SEVERE CONVECTIVE STORMS -- AN OVERVIEW

Chapter 1 in

Severe Convective Storms

A Meteorological Monograph

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1. Basic concepts of convection

A What is convection?

In general, convection refers to the transport of some property by fluid movement, most often with reference to heat transport. As such, it is one of the three main processes by which heat is transported: radiation, conduction, and convection. Meteorologists typically use the term convection to refer to heat transport by the *vertical* component of the flow associated with buoyancy. Transport of heat (or any other property) by the non-buoyant part of the atmospheric flow is usually called *advection* by meteorologists; advection can be either horizontal or vertical.

Convection takes many forms in the atmosphere; a comprehensive treatment of the topic can be found in Emanuel (1994). This monograph's concern is *severe* convection: that is, the variety of hazardous events produced by deep, moist convection. Hazardous weather events (large hail, damaging wind gusts, tornadoes, and heavy rainfall) are generally the result of the energy released by phase changes of water. A circular convective cloud with a 5 km radius and 10 km deep contains, at any given instant, about 8×10^8 kg of condensed water, assuming an average condensed water content of 1 g m^{-3}. During the condensation of that water, roughly 10^{14} J of latent heat energy is released over a time scale of roughly 25 min (see below). For comparison purposes, a "one-megaton" bomb releases about 4×10^{15} J of heat (see Shortley and Williams 1961; p. 903), albeit in a tiny fraction of a second. Thus, at least in terms of released energy, this modest convective cloud is comparable to a "25 kiloton" bomb. It is this released heat that powers convective storms. Most of the energy is expended against gravity, but some portion also may create hazardous weather.

The released heat contributes to buoyancy, *B*, an essential aspect of convective storms. Buoyancy is defined most simply by

$$B \equiv g\frac{T - T'}{T'}, \qquad (1)$$

where g is the acceleration due to gravity, T is the temperature of a parcel, and T' is the temperature of the surrounding environment. Buoyancy, of course, can be either negative or positive. If B is integrated from the level of free convection (LFC) to the equilibrium level (EL) above the LFC, the result is convective available potential energy (CAPE). It is this energy that is responsible for the convective updraft and for many of the hazards produced by the convection. Downdrafts have their own source of energy, however. Downdrafts are driven by *negative* buoyancy, also derived from phase changes (mostly evaporation) and from the "loading" effect of precipitation. Whereas updrafts transport warm air upward, downdrafts transport cold air downward. Downdrafts also are responsible for some hazardous weather. In either updrafts or downdrafts, the net result is stabilization but the mechanisms are distinct, to be shown later.

B. Thunderstorms and deep, moist convection

I will use "deep, moist convection" (DMC) frequently in what follows, in lieu of the most common word associated with DMC: thunderstorms. This is because, in some instances, hazardous weather can be produced by non-thundering convection. Irrespective of this minor semantic distinction, DMC is the result of a type of instability. Consider the inviscid vertical momentum equation:

$$\frac{dw}{dt} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g, \qquad (2)$$

where $w \equiv dz/dt$ is the vertical component of the flow, z is geometric height, ρ is the density, and p is the pressure. The vertical pressure gradient force is the first term on the rhs of (2). Since the vertical acceleration is zero in a hydrostatic atmosphere, buoyancy is associated with an *unbalanced* pressure gradient force, caused by density perturbations. Equation (2) can be transformed using the definition of vertical motion and textbook linearization methods (e.g., Hess 1957; p. 95 ff.) to yield:

$$\frac{dw}{dt} = \frac{d^2 z}{dt^2} = B = \square\frac{g}{T\square}\left(\square\ \square\square\right)z\,, \qquad (3)$$

where T' is the environmental temperature, □ is the parcel lapse rate ($-dT/dz$), and □is the environmental lapse rate ($-dT'/dz$).[1] When the coefficients are constant, Eqn. (3) is a simple, second-order differential equation that has a simple solution:

$$z(t) = z_o \exp\left[iNt\right], \qquad (4)$$

where z_o is the initial height of the parcel and N is the so-called Brunt-Väisälä, or buoyancy frequency

$$N^2 = \frac{g}{T\square}\left(\square\ \square\square\right)z\,. \qquad (5)$$

The solution (4) implies an instability (i.e., exponential growth of an infinitesemal upward displacement) whenever the square root of N^2 is imaginary; this occurs whenever the environmental lapse rate exceeds that of an ascending parcel (typically assumed to be adiabatic). Since □is normally not greater than the *dry* adiabatic lapse rate, the context clearly is associated with *conditional instability* (i.e., □> $\square_m$, where $\square_m$ is the *moist* adiabatic lapse rate). The analysis of parcel instability leading to (4) is only appropriate when the textbook linearization assumptions are valid. Actual parcel instability leading to DMC is primarily associated with finite vertical displacements; hence, the key to the possibility for growth of convective storms is the presence of CAPE, not the environmental lapse rates alone (see Sherwood 2001; Schultz et al. 2001). Not all situations with conditional

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[1] The linearization leading to (3) ends up equating buoyancy with conditional instability, which is not quite correct. See Hess's textbook and Schultz et al. (2001) for a discussion of the approximations used to linearize the equation this way.

instability are characterized by parcels with CAPE.[2] Thus, the moisture content of the air is critical in knowing whether conditional instability actually contains the potential for parcels to become buoyant (i.e., to have CAPE). In most cases, energy must be supplied to lift the parcel through its condensation level to its LFC; the amount of this supplied energy is known as the convective inhibition (CIN). From the LFC to the EL, the parcel accelerates vertically, drawing the energy for this acceleration from the CAPE. Generally, parcels will overshoot the EL and then experience the *stable* version of (4), undergoing what are called Brunt-Väisälä oscillations that ultimately are damped by viscosity, so the rising parcels should (at least theoretically) accumulate in an anvil cloud at the height of the EL.

The origin of buoyant instability is heat, both latent and sensible, that is produced at low levels in the atmosphere as a result of solar heating and evapotranspiration of water vapor (also due to solar heating) into the lower troposphere.[3] The process of convection alleviates the instability created by the accumulation of heat at low levels. DMC takes the excess sensible heat and water vapor from low levels and expels it into the upper troposphere, and transports potentially cold, dry air downward, thereby alleviating the instability. If DMC begins, as long as there is instability of this special sort available and there is enough lift to realize it, DMC will continue until the instability is removed, whereupon the convection ceases.

According to Emanuel (1994, p.479 ff.), in most of the tropics the atmosphere is approximately in a state of convective near-equilibrium because DMC stabilizes the environment much more quickly than the large-scale processes can act to destabilize the atmosphere. In other words, the instability is released soon after it is created, and the

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[2] When discussing CAPE in specific cases, it is critical to know *which* parcel is being lifted, as discussed by Doswell and Rasmussen (1994). For my purposes in this chapter, I am not specifying which parcel is being used, as this discussion is general.

[3] In some instances, the instability may be driven or maintained by sensible heat *loss* at upper levels, owing to radiative processes, rather than heat *gain* at lower levels. This is not likely to be at work in most forms of severe convection.

tropical atmosphere tends to stay rather close to neutral stability conditions with respect to deep convection. In midlatitude continental convection, the instability is *not* always realized as soon as it is created. Rather, the instability can be "stored" in the environment, owing to convective inhibition (or CIN), and can increase over a period of up to several days, finally to be released explosively in the form of *severe* convection.

Updraft instability is not necessarily equivalent to *downdraft* instability (see Johns and Doswell 1992). The processes associated with downdraft instability are discussed in considerable detail in Ch. 7 of this monograph. The formation of precipitation inhibits updrafts owing to water loading, but it enhances downdrafts. However, without the precipitation caused by updrafts, no evaporation can take place to chill the air, creating the negative buoyancy that is a major factor in creating downdrafts. Hence, updrafts are necessary but not sufficient for downdraft instability. Destructive downdrafts can be associated with weak updrafts (Johns and Doswell 1992), so that parameters focused on updraft instability may not reveal such situations.

Although DMC is responsible for considerable destruction and perhaps thousands of casualties per year worldwide, there can be little doubt that most DMC is benign. The primary benefit of convection is rainfall, and much of the world's rainfall results from DMC, especially in the tropics. There also is a contribution by lightning to the transformation of atmospheric nitrogen into forms useful to plants.

C. Storm electrification

The occurrence of electrification in DMC is common enough that most hazardous weather associated with convection is, indeed, produced by thunderstorms. Lightning arises in electrified clouds to alleviate the charge build-up associated with the DMC. Unfortunately, the charging mechanism continues to resist a definitive explanation (Vonnegut 1994). Various hypotheses exist (Vonnegut 1963; Williams 1985; Saunders 1993) and it might be that all these hypotheses are appropriate explanations in some cases.

Even the basic conceptual models of charge distribution are under scrutiny at the moment (see Rust and Marshall 1996). Storm electrification in the context of severe convection is described in detail in Ch. 13 of this monograph.

Lightning is arguably the most dramatic aspect of thunderstorms in general and it can be quite hazardous in its own right. Lightning casualties are as high as those associated with other DMC hazards, such as tornadoes, but tend to be singular rather than in groups and so may not be as well-reported as tornado casualties (López et al 1993). Because a thunderstorm need not be severe in any of the conventional ways for its lightning to pose a threat, no thunderstorm can be viewed as completely non-hazardous.

The distribution of thunderstorms worldwide has been known historically only in terms of human observers hearing thunder and reporting it, which creates biases in the perceived distribution of thunderstorms. Recently, however, remote sensing systems have been developed to detect lightning. The most widespread such systems, as of this writing, detect cloud-to-ground (CG) lightning strikes (Orville and Henderson 1986). In the near future, it is likely that intracloud (IC) lightning also will be detectable via sensitive optical systems to be carried aboard spacecraft (Christian et al. 1989). Thus, it may soon be possible to have a realistic picture of the worldwide distribution of thunderstorms.

In spite of the drama and importance of lightning, it appears that it is no more than a trivial component of a thunderstorm's energy budget. That is, the total energy expended in lightning flashes in a single thunderstorm cell is on the order of 10^9-10^{10} J (Williams and Lhermitte 1983), whereas we have seen the energy released by condensation of the input water vapor is on the order of 10^{14} J. This should not be interpreted to mean that electrification is not important for processes within DMC. For example, it has long been known that electric field affect coalescence efficiency (Byers 1965; pp. 158 ff.). Moreover, lightning activity should be considered a potentially useful indicator of DMC processes (MacGorman and Rust 1998), especially when combined with other data (e.g., radar, radiosondes, etc.).

D. The cell as a building block in organized convective systems

Modern concepts of DMC have their origins with the post-World War II Thunderstorm Project, culminating in the publication of the report by Byers and Braham (1949). This archetypal project set the pattern for many subsequent projects aimed at understanding more about convective storms (e.g., the mesonetwork used by Fujita 1955; the NSSL mesonetworks analyzed by Barnes 1978; the National Hail Research Experiment described by Foote and Knight 1979, or the Florida Area Cumulus Experiment described by Barnston et al. 1983). A key concept grew out of this project: *the thunderstorm cell.* As depicted in Byers and Braham (1949), the cell is the basic organizational structure of all thunderstorms (Fig. 2) and this notion became the fundamental paradigm for thunderstorms. Browning (1964) used it as a basis for developing his pioneering ideas associated with a special form of severe convection, the supercell. The cell also was the basis for a taxonomy of severe hailstorms developed by Marwitz (1972a,b,c).

The survival of the cell concept to this day is a tribute to the fundamental insights arising from the pioneering Thunderstorm Project studies. However, as with any conceptual model, it has limitations that tend to become more apparent with time. Although no conceptual model should be taken literally, a troubling aspect of the model is the depiction of convective cloud within regions of downdraft; generally, downdrafts are characterized by the *disappearance* of cloud particles, since they are small and tend to evaporate quickly (Kamburova and Ludlam 1962). This minor cosmetic modification was performed in Doswell (1985; Figs. 2.16, 2.18, 2.19).

Much controversy has centered on how *entrainment* occurs in thunderstorms (see Warner 1970, 1972; Simpson 1971, 1972; and the article by Newton 1963; his Fig. 12). Entrainment has been a troublesome issue related to DMC for a considerable time. As originally envisioned (Stommel 1947; Scorer and Ludlam 1953; Squires and Turner 1962), entrainment of environmental air occurs along the lateral boundaries of the cloud. A competing concept, discussed in Squires (1958), Paluch (1979), Deardorff (1980), and Emanuel (1981), has been the notion that penetrative downdrafts within the cloud might contribute substantially to entrainment.

Some time ago, Levine (1959) proposed entrainment based on a bubble theory. More recently, Blyth (1993) has revisited Levine's model, proposing that the major form of entrainment for convection is via the "toroidal" circulation (i.e., like a smoke ring) associated with the "thermal" (i.e., bubble) model of a convective cloud. Note that the "thermal" envisioned in this bubble theory of DMC is much larger than the small "thermals" arising out of the convective boundary layer in shallow convection that give rise to ordinary cumulus clouds.

Another interesting aspect about DMC is the *steadiness* of the updraft. DMC has been modeled as either plumes or thermals (bubbles), and some controversy has continued for years about which is most appropriate (see, e.g., Scorer and Ludlam 1953; Squires and Turner 1962). Real thunderstorms can have drafts ranging from quasisteady plume-like to bubble-like in character. The steadiness of the drafts is used often in thunderstorm taxonomies like those developed by Marwitz. Unfortunately, *real* storms tend to resist being put into polarized categories (see Foote and Frank 1983).

For my purposes in this discussion, the protoypical thunderstorm cell is considered to be a single thermal/bubble: a collection of buoyant air parcels. I do not consider it to be an accident that the typical lifecycle of the cells observed in the Thunderstorm Project was over a time scale corresponding closely to the time it takes for a lifted parcel to rise from its low-level origins to the EL; this is the *convective time scale*, $\square_c$. If a characteristic scale for vertical motion of 10 m s^{-1} is assumed, and the depth of the convection scales as 10 km, then it takes on the order of $\square_c = 10^3$ s (~25 min) for a parcel to rise through the depth of the storm.

Using this concept, a modified thunderstorm cell life cycle is illustrated in Fig. 3. This life cycle has stages corresponding to those depicted in Fig. 2, but show the cell in terms of a rising bubble of buoyant air. Note that the air motion on the exterior of the ascending bubble is downward (bubble-relative). Time-lapse images of convective clouds indicate clearly that this is the case. It is also noteworthy that the rise rate of the bubble is not necessarily equal to the vertical motion at the center of the spherical vortex circulation that defines the bubble (Turner 1973, p. 186 ff.). Figure 3 is very much in the spirit of that proposed by Scorer and Ludlam (1953). In Fig. 3a, the thermal has passed the LFC and is rising rapidly during the "towering cumulus" stage. This is followed by the "mature" stage, as precipitation has reached the surface (Fig. 3b). The downdraft in such a cell perhaps fits the "starting plume" model of Turner (1962) rather well, with a descending, negatively-buoyant "bubble" leading a more or less continuing plume of downdraft in the precipitation cascade. When the rising bubble reaches its EL, the cell has reached its "dissipating" stage (Fig. 3c).

Such an isolated cell is unlikely in the real world; perhaps the initial developments of some DMC most resemble this prototypical single, isolated bubble (Fig. 4). However, the instability giving rise to the development of a cell almost certainly will involve the necessity for *more* such bubbles before that instability is alleviated. It is common for new cells to be initiated preferentially along the outflow boundary spreading out from the previous cells (Purdom 1976; Weisman and Klemp 1986; Fovell and Dailey 1995). In Fig. 3, unlike Fig. 2, the "updraft" is a bubble-like entity. This means that the notion of a "tilted updraft" is not relevant; no *plume* of updraft is present to be tilted, although the thermals may follow a tilted path. A common notion is that the updraft can be "unloaded" of its precipitation only if it is tilted by shear (e.g., Ludlam 1963); otherwise, according to this concept, the cell's precipitation simply collapses downward upon the updraft. Within a prototypical cell in which the dynamics fits a buoyant bubble model rather than a plume, the tilted plume concept is simply irrelevant.

As first mentioned in Scorer and Ludlam (1953), the thermal model makes an interesting prediction. The buoyant bubble has a "form drag" associated with it, due to having to rise through still air (see Turner 1973, p. 188); energy is consumed pushing aside the overlying air during the bubble's ascent. Recently, Renno and Williams (1995) have presented quasi-Lagrangian observations of convective boundary layer (CBL) thermals, noting that such thermals have roughly constant rise rates in spite of exhibiting positive buoyancy (thermal excesses ranging from 0.1 C to more than 1.0 C) through virtually all of their ascent. If buoyancy remains positive, the only way for vertical velocity to remain constant is for some equal, but opposite force to exist that opposes the buoyancy. Renno and Williams postulated a mixing argument that would allow buoyancy to remain positive even as momentum mixing produces drag that opposes buoyancy. I believe that the opposing force should be viewed in terms of the form drag associated with the rising thermal; Young (1988) describes such an opposing force in terms of perturbation pressure gradients. Schumann and Moeng (1991) have shown that pressure gradients accelerate rising buoyant thermals low in the CBL, but oppose the buoyancy higher up in the CBL.

