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Severe Convective Weather and Associated Disasters in North America

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SUMMARY

Disaster-producing severe convective weather phenomena in North America are reviewed, including several aspects of human activity by which the events create disastrous effects. The primary emphasis is on the meteorological processes on different scales that create the weather events (tornadoes, large hail, damaging convective wind gusts, and heavy rainfall). However, a weather-related disaster results from the concatenation of weather events with humans and their affairs. Therefore, some consideration of the relationship between human activities and the weather is provided.

1. Introduction

Severe convection is quite common in much of North America, owing to continental geography: there are several topographic aspects of the continent that favor a high frequency of intense convection in the continental interior. First of all, the continent extends meridionally from the polar regions to the subtropics, with most of its land mass in middle latitudes. However, the primary mountain barriers run north and south, so baroclinic zones can move north and south freely with the seasons, providing sources of mesoscale lift for initiating convection in a backdrop of relatively strong vertical wind shear.

Second, the elevated terrain in the western parts of the continent acts as as source of dry air with high lapse rates. Moisture flowing eastward from the Pacific falls out mostly near the coast, wrung out by the abrupt forced lifting of the coastal mountains. In the high plateaus and mountain ranges of the western continental interior, much of the remaining moisture falls out and the generally arid country acts to put sensible heat into the bottom of the airmass flowing overhead. Rock and thin soils under mostly sunny skies in relatively thin air absorb radiation and transfer it to the air above, creating a deep surface-based boundary layer. This boundary layer can be advected away from the high terrain as an elevated mixed layer (Carlson and Ludlam 1968).

Third, the relatively shallow and warm waters of the Gulf of Mexico provide a ready moisture source that can penetrate a substantial ways poleward during the warm season. Of course, air of tropical origins, already quite moist, also can pass over the Gulf on its way inland. Either way, a cycle of moisture return into the continental interior is enhanced by the poleward low-level jet stream created in the lee of the mountains to the west. The cycle of moisture return is driven by the passage of synoptic scale weather systems (Lanicci and Warner 1991). During the transitional seasons of spring and fall, the moisture availability for convection in association can be quite variable. In the summer, as the active baroclinic zone moves poleward, copious moisture can be present quite far inland, sustained by poleward flow off the Gulf of Mexico and enhanced by transpiration from plants.

Johns and Doswell (1992) have presented a view of severe convection that focuses on the physical mechanisms that produce the severe events. Different severe events are associated with different mechanisms, so it is not possible to discuss severe convective weather without being specific about the events under consideration. Moreover, since a convective weather-related disaster is the result of the meteorological event being concatenated with human activities, it should become clear in what follows that not all disasters are associated with meteorological events that are especially severe. Human activities can put people and their property at risk from convective storms that are not all that intense. As I describe the meteorology associated with different convective weather events, I will discuss human activities of particular vulnerability to those events.

2. Tornadoes

Tornadic events are distributed worldwide, but North America has by far the largest number of such events, and North American tornadoes are far more likely to be of extreme intensity than tornadoes elsewhere. Strong and violent tornadoes (F2-F3, and F4-F5, respectively, on the intensity scale developed by Fujita 1971) are almost always associated with supercell thunderstorms (Browning

1964), so it follows that supercells are most common in North America. It is likely that this is the result of the unique geography of North America, but it does not follow that supercells do not occur elsewhere. Tornadoes not associated with supercells do arise (see, e.g., Wakimoto and Wilson 1989), but they apparently are less likely to achieve high intensity than those spawned by supercells.

Although Browning's original work on supercells concentrated on identifying supercells with radar reflectivity morphology and evolution, it has become increasingly apparent that the definition of a supercell should be tied to clearly identifiable physical characteristics of a convective storm. Thus, to the maximum extent possible, supercell

