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Progress toward developing a practical societal response to severe convection (2005 EGU Sergei Soloviev Medal Lecture)

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Abstract. A review of severe convection in the context of geophysical hazards is given. Societal responses to geophysical hazards depend, in part, on the ability to forecast the events and the degree of certainty with which forecasts can be made. In particular, the spatio-temporal specificity and lead time of those forecasts are critical issues. However, societal responses to geophysical hazards are not only dependent on forecasting. Even perfect forecasts might not be sufficient for a meaningful societal response without the development of considerable infrastructure to allow a society to respond properly and in time to mitigate the hazard. Geophysical hazards of extreme magnitude are rare events, a fact that tends to make funding support for appropriate preparations difficult to obtain. Focusing on tornadoes as a prototypical hazard from severe convective storms, the infrastructure for dealing with them in the USA is reviewed. Worldwide implications of the experience with severe convective storms in the USA are discussed, with an emphasis on its relevance to the situation in Europe.

1 Introduction

Societies around the world are threatened by a wide variety of geophysical hazards, including earthquakes, volcanoes, tsunamis, landslides, floods, tropical cyclones, heat waves, winter storms, tornadoes, hail, windstorms of various scales, droughts, and so on. Nowhere on this Earth can it be said that geophysical hazards are completely absent. This discussion is focused on the hazards posed by severe convective storms, particularly tornadoes, but some parts of it also can be applied to other geophysical hazards. Compared with most high-impact geological processes, the recurrence interval for important meteorological events is quite short. For severe convective storms, the time scale is at most on the order of a few hours, which has important implications for how society can respond to forecasts of impending events.

This paper will focus mostly on the societal response to the threat from tornadoes, which, although commonly thought to be confined to the United States of America (USA), is actually present at some finite level throughout most of the world, with the possible exception of the near-polar regions. In the USA, considerable infrastructure has developed as a response to the threat posed by tornadoes, as well as the other hazards produced by convective storms (primarily hail, wind, flash floods, and lightning strikes). Although no single event associated with severe convective storms can approach the magnitudes associated with, for example, tropical cyclones or earthquakes, severe convective storms occur with considerable regularity throughout the world, and so the losses associated with these events can become quite large in the aggregate. On the average, most of the losses due to geophysical hazards in the USA are weather-related, and severe convective storms (including those that produce flash floods) account for the majority of those impacts in most years (Table 1).

There are several facets of the hazards posed by severe convection that are unique, as well as a number of characteristics they share with all other geophysical hazards. Thus, many of the processes by which one hazard can be mitigated can be used for other hazards, as well. However, the short time scale associated with severe convective storms makes for a considerable challenge if society is to develop practical methods for public safety and welfare. After the event, of course, there is another form of infrastructure for dealing with the immediate, short-term responses to the devastation produced by severe convection, and still more infrastructure needed to consider long-term societal impacts.

In this paper, certain common themes associated with geophysical hazards are reviewed in Sect. 2. A climatological description of the severe convective storm hazard in the USA is provided in Sect. 3, which also focuses on the unique aspects of the hazards posed by severe convective storms. The infrastructure in the USA for dealing with the threat from

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Table 1. Summary of hazard impacts for the period 1975–1998, with damage and loss values adjusted to 1999 US$. Source: Table 5-1 in Mitchell and Thomas (2001).

Hazard	Events	Deaths	Injuries	Damage (millions of dollars)	Average annual losses (millions of dollars)
Drought	n/a[a]	0	0	14 693.7	612.2
Earthquakes[b]	784 439	149	n/a	31 454.4	1310.6
Extreme cold	n/a	228	406	2847.7	118.7
Extreme heat	n/a	566	1328	1048.1	43.7
Floods	n/a	2495	n/a	105 868.0	4411.2
Hail	103 243	15	569	4863.7	202.7
Hazardous materials	259 384	580	12 897	775.5	32.3
Hurricanes[c]	82	394	4026	75 717.7	3154.9
Lightning	n/a	1667	7566	604.1	25.2
Tornadoes	22 409	1344	29 437	36 627.3	1526.1
Volcano[d]	n/a	32	n/a	2221.0	92.5
Wildfires	n/a	10	278	1532.6	63.9
Wind	126 667	470	5628	4002.7	166.8
Winter hazards	n/a	1049	11 364	19 931.3	830.5
TOTAL	n/a	8999	73 499	302 187.8	12 591.3

[a] n/a = not available.
[b] Earthquake epicenters falling within state boundaries. There were 45 considered "significant".
[c] Includes any storm track collected by the National Hurricane Center that made landfall in the United Stated 1975–1998. Injuries were derived from Storm Data.
[d] This only includes eruptions of Mt. St. Hellens, Washington, Kilauea, Hawaii, and Redout, Alaska.

such storms before, during, and after the storms will be reviewed in Sect. 4. Finally, Sect. 5 provides a discussion of how societies around the world can proceed toward practical responses to the hazards posed by severe convection.