There are only limited observations of the rise rates of thunderstorm *cloud* tops[4] during their development (e.g., Scorer and Ludlam 1953), but it is quite possible that if the thermal/bubble model of cells is correct, the rise rate of the cloud tops would not be the same as, and likely to be slower than, the vertical velocities in the core of the thermals. At this point, it is not known if the approximately linear relationship between rise rate and buoyancy shown in Scorer and Ludlam (1953) extends into high CAPE, severe DMC ranges.

Other evidence suggesting a bubble-like character to DMC can be found in Hane and Ray (1985). Their Fig. 13 reveals considerable structure in the buoyancy field, even for a mesocyclonic thunderstorm. This implies that buoyant thermals pass through even quasi-steady supercell thunderstorm flows, typically in an episodic, rather than steady manner.

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[4] Numerous observations of the storm's summit as depicted by *radar* are available, but this is not necessarily equivalent to its cloud top.

A persistent idea about DMC cells is that the outflow chokes off the updraft (e.g., Emanuel 1994; p. 233). This seems a rather unlikely general explanation for cell dissipation; an important problem for this hypothesis is that it cannot explain the finite life cycles of elevated DMC on the cold side of a surface front. Such thunderstorm cells are *initiated* above a cool, stable pool of surface-based air, and apparently are not choked by it. Yet, observations suggest such elevated convective storms have cells that go through life cycles similar to DMC that does *not* develop above a cool pool. It is difficult to explain such events if the cessation of a plume-like cell updraft depends only on being cut off by outflow.

Our perceptions of convective structure are highly dependent on the observing system being employed. Classifications based on radar are not necessarily equivalent to those developed from satellite imagery, and so on. Although this topic will be expanded upon in subsequent chapters within this monograph, the likelihood of severe weather tends to increase with the degree of organization to the convection. The most intense severe convective weather is associated with *organized* DMC.

1) Linear organization

Linear organization is arguably the most common form of DMC organization. Since outflow is an effective mechanism for lifting near-surface parcels to their LFCs, once outflow develops it can have a dominant role in the development of subsequent cells. The horizontal convergence along outflow boundaries can be on the order of 10^{-3} s^{-1} or larger. If a value of 10^{-2} s^{-1} is sustained through a layer as deep as one km, the resulting upward motions at a height of one km are of order 10 m s^{-1}, quite likely to be capable of initiating deep convection. As convection continues, the merger of new outflows with old ones results in an expanding pool of cold, stable air at low levels, often with new convection on its leading edge, as the outflow pushes into untapped, potentially buoyant air ahead of the outflow. It is common to refer to DMC organized linearly as a *squall line*, although the term *instability line* was in common use for a time (see House 1959).

How might the term “squall line” be defined? The term first arose in the context of synoptic analysis by the Norwegian school; the term was applied first to what we now call a cold front (see Friedmann 1999; p. 31). The word "squall" is derived from what is now a largely archaic description of a gusty wind with a specific character: a gust of 16 knots (~8 m s^{-1}) or higher that is sustained for at least two minutes. According to this criterion, a squall line presumably would involve "squally" winds meeting this criterion, observed at two or more locations along the line. In practice, no one requires this criterion to be met in using the term squall line as applied to DMC, nor do I believe it should be. Perhaps it was the association between DMC and cold fronts so often seen in the conceptual models of the Norwegian school that led eventually to the use of the term in connection with lines of convection. A minimal definition of squall line in the context of DMC could begin with as few as two isolated cells; two points define a line, after all. However, if the linear organization is to be the dominant characteristic, a more reasonable definition should require that the cells be close enough together that the perturbation flows they generate are interacting. An outflow boundary with gusty post-boundary winds (virtually all such outflows are gusty and probably meet the “squall” criteria most of the time) should suffice for a linear organization of convective cells to constitute a squall line.

A related factor in developing a linear structure is the nature of the process responsible for the first convective cell initiation. Often the lifting mechanism is a front, a dryline, or a pre-frontal trough (perhaps associated with an upper-level front). There typically are along-line variations in the lift associated with such processes, as well as variability in the thermodynamic characteristics of the air being lifted. Therefore, the first developments occur at relatively isolated points as individual cells but the overall linear nature of the initiating mechanism for DMC often results in a rapid filling-in of convective elements along the line. Subsequent development of cold outflows serves to reinforce this evolution; hence, the high frequency of this sort of organization to convective systems.

Severe weather may or may not be closely associated with linear structures. If the constituent cells are competing with each other on a nearly equal footing, as when the squall line exhibits a quasi-two-dimensional (or Q2D) character (Fig. 5), no cell is particularly favored. Whereas *marginal* severe events (at or just above the arbitrary limits of "severe" winds and hail) are not uncommon and may indeed be widespread, the *extremes* of severe convective weather are unlikely in such situations, although not impossible. Note that whereas Fig. 5a shows a nearly constant band of reflectivity at low levels, even such a Q2D example breaks into separate convective cells aloft (Fig. 5b). Another form of squall lines is a line of *supercells* (Fig. 6). Although the cells are aligned laterally, they are not necessarily competing with one another (Fujita 1975). Finally, parts of a Q2D line may not move equally fast, creating the so-called Line Echo Wave Pattern (LEWP; see Nolen 1959) structure, or Bow Echoes (Przybylinski 1995). Bow echoes often are associated with damaging convective wind gusts.

A Q2D structure is a very efficient way of overturning an unstable stratification in comparison with isolated convective cells, even when the updrafts are not especially intense. The development of new convection at the leading edge of the outflow with a front-to-rear ascending inflow and embedded convective cells can "process" the warm moist air from low levels quite readily. The precipitation falling out of the cells maturing rearward of the leading edge promotes the downdraft that maintains the outflow boundary. Often, a rear-to-front flow develops in the wake of the leading edge that promotes the advancement of the outflow. This overall structure, illustrated schematically in Fig. 7, can stabilize the stratification over a large area when a laterally extensive squall line moves rapidly.

2) Mesoscale convective systems

The term Mesoscale Convective System (MCS) is virtually uniquely associated with the satellite perspective. Maddox (1980) developed the term Mesoscale Convective Complex (MCC) with a specific set of criteria (Table 1) related to the infrared (IR) imagery views of convective systems. MCC criteria were designed in Maddox's study to limit the initial study to the largest, most circular, and longest-lasting examples within a large class of such systems. Subsequently, the entire class of convective systems observed via IR imagery has been dubbed MCSs (Zipser 1982); the MCC criteria are essentially arbitrary and have no particular physical significance, other than that they refer to particularly evident forms in the IR images. MCSs are covered in detail in Ch. 9 within this monograph, and in Ch. 3, as well.

The typical life cycle of an MCS is illustrated in Fig. 8, as seen in a series of IR satellite images. The convective system begins as a number of relatively isolated convective cells, usually during the afternoon. By late evening, the anvils of the individual cells merge, and the characteristic cold cloud shield develops toward maturity sometime after midnight, local time. Dissipation then occurs typically sometime in the morning. Although by no means restricted to the nocturnal hours, MCSs most frequently reach maturity after sunset.

MCS circular cloud tops often mask a linear structure of the convective cells when viewed on radar. The deep, intense convection in MCSs is usually organized in a linear structure on the leading edge of the cold outflow, with weaker "stratiform" precipitation trailing behind, over the outflow. Other organizations are possible, including having the deep convection on the *trailing* edge of the outflow, but are not as frequent as cases where the deep convection is on the forward side of the MCS. Severe weather events tend to occur during the early stages of MCS development, when the individual convective cells have not yet agglomerated into the characteristic MCS structure. However, widespread severe windstorms known as "derechos" (Johns and Hirt 1987) often are associated with mature MCSs. When MCSs generate heavy precipitation, they can be well into the mature MCS phase.

Occasionally, MCSs can produce a persistent mesoscale circulation (Bosart and Sanders 1981; Bartels and Maddox 1991; Davis and Weisman 1994), apparently above the cool, stable pool of outflow, that can persist well after the convection dissipates. These circulations have been observed to be associated with redevelopment of another MCS (e.g., Bosart and Sanders 1981; Menard and Fritsch 1989), so that the system as a whole can live longer than 24 h. In fact, some examples of long-lived MCSs have persisted as deep convective systems continuously for more than 24 h, defying the trend for dissipation by late morning.

Although most case studies of MCSs have been located in the United States, they are by no means confined to there, or even to North America. MCSs occur in virtually all convective-prone areas of the world (see, e.g., Velasco and Fritsch 1987; Smull 1995; Laing and Fritsch 1997), notably including the Tropics. Within the Tropics (see Ch. 10), convection tends to develop in loosely organized "clusters" that contain individual elements that might or might not meet MCS criteria individually, depending on how the essentially arbitrary MCS criteria are chosen. Except in tropical cyclones, tropical convection generally is not as persistent as mid-latitude convective systems.

Not all MCSs are nearly circular. Included within the category of MCS is a linearly-organized band of cold cloud tops (Fig. 9). Such a structure is nearly always associated with a frontal boundary and/or with a cold front aloft (Locatelli et al. 1998). The individual convective elements in such a line may or may not be made up of radar-observed linear convective structures.

3) Supercells

The most dramatic form of organized convection arguably is the supercell. First proposed by Browning (1964), the supercell model initially was conceived as a quasi-steady form of an ordinary cell. Browning himself (1977) later developed a new definition of a supercell as a convective storm having a mesocyclonic circulation. Weisman and Klemp

(1982) adopted this definition as the means by which they could distinguish supercells from "ordinary" cells. Doswell and Burgess (1993) suggested a slightly modified version of Browning's (1977) definition of a supercell, incorporating somewhat arbitrary criteria. Although debate continues about the details of the definition, Browning's basic notions remain as the heart of whatever consensus exists. Supercells are discussed in detail in Ch. 5 of this monograph.

A supercell is made distinguishable from non-supercells by the presence of its mesocyclone. The mesocyclone creates the radar reflectivity morphology ("distinctive" features [Forbes 1981] such as hook echo structures and LEWPs) typically associated with supercells. With the pioneering numerical simulations by Schlesinger (1975), Klemp and Wilhelmson (1978), and Weisman and Klemp (1982; 1984), it also has become clear that the supercell storm involves dynamical processes that do not arise in ordinary DMC. The interaction of the updraft with an environment characterized by strong vertical shear of the horizontal wind permits some storms to develop nonhydrostatic vertical pressure gradients that can be as influential in developing updrafts as the buoyancy effects (Weisman and Klemp 1984). Therefore, such storms can have strong updrafts even when the static instability, as measured by CAPE, is modest (McCaul 1993).

Storms with large, strong, and persistent updrafts process substantial amounts of mass; if the average updraft over a 5 km radius is 10 m s^{-1} and the average density of the inflowing moist air is 1 kg m^{-3}, the mass flux is roughly 10^9 kg s^{-1}. For a water vapor mixing ratio of 10 g kg^{-1}, the water mass flux in the updraft is 10^7 kg s^{-1}.[5] The mass flux is most sensitive to the *size* of the updraft (it increases as the square of the radius), and supercells generally have larger updrafts than ordinary storms. It appears that supercells tend to dominate their near-environments, out-competing nonsupercellular neighbors for the

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[5] If 100 percent of that condensing water were to fall out as precipitation over a circle 5 km in radius, it would represent a rainfall rate of about 250 mm hr^{-1} (roughly 10 in hr^{-1}). Precipitation efficiencies are typically much less than 100 percent, of course.

low-level warm, moist air that sustains them. Mass continuity requires the development of compensating subsidence around DMC storms, since the convective downdrafts typically do not process as much mass as the updrafts (Fritsch 1975; Wetzel et al. 1983). Thus, the most intense updrafts will virtually always be isolated (cf. Fig. 6). In clear contradistinction to the Q2D squall line, with its numerous competing cells, supercells are relatively isolated storms that, nevertheless, also can "process" large quantities of air and water vapor. A dominant factor in the development of supercells versus Q2D squall lines is the vertical wind shear structure in the environment of the developing convection. The magnitude of the shear (Weisman and Klemp 1982; 1984) and the character of the hodograph associated with that shear (Davies-Jones et al. 1990; Brooks et al. 1994) appear to be quite pertinent issues, although debate continues about the relative importance of various measures of the vertical wind shear.

Supercells are relatively rare events, and are predominantly a midlatitude phenomenon. Tropical environments usually do not have adequate shear to develop deep, persistent convective mesocyclones (as noted in Ch. 10). Given the windshear of midlatitudes associated with near-geostrophic wind balance, coupled with sufficient instability from the thermal and moisture stratification, it is obvious that mid-latitudes are the normal spawning grounds for supercellular DMC. There is growing evidence that supercells are more common around the world than formerly thought (e.g., Houze et al. 1993; Dessens and Snow 1993; Colquhoun 1995); the perception that supercells are primarily a phenomenon confined to the central plains of North America is simply false. Even within the United States, data are accumulating from the newly-implemented WSR-88D Doppler radars to indicate that supercells might form a larger fraction of the overall thunderstorm population than once believed. Nevertheless, it seems clear that supercells are by no means frequent compared to other forms of organized DMC; the ratio of supercells to non-supercells is probably on the order of 10 percent. Comprehensive studies to determine this ratio remain undone, unfortunately.[6]

By virtue of their large, intense vertical drafts, supercells create a disproportionate share of the most intense forms of convective severe weather, excluding heavy precipitation. Non-supercells probably account for the majority of convective severe weather overall, but non-supercellular severe weather events do not attain the extremes most typically associated with supercells. Suppose that meteorologically *significant*[7] severe convective hailfall events are defined to be those producing hailstones with diameters of 5 cm (~2 in) or larger, *significant* severe convective windgust events are defined to be those with speeds 33 m s^{-1} (~65 knots) or greater, and *significant* tornadoes are defined to be those with intensities F3 or greater (using the Fujita damage/intensity scale; Fujita 1971). Then a large fraction of meteorologically significant events is produced by supercells, with perhaps a *majority* of significant hailfalls and tornadoes being supercell-associated. Recently, it has been recognized that supercell storms also can produce prodigious rainfall rates at times (Doswell 1994; 1999), simply by virtue of their intense updrafts. Nevertheless, supercell storms are not associated with the majority of heavy rainfall events.

2. Severe Convection

A. Definitions

There is considerable arbitrariness in defining severe forms of hail, wind, and precipitation (Doswell 1985). That is, the typical method for deciding whether an event is

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[6] It is far from obvious just how such a study might be done, since it is not clear just how a "thunderstorm" is defined. How many thunderstorms does a convective line or a convective complex contain at a given instant?

[7] *Meteorological* significance is tied to the intensity of the event, rather than the effect of an event on humans, which is contingent on the meteorological event's interaction with human habitation and use of a location.

"severe" involves some threshold criterion. In the United States, for a hailfall to be considered severe, the hailstone diameters must be ~2 cm (3/4 inch) or larger, and severe convective wind gusts must be ~25 m s^{-1} (50 knots) or greater. Is there a meaningful *physical* distinction between a storm that produces hailstones that are 1.9 cm in diameter, compared to one producing hailstones 2.1 cm in diameter? Is a convective storm that produces a wind gust of 24 m s^{-1} physically different in some unambiguous way from a storm that can muster a 26 m s^{-1} gust? The answers to both these questions obviously are negative, but some sort of threshold is required for classification purposes. The basic principle behind the existing thresholds for defining severe convective weather in the United States is that the probability of damage increases substantially as hailstone diameters and wind gust speeds increase beyond the current thresholds.

There are other issues, however. Substantial accumulations of sub-threshold hail might well cause significant damage, especially to crops when wind-driven. If there is a population of hailstone sizes (which is typical), with only one or two isolated examples meeting or exceeding the threshold to be considered "severe," is the storm considered severe? In the United States, the answer is "yes." Real hailfalls are associated with swaths of hail, and it is quite possible that somewhere within an extensive swath of sub-threshold hailstones, a stone or two equaling or exceeding the threshold could be found. Will someone see and report the isolated examples that exceed the thresholds? Should we be reporting the *average* hailstone size rather than the largest observed?

The same sorts of problems arise with respect to convective wind gusts. Sub-threshold windspeed might well be capable of creating damage; for example, aircraft in the process of taking off and landing are very vulnerable to convective winds (see Fujita and Caracena 1977). As with hailfalls, strong convective winds arise in swaths of varying length and width, and it is basically just an accident when what might be only a momentary peak within the swath ends up being either measured or results in damage, leading to a report of the event.

Damaging convective winds, hailfalls, and tornadoes all occur over some *area* (typically a swath), but severe reports are in terms of *points*, with the exception of tornadoes; for most tornadoes, a path length and width are reported. Although the width usually varies along the track, only the widest portion is recorded. In any case, with the exception of tornadoes, there is a clear mismatch between the *events* and the *reports* of the events. This mismatch leads to a reduction in the fidelity with which our climatological records of severe convective events portray the reality of the events themselves. At the moment, there appears to be little we can do to change this situation.

In the United States there is no officially-defined threshold for precipitation, beyond which the rainfall is considered to be severe. Officially, heavy rain is not considered to be severe weather. Generally speaking, the highest sampling frequency for precipitation rates is hourly, but the majority of our precipitation measurements are 24-h totals. Hourly rates of ~25 mm (1 in) or more generally are considered minimally intense, but it is unlikely that such a rate would produce an important event if sustained for only one hour. Heavy precipitation's greatest threat to life is associated with flash floods (Ch. 12 of this monograph). Flash floods are the result of heavy rainfalls (Ch. 8 in this monograph) in combination with various types of hydrological situations (e.g., terrain relief, antecedent precipitation, drainage basin soil and usage characteristics, etc.). It is possible for heavy rainfalls to produce little or no danger, owing to the hydrological factors (Doswell et al. 1996). By the same token, rainfalls of only moderate intensities can result in flash flood disasters (as with the Shadyside, Ohio event of 14 June 1990; see National Weather Service 1991 and Ch. 2 in this monograph) in some hydrologic circumstances.