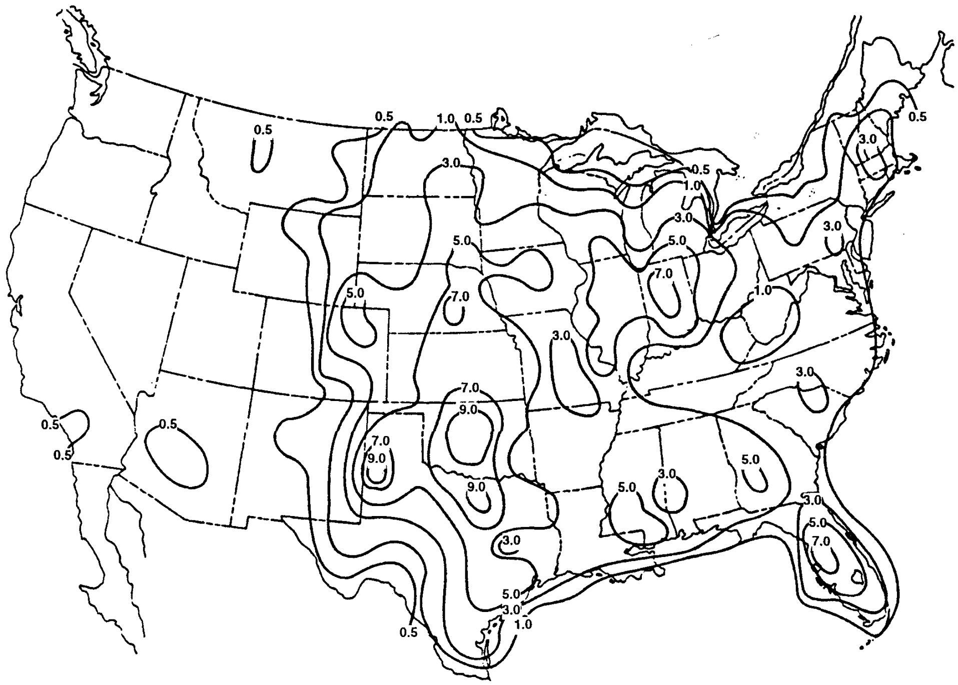

Fig. 1. Average annual tornado frequency per 10,000 mi^2 (25,900 km^2), during the period 1953-1980.

identification should be made by the presence of a deep, persistent mesocyclone (Browning 1977, Weisman and Klemp 1982, Doswell and Burgess 1993). Although there is some degree of arbitrariness in the definition, it has been widely accepted that mesocyclonic vorticity is of order 10^{-2} s^{-1}; such vorticity should be present and vertically-connected through a significant fraction of the depth of a convective storm (say, more than 1/4), and persist for a time that is at least as long as the convective time scale (say, on the order of 15 min).

It has been shown by observations (e.g., Ludlam 1963), theory (e.g., Davies-Jones 1984), and numerical simulations (e.g., Weisman and Klemp 1984) that convection becomes supercellular when the vertical wind shear has the appropriate structure. That structure is discussed in Doswell (1993), in the context of tornado forecasting. In this paper, it suffices to suggest that mesocyclonic vorticity at mid-levels in a supercell arises primarily from the updraft tilting the horizontal vorticity associated with the environmental wind shear into the vertical. It is not yet known clearly how mesocyclonic vorticity develops near the surface, but it appears likely that some mechanism associated with downdrafts is responsible (Brooks et al. 1993). Not all supercells produce tornadoes, but when mesocyclonic vorticity is present near the surface, the probability of one or more tornadoes increases substantially (Davies-Jones and Brooks 1993).

Although it is not yet possible to know the supercell frequency over North America, it is likely that its distribution corresponds roughly with the reported frequency distribution of tornadoes (Fig. 1) over the United States, assuming a reasonable extrapolation into Canada and Mexico. Naturally, the reported distribution may not correspond to the actual distribution (see Doswell and Burgess 1988).

Tornadoes, and especially strong and violent tornadoes, are primarily confined to the central plains of North America, with a marked secondary frequency maximum in the states bordering the Gulf of Mexico (see Kelly et al. 1978). Elsewhere, tornadoes are sufficiently rare that their threat often is widely ignored.