2 Common themes of natural hazards

It can be said that human existence on this Earth is subject to astrophysical, geological, and meteorological consent, which can be withdrawn at any time, and perhaps without warning. I am not going to be concerned with astrophysical and geological hazards, but all these have certain common aspects. The Earth is, for the most part, a fairly benign environment for humans most of the time, but the aforementioned natural hazards are a constant threat for all societies. Of considerable interest is the time required for the recurrence of these threatening events, and this is related to the *magnitude* of the threats. An asteroid or comet impact of sufficient size could result in what is referred to as a "mass extinction" and would represent a threat to the entire human species. Astrophysical time scales for impacts of the magnitude associated with such a cataclysm are of order 100 million years. As such, given enough time, an event of this sort is inevitable, but extremely unlikely during a given human lifetime.

For geological hazards, the largest magnitude of prehistorical events has been shown to be nearly comparable to a world-shattering astrophysical event. Enormous explosive volcanic eruptions (Smith and Braile, 1984) and landslide-triggered tsunamis (Carracedo et al., 1999) can exceed any such event seen in human history. Again, events of that colossal intensity are infrequent, perhaps on a time scale of order one million years and longer. Most geological events are not of such proportions – geological hazards nevertheless pose a considerable threat to individual societies and vulnerable locations (e.g. near volcanoes or fault zones). As with astrophysical hazards, there is an inevitability associated with the passage of time – gigantic events are going to happen but are unlikely during the lifetime of any human alive today.

Devastating meteorological events associated with long-term climate change might also be capable of enormous impact that would threaten human existence around the world. For example, it has been proposed that at some time in the distant past, most, if not all, of the Earth was frozen into a world of ice and snow. That this actually happened is still a matter of debate, but a drastic climate change of that order clearly would be disastrous for all humans on the planet. As the time scale decreases, weather events generally follow the pattern of other geophysical hazards – their intensity and affected area diminish. For example, major cyclones, particularly tropical storms, can cause substantial damage over length scales on the order of 100 km when they make landfall in populated areas, not only from winds, but also from storm surge and extremely heavy rainfalls. An example of this is Hurricane Mitch (Fig. 1) during October of 1998, which devastated the relatively poor nations of Honduras and Nicaragua in Central America, ruining a substantial part of the infrastructure of these nations, mostly as a result of heavy rainfalls and associated landslides. Assessed damages were on the order of 60% of the gross domestic product for those national economies and it may be decades before these nations can be said to have completely recovered. Major disasters somewhere around the world in association with tropical (and extratropical) cyclones occur on a time scale of roughly 10 years or so, but noteworthy events occur more frequently. As will be discussed in more detail in the next section, societal impacts of major proportions from single convective storms are limited by the relatively small size of such storms. However, the relatively high frequency of severe convective storms means that the aggregate impact for a nation the size of the USA is important virtually every year (recall Table 1). Like all other geophysical hazards, however, a societal impact of significant proportions from severe convective storms results from the more or less random concatenation of an intense convective storm event with a populated area. Consider the history of fatalities associated with tornadoes in the USA (Fig. 2).

There are several implications of this figure, but for the moment, consider only the obvious – the interannual variability. This clearly is the result of the aforementioned relatively infrequent intersection of a tornado path with populated areas. In many years, this does not occur at all within the USA, but about every five years or so, a significant event occurs. In some examples of high-fatality years, the majority of the deaths are from a single day and, on occasion, from a single tornado. The largest one-year total occurred in 1925, when what appears to have been a single tornado on 18 March resulted in 695 fatalities along a long path across three states (Missouri, Illinois, and Indiana). This is by far the worst single fatality toll from a single tornado since records have been kept in the USA.

A similar figure could be constructed for the annual assessed damage due to tornadoes in the USA (e.g. Fig. 5 in Doswell, 2003). Although the relationship between fatalities and damage is not one-to-one, high fatality totals are typically associated with tornadoes doing a substantial amount of damage. During the period 1970–2003, the most important tornado outbreak, by far, is 3 April 1974 – which may be the most significant tornado outbreak day in the recorded history of the USA. Unfortunately, the existence of nonmeteorological trends in severe storm reporting (Brooks et al., 2003b; Doswell et al., 2005) make it difficult to compare events of the modern era with those before 1970. It is characteristic of the climatology of the most intense tornadoes in the USA that the existing record is dominated by a small number of singular events, suggesting that during the relatively brief history of the nation, we have only marginally sampled the extreme events that can become major tornado disasters. Thus, it is difficult to make a reasonable estimate of reccurrence intervals for singular events like the Tri-State tornado of 1925 or the 3 April 1974 outbreak.

An important factor in the occurrence of a disaster from convective storms is the *vulnerability* of human populations and their infrastructure. For example, people living or vacationing in close association with a mountain stream are vulnerable to flash flooding, as several disasters in recent history have shown (e.g. Romero et al., 2001; Maddox et al., 1978). Similarly, major population centers near rivers are found around the world, so that riverine floods (that occur on longer time scales than flash floods) pose a serious threat for those populated areas – for example, along the Mississippi River in the USA in 1993, and in central Europe in 2002. For tornadoes, the expansion of metropolitan areas surrounding major cities in certain parts of the USA provides a dense population at risk, and that population at risk is growing. It is likely that population expansion in vulnerable locations is creating the current growth in the number of disasters associated with geophysical hazards around the world (El-Sabh et al., 1994; Changnon et al., 2000). In effect, humans are putting themselves in harm's way, which is largely responsible for the perception that the weather is changing for the worse.