All tornadoes are considered severe, and are the focus of Ch. 5 in this monograph. However, even in this category, there are gray areas. For instance, roughly two-thirds of all tornadoes are relatively weak, being rated F0 or F1 on the Fujita scale (Kelly et al. 1978). Further, although waterspouts are simply tornadoes over water, in the United States they are not entered in the climatological record of severe events unless they move onshore as tornadoes. As we learn more about tornadoes, it seems there are many aspects of the tornado identification problem that we are probably only beginning to recognize (see Forbes and Wakimoto 1983; Doswell and Burgess 1993).

There is no easy way around these problems with defining convective event severity using essentially arbitrary thresholds. It is clear that virtually *any* set of thresholds will miss some important events and might include events that arguably might not deserve to be considered severe. Hales (1993) has proposed a two-tiered system that retains the current United States thresholds but adds a set of higher thresholds to define "significant" severe weather, similar to the definitions described above. Hales presents some evidence that the observed frequency of *significant* events (by his criteria) in the United States has been much more nearly constant over a long period than the frequency of events that are *marginally* severe (i.e., that meet the current criteria but do not attain the thresholds he has defined as significant).

Worldwide, there has been even less agreement over the definitions of severe convective weather events than in the United States. Therefore, the climatological record of severe convective weather worldwide is correspondingly uncertain. It has been my experience that the reporting of severe weather worldwide is pretty erratic, with only major disasters having much chance of being recorded. The situation is not unlike a good part of the record of severe weather in the United States prior to the institution of the severe weather watch/warning program in 1950s (see Galway 1989). In effect, the chances of severe weather being reported are in direct proportion to the effort expended trying to mitigate the effects of severe forms of DMC. When the *awareness* of the threat posed by severe DMC grows, the probability that a given event will be reported also grows. Hence, a significant contribution to the climatological record is associated with perceptions, both within the public and within the local meteorological community, of how important severe forms of DMC are in a given region. I shall return to this point later.

B. The distinction between severe and non-severe convection

The potential impacts of severe forms of DMC on society virtually demand that forecasters make the attempt to distinguish between severe and non-severe storms, irrespective of the scientific problems with arbitrary thresholds. The only logical basis for making the distinction between severe and non-severe DMC is to determine the likelihood of severe convective events, given the available information. The subject of severe convective weather forecasting is covered in detail in Ch. 11 of this monograph, from the perspective of the local forecaster.

This distinction is closely connected to the association between DMC storm types (i.e., DMC taxonomies) and the weather events they produce. For example, if it can be established that a DMC storm is a supercell, then the probability of significant severe convective weather increases substantially over non-supercellular types. To the extent that a taxonomy allows one to make this sort of distinction among the categories, that taxonomy has value, either in a practical (forecasting) sense, or in a scientific classification. Storm *classification* is not always given a great deal of respect in comparison to, for example, studies of storm *dynamics*. Nevertheless, as I have noted elsewhere (Doswell 1991), taxonomy inevitably influences our scientific perceptions to the extent that we may overlook obvious real aspects of storm structure and behavior because of the way we see such storms.

3. Observations of severe convection

A. Observations of processes leading to severe convection

1) Large-scale

The primary observational tool for assessing the large-scale structure of the atmosphere remains the rawinsonde. New observations are becoming an important component world-wide, notably satellite images, quantitative satellite data (e.g., Chesters et al. 1982; Spencer et al. 1989), observations from commercial aircraft (Schwartz and Benjamin 1995), etc. However, much of what we know about synoptic-scale structure and evolution today has been derived from balloon soundings. The network of such observations has some large gaps, notably over the oceans (especially in the Southern Hemisphere), in sparsely-populated regions, and within economically disadvantaged nations. Therefore, our understanding of the synoptic-scale structures associated with severe convection tends to be dominated by continental, northern hemispheric, American and western European systems. Chapter 2 gives a summary of that understanding.

To a considerable extent, the synoptic-scale situations chosen for detailed analysis have tended to be large "outbreak"-type events (e.g., 11 April 1965 [the "Palm Sunday" outbreak] or 3-4 April 1974 [the "Super" outbreak]). As noted in Johns and Doswell (1992), there are relatively few such cases in any given year. In their summary, Barnes and Newton (1983) present this outbreak-centered view (Fig. 10), noting that their composite chart [i.e., a depiction of features at different levels on a single chart, pioneered by R.C. Miller (see, e.g., Miller 1972)] is "especially favorable" for severe weather. Whereas outbreak days are relatively uncommon during the year, when they *do* happen, they contribute a significant fraction of the total number of severe events (see Galway 1977). Moreover, the severe convective events during outbreaks often achieve high impact because the intensity of the events tends to be high. For example, Galway (1977) notes that in the period 1950-1975, outbreak tornadoes contributed more than 20% of the total number of tornadoes for the period, and accounted for more than half the tornado fatalities.

Nevertheless, most severe convective event days are *not* outbreaks (e.g., Maddox and Doswell 1982) and so any description of the "typical" synoptic situation for severe convection might prove to be an elusive goal. Doswell et al. (1996) have suggested that an "ingredients-based" approach to understanding weather events is preferable to trying to define characteristic synoptic-scale patterns. If the ingredients for a particular event can be brought together in an uncharacteristic pattern, the event still ensues (as illustrated by Bosart and Lackmann 1995, albeit in a different context).

Poleward of the tropics, synoptic-scale processes are dominated by quasigeostrophic (QG) processes. Although there are non-QG aspects to the large-scale weather systems that affect severe convection, most of the basic elements of those systems are described remarkably well by the relatively simple notions of QG theory.

Within the Tropics, however, the relative unimportance of geostrophic balance means that "higher order" balances (see, e.g., McWilliams and Gent 1980; Davies-Jones 1991) must be considered at synoptic scales. Convection plays a large role in tropical meteorology, and synoptic-scale systems are much less apparent, whereas mesoscale systems are clearly important. It does not help that so much of the Tropics is oceanic and so in situ observations tend to be sparse; nevertheless, considerable areas on several continents are within the tropics. Notably, tropical regions in Africa, Latin America, Asia, and Australia all have monsoon-dominated convection (see Chapters 2 and 10 in this monograph).

2) Mesoscale

Mesoscale observations have until recently tended to be associated with research-driven special observing networks. The routine surface observations can only arguably be considered "mesoscale"; no one would suggest that the routine rawinsonde observations offer any mesoscale resolution. Of course, meteorological satellite images have offered considerable mesoscale detail (see Purdom 1976; Zehr et al. 1988). However, the images are qualitative rather than quantitative. Efforts to obtain quantitative information on the mesoscale from satellite platforms are both useful and difficult to achieve (e.g., Hilger and Purdom 1990). Radar also could be considered to be a source for some mesoscale information, but its line-of-sight geometry makes it marginal as a source for mesoscale information and, like satellites, does not collect quantitative information about common meteorological variables (temperature, pressure, humidity). Doppler radars can collect wind information in a "clear air" mode (see Matejka and Srivastrava 1991; Boccippio 1995) and with the implementation of a network of Doppler radars in the United States, those wind data may become an important part of a mesoscale analysis. Fujita (1963) provides an excellent summary of the state of mesoscale analysis prior to the introduction of the new observing technologies. In Ch. 3, a discussion of mesoscale aspects of severe convection is given.

There is no completely satisfactory way to delineate scale "boundaries" (for different perspectives, see Orlanski 1975; Fujita 1981; Doswell 1987), so some arbitrariness is inevitable. In spite of this difficulty, there doesn't seem to be much dispute about the mesoscale issues relevant to severe convection. Certainly, an important mesoscale aspect associated with convection is *convective outflow*. Precipitation-cooled air from DMC processes tends to spread out, with outflows from nearby convection interacting and merging to form regions that can approach 10^6 km^2. The larger and stronger the initial airmass contrast with the undisturbed environment, the longer such outflow structures can exist beyond the end of the DMC that produced them. Note that convective outflow also occurs at the storm top, where the updraft spreads out at its level of neutral buoyancy. Thus, convective outflow can have an important role in subsequent convection, by altering the "environment" in which new convection develops (see e.g., Ninomiya 1971; Maddox et al. 1980) and by serving to initiate new convective cells.

Mesoscale processes other than those created by DMC can be thought of in several groups: free "internal" instabilities, forced "external" processes, fronts, and gravity waves. Not many free internal instabilities have been identified that have maximum growth rates (from linear, normal mode analysis) in the mesoscale; "symmetric" instabilities (see Emanuel 1985; Xu 1987) are perhaps the best-known. There may be other, fundamentally nonlinear processes that result in mesoscale instabilities but nonlinearity inhibits the development of clear physical understanding.

Forced, *external* mesoscale processes, many of which owe their existence to various topographical characteristics, are relatively common. Mountain-valley and sea-land breeze circulations result from diurnal heating differences; they are driven by mesoscale baroclinity. Topographic effects include strong downslope winds (Klemp and Lilly 1975; Peltier and Clark 1979; Durran 1986), horizontal mesoscale vortices (i.e., with vertical vorticity) created as wind interacts with terrain (Wilczak and Glendening 1988; Mass and Albright 1989), flow changes associated with differences in surface roughness, and such subtle concepts as mesoscale variations in evapotranspiration (Lanicci et al. 1987; Segal et al. 1995; Pan et al. 1996; Lynn et al. 1998).

Fronts form a special class of mesoscale processes.[8] Generally, their mesoscale aspects are in the direction normal to the boundary, whereas tangent to the boundary, their spatial scales can fit readily into the domain of "synoptic-scale." It has been shown that QG processes are unable to describe fronts satisfactorily (see e.g., Williams and Plotkin 1968; Hoskins and Bretherton 1972). To the extent that QG dynamics can be equated with mid-latitude synoptic-scale processes, then fronts should *not* be considered synoptic-scale. Although fronts per se have been under study for many decades, the dynamics of non-traditional boundaries (e.g., the dryline, pre-frontal windshifts and troughs, etc.) are relatively poorly known. During the 1950s and early 1960s, there was considerable attention to pre-frontal "instability lines" (e.g., Newton 1950; House 1959, 1963). However, this work has not been pursued to the extent that a clear understanding of such boundaries is available. For example, the dryline has long been known to be a locus for convective initiation (Rhea 1966) in spite of weak (or non existent) baroclinity at the time convection commences. Schaefer (1975) suggested one explanation (nonlinear

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[8] By "front," I am including boundaries that may or may not have substantial baroclinity. Thus, for purposes of this discussion, I am specifically including drylines, and other forms of non-frontal boundaries. According to Sanders and Doswell (1994), many such boundaries are not *true* fronts, but they have in common with fronts that some atmospheric variable has strong variability in the direction normal to the boundary.

biconstituent diffusion) to create ascent along the dryline in the absence of baroclinity, but Lilly and Gal-Chen (1990) showed that Schaefer's proposed mechanism is an unlikely solution. To date, no completely satisfactory explanation for ascent along the dryline exists, although that ascent's existence is undeniable (see Ziegler et al. 1995).

In general, since lapse rates are almost always less than dry adiabatic through most of the troposphere, gravity waves are possible and so common as to be nearly ubiquitous (see Hooke 1986). However, only occasionally do their amplitudes and size make them obviously important to DMC (see Eom 1975; Uccellini 1975). If a gravity wave is to initiate convection, it must exist at low levels where potentially buoyant parcels exist. However, gravity wave energy tends to "leak" upward with time, so a waveguide or duct must exist to trap that energy, allowing the wave to retain its amplitude over time and distance (Lindzen and Tung 1976). It appears that the conditions favorable for large-amplitude gravity waves to propagate for significant time and distance and also to initiate DMC are relatively infrequent, occurring perhaps a few times per year in the United States (see Hoffman et al. 1995, Koppel et al. 2000).

4. Prediction of Severe Convection

In Chapters 11 and 12, discussions of the severe convection forecasting problem (including flash floods) from the local forecast office viewpoint are given. It is not my intent here to repeat that content. Further, there have been recent reviews of various aspects of forecasting severe convection (including heavy precipitation) at a national level (Johns and Doswell 1992; Doswell et al. 1993; Olson et al. 1995). My intentions here are: 1) to provide a brief summary of current forecasting accuracy for severe convective events and 2) to suggest some goals for any implementation of severe convective storm forecasting aimed at mitigating the threats posed by such storms.

A. Current levels of accuracy

The forecasting situation is presently a mixture of clear progress and frustration over a lack of understanding of essential issues. In the United States, the hazardous convection problem is pervasive and important, so progress has been made in forecasting of severe thunderstorms (and, especially, tornadoes) since the effort began in earnest in the early 1950s (when the U.S. public weather service began to issue severe thunderstorm and tornado forecasts). See Galway (1989) for some historical perspectives on the forecasting effort.

Grazulis (1993; pp. 14 ff.) notes several items about the tornado casualty figures in the United States. A trend toward decreasing annual fatalities seems to have begun in the late 1930s and has continued to the present. Whereas early in the century, U.S. annual tornado fatalities often exceeded 200, that figure has not been reached since 1974, in spite of a continued upward trend in the number of reported tornadoes, and an increasing population. Virtually all of the increase in tornadoes reported annually are in the "weak" category (F0 and F1 on the Fujita scale) of events, and these meteorologically minor events only account for only about two percent of the casualties (Kelly et al. 1978). As shown in Fig. 11, the increase in reporting of weaker tornadoes is indicative of an exponential distribution of tornadoes with intensity. Over the last 80 years, the majority of the increase in the annual number of reported tornadoes has been in the “weak” categories. The number of "violent" events (F4 and F5) per year has not changed much with time, and these strongest tornadoes typically account for a disproportionate share (more than 50 percent) of the annual casualties. Some of the decrease in fatalities is simply related to enhanced public awareness and communication (notably radio and television). Nevertheless, there is evidence that indicates increasing accuracy in severe thunderstorm and tornado prediction over the period from the 1950s to the present. Doswell et al. (1990) have suggested that the skill of forecasting severe convection has increased by roughly a factor of two (Fig. 12), after accounting for the "inflation" in the number of severe thunderstorm reports over the decades. It appears that the infrastructure created by the public weather service in the 1950s for dealing with the severe thunderstorm and tornado hazard has helped reduce the tornadic fatality figures. Major tornado events continue to cause extensive damage, but the fatality rate relative to the inflation-adjusted damage figures has decreased since 1953 (Doswell et al. 1999)

Nontornadic severe thunderstorm forecasting has not received as much attention as tornadic storm forecasting in the U.S. Casualties from nontornadic severe convection are relatively rare, but only because the official U. S. definition of severe convection excludes heavy precipitation. Flash flood-related fatality figures on the order of 100 persons annually are an indication that heavy precipitation forecasting can still be improved. Flash flood forecasting is a combination of meteorological and hydrological factors, and as noted by several authors (e.g., Larson et al. 1995; Doswell et al. 1996) there is considerable difficulty associated with the quantitative aspects of precipitation forecasting. A factor in the continued relatively high death tolls from flash floods is the challenge to convey an appropriate sense of urgency in flash flood situations. Whereas there is little difficulty recognizing a tornado as a threat to life, even *observations* of heavy rainfall may not be frightening enough to trigger appropriate responses in some situations (see, e.g., the anecdotes compiled by Anderson and Wamsley 1996).

Hail formation (Ch. 6) is difficult to predict in detail, especially in terms that are accessible and useful to operational forecasters. Moreover, short-term mitigation of hail damage[9] is difficult; not much can be done to reduce hail damage to crops and buildings, even when a reasonably accurate forecast of an impending event is available on the day of the event. Although forecasting of *severe* hail is done as part of the severe weather watch and warning process in the U.S., a separate verification of hail events is not done, perhaps because results of such a verification have not been very encouraging (Doswell et al. 1982).

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[9] This ignores the issue of the ongoing controversial attempts to prevent hail, or reduce its size, by seeding (Foote and Frank 1979).

This lack of verification may be at least partially explained by the inadequate *observations* of hailfalls (see section 2.A above). Physically, most hail forecasting methods depend on prediction of a strong updraft, with the assumptions being that large hail requires strong updrafts and that hail size is positively correlated with updraft strength. Although these assumptions may well be valid, there seems to be much more to hailstone size prediction than updraft strength (including, possibly, microphysical factors).

Forecasts for damaging convective wind events are relatively easy to do in principle but not so easy to do in practice (as noted in Doswell et al. 1982). Convective wind gusts are driven by downdrafts, and the physical processes associated with downdrafts are reasonably well-understood. Like hailfalls, convective wind gust damage is also difficult to mitigate with short-range forecasts and warnings. Convective storm-associated wind gust casualty statistics been compiled only for a short time in the United States, so it is not possible to assess how the figures may have changed over the decades. It appears that, with the important exception of aviation accidents associated with microbursts, convective wind gusts are not particularly threatening to human life; recreational boaters are at risk and there currently are a few fatalities per year attributed to falling trees or tree limbs.