The challenge to preventing casualties is different in areas where tornadoes are widely recognized to be a threat, compared to areas where tornadoes are possible but not considered to be a danger. In the former case, it is the rare, but devastatingly destructive violent tornadoes that form the major threat; such events are sufficiently intense that casualties will result when the event strikes a populated area even when the citizens are warned and take the proper precautions. In the latter case, even weak tornadoes are potentially lethal because it is unlikely that they will be forecasted properly, or even recognized for what they are as they occur. Moreover, the citizens are unlikely to be prepared to take proper precautions. Tornado disasters, at least in terms of casualties, can be averted when an active program of preparing communities to respond to tornado danger is in place (Moller and Boots 1983).

Obviously, tornadoes that do not strike human habitations are unlikely to create disasters, no matter how intense they are. Conversely, if a weak tornado strikes without warning at structures that afford the occupants little or no shelter (such as mobile homes), even though the event itself is of modest meteorological significance, its human significance can be substantial. It is widely recognized that tornado deaths occur disproportionately often with mobile homes in North America. Yet, for many citizens, mobile homes are the only way they can afford to own their own home. In tornado-prone areas of North America, living in a mobile home is a risky proposition. Urbanization also tends to be accompanied by increasing populations living in either mobile homes or poorly constructed housing offering little or no shelter from tornadoes. Concentrations of population are covering an ever-increasing fraction of the area of North America (and elsewhere), increasing the overall threat of a disastrous tornado event.

3. Large hail

The processes that create large hail are relatively simple to state, but only in principle. Large hailstones arise through keeping precipitation aloft in the updraft; a hailstone the size of a grapefruit (~10 cm in diameter) has a terminal fallspeed of around 75 m s^{-1}. Thus, storms without strong updrafts are unlikely to produce large hail. It appears that the so-called "recycling hypothesis," in which is was proposed that hailstones cycle up and down several times within the storm, is not necessary to explain the "growth rings" seen within large hailstones. However, the updraft needs to be relatively persistent, as well as strong, to grow large hailstones.

Therefore, supercells are prime candidates to produce large hail, and that is indeed what is observed. Really large hailstones (say, exceeding 5 cm) are fairly common in supercells, and relatively rare in non-supercells. Although it is not necessary for supercells (Johns et al. 1993), such storms frequently occur within environments of large convective available potential energy (or CAPE). Environments with large values of CAPE (say, exceeding 2000 J kg^{-1}) certainly favor strong updrafts. However, supercells also can create strong updrafts even in environments with only modest CAPE, through vertical perturbation pressure forces arising from interaction of the updraft with the environmental winds (see Rotunno and Klemp 1982, Brooks and Wilhelmson 1993).

Shown in Fig. 2 is the frequency distribution of hail reports exceeding 1.9 cm in the United States. As with the tornado distribution map, reporting problems render the details debatable, but the general distribution is not dissimilar from that of tornadoes.

One issue concerning the importance of hail events on human activities is that hailstone size is not necessarily the only factor in determining its damage potential. A large amount of crop damage associated with hail is associated with hailfalls of only marginal severity (an *officially* severe hail event in the United States is one that produces hailstones 1.9 cm in diameter or larger). In fact. the density of hailstones per unit area at the surface is inversely related to hailstone size: the very largest stones virtually always occur at relatively low numbers per unit area, while small stones can occur in large numbers occasionally. Storms producing copious amounts of relatively small hailstones may not be supercells and so can occur in situations not obviously conducive to severe weather.

