and timely response.

Suppose that a synoptic situation is developing whereby all the key ingredients are being brought together except low-level moisture. Then that low level moisture is the *key variable* to the situation. Often, the situation regarding the key variable is not black and white; it is unclear whether or not the key variable will be in place. If the forecaster then keeps a close watch on the evolution of, say, the low-level moisture, then when events indicate with some certainty that that key variable is coming into place, then the forecaster can respond immediately and with some confidence. Assuming that at least some attention is paid to the other ingredients to assure they are evolving as expected, the operational forecaster's limited time can be spent most efficiently on analyses relevant to the key variable.

This generalization of Maddox' methodology is what I have in mind when I describe *scientific* forecasting approaches for severe convective storms (or any other forecasting, for that matter). Simply following this approach does not guarantee success, because judgment is required, and even the best forecasters make errors in judgment. In deciding what is a *possible* evolution in a given synoptic situation, this does not necessarily imply that this is a *probable* evolution. Forecasts made public are based on what is felt to be probable, but forecasters still need to consider what is possible. By having possible (and dangerous), as well as the most probable scenarios in mind, the forecaster is equipped to recognize, by studying the key variable(s), when the situation is evolving toward a dangerous event. Experience suggests that when a forecaster is unprepared for important events, considerable time can be lost just trying to figure out what is happening. By the time a forecaster does manage to figure out the situation, the serious part of the episode well may be over and the chance for timely warnings has passed.

It is not uncommon for officially severe weather (tornadoes, hail, damaging convective winds) to occur in close association with heavy rainfall (see Schwartz et al. 1990, Maddox and Dietrich 1983). Given the high priority put on severe thunderstorms, heavy rainfall leading to flash floods can be overlooked. In fact, the relatively high frequency of supercells in the United States means it is not uncommon for a single storm to produce the entire spectrum of severe convective weather: all forms of officially severe weather plus heavy precipitation. In the event that one form of severe convective weather is possible, forecasters should be alert to all other forms, as well, particularly in potential supercell situations.

Doswell and Maddox (1986) have described how important it is to understand how the atmosphere has come to its current state, if there is to be some chance to predict its short-term evolution. This involves a "vocabulary" of scientific conceptual models that enable one to understand the flow of meteorological events. Therefore, considerable effort needs to be expended in training human forecasters how to do this formidable task. Regrettably, in the United States, forecaster training has not ever had a very high priority for funding, especially training that involves taking the forecaster off duty and sending him or her to a remote training site (see Doswell 1986)

Severe weather forecasting is quite challenging in that it requires use of all available data in a constantly-changing image of the relevant atmospheric processes (covering a broad range of scales). The task of integrating a wide variety of data is likely to require human intervention for the foreseeable future, since not all the useful data can

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be treated quantitatively. Analytical methods for assimilating diverse data (see, e.g., Thacker and Long 1988) are still in their infancy and a long ways from being comprehensive and operationally practical. While technological approaches are beginning to dominate synoptic scale forecasting, it is not yet clear how to extrapolate the use of technology into mesoscale (and convective storm-scale) forecasting, as noted by Brooks et al. (1992). Therefore, it seems plausible to suggest that, for the time being, human forecasters remain an essential part of the process of disaster mitigation.

If the assumption is granted that humans will have a meaningful role to play, then a revival of that brand of meteorological knowledge that used to be called "synoptic" meteorology is needed. Apart from pure physics, there is a body of knowledge about the atmosphere and the way it works that cannot be captured by pure mathematical expression. This has fallen into disrepute with the advent of numerical weather prediction, but the need for it remains. The present state of affairs exists in spite of the insightful admonitions of Petterssen (1956):

> While the machines provide the answers that can be computed routinely, the forecaster will have the opportunity to concentrate on the problems which can be resolved only by scientific insight and experience. Furthermore, since the machine-made forecasts are derived, at least in part, from idealized models, there will always be an unexplained residual which invites study. It is important, therefore, that the forecaster be conversant with the underlying theories, assumptions, and models. In particular it is important that he be able to identify the "abnormal situation" when the idealized models (be they dynamical or statistical) are likely to be inadequate.
>
> It appears, therefore, that the time has come for a reorientation of the training of forecasters. This reorientation should aim at minimizing (and, if possible, eliminating) the difference between what is common called *synoptic* and *dynamic* meteorology. (from Pettersen's preface)

Severe convective weather clearly is in what Petterssen has termed an "abnormal situation" and so his admonition has particular relevance in this arena. Although numerical models (and all of the recent technological advances) need to have a large role in forecasting severe convective storms, I concur totally with Petterssen. It is unfortunate that this remains a minority opinion.

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