Brooks and Doswell (1993) have indicated that a few times per year in North America, a particularly dangerous form of high wind-producing convective storm can occur. Such storms can produce swaths of intense winds more than 20 km wide, affecting areas as large as 2000 km^2, with peak winds exceeding 35 $m\ s^{-1}$ (perhaps also including large hail within the winds). These events apparently are the result of supercell convective storms that can at times be embedded within a larger scale damaging wind event (i.e., a *derecho*; Johns and Hirt 1987). Such events are not specifically identified in operational forecasts.

An important facet to nontornadic convective wind events is the *microburst* that affects aviation (Fujita and Caracena 1977). Downdrafts (including microbursts) need not be "officially severe" to be hazardous to aviation, notably during takeoffs and landings. There is some informal literature (e.g., Caracena et al. 1983) devoted to forecasting microbursts but formal papers (e.g., Wakimoto 1985) on the topic are not numerous. A possible explanation for this dearth of microburst forecasting studies is that the historical record of convective wind events does not distinguish the meteorological character of severe convective winds in the U.S.; that is, the fact that a reported convective wind event was caused by a microburst is not recorded. This situation is certain closely tied to the absence in the public forecasts of operational convective wind forecasts formally identified as due to microbursts.

B. As applied to disaster mitigation

If a nation's forecasting service is going to take on the task of predicting the likelihood of severe convection, the perception already has to exist within the political sphere that the threat posed by DMC is significant. It has been my experience that in many nations outside of North America, residents have little or no appreciation for the threats associated with DMC storms. In such countries, there is no systematic reporting of severe convective events, so when residents experience severe convective storms, no mechanism exists for including the events in a climatological database. Without such a database, there is no factual information useful for informing citizens about the threat, so this ignorance tends to perpetuate itself. Those unfortunates affected are on their own to deal with the events when they occur, and the occurrence often is unforecast.

When it is perceived that severe convective weather is rare in a particular nation or region, it is unlikely that *planning* for such an event has been done. It is precisely the relative *rarity* of such events, in regions where severe convection remains possible (albeit unlikely) that creates a potential for disastrous events when the occasional significant event *does* occur. If it is decided, for whatever reason, that some sort of forecasting process for severe convective weather is needed, some basic elements must be considered in designing a system for mitigating the effects of severe convection through forecasting.

1) Basic forecast verification and climatology

An infrastructure for obtaining and saving basic information about the occurrence of severe convection has several important uses, including hazard planning and developing public awareness. Moreover, it is an essential component of any substantive forecast verification program. Any forecast that is not verified does not receive, nor does it deserve, much credibility. Of course, the verification must be done properly (see Murphy and Winkler 1987; Brooks and Doswell 1996) if it is to have much value. A critical point to establish in doing verification is that the primary objective is *forecast improvement*. It is difficult to imagine any systematic approach to forecast improvement that is not based on verification and, in turn, verification is based on knowledge of what weather events actually occurred. Hence, a serious severe convective storms forecast program must begin with as thorough a knowledge of the occurrence of severe convective weather events as is economically feasible.

2) Scientific forecasting approaches

Forecasting, per se, can use any of several different bases: empiricism, numerical prediction, statistical modeling, conceptual models (pattern recognition), and combinations of these. Forecasting severe convection has its roots in empirical checklists and subjective decision trees (see Miller 1972; Schaefer 1986; Colquhoun 1987), with parameters often chosen on the basis of perceived utility and subjective arguments. If the parameters have been chosen objectively, the approach tends to be statistical (see, e.g., Reap and Foster 1979; Charba 1979). Because statistical methods focus on statistical correlations between predictors and predictands, they can make no direct statement about physical cause-and-effect. However, arguments can be raised (e.g., Doswell et al. 1996) that with the growth of research into severe convective storms, more physically-based concepts can be used to develop forecasting methods. Purely associative methods, wherein weather events are associated with parameters, either statistically or via such approaches as checklists, are difficult to adapt to new concepts arising from research. Further, it is not easy to predict when such associative methods will succeed and when they will fail. Statistical techniques tend to have difficulty with events that are not "typical" in a statistical sense; the most important severe convective storms are inevitably rare events. Therefore, statistical approaches often fail to be useful in situations where a forecaster needs guidance the most. Using methods having minimal physical bases means it will be difficult to predict when it will fail because the understanding of *how* it works is not available.

3) Event mitigation plans

Even when forecasters do their job perfectly and identify the severe convective weather threat accurately in their forecast products, the effort can have no value if there is no plan in place to *use* those forecasts. Residents and businesses need to be aware not only of the forthcoming severe convective weather, but how to act to mitigate its effects. In many cases, relatively little can be done on short notice to reduce the damage from severe convective storms. The time scale of such events is usually too short to permit hazard reduction efforts like evacuations and efforts to reinforce construction (e.g., boarding up windows). Any efforts at damage mitigation from severe convective storms, typically involving building construction practice (see FEMA 1999), have to take place long before the event is underway or even forecast to be underway. With short range forecasts and warnings, the main object is to reduce casualties, not damage.

Casualty reduction, in turn, requires considerable effort at making residents aware of what to do. Historically, especially with regard to tornadoes but also with other severe convective weather, we have made errors based on ignorance and misconceptions in telling citizens what to do. The case with regard to opening windows as tornadoes approach is typical of this sort of error. In times past, it was felt that tornadoes had such low pressure in their cores that buildings would simply explode from the rapid drop in external pressure. Residents were instructed to open windows in an effort to minimize the likelihood of their homes exploding if struck by a tornado. This notion has been thoroughly studied by structural engineers and is now discredited (Marshall 1993). Unfortunately, this means we have to "unteach" the public something that we had been teaching them for years. This is by no means the only such mistake we have made in the past in our well-intentioned efforts to educate the public. We need to make residents aware that our ideas can change and to be tolerant of, and receptive to, such changes.

In the case of severe convective storms, *damage* mitigation is possible but, as already noted, not on short notice. Engineering studies (Mehta 1976; Minor and Mehta 1979; McDonald 1993, FEMA 1999) have shown that a large part of structural wind damage (including that from tornadoes) can be prevented or minimized through sound construction practices and building code enforcement. Even in a violent tornado, the strongest winds occur only in a small fraction of the total damage area. Homes that are not hit by the strongest winds can survive on the periphery of a violent tornado with minimal effects if they have been constructed properly (FEMA 1999). In the case of tornadoes especially, damage mitigation can even reduce casualties by reducing airborne debris, a major cause for tornado casualties.

To a considerable extent, the public needs to be made aware that they have a share of the responsibility for their own safety and property in severe convective weather. Making the public aware of the threat on the day of the event is just *part* of the story. Residents need to be well-informed about the risks they face from such actions as building a home on a flood plain, living in a mobile home in tornado-prone parts of the country, driving in hazardous weather situations, etc. Public officials have a responsibility to make information available but it remains the duty of the inhabitants to avail themselves of the opportunity to read and heed the available information. Local communities need to develop an infrastructure for dealing with weather-related hazards (tornado spotters, emergency operations centers, school and workplace safety training, etc.) even if those hazards are relatively rare. Preparatory activities require resources and many communities only take serious steps to mitigate a disaster in the immediate *aftermath* of the disaster itself. It is all too easy to dismiss the hazard as too infrequent to spend time and resources to develop a mitigation infrastructure.

5. Prospects and unsolved problems

A. Forecasting

Tornado forecasting in the United States is the subject of continuing research (see Rasmussen et al. 1994). It is likely that tornado forecasting skill is going to continue to improve as more is learned from the newly-implemented WSR-88D radar system, as well as other new observing systems (see section 5C, below). Some early results related to tornado *warnings* (e.g., Polger et al. 1994) seem to indicate this is already happening. These early findings, however, can be misleading since the effects of other aspects of the warning system (including human factors) are convolved with the effects of installing the new radars and no effort has been made as yet to account for these other effects on warning performance (see Maddox and Forsyth 1994; Polger 1994). Dramatic further gains, especially in differentiating tornadic from nontornadic supercells and in forecasting nonsupercell tornado situations, may be difficult to achieve. Further, the fatality figures from tornadoes in the U.S. may well be approaching some nearly irreducible minimum. I hasten to add that we still have things we can do to improve upon our tornado warnings and forecasts, so I am not saying that we have attained that irreducible minimum. Nevertheless, it is unrealistic to believe there will ever be a time when tornadoes will cause zero fatalities owing to the perfection of the forecasts and warnings (and the responses by the citizens).

I believe the time is ripe to develop improvements in the total system for mitigating flash floods. With mesoscale and cloud scale numerical simulation models, it is quite likely that we will develop new and useful understanding upon which to base improved precipitation forecasts. I am hoping to see the implementation of probabilistic approaches (e.g., Krzysztofowicz et al. 1993) that will offer not only improvements in forecasting skill, but also improvements in forecasting *value* for heavy precipitation events (Murphy 1993). At the time of this writing, the research investments aimed at improvement of quantitative precipitation forecasting are just beginning. Moreover, there is as yet relatively little being done to couple precipitation forecast models with hydrological models to produce flood and flash flood forecasts directly. Thus, flash flood forecasting is open to considerable experimentation with burgeoning new techniques and technologies. New methods for quantitative rainfall estimation (e.g., Ryzhkov and Zrnić 1996) and automated streamflow measurements are promising better flash flood detection and warning capability.

Because of the importance of aviation, convective wind gust forecasting and warning should continue to see investments in infrastructure and research. This should lead to some continued improvement in forecasting convective wind events, notably microbursts.

Although by no means unimportant in terms of damages, hailstorms remain difficult to mitigate. Unless it can be demonstrated that short-term mitigation is possible, it is going to be a challenge to find resources for sustained hailstorm research. Perhaps the best source for support will come from the insurance industry, which already is concerned about their losses to severe convective storms and so is interested in refined hail climatology information. Improved climatological databases do nothing for understanding the processes by which hail is formed, but knowing more accurately than at present where and when hailstorms are most common can be a good starting point for both basic and applied research.

B. Modification

The idea of weather modification appeals to many citizens, especially in the wake of an especially damaging event. It seems logical to ask why a society that can develop hydrogen bombs, travel to the moon, and accomplish other technological feats cannot prevent weather-related disasters. Moreover, weather modification offers an apparent cure for all the ills produced by the weather. It appears that we are engaged in substantial weather modification, both planned and inadvertent, at the present, so why not do something about severe convective storms? Unless some mechanism can be exploited, like the metastability of clouds containing supercooled water, the titanic energies involved in convective storms make it pretty daunting to imagine making beneficial modifications. Furthermore, with our current lack of understanding of many of the processes associated with severe convective weather, it seems potentially dangerous to make a concerted effort to alter the weather. The results could be negative in ways we might not be able to anticipate. In spite of several ongoing private weather modification programs, it is by no means certain that they can validate claims of a purely beneficial effect. Several federally-sponsored convective weather modification programs; for example, NHRE (Foote and Knight 1979) and FACE (Barnston et al. 1983), were terminated by the early 1980s, with the realization that any substantial effects were at best only marginally detectable. Thus, I have little optimism for future benefits associated with modification of convective severe storms.

C. New observations

The prospects for new observations continue to be relatively bright. The implementation of a network of Doppler radars is not likely to be the end improvements to radar; as noted earlier, the potential value of polarimetric capability for rainfall measurement means that the retrofitting of the WSR-88D radars with the means for dual polarization observations is possible. This can have a beneficial impact on hail detection (Ryzhkov and Zrnić 1994) as well as improving rainfall estimates. Algorithm development for utilizing the capabilities of the new radars for automated detection of a variety of important convective weather events certainly will continue (Eilts et al. 1996). New strategies for faster and more thorough volumetric scanning by radars, including considering the employment of phased array radars, will be an important contribution to the value of radar in severe convective storms of all sorts.

Improvements to the overall sampling of atmospheric processes are also on the near horizon. Meteorological measurements by commercial aircraft (Schwartz and Benjamin 1995) are likely to make a large impact on the global observing system. Although the vertical wind profilers using Doppler radar (Gage and Balsley 1978) have encountered a number of problems in their implementation, they clearly demonstrate the value of such observations (e.g., Neiman and Shapiro 1989; Spencer et al. 1996).

Other technologies like radio acoustic sounding systems (RASS; see Moran et al. 1991; Neiman et al. 1992) and systems using the Global Positioning Satellites (e.g., Ware et al. 2000) promise additional remote measurement of profiles of thermodynamic variables. Although wind observations are important by themselves, the importance of thermodynamic structure (including details of the moisture distribution) for DMC processes cannot be underestimated. Perhaps pure wind observations might be very useful on larger scales, where "balance" relationships can be exploited to infer a lot about the thermodynamic structure from wind observations alone, but it is obvious that we should not be satisfied with "wind-only" enhancements to the observing system for severe convection-related problems.

Satellite-borne remote sensors continue to improve and the multispectral character of geostationary platforms, along with the high temporal resolution capability afforded by the current and future generations of meteorological satellites offer much promise. The difficulties with inversion of the radiative transfer equation (associated with non-uniqueness when solving an integro-differential equation) are not likely to disappear, but there is reason to believe that methods for dealing with the problem will evolve to fit a new mix of observational capabilities.

The picture is not entirely rosy, of course. Economic difficulties are driving national observing capabilities toward cheaper alternatives. In addition to reduced spatial density and perhaps even the temporal frequency of rawinsonde observations, this also means an increasing dependence on automated surface observations. The latter is a mixed blessing, offering greater density and consistency of observations at the price of not being able to provide the full suite of observations performed by a human observer. The implementation of small "mesonetworks" funded locally rather than federally (e.g., the Oklahoma Mesonetwork described by Brock et al. 1995) is likely to continue simply because the data are useful and the technology is affordable. Of course, the *affordable* instruments may not be "state of the art" sensors; for example, a dewcel (a humidity instrument involving a temperature-controlled mirror for sensing the formation of dew or frost) typically is a better humidity sensor than a humicap (an electronic sensor whose capacitance is a function of humidity), but the cost and power requirement differentials make the humicap a logical choice for inexpensive networks of automated surface observations.

D. Scale Interactions and chaos

Although synoptic-scale meteorology has been quite successful in describing the general features of weather systems, the majority of the weather events that affect people substantially are associated with mesoscale and smaller processes. To a great extent, this "sensible" weather (i.e., that which most people "sense") is dominated by the presence of ascending moist air: clouds and precipitation. Mesoscale processes and DMC are notoriously intermittent; that is, they are not ubiquitous and omnipresent. Whereas it would be an extremely unusual situation to look at a hemispheric weather map and not see one or more synoptic-scale extratropical weather systems in mid-latitudes, mesoscale weather and deep convection are not present every day within large regions. Intermittency is characteristic of the nonlinear dynamics associated with "chaotic" systems. The sensitive dependence on initial conditions that is central to the development of chaos (Lorenz 1993) is almost certainly at work in situations of DMC. The difference between a major outbreak of severe convective weather and no convection at all might be associated with a very small difference in, for example, the initial convective inhibition. Even forecasts of the meteorological environment for DMC that we now consider to be relatively good might be inadequate, as noted by Brooks et al. (1993).

It is the nonlinear dynamics that makes both understanding the physical processes and the forecasting so difficult. Scale interaction is virtually by definition a product of this nonlinearity, so a treatment of scale interactions necessarily must include a nonlinear treatment of the physical processes. Since analytical solutions to nonlinear problems are confined to special cases that tend to be of only marginal application to real events, it is inevitable that numerical simulations are going to be essential both to gaining understanding and to forecasting of the real events. To date, numerical simulations have indeed been of considerable value in gaining insights into severe convective storms. Chapter 4 in this volume addresses numerical modeling in the context of DMC. However, simulations alone are not going to "solve" all our problems. We need observations to validate the simulations and it is quite likely that there are many physically important processes we have yet to observe. The history of our science suggests that theory and modeling in the absence of observations has not been very productive.

E. Important Unobservables

It is an unfortunate reality that potentially important observations are presently unavailable and are not likely to be obtained in the near future. Perhaps the most frustrating class of unobservables is the suite of measurements associated with the *microphysics* of convection. It is possible to infer various aspects of the distribution of water substance in clouds with radar (see Jameson and Johnson 1990). Unfortunately, short of flying an aircraft into a cloud and attempting to gather up the various forms of condensed water (not an easy task to accomplish successfully), there is no simple way to *validate* those inferred measurements. Moreover, measurements of in-cloud water distributions are not sufficient; in a sense, such knowledge is only *part* of a successful understanding that would lead to improved forecasts. For instance, we have virtually nothing available in terms of condensation and/or freezing nuclei counts as a function of space and time in and near DMC, and prior to DMC onset. These unobserved variables might have a large impact on how water substance is distributed in the ensuing convection. In turn, the distribution of water substance in convective clouds plays an important role in cloud dynamics (Kessler 1969). Regrettably, there is virtually no information available *operationally* that could be used to take advantage of any new scientific understanding based on microphysical aspects of DMC. As of this writing, I see no feasible methods even being proposed to provide a set of microphysical observations on a *routine* basis.