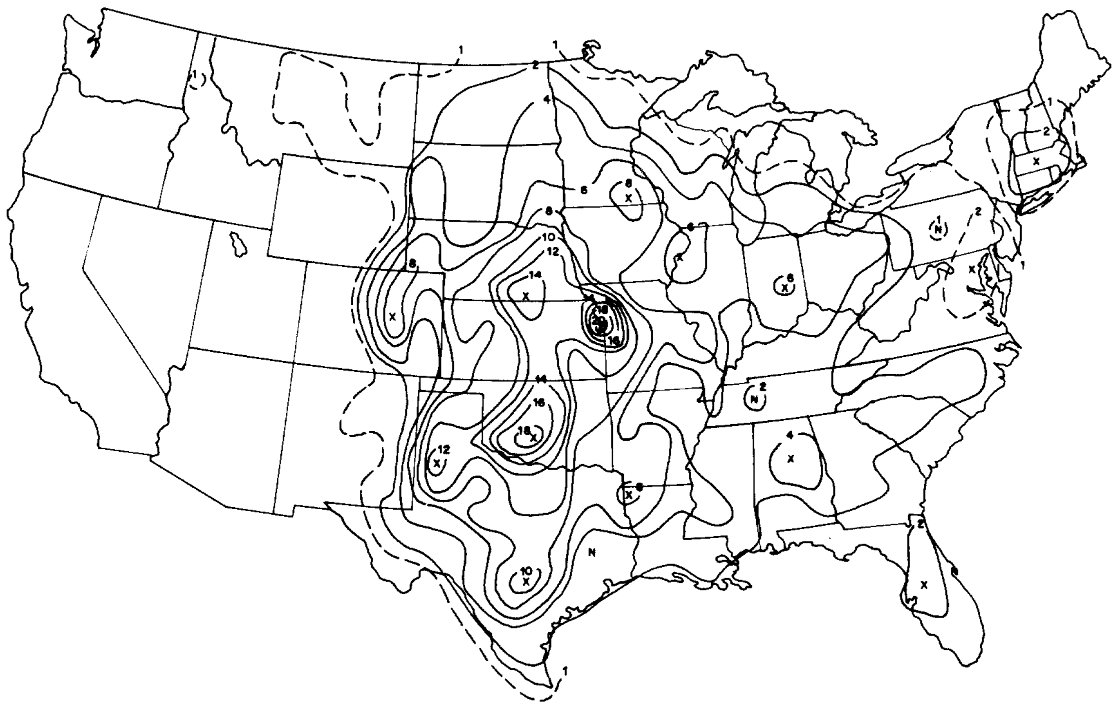

Fig. 2. Average annual frequency of hail $\geq$ 1.9 cm in diameter per 10,000 mi^2 (29,500 km^2) for the period 1955-1982 (from Doswell 1985).

Casualties associated with hailfalls are uncommon in North America, whereas the damage caused by hail can be quite costly. In many cases, especially when crop damage is the major problem, there is virtually nothing one can do to mitigate the damage. In urban areas, vehicle and window damage begins when stones reach diameters of about 5 cm, although this can vary depending on the hardness of the stones and on whether or not the hailfall is accompanied by high winds. Although roof and window damage is essentially unavoidable, automobiles and other property small enough to be brought under shelter can be saved with timely warnings. Icreasing urbanization in North America (and elsewhere, of course) increases the potential for affecting large numbers of humans adversely with large hail events.

4. Convective wind gusts

Whereas hailstones are associated with strong updrafts, damaging convective wind gusts are the product of strong downdrafts. The environments that favor strong updrafts are not necessarily the same as those that have strong downdraft potential. Downdrafts are caused by one or more of the following: precipitation loading, negative buoyancy caused by cooling associated with phase changes (evaporation and melting), and vertical perturbation pressure gradients. Updraft instability is associated with positive buoyancy arising from the difference between a parcel rising along a moist adiabat and the environmental lapse rate. Unstable updrafts are virtually all saturated, and precipitation loading has the effect of retarding the updraft.

Downdraft instability can result from negative buoyancy. Unlike updrafts, however, unstable downdrafts can be either saturated or unsaturated. If the parcel descends unsaturated, an environmental lapse rate very close to dry adiabatic is required, and the descending air must not mix excessively with its environment; otherwise, any negative buoyancy is quickly overcome by adiabatic warming. In saturated descent, if it is to *remain* saturated, there must be a continuing supply of water substance undergoing phase change during the descent, to maintain saturation. Again, if this condition is not met, the downdraft will be braked quickly through adiabatic warming. Water loading always enhances a downdraft.