The *occurrence* of severe convective events continues to be beyond the capabilities of our observing system; recall the “mismatch” between the real events and the mostly pointwise reports of the events discussed earlier. In order to observe severe convective weather properly, we need to be able to detect and record the actual distributions of tornadoes, hail, wind, and precipitation on scales well below the size of a convective cloud. Anything less means that we are not obtaining an accurate picture of the events and it is obvious we are indeed not able to assume an accurate climatology; see Kelly et al. (1985) or Doswell and Burgess (1988) for some discussion. The consequences of this lack of knowledge have already been described in section 4.A. Any progress beyond the capacity of existing systems is going to require resources at a time when most economic indicators suggest retrenchment, not expansion. Therefore, it is difficult to be optimistic that the future holds much promise for increasing the quality of our event observations.

The VORTEX project (Rasmussen et al. 1994) has made it clear that there is considerable structure in atmospheric variables present on scales not much larger than that of large convective systems. A few examples have appeared (e.g., Brooks et al. 1995) that offer hints of structures that might be important. Doppler radars operating in "clear air" mode and high-resolution satellite images present us with a complex picture of things happening in the lower troposphere, especially apparent lines of discontinuity. In many cases, we currently know relatively little about these features. When we have access to high-resolution data throughout the atmosphere, we invariably find structures of which we had not previously been aware (e.g., "profiler" data as in Carr et al. 1995). The extent to which these structures influence DMC and the associated severe weather events remains problematic because we are not reliably able to observe these features, at present. It takes time to integrate new observations into our scientific understanding. Thus, as long as there are unobserved phenomena and unobserved physically-relevant variables, there always will be gaps in our understanding and corresponding ability to forecast. This is the paradox of all science: we are both excited and frustrated by what we do *not* know, even as we create new understanding.

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REFERENCES

Anderson, B., and S. Wamsley, 1996: *Reflection of the Hearts. (The Big Thompson Canyon Flood of July 31, 1976)* (G. Wamsley and L. Roesener, Eds.). C&M Press, Denver, CO, 272 pp.

Barnes, S.L., 1978: Oklahoma thunderstorms on 29-30 April 1970. Part I: Morphology of a tornadic storm. *Mon. Wea. Rev.*, **106**, 673-684.

______, and C.W. Newton, 1983: Thunderstorms in the synoptic setting. In *Thunderstorm Morphology and Dynamics* (E. Kessler, Ed.), Univ. of Oklahoma, 75-112.

Barnston, A.G., W.L. Woodley, J.A. Flueck, and M.H. Brown, 1983: The Florida Area Cumulus Experiment's second phase (FACE-2). Part I: The experimental design, implementation and basic data. *J. Clim. Appl. Meteor.*, **22**, 1504-1528.

Bartels, D.L., and R.A. Maddox, 1991: Midlevel cyclonic vortices generated by mesoscale convective systems. *Mon. Wea. Rev.*, **119**, 104-118.

Blyth, A. M., 1993: Entrainment in cumulus clouds. *J. Appl. Meteor.*, **32**, 626-641.

Boccippio, D.J, 1995: A diagnostic analysis of the VVP single-Doppler retrieval technique. *J. Atmos. Oceanic Technol.*, **12**, 230-248.

Bosart, L.F., and F. Sanders, 1981: The Johnstown flood of July 1977: A long-lived convective system. *J. Atmos. Sci.*, **38**, 1616-1642.

______, and G.M. Lackmann, 1995: Postlandfall tropical cyclone reintensification in a weakly baroclinic environment: A case study of Hurricane David (September 1979). *Mon. Wea. Rev.*, **123**, 3268-3291.

Brock, F.V., K.C. Crawford, R.L. Elliott, G.W. Cuperus, S.J. Stadler, H.L. Johnson, and M.D. Eilts, 1995: The Oklahoma mesonet: A technical overview. *J. Atmos. Oceanic Technol.*, **12**, 5-19.

Brooks, H.E., and C.A. Doswell III, 1993: Extreme winds in high-precipitation supercells. Preprints, *17th Conf. Severe Local Storms* (St. Louis, MO), Amer. Meteor. Soc., 173-177.

______, and ______, 1996: A comparison between measures-oriented and distributions-oriented approaches to forecast verification. *Wea. Forecasting*, **10**, 288-303.

______, ______, and L.J. Wicker, 1993: STORMTIPE: A forecasting experiment using a three-dimensional cloud model. *Wea. Forecasting*, **8**, 352-362.

______, ______, and R.B. Wilhelmson, 1994: The role of midtropospheric winds in the evolution and maintenance of low-level mesocyclones. *Mon. Wea. Rev.*, **122**, 126-136.

______, ______, E.N. Rasmussen, and S. Lasher-Trapp, 1995: Detailed observations of complex dryline structure in Oklahoma on 14 April, 1994. Preprints, *14th Conf. Wea. Analysis and Forecasting* (Vienna, VA), Amer. Meteor. Soc., 62-67.

Browning, K.A., 1964: Airflow and precipitation trajectories within severe local storms which travel to the right of the winds. *J. Atmos. Sci.*, **21**, 634-639.

______, 1977: The structure and mechanism of hailstorms. *Meteor. Monogr.*, **38**, 1-39.

Byers, H.R., 1965: *Elements of Cloud Physics*. Univ. of Chicago Press, 191 pp.

______, and R.R. Braham, Jr., 1949: *The Thunderstorm.* U.S. Government Printing Office, Washington, D.C., 287 pp. [out of print]

Caracena, F., J. McCarthy, and J.A. Flueck, 1983: Forecasting the likelihood of microbursts along the front range of Colorado. Preprints, *13th Conf. Severe Local Storms* (Tulsa, OK), Amer. Meteor. Soc., 261-264.

Carr, F.H., P.L. Spencer, C.A. Doswell III and J.D. Powell, 1995: A comparison of two objective analysis techniques for profiler time-height data. *Mon. Wea. Rev.*, **123**, 2165-2180.

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

Chesters, D.L., L.W. Uccellini, and A. Mostek, 1982: VISSR Atmospheric Sounder (VAS) simulation experiment for a severe storm environment. *Mon. Wea. Rev.*, **110**, 198-216.

Christian, H.J., R.J. Blakeslee, and S.L. Goodman, 1989: The detection of lightning from geostationary orbit. *J. Geophys. Res.*, **94**, 13,329-13,337.

Colquhoun, J.R., 1987: A decision tree method of forecasting thunderstorms, severe thunderstorms, and tornadoes. *Wea. Forecasting*, **2**, 337-345.

______, 1995: The Sydney supercell thunderstorm? *Weather*, **50**,15-18.

Davies-Jones, R., 1991: The frontogenetical forcing of secondary circulations. Part I: The duality and generalization of the Q vector. *J. Atmos. Sci.*, **48**, 497-509.

______, D. Burgess, and M. Foster, 1990: Test of helicity as a forecast parameter. Preprints, *16th Conf. Severe Local Storms* (Kananaskis Park, ALTA, Canada), Amer. Meteor. Soc., 588-592.

Davis, C.A., and M.L. Weisman, 1994: Balanced dynamics of mesoscale vortices produced in simulated convective systems. *J. Atmos. Sci.*, **51**, 2005-2030.

Deardorff, J.W., 1980: Cloud top entrainment instability. *J. Atmos. Sci.*, **37**, 131-147.

Dessens, J., and J.T. Snow, 1993: Comparative description of tornadoes in France and the United States. *The Tornado: Its Structure, Dynamics, Prediction, and Hazards* (C. Church et al., Eds.), *Geophys. Monogr.* 79, Amer. Geophys. Union, 427-434

Doswell, C.A. III, 1985: The Operational Meteorology of Convective Weather. Vol. II: Storm Scale Analysis. NOAA Tech. Memo. ERL ESG-15, NTIS Accession No. PB85-226959, 240 pp.

______, 1987: The distinction between large-scale and mesoscale contribution to severe convection: A case study example. *Wea. Forecasting*, **2**, 3-16.

______, 1991: Comments on "Mesoscale convective patterns of the southern High Plains." *Bull. Amer. Meteor. Soc.*, **72**, 389-390.

______, 1994: Flash flood-producing convective storms: Current understanding and research. Report of the proceedings, *U.S.-Spain Workshop on Natural Hazards* (Barcelona, Spain), National Science Foundation, 97-107.

______, 1999: Seeing supercells as heavy rain producers. *Preprints*, 13th Conf. Hydrology (Dallas, TX), 73-76.

______, and D.W. Burgess, 1988: On some issues of United States tornado climatology. *Mon. Wea. Rev.*, **116**, 495-501.

______, and ______, 1993: Tornadoes and tornadic storms: A review of conceptual models. *The Tornado: Its Structure, Dynamics, Prediction, and Hazards* (C. Church et al., Eds.), *Geophys. Monogr.* 79, Amer. Geophys. Union, 161-172.

______, and E.N. Rasmussen, 1994: The effect of neglecting the virtual temperature correction on CAPE calculations. *Wea. Forecasting*, **9**, 625-629.

______, J.T. Schaefer, D.W. McCann, T.W. Schlatter, and H.B. Wobus, 1982: Thermodynamic analysis procedures at the National Severe Storms Forecast Center. Preprints, *9th Conf. Wea. Forecasting and Analysis* (Seattle, WA), 304-309.

______, D.L. Keller and S.J. Weiss, 1990: An analysis of the temporal and spatial variation of tornado and severe thunderstorm watch verification. Preprints, *16th Conf. Severe Local Storms* (Kananaskis Park, Alberta, Canada), Amer. Meteor. Soc., 294-299.

______, R.H. Johns and S.J. Weiss, 1993: Tornado forecasting: A review. *The Tornado: Its Structure, Dynamics, Hazards, and Prediction* (Geophys. Monogr. 79), Amer. Geophys. Union, 557-571.

______, H.E. Brooks and R.A. Maddox, 1996: Flash flood forecasting: An ingredients-based methodology. *Wea. Forecasting*, **11**, 560-581.

______, A.R. Moller and H.E. Brooks, 1999: Storm spotting and public awareness since the first tornado forecasts of 1948. *Wea. Forecasting*, **14**, 544-557.

Durran, D.R., 1986: Mountain waves. In *Mesoscale Meteorology and Forecasting* (P.S. Ray, ed.), Amer. Meteor. Soc., 472-492.

Eilts, M.D., J.T. Johnson, E.D. Mitchell, S. Sanger, G. Stumpf, A. Witt, K.W. Thomas, K.D. Hondl, D. Rhue, and M. Jain, 1996: Severe weather warning decision support system. Preprints, *18th Conf. Severe Local Storms* (San Francisco, CA), Amer. Meteor. Soc., 536-540

Emanuel, K.A., 1981: A similarity theory for unsaturated downdrafts within clouds. *J. Atmos. Sci.*, **38**, 1541-1557.

______, 1985: Frontal circulations in the presence of small moist symmetric instability. *J. Atmos. Sci.*, **42**, 1062-1071.

______, 1994: *Atmospheric Convection.* Oxford University Press, 580 pp.

Eom, J., 1975: Analysis of the internal gravity wave occurrence of April 19, 1970 in the Midwest. *Mon. Wea. Rev.*, **103**, 217-226.

FEMA, 1999: Midwest tornadoes of May 3, 1999: Observations, Recommendations and Technical Guidance. Building Performance Assessment Report, FEMA-342, Federal Emergency Management Agency, Washington, D.C., 189 pp.

Friedman, R.M., 1999: Constituting the polar front, 1919-1920. *The Life Cycle of Extratropical Cyclones* (M.A. Shapiro and S. GrØnas, Eds.), Amer. Meteor. Soc., 29-39.

Fritsch, J.M., 1975: Cumulus dynamics: Local compensating subsidence and its implications for cumulus parameterization. *Pure Appl. Geophys.*, **113**, 851-867.

Foote, G.B., and C.A. Knight, 1979: Results of a randomized hail suppression experiment in northeast Colorado. Part I: Design and conduct of the experiment. J. Appl. Meteor., 18, 1526-1537

______, and H.W. Frank, 1983: Case study of a hailstorm in Colorado. Part III: Airflow from triple-Doppler measurements. *J. Atmos. Sci.*, **40**, 686-707.

Forbes, G.S., 1981: On the reliability of hook echoes as tornado indicators. *Mon. Wea. Rev.*, **109**, 1457-1466.

______, and R. Wakimoto, 1983: A concentrated outbreak of tornadoes, downbursts and microbursts, and implications regarding vortex classification. *Mon. Wea. Rev.*, **111**, 220-235.

Fovell, R.G., and P.S. Dailey, 1995: The temporal behavior of numerically simulated multicell-type storms. Part I: Modes of behavior. *J. Atmos. Sci.*, **52**, 2073-2095.

Fujita, T.T., 1955: Results of detailed synoptic studies of squall lines. *Tellus*, **4**, 405-436.

______, 1963: Analytical mesometeorology: A review. *Meteor. Monogr.*, **5**, No. 27, Amer. Meteor. Soc., 77-125.

______, 1971: Proposed characterization of tornadoes and hurricanes by area and intensity. SMRP Research Paper No. 91, University of Chicago, Chicago, IL, 42 pp.

______, 1975: New evidence from April 3-4, 1974 tornadoes. Preprints, *9th Conf. Severe Local Storms* (Norman, OK), Amer. Meteor. Soc., 248-255.

______, 1981: Tornadoes and downbursts in the context of generalized planetary scales. *J. Atmos. Sci.*, **38**, 1511-1534.

______, and F. Caracena, 1977: An analysis of three weather-related aircraft accidents. *Bull. Amer. Meteor. Soc.*, **58**, 1164-1181.

Gage, K.S., and B.B. Balsley, 1978: Doppler radar probing of the clear atmosphere. *Bull. Amer. Meteor. Soc.*, **59**, 1074-1093.

Galway, J.G., 1977: Some climatological aspects of tornado outbreaks. *Mon. Wea. Rev.*, **105**, 477-484.

______, 1989: The evolution of severe thunderstorm criteria within the Weather Service. *Wea. Forecasting*, **4**, 585-592.

Grazulis, T.P, 1993: *Significant Tornadoes 1680-1991*. Environmental Films, St. Johnsbury, VT, 1326 pp.

Hales, J.E., Jr., 1993: Biases in the severe thunderstorm data base: Ramifications and solutions. Preprints, *13th Conf. Wea. Analysis and Forecasting* (Vienna, VA), Amer. Meteor. Soc., 504-507.

Hane, C.E., and P.S. Ray, 1985: Pressure and buoyancy fields derived from Doppler radar data in a tornadic thunderstorm. *J. Atmos. Sci.*, **42**, 18-35.

Hess, S.L., 1957: *Introduction to Theoretical Meteorology.* Holt, Rhinehart and Winston, 362 pp.

Hilger, D.W., and J.F.W. Purdom, 1990: Clustering of satellite sounding radiances to enhance mesoscale meteorological retrievals. *J. Appl. Meteor.*, **29**, 1344-1351.

Hoffman, E.G., L.F. Bosart and D. Keyser, 1995: Large-amplitude inertia-gravity wave environments: Vertical structure and evolution. Preprints, 15th Conf. Wea. Analysis and Forecasting, Norfolk, VA, Amer. Meteor. Soc., 245- 248.

Hooke, W.H., 1986: Gravity waves. *Mesoscale Meteorology and Forecasting* (P. Ray, Ed.), Amer. Meteor. Soc. 272-288.

Hoskins, B.J., and F.P. Bretherton, 1972: Atmospheric frontogenesis models: Mathematical formulation and solution. *J. Atmos. Sci.*, **29**, 11-37.

House, D.C., 1959: The mechanics of instability line formation. *J. Meteor.*, **16**, 108-120.

______, 1963: Forecasting tornadoes and severe thunderstorms. *Meteor. Monogr.*, **5**, No. 27, Amer. Meteor. Soc., 141-155.

Houze, R.A. Jr., W. Schmid, R.G. Fovell, and H.H. Schiesser, 1993: Hailstorms in Switzerland: Left movers, right movers, and false hooks. *Mon. Wea. Rev.*, **121**, 3345-3370.

Jameson, A.R., and D.B. Johnson, 1990: Cloud microphysics and radar. *Radar in Meteorology* (D. Atlas, Ed.), Amer. Meteor. Soc., 323-340.

Johns, R.H., and W.D. Hirt, 1987: Derechos: Widespread convectively induced windstorms. *Wea. Forecasting*, **2**, 32-49.

______, and C.A. Doswell III, 1992: Severe local storms forecasting. *Wea. Forecasting*, **7**, 588-612.

Kamburova, P.L., and F.H. Ludlam, 1962: Rainfall evaporation in thunderstorm downdraughts. *Quart. J. Roy. Meteor. Soc.*, **92**, 510-518.

Kelly, D.L., J.T. Schaefer, R.P. McNulty, C.A. Doswell III, and R.F. Abbey, Jr., 1978: An augmented tornado climatology. *Mon. Wea. Rev.*, **106**, 1172-1183.

______, ______, and C.A. Doswell III, 1985: Climatology of nontornadic severe thunderstorm events in the United States. *Mon. Wea. Rev.*, **113**, 1997-2014.

Kessler, E., 1969: On the distribution and continuity of water substance in atmospheric circulation. *Meteor. Monogr.*, No. 32, **10**, 84 pp.

Klemp, J.B., and D.K. Lilly, 1975: The dynamics of wave-induced downslope winds. *J. Atmos. Sci.*, **32**, 320-339.

______ and R.B. Wilhelmson, 1978: The simulation of three-dimensional convective storm dynamics. *J. Atmos. Sci.*, **35**, 1070-1096.

Koppel, L.L., L.F. Bosart and D. Keyser, 2000: A 25-yr climatology of large-amplitude hourly surface pressure changes over the conterminous United States. *Mon. Wea. Rev.*, **128**, 51-68.

Krzysztofowicz, R., W.J. Drzal, T.R. Drake, J.C. Weyman, and L.A. Giordano, 1993: Probabilistic quantitative precipitation forecasts for river basins. *Wea. Forecasting*, **8**, 424-439.

Laing, A.G., and J.M. Fritsch, 1997: The global population of mesoscale convective complexes. *Quart. J. Roy. Meteor. Soc.*, **123**, 389-405.

Lanicci, J.M., T.N. Carlson, and T.T. Warner, 1987: Sensitivity of the Great Plains severe-storm environment to soil-moisture distribution. *Mon. Wea. Rev.*, **115**, 2660-2673.

Larson, L.W., R.L. Ferral, T.T. Strem, A.J. Morin, B. Armstrong, T.R. Carroll, M.D. Hudlow, L.A. Wenzel, G.L. Schaefer, and D. E. Johnson. Operational responsibilities of the National Weather Service river and flood program. *Wea. Forecasting*, **10**, 465-476.

Levine, J., 1959: Spherical vortex theory of bubble-like motion in cumulus clouds. *J. Meteor.*, **16**, 653-662.

Lilly, D.K. and T. Gal-Chen, 1990: Can dryline mixing create buoyancy? *J. Atmos. Sci.*, **47**, 1170-1171.

Lindzen, R.S., and K.K. Tung, 1976: Banded convective activity and ducted gravity waves. *Mon. Wea. Rev.*, **104**, 1602-1617.

Locatelli, J.D., M.T. Stoelinga and P.V. Hobbs, 1998: Structure and evolution of winter cyclones in the central United States and their effects on the distribution of precipitation. Part V: Thermodynamic and dual-Doppler radar analysis of a squall line associated with a cold front aloft. *Mon. Wea. Rev.*, **126**, 860-875.

López, R.E., R.L. Holle, T.A. Heitkamp, M. Boyson, M. Cherington, and K. Langford, 1993: The underreporting of lighting injuries and deaths. Preprints, *17th Conf. Severe Local Storms/Conf. on Atmos. Electricity* (Kananaskis Park, ALTA, Canada), Amer. Meteor. Soc. 775-778.

Lorenz, E.N., 1993: *The Essence of Chaos*. Univ. of Washington, 227 pp.

Ludlam, F.H., 1963: Severe local storms: A review. *Meteor. Monogr.* (D. Atlas, Ed.), **5**, No. 27, 1-30.

Lynn. B.H., W.-K. Tao and P.J. Wetzel, 1998: A study of landscape-generated deep moist convection. *Mon. Wea. Rev.*, **126**, 928-942.

MacGorman, D.R., and W.D. Rust, 1988: *The Electrical Nature of Storms*. Oxford University Press, 422 pp.

McCaul, E.W., Jr., 1993: Observations and simulation of hurricane-spawned tornadic storms. *The Tornado: Its Structure, Dynamics, Prediction, and Hazards* (C. Church et al., Eds), *Geophys. Monogr.* 79, Amer. Geophys. Union, 119-142.

McDonald, J.R., 1993: Damage mitigation and occupant safety. *The Tornado: Its Structure, Dynamics, Prediction, and Hazards* (C. Church et al., Eds), *Geophys. Monogr.* 79, Amer. Geophys. Union, 523-528.

McWilliams, J.C., and P.R. Gent, 1980: Intermediate models of planetary circulations in the atmosphere and ocean. *J. Atmos. Sci.*, **37**, 1657-1678.

Maddox, R.A., 1980: Mesoscale convective complexes. *Bull. Amer. Meteor. Soc.*, **61**, 1374-1387.

______, L.R. Hoxit and C.F. Chappell, 1980: A study of tornadic thunderstorms interactions with thermal boundaries. *Mon. Wea. Rev.*, **108**, 1866-1877.

______, and C.A. Doswell III, 1982: An examination of jet stream configurations, 500 mb vorticity advection and low-level thermal advection patterns during extended periods of intense convection. *Mon. Wea. Rev.*, **110**, 184-197.

_____, and D.E. Forsyth, 1994: Comments on "National Weather Service warning performance based on the WSR-88D." *Bull. Amer. Meteor. Soc.*, **74**, 2175.

Marshall, T.P., 1993: Lessons learned from analyzing tornado damage. *The Tornado: Its Structure, Dynamics, Prediction, and Hazards* (C. Church et al., Eds), *Geophys. Monogr.* 79, Amer. Geophys. Union, 495-499.

Marwitz, J.D., 1972a: The structure and motion of severe hailstorms. Part I: Supercell storms. *J. Appl. Meteor.*, **11**, 166-179.

______, 1972b: The structure and motion of severe hailstorms. Part II: Multi-cell storms. *J. Appl. Meteor.*, **11**, 180-188.

______, 1972c: The structure and motion of severe hailstorms. Part III: Severely sheared storms. *J. Appl. Meteor.*, **11**, 189-201.

Mass, C.F., and M.D. Albright, 1989: Origin of the Catalina eddy. *Mon. Wea. Rev.*, **117**, 2406-2436.

Matejka, T., and R.C. Srivastrava, 1991: An improved version of the extended VAD analysis of single-Doppler radar data. *J. Atmos. Oceanic Technol.*, **8**, 435-466.

Mehta, K.C., 1976: Windspeed estimates: Engineering analyses. Proceedings, *Symposium on Tornadoes*(Lubbock, TX), Texas Tech. University, 89-103.

Menard, R.D., and J.M. Fritsch, 1989: A mesoscale convective complex-generated inertial stable warm core vortex. *Mon. Wea. Rev.*, **117**, 1237-1261.

Miller, R.C., 1972: Notes on the Analysis and Severe-Storm Forecasting Procedures of the Air Force Global Weather Central. AWS Tech. Rept. 200 (Rev.), Headquarters, Air Weather Service, Scott Air Force Base, IL _____, 190 pp.

Minor, J.E., and K.C. Mehta, 1979: Wind damage observations and implications. *J. Struc. Div.*, Amer. Soc. Civ. Eng., **105**, 2279-2291.

Moran, K.P., D.B. Wuertz, R.G. Strauch, N.L. Abshire, and D.C. Law, 1991: Temperature sounding with wind profiler radars. *J. Atmos. Oceanic Technol.*, **8**, 606-611.

Murphy, A. H., 1993: What is a good forecast? An essay on the nature of goodness in forecasting. *Wea. Forecasting*, **8**, 281-293.

______, and R. L. Winkler, 1987: A general framework for forecast verification. *Mon. Wea. Rev.*, **115**, 1330-1338

National Weather Service, 1991: *Shadyside, Ohio, Flash Floods -- June 14, 1990.* Natural Disaster Survey Report (January 1991), available from NOAA/National Weather Service, 1325 East-West Highway, Silver Spring, MD 20910, 124 pp.

Neiman, P.J., and M.A. Shapiro, 1989: Retrieving horizontal temperature gradients and advections from single-station wind profiler observations. *Wea. Forecasting*, **4**, 222-233.

______, P.T. May, and M.A. Shapiro, 1992: Radio acoustic sounding system (RASS) and wind profiler observations of lower- and midtropospheric weather systems. *Mon. Wea. Rev.*, **120**, 2298-2313.

Newton, C.W., 1950: Structure and mechanism of the pre-frontal squall line. *J. Meteor.*, **7**, 210-222.

______, 1963: Dynamics of severe convective storms. *Meteor. Monogr.* (D. Atlas, Ed.), **5**, No. 27, 33-58.

Ninomiya, K., 1971: Mesoscale modification of synoptic situations from thunderstorm development as revealed by ATS III and aerological data. *J. Appl. Meteor.*, **10**, 1103-1121.

Nolen, R.H., 1959: A radar pattern associated with tornadoes. *Bull. Amer. Meteor. Soc.*, **40**, 277-279.

Olson, D.A., N.W. Junker, and B. Korty, 1995: Evaluation of 33 years of quantitative precipitation forecasting at the NMC. *Wea. Forecasting*, **10**, 498-511.

Orlanski, I., 1975: A rational subdivision of scales for atmospheric processes. *Bull. Amer. Meteor. Soc.*, **56**, 527-530.

Orville, R.E., and R.W. Henderson, 1986: Global distribution of midnight lightning: September 1977 to August 1978. *Mon. Wea. Rev.*, **114**, 2640-2653.

Paluch, I.R., 1979: The entrainment mechanism in Colorado cumuli. *J. Atmos. Sci.*, **36**, 2467-2478.

Pan, Z., E. Takle, M. Segal, and R. Turner: Influences of model parameterization schemes on the response of rainfall to soil moisture in the central United States. *Mon. Wea. Rev.*, **124**, 1786-1802.

Peltier, W.R., and T.L. Clark, 1979: The evolution and stability of finite-amplitude mountain waves. Part II: Surface wave drag and severe downslope windstorms. *J. Atmos. Sci.*, **36**, 1498-1529.

Polger, P.D., 1994: Reply to "Comments." *Bull. Amer. Meteor. Soc.*, **75**, 2175-2176.

______, B.S. Goldsmith, R.C. Przywarty, and J.R. Bocchieri, 1994: National Weather Service warning performance based on the WSR-88D. *Bull. Amer. Meteor. Soc.*, **75**, 203-214.

Przybylinski, R.W., 1995: The bow echo: Observations, numerical simulations, and severe weather detection methods. *Wea. Forecasting*, **10**, 203-217.

Purdom, J.F.W., 1976: Some uses of high-resolution GOES imagery in the mesoscale forecasting of convection and its behavior. *Mon. Wea. Rev.*, **104**, 1474-1483.

Rasmussen, E.N., J.M. Straka, R. Davies-Jones, C.A. Doswell III, F.H. Carr, M.D. Eilts, and D.R. MacGorman, 1994: Verification of the Origins of Rotation in Tornadoes EXperiment: VORTEX. *Bull. Amer. Meteor. Soc.*, **75**, 995-1006.

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

Renno, N.O., and E.R. Williams, 1995: Quasi-Lagrangian measurements in convective boundary layer plumes and their implications for the calculation of CAPE. *Mon. Wea. Rev.*, **123**, 2733-2742.

Rhea, J.O., 1966: A study of thunderstorm formation along dry lines. *J. Appl. Meteor.*, **5**, 59-63.

Rust, W.D., and T.C. Marshall, 1996: On abandoning the thunderstorm tripole charge paradigm. *J. Geophys. Res.*, **101**, 23,499-23,504.

Ryzhkov, A., and D. Zrnić , 1994: Precipitation observed in Oklahoma mesoscale convective systems with a polarimetric radar. *J. Appl. Meteor.*, **33**, 455-464.

______, and ______, 1996: Assessment of rainfall measurement that uses specific differential phase. *J. Appl. Meteor.*, **35**, 2080-2090.

Sanders, F., and C.A. Doswell III: A case for detailed surface analysis. *Bull. Amer. Meteor. Soc..*, **76**, 505-521.

Saunders, C.P.R., 1993: A review of thunderstorm electrification processes. *J. Appl. Meteor.*, **32**, 642-655.

Schaefer, J.T., 1975: Nonlinear biconstituent diffusion: A possible trigger of convection. *J. Atmos. Sci.*, **32**, 2278-2284.

______, 1986: Severe thunderstorm forecasting: A historical perspective. *Wea. Forecasting*, **1**, 164-189.

Schlesinger, R.E., 1975: A three-dimensional numerical model of an isolated deep convective cloud: Preliminary results. *J. Atmos. Sci.*, **32**, 934-957.

Schultz, D. M., P. N. Schumacher and C. A. Doswell III, 2001: The instauration of instabilities. *Mon. Wea. Rev.* [accepted conditionally].

Schumann, U., and C.-H. Moeng, 1991: Plume budgets in clear and cloudy convective boundary layers. *J. Atmos. Sci.*, **48**, 1758-1770.

Schwartz, B., and S.G. Benjamin, 1995: A comparison of temperature and wind measurements from ACARS-equipped aircraft and rawinsondes. *Wea. Forecasting*, **10**, 528-544.

Scorer, R.S., and F.H. Ludlam, 1953: Bubble theory of penetrative convection. *Quart. J. Roy. Meteor. Soc.*, **79**, 94-103.

Segal, M., R.W. Arritt, C. Clark, R. Rabin, and J.M. Brown, 1995: Scaling evaluation of the effect of surface characteristics on potential for deep convection over uniform terrain. *Mon. Wea. Rev.*, **123**, 383-400.

Sherwood, S.C., 2001: On moist instability. *Mon. Wea. Rev.* [accepted conditionally].

Shortley, G., and D. Williams, 1961: *Elements of Physics.* Prentice-Hall, 928 pp.

Simpson, J., 1971: On cumulus entrainment and one-dimensional models. *J. Atmos. Sci.*, **28**, 449-455.

______, 1972. Reply to comments. *J. Atmos. Sci.*, **29**, 220-225.

Smull, B.F., 1995: Convectively induced mesoscale weather systems in the tropical and warm-season midlatitude atmosphere. *Rev. Geophys.*, **33** (supplement), 897-906

______, and R.A. Houze, Jr., 1987: Rear inflow in squall lines with trailing stratiform precipitation. *Mon. Wea. Rev.*, **115**, 2869-2889.

Spencer, P.L., F.H. Carr, and C.A. Doswell III, 1996: Investigation of an amplifying and a decaying wave using a network of wind profilers. *Mon. Wea. Rev.*, **124**, 209-223.

Spencer, R.W., H.M. Goodman, and R.E. Hood, 1989: Precipitation retrieval over land and ocean with the SSM/I: Identification and characteristics of the scattering signal. J. Atmos. Oceanic Technol., **6**, 254-273.

Squires, P., 1958: Penetrative downdraughts in cumuli. *Tellus*, **10**, 381-393.

______, and J.S. Turner, 1962: An entraining jet model for cumulonimbus updraughts. *Tellus*, **14**, 422-434.

Stommel, H., 1947. Entrainment of air into a cumulus cloud. *J. Meteor.*, **4**, 91-94.

Turner, J.S., 1962: The starting plume in neutral surroundings. *J. Fluid Mech.*, **13**, 356-368.

______, 1973: *Buoyancy Effects in Fluids*. Cambridge University Press, 367 pp.

Uccellini, L.W., 1975: A case study of apparent gravity wave initiation of severe convective storms. *Mon. Wea. Rev.*, **103**, 497-513.

Velasco, I., and J.M. Fritsch, 1987: Mesoscale convective complexes in the Americas. *J. Geophys. Res.*, **92**, 9591-9613.

Vonnegut, B., 1963: Some facts and speculations concerning the origin and role of thunderstorm electricity. *Meteor. Monogr.*, **5**, No. 27, Amer. Meteor. Soc., 224-241.

______, 1994: The atmospheric electricity paradigm. *Bull. Amer. Meteor. Soc.*, **75**, 53-61.

Wakimoto, R.M., 1985: Forecasting dry microburst activity over the High Plains. *Mon. Wea. Rev.*, **113**, 1131-1143.

Ware, R. H., et al., 2000: SuomiNet: A real-time national GPS network for atmospheric research and education. *Bull. Amer. Meteor. Soc.*, **81**, 677-694.

Warner, J., 1970: On steady-state one-dimensional models of cumulus convection. *J. Atmos. Sci.*, **27**, 1035-1040.

______, 1972: Comments on "On cumulus entrainment and one-dimensional models." *J. Atmos. Sci.*, **29**, 218-219.

Weisman, M.L, and J.B. Klemp, 1982: The dependence of numerically simulated convective storms on vertical wind shear and buoyancy. *Mon. Wea. Rev.*, **110**, 504-520.

______, and ______, 1984: The structure and classification of numerically simulated convective storms in directionally-varying wind shears. *Mon. Wea. Rev.*, **112**, 2479-2498.

______, and ______, 1986. Characteristics of isolated convective storms. In *Mesoscale Meteorology and Forecasting* (P.S. Ray, ed.), Amer. Meteor. Soc., 331-358.

Wetzel, P.J., W.R. Cotton and R.L. McAnelly, 1983: A long-lived mesoscale convective complex. Part II: Evolution and structure of the mature complex. *Mon. Wea. Rev.*, **111**, 1919-1937.

Wilczak, J.M., and J.W. Glendening, 1988: Observations and mixed-layer modeling of a terrain-induced mesoscale gyre: The Denver cyclone. *Mon. Wea. Rev.*, **116**, 2688-2711.

Williams, E.R., 1985: Large-scale charge separation in thunderclouds. *J. Geophys. Res.*, **90**, 6013-6025.

______, and R.M. Lhermitte, 1983: Radar test of the precipitation hypothesis for thunderstorm electrification. *J. Geophys. Res.*, **88**, 10,984-10,992.

Williams, R.T., and J. Plotkin, 1968: Quasi-geostrophic frontogenesis. *J. Atmos. Sci.*, **25**, 201-206.

Xu, Q., 1987: The existence and stability of steady circulations in a conditionally symmetrically unstable basic flow. *J. Atmos. Sci.*, **44**, 3020-3029.

Young, G., 1988: Convection in the atmospheric boundary layer. *Earth-Science Review*s, **25**, 179-188.

Zehr, R.M., J.F.W. Purdom, J.F. Weaver, and R.N. Green, 1988: Use of VAS data to diagnose the mesoscale environment of convective storms. *Wea. Forecasting*, **3**, 33-49.