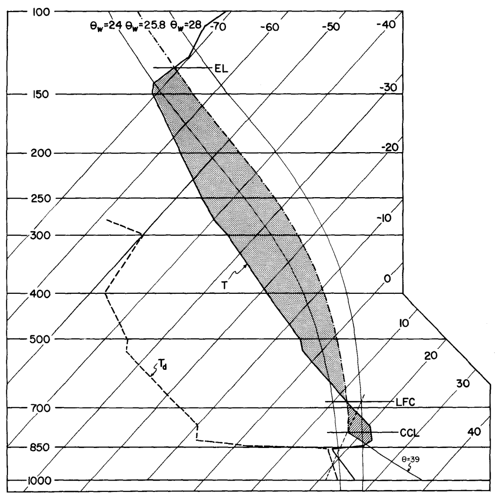

Fig. 3. Skew-T, log p diagram of a the sounding from Tinker Air Force Base, Oklahoma, on 8 June 1974, during which an outbreak of tornadoes occurred in Kansas and Oklahoma. Temperature (T- solid line) and dewpoint temperature (T_d - dashed line) are shown, along with selected moist adiabats and the 16 g kg^{-1} mixing ratio line. Also shown is the parcel ascent curve, with the positive and negative areas shaded; EL denotes the equilibrium level, LFC the level of free convection, and CCL the convective condensation level.

Since downdraft instability can arise in environments that do not favor strong updrafts, it is possible that damaging convective wind gusts can occur in situations that do not appear to have much severe weather potential. In the western parts of North America over the dry high terrain, the well-mixed surface boundary layer can extend above 500 mb. This means that high-based convective showers drop precipitation into sub-cloud air that is both dry and exhibits near-dry adiabatic lapse rates. This can produce strong convective wind gusts with convection that may not even have any lightning activity at all! Such events are the prototypical *dry microbursts* (see Wakimoto 1985).

In contrast, in weakly unstable updrafts arising in very moist environments, it is possible to develop strong downdrafts through water loading, and to maintain negative buoyancy through small amounts of evaporation. Such storms can occur in the warm season in North America, with heavy rain-producing showers that, once again, may not even be thundering. Such events are the prototypical *wet microbursts* (see Atkins and Wakimoto 1991).

Of course, real convective wind events do not necessary conform to these prototypes in all regards. Moreover, convective wind events occur over a fairly wide range of scales, from a few km to several hundred km. Microbursts are at the small end of the scale; on the large end of the scale are widespread damaging wind events called *derechos* (Johns and Hirt 1987). Derechos can produce large damage areas, in excess of 1000 km^2 (see Cummine et al. 1992), within which peak winds can exceed 50 m s^{-1}.

As might be anticipated, supercells can be associated with strong convective wind gusts, in addition to tornadoes and large hail. The environments that favor supercells also favor development of strong downdrafts. The classic sounding associated with supercells (see Fawbush and Miller 1954), often called the "loaded gun" sounding (Fig. 3) favors both strong updrafts and strong downdrafts. Thus, supercells are capable of producing the full range of officially severe weather phenomena.

Because convective wind gusts can be produced in situations that do not appear, at least to superficial examination, to be situations where the environment is favorable for severe weather, these situations can be especially troublesome to forecast. However, in such situations, it is likely that the severity of the gusts will be of marginal magnitude. Thus, one might be led to believe that the disaster potential is limited. As in other forms of severe weather, nevertheless, certain human activities imply a much greater disaster threat than the magnitude of the event suggests.

In particular, aviation is extremely vulnerable to downdrafts (and their associated downbursts). The number of convective events (some of which may not even be thundering) in a year that cause at least a 15-20 m s^{-1} peak outflow gust is rather large; certainly on the order of a thousand in North America, perhaps as many as tens of thousands. Therefore, microbursts are far from rare phenomena. Similarly, there is a huge number of aircraft landings and take-offs during a year; probably in the millions. The disaster potential arises from the relatively rare concatenation of two events that are themselves rather common. What is even more worrisome is that the *meteorological* significance of the event is not very large. One might say that the event is more or less *ordinary*, in fact.

Severe convective wind gusts, then, arise in what is probably the widest range of conditions of any of the official severe weather types. They are potentially dangerous, especially to aviation, even when their severity is below the official limits. As with hail, there is relatively little that can be done to mitigate property loss, but in certain situations (like boating, or hiking in a forest) falling and flying debris can pose a serious hazard. Fatalities from convective gusts are relatively rare in North America, but injuries are not at all uncommon. The growth of recreation in severe thunderstorm-prone areas poses an increasing hazard from such events. A distribution map of wind gusts in the United States exceeding 25 m s^{-1} and/or unmeasured gusts producing significant damage is shown in Fig. 4, with the usual caveats and extrapolations to other parts of North America.