Ziegler, C.L., W.J. Martin, R.A. Pielke, and R.L. Walko, 1995: A modeling study of the dryline. *J. Atmos. Sci.*, **52**, 263-285.

Zipser, E.J., 1982: Use of a conceptual model of the life-cycle of mesoscale convective systems to improve very short-range forecasts. *Nowcasting* (K.A. Browning, Ed.), Academic Press, 191-204.

Table 1. Physical characteristics of a Mesoscale Convective Complex (MCC), based on an analysis of the enhanced IR satellite imagery; criteria developed by Maddox (1980). The intent was to select the largest, most persistent, most nearly circular Mesoscale Convective Systems (MCSs) and to define their initiation, maximum extend, and termination.

Size	A -- cloud shield with continuously low IR temperature $\leq$-32˚C, must have an area $\geq$ 100 000 km^2 B -- Interior cold cloud region with temperature $\leq$-52˚C, must have an area $\geq$ 50 000 km^2
Initiate:	Size definitions A and B are first satisfied
Duration:	Size definitions A and B must be met for a period $\geq$ 6 h.
Maximum extent:	Contiguous cold cloud shield (IR temperature $\leq$-32˚C) reaches maximum extent
Shape:	Eccentricity (minor axis/major axis) $>$ 0.7 at time of maximum extent
Terminate:	Size definitions A and B are no longer satisfied

FIGURE CAPTIONS

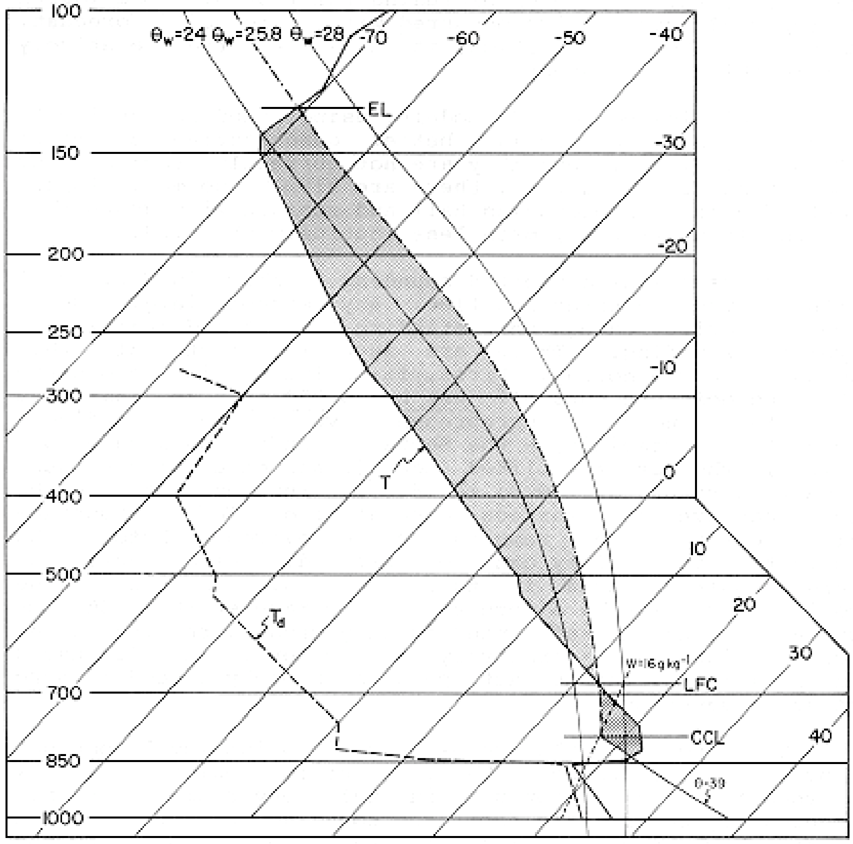

Fig. 1. Example of a sounding (Tinker Air Force Base, Oklahoma at 1200 UTC on 08 June 1974; a day with significant tornadoes in the area) plotted on a skew T-log p diagram; thin slanting solid lines are isotherms in ˚C, whereas the horizontal thin solid lines are isobars in hPa. The heavy solid line marked "T" is the temperature observation during balloon ascent and the heavy dashed line marked "T_d" is the observed dewpoint temperature. Two pseudoabiabats (thin curved lines labeled θ_w=24 [˚C] and θ_w=28, where is the wet-bulb potential temperature) are shown, as well as one mixing ratio line (thin dashed line labeled w=16 g kg^{-1}). The thin solid line labeled θ=39 is the dry adiabat through the forecast maximum surface temperature and the dash-dotted line labeled θ_w=25.8 is pseudoadiabat associated with the lifted parcel ascent curve. The solid line labeled CCL is the condensation level for the forecast surface parcel; that labeled LFC is the parcel's level of free convection; and that labeled EL is the parcel's equilibrium level. The stippled area between the LFC and the EL represents the CAPE of the lifted parcel and the hatched area below the LFC represents CIN of the lifted parcel.

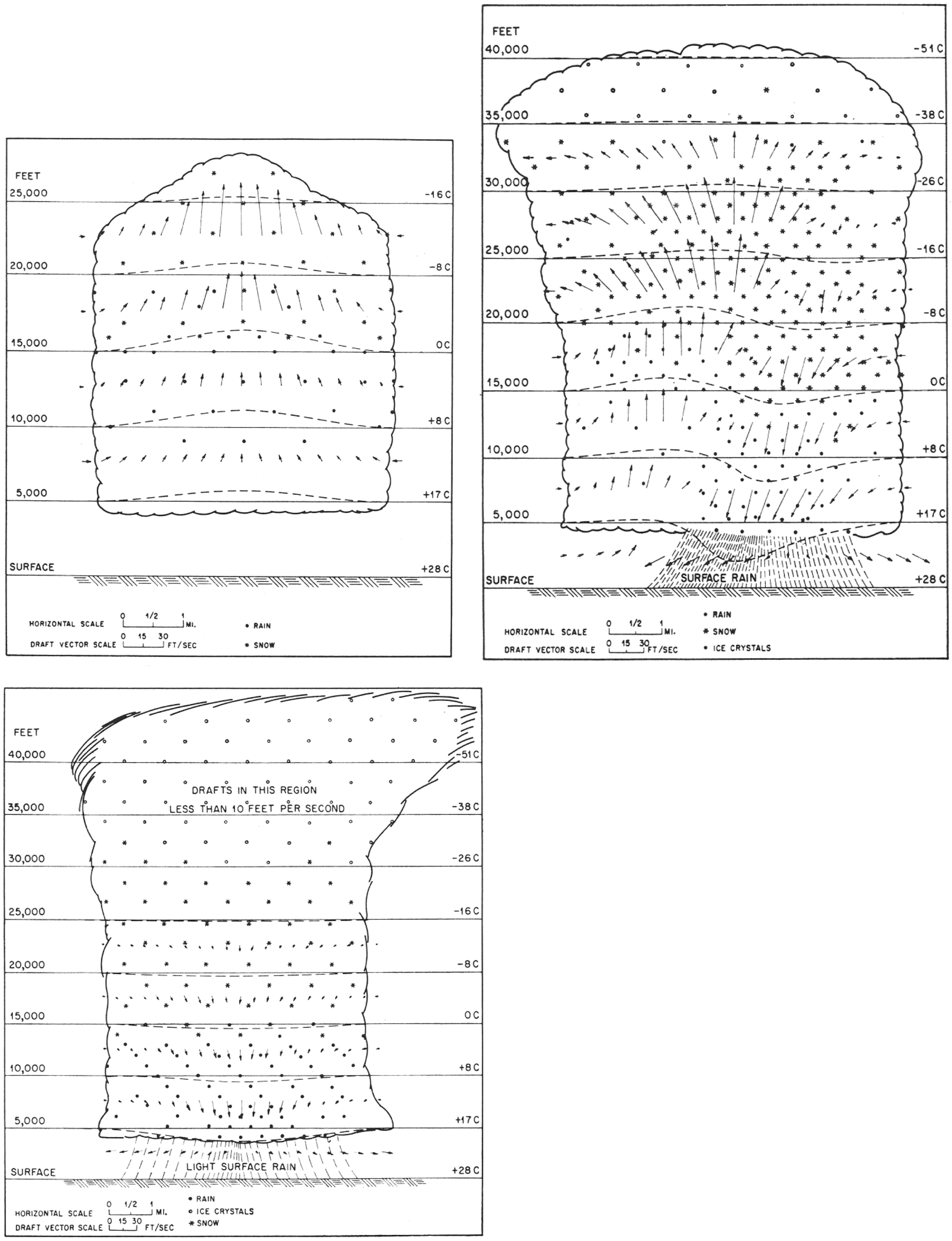

Fig. 2. Classic thunderstorm cell schematics from Byers and Braham (1949) showing a) the Cumulus stage, b) the Mature stage, and c) the Dissipating stage.

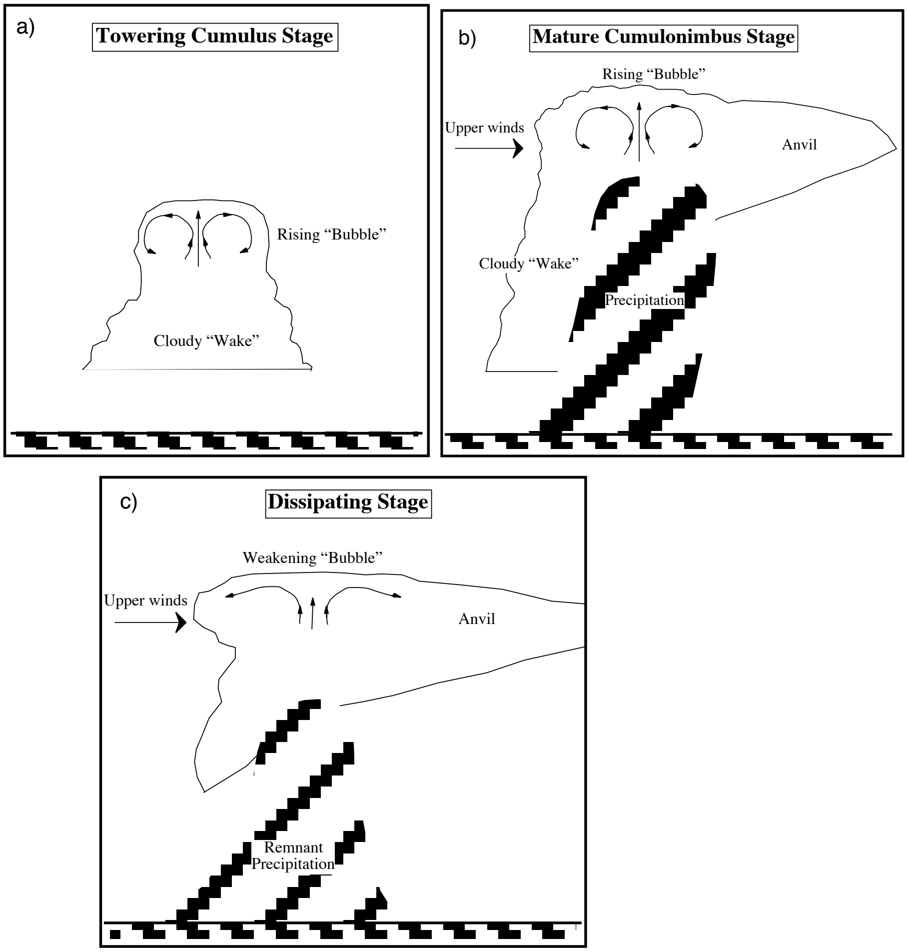

Fig. 3. A modified version of the life cycle of a single convective cell, showing the progression of a "bubble" of buoyant air. Features on the figure are labeled; (a) corresponds to the "towering cumulus" stage, (b) to the "mature" stage, and (c) to the "dissipating" stage of Fig. 2.

Fig. 4. Example of so-called "turkey towers" (due to their resemblance to the heads of turkeys) on 20 May 1992 in western South Dakota (photo © 1992 C. Doswell).

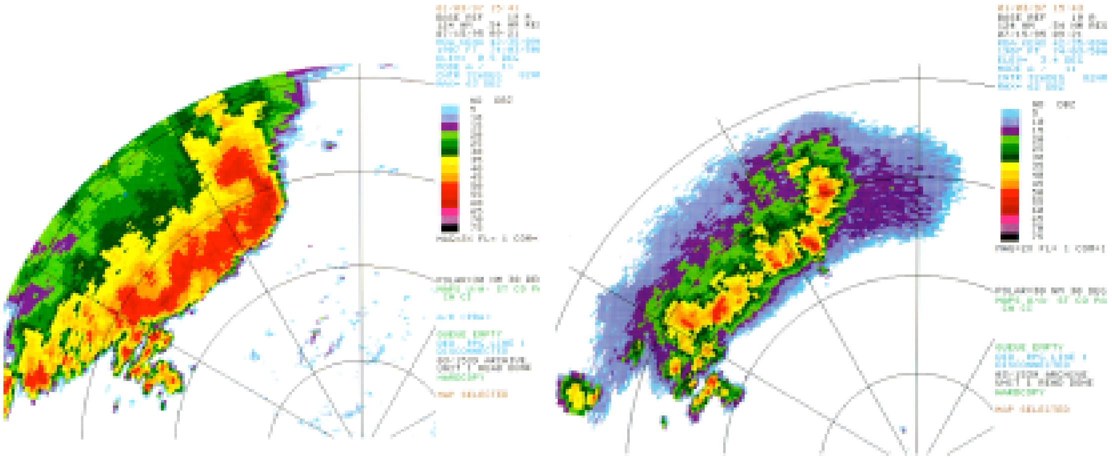

Fig. 5. Example of a squall line, as seen from the Albany, NY, WSR-88D radar, showing (a) relatively little along-line variation in intensity at the lowest elevation (0.5 deg), but which (b) breaks down into individual convective cells at higher levels (3.4 deg), on 15 July 1995 at 0921 UTC.

Fig. 6. A line of isolated tornadic supercell convective storms in eastern Oklahoma on 26 May 1973 (photo taken from an aircraft by P. Sinclair).

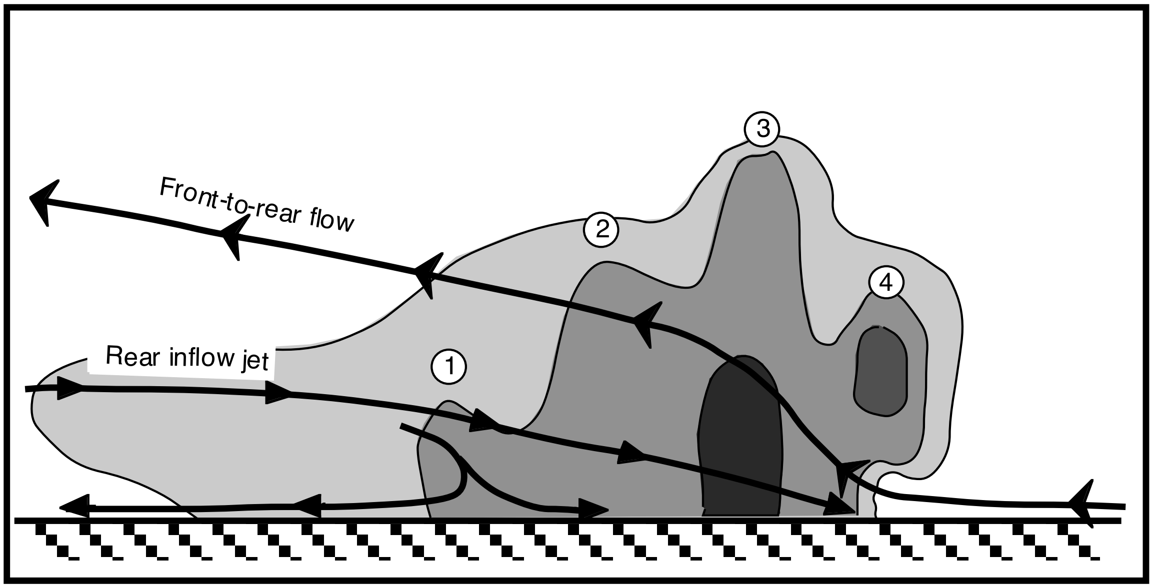

Fig. 7. Schematic cross section of the airflow in an MCS; the stippling denotes low, moderate and high radar reflectivities by progressively darker stippling; the front-to-rear flow and rear inflow jet are indicated, and the circled numbers 1-4 represent individual convective cells in the order in which they have developed. Since the MCS movement includes a component due to development of new convective cells on its leading edge, the cells tend to move rearward through the MCS as they mature and dissipate (see Smull and Houze 1987)