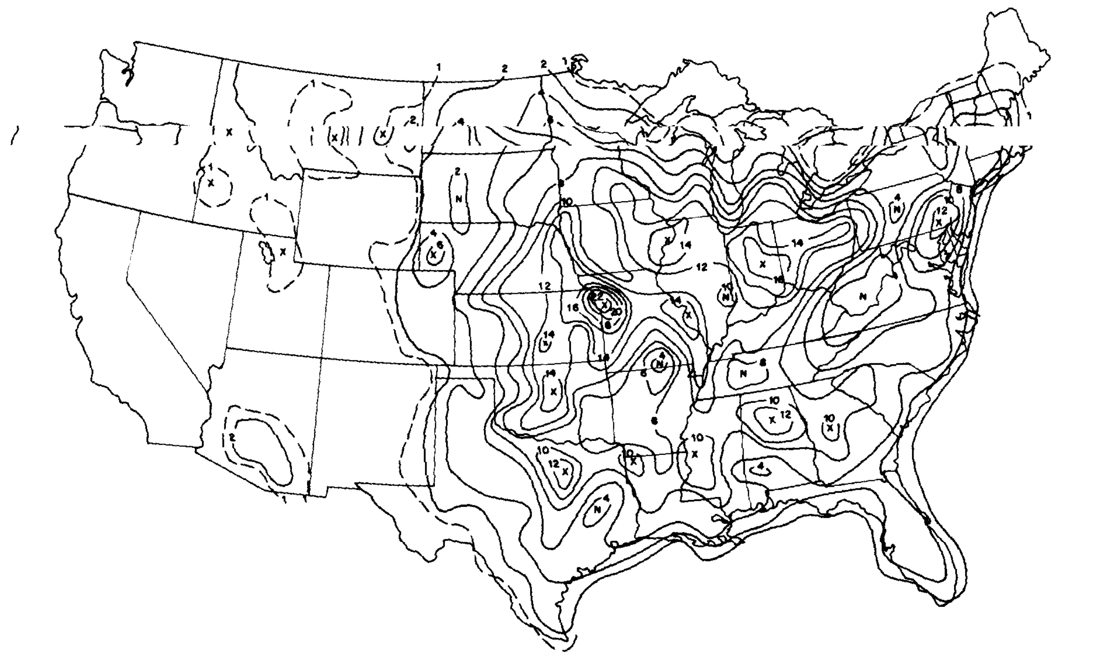

Fig. 4. Average annual frequency of damaging convective winds, meeting the official criteria (see text) per 10,000 mi^2 (29,500 km^2) for the period 1955-1982 (from Doswell 1985).

5. Heavy rainfall

Officially, heavy rainfall in the United States is not considered a "severe weather" event at all, (Canada does consider heavy rainfall to be officially severe). This is in direct contrast to the reality that flash floods have caused more fatalities over recent years than tornadoes; they have become the major natural disaster warning problem in the United States (Maddox et al. 1978), and remain so. By far the majority of the flash floods in North America are associated with convection, often at night. It is common to distinguish flash flooding from general river flooding by the rapidity of the rise in streamflow as a result of the causative rains, and by the limited area affected, normally within the watershed of a single tributary of a major river. The details of this distinction are not precisely defined, however.

Flash flooding is the result of both meteorological and hydrological factors. At times, the occurrence of heavy rain alone is not sufficient to produce flash flooding disasters. Conversely, even relatively modest rainfalls can result in flash flooding. When the rainfall is concentrated within a watershed, and when the runoff is enhanced (e.g., by rocky, steeply-sloping terrain or by antecedent precipitation), then flash flooding is a common result.

Heavy convective precipitation in North America typically is associated with *quasi-stationary* rain systems (Chappell 1986). These result when the contributions to storm motion from advection and propagation (i.e., development of new convection) oppose each other and are of comparable magnitude. Note that the individual convective cells can be moving rather rapidly; it is the movement of the rain system as a whole that is relevant. In any case, the result is a succession of convective cells, each maturing and producing its heaviest fall of precipitation over the same drainage basin. Such events can produce rainfalls on the order of 70-200 mm of precipitation in a few hours. Given the right hydrological conditions, this can be disastrous.