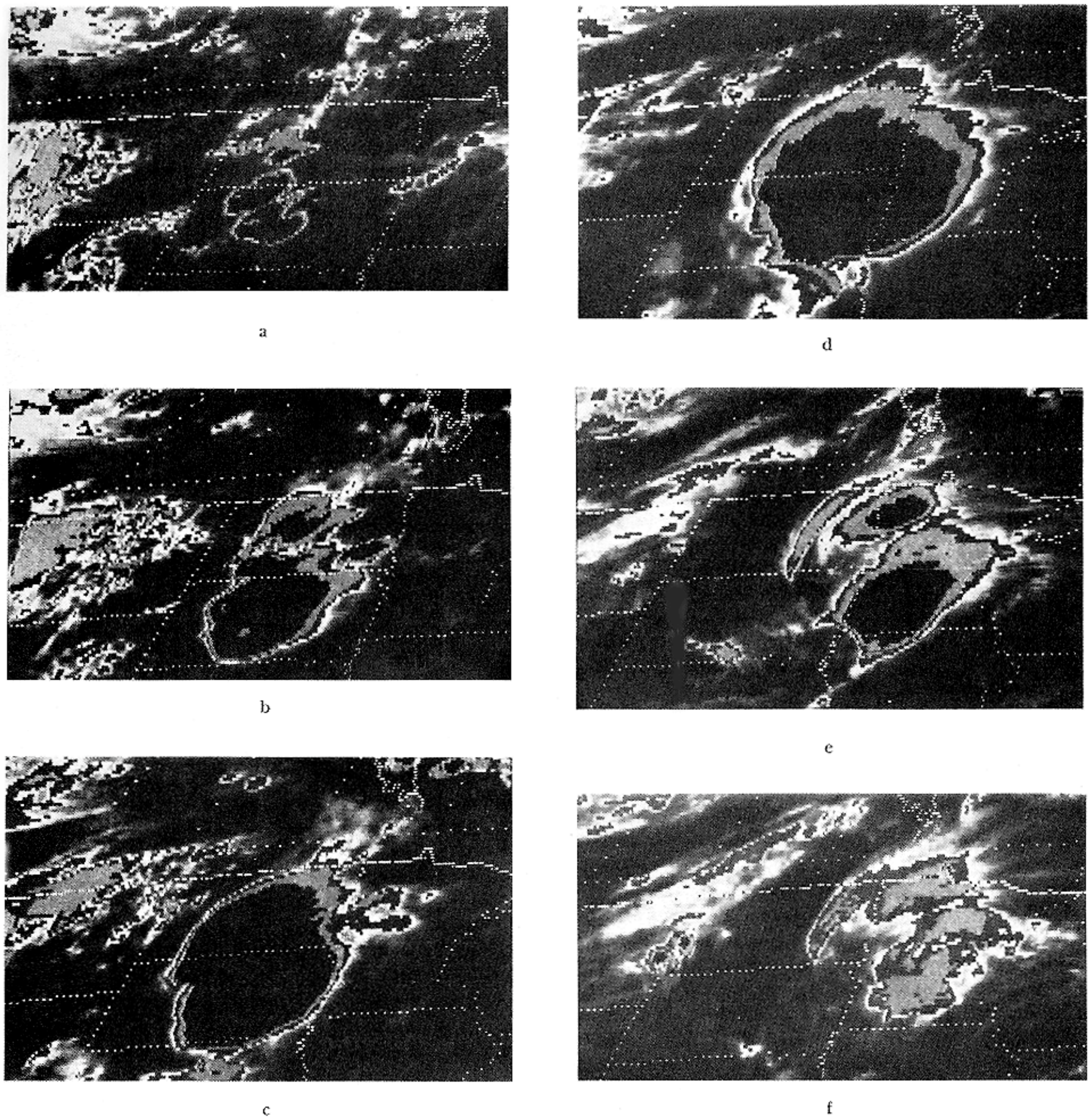

Fig. 8. Life cycle of an MCS as seen in IR satellite imagery for an MCC on 12 July 1979 at a) 0030 UTC, b) 0300 UTC, c) 0600 UTC, d) 0900 UTC, e) 1430 UTC, and f) 1630 UTC (from Maddox 1980).

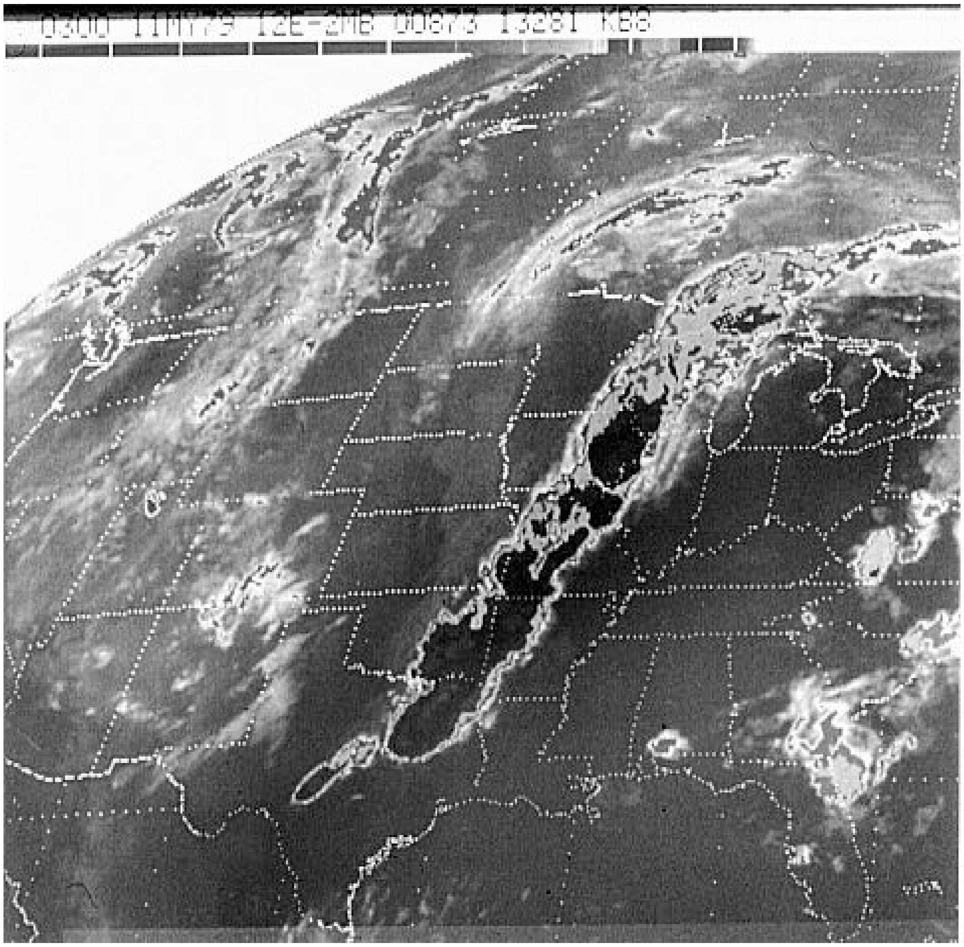

Fig. 9. An infrared satellite image (using a standard "MB" enhancement) depicting a linearly-organized MCS, on 11 May 1973 at 0300 UTC.

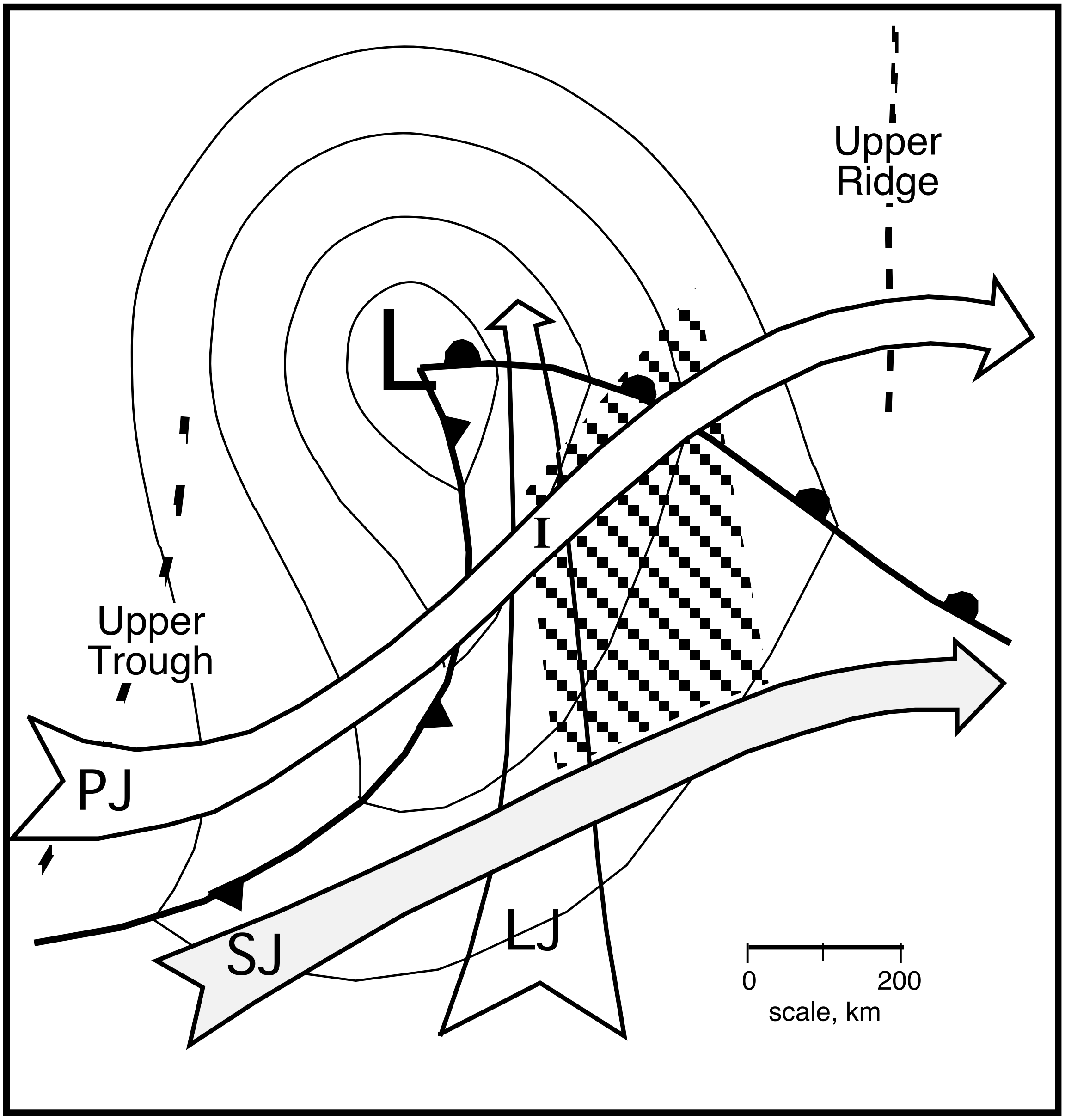

Fig. 10. Idealized example of important synoptic scale features in an outbreak of severe convective storms; thin lines are sea-level isobars, surface feature symbols are conventional, the broad arrow labeled "LJ" is the low-level jetstream, that labeled "PJ" denotes the polar jetstream aloft, the shaded broad arrow labeled "SJ" depicts the subtropical jetstream aloft (that may not always be present). The hatched area shows where severe convective storms are most likely during the ensuing 6-12 h; the severe storms are considered most likely to begin near the point labeled "I" where the LJ and PJ intersect. Nonsevere convection can occur outside the hatched region. (after Barnes and Newton 1983)

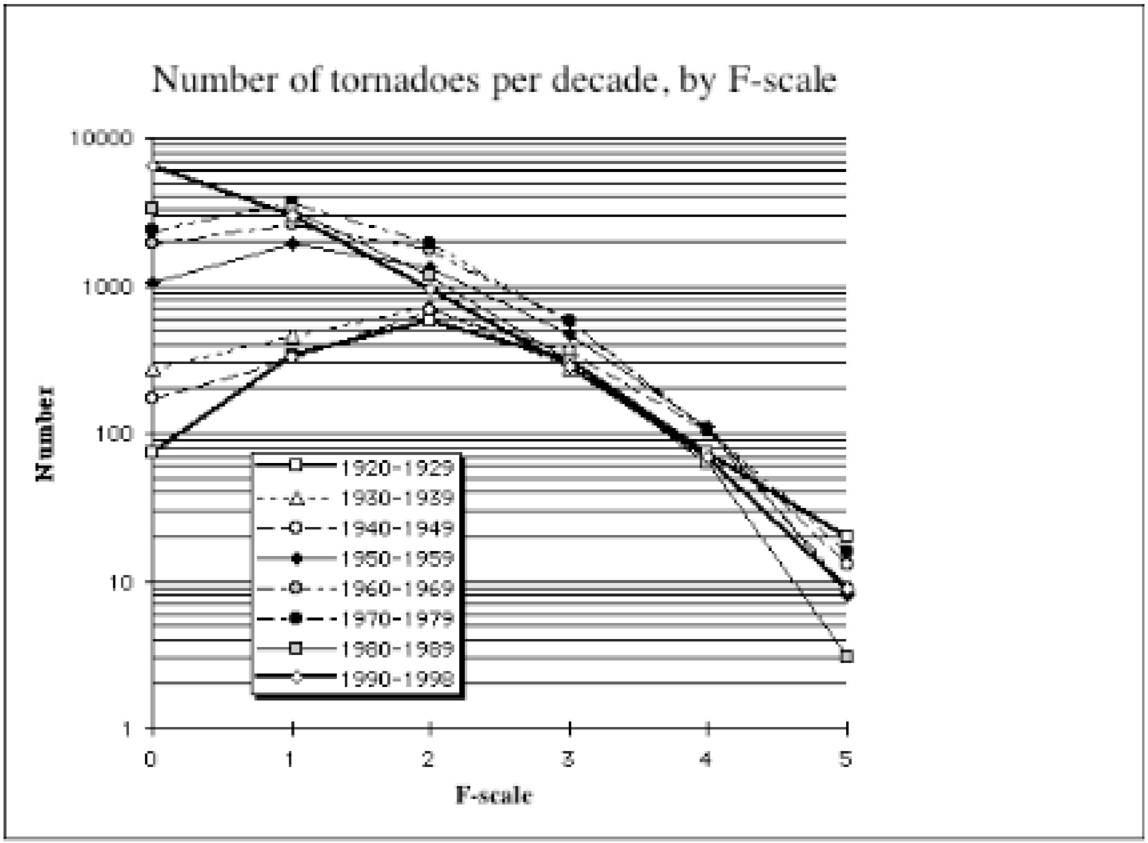

Fig. 11. Plot of the distribution of United States tornadoes as a function of F-scale, by decade. The number of events is shown on a logarithmic scale.

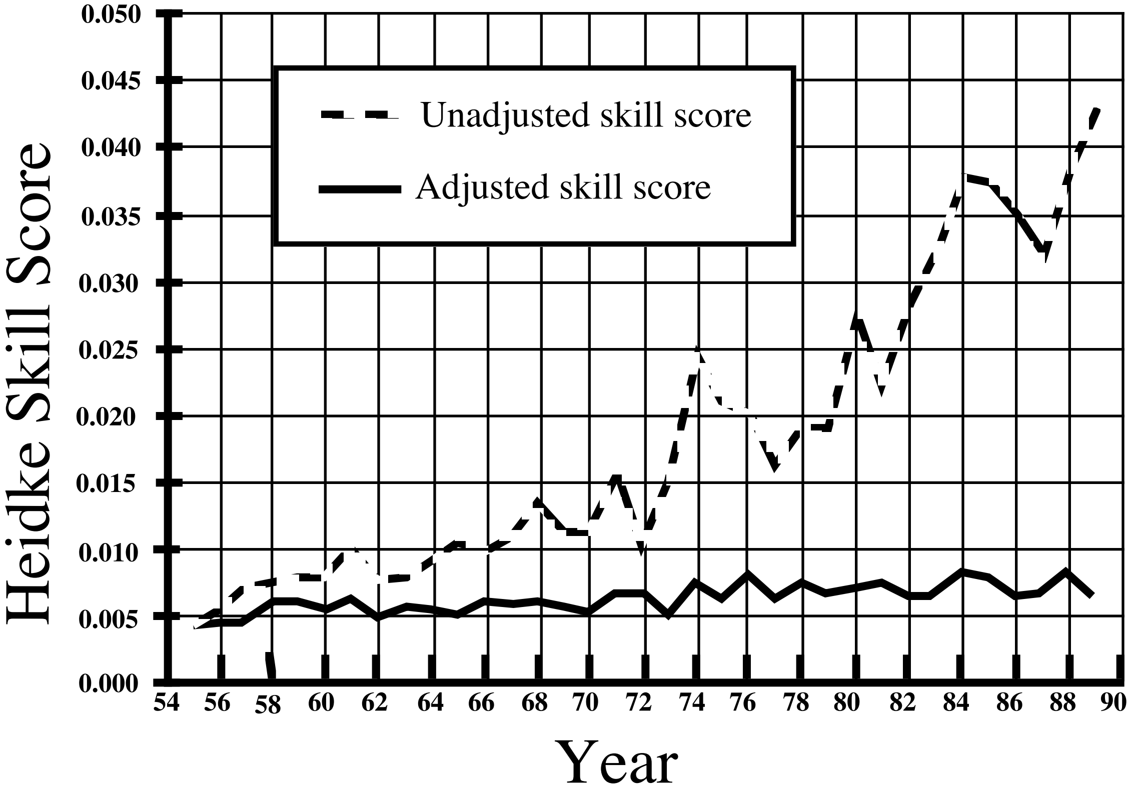

Fig. 12. Yearly values of Heidke skill score for tornado and severe thunderstorm watches, showing the effect of "adjusting" for the inflation of severe weather reports as described in Doswell et al. (1990).