Precipitation amounts are affected by precipitation efficiency, which is defined as the ratio of precipitation at the surface to the amount of water vapor input to the system producing the precipitation. Clearly, this must be considered over some extended time period (preferably the lifetime of the rain-producing system); such a ratio computed instantaneously has little value. Such factors as the environmental moisture and wind profiles affect the precipitation efficiency. High environmental humidity and weak winds favor efficient convective rain production.

These conditions do not suggest supercells as a likely contributor to heavy rains, but such a conclusion would be a mistake. Under certain circumstances, even though a supercell may not be the most *efficient* rain producer, the sheer magnitude of the mass flux through the powerful, quasi-steady updrafts of a supercell can produce torrential rain. If the supercell is slow-moving (and they can be, especially during the warmer parts of the year), then supercells can be associated with flash flooding (Moller et al. 1992).

While flash flooding over North America arises in a variety of synoptic situations, by far the majority are the aforementioned quasi-stationary rain systems. The time and space scales of such events cover a range, of course, but they often are rather localized and are over in a few hours. As there is a tendency for such systems to occur at night, when it can be difficult to reach citizens with warnings, they can be a challenging operational forecast/warning problem. Furthermore, they may be over before forecasters even recognize that something important is happening. When flooding occurs with other forms of severe weather, a not uncommon situation in North America (especially when high-precipitation supercells are involved) the forecast and warning system often is severely stressed (Schwartz et al. 1990).

Flash flooding is simply not considered by most citizens to be a really serious problem. This is a misperception which, while in direct contrast to reality, is widely held, even by the media, who may not give flash flood warnings the same priority they assign to tornadoes. Unless someone has experienced a flash flood for themselves, it is difficult to appreciate how dangerous ordinary rainfall can become under certain circumstances.

As with other forms of severe weather, urbanization contributes to the disaster potential with heavy precipitation. Not only does this increase the risks to concentrations of people, but cities experience more run-off than rural areas, owing to the replacement of soil with structures and pavement. Increasing recreational use of flash flood-prone watersheds (especially in mountainous terrain) enlarges the population at risk every year. Perhaps most vexing is the continuing development of floodplains for homes and commercial use. Developers simply are not interested in the danger from flooding and flood insurance allows those experiencing flood damage simply to rebuild and remain in high risk areas.

6. Discussion

Increasingly urban population in North America implies an ever-growing threat of disasters caused by severe convective storms. Rural, agricultural populations are dispersed and tend to be very weather-conscious, wheras urban populations are concentrated and tend to not be very knowledgeable about local weather. This tendency is enhanced by mobility; urban citizens may not have grown up in the area and have a clear understanding about the local weather threats. It is a human failing that without direct experience of a particular event we tend not to be very concerned about it, especially if it is a rare event. Even in the most severe-weather prone areas of the United States, a tornado, a fall of giant hailstones, a violent convective wind gust, or an extreme rainfall event are all rare. One can live an entire lifetime without having such an experience, even in Oklahoma, Texas, and Kansas.

There is no simple formula to cope with natural disasters. Community leaders must urge caution upon their citizens even when the threat seems remote, a difficult (and politically dangerous) task in troubled economic times. Forecast meteorologists must develop the scientific knowledge to deal effectively with rare events, and maintain their vigilance even though they might never have to deal with an extreme event.

It is not clear to me that there is a simple technological "fix" for this challenge. Rare events, by their very definition, do not lend themselves to statistical treatment, while numerical models have difficulty with most extreme events and mesoscale processes in general. The current state of knowledge about mesoscale meteorology does not bode well for numerical models to take over the task of forecasting mesoscale-related events (see the discussion by Brooks et al. 1992). I see no easy alternatives to mitigating the disaster threat posed by severe convective storms short of a major initiative that involves meteorologists, hdrologists, all levels of government, and ordinary citizens (making the informed choice to accept responsibility for their own safety). We are living on borrowed time: if the threat is to be dealt with, the time to begin the process is at hand.

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