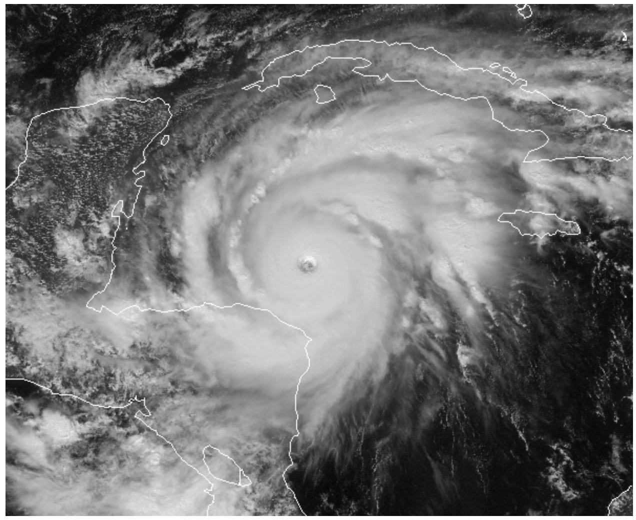

Fig. 1. Hurricane Mitch as seen by geostationary satellite GOES-8 in visible light at 17:45 UTC on 26 October 1998. (NOAA image).

Mitigation of geophysical hazards is a complex task, with scientific, economic, psychological, and political issues commingled. Competing interests and popular misconceptions often make developing practical responses to these hazards more difficult. For many people around the world, the relative rarity of intense geophysical hazards leads to an "it can't happen here" mindset that can be hard to overcome in making appropriate societal responses to inevitable hazardous events, as shown recently by the impacts of Hurricane Katrina in the USA on 29 August 2005. Thus, if an event is rare in some location, but definitely *possible*, then convincing people to prepare for an event that likely will not happen in their lifetimes is challenging. People voicing concern about rare events are often accused of fear-mongering. Many people believe, incorrectly, that little can be done to mitigate the impacts of tornadoes. This can be another cause for a lack of preparation.

Once such an event is underway, however, there is insufficient time to do anything to mitigate damage, and the main

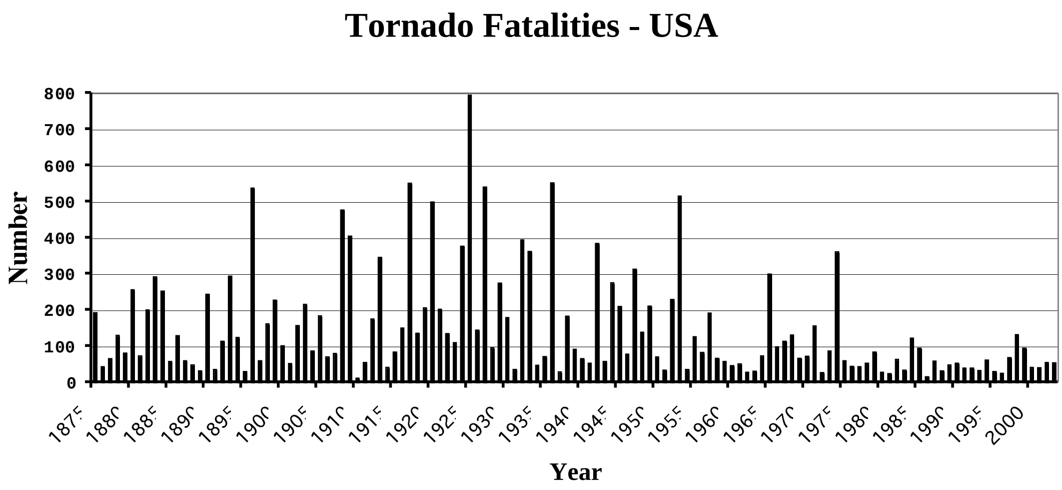

Fig. 2. Tornado fatalities in the USA, by year, for the period 1875–2003.

goal becomes casualty reduction. Preparation in the time *before* the event happens is the primary hope for damage mitigation and can have important implications for casualty mitigation, as well. Many people are unaware of their vulnerability to geophysical hazards, or believe it will never happen to them, and so typically are not only vulnerable but also ill-prepared to respond properly once a hazardous event begins. Individuals can panic, which often leads to poor survival choices. Education about what to do can be a factor in reducing casualties (Brooks and Doswell, 2002) if that education is offered.

This is especially the case for severe convective storms in many places around the world. Within some parts of the USA, the so-called "Tornado Alley" (Brooks et al., 2003b), most residents are prepared for tornadoes (although *transient* populations in the area may not be so), but the same cannot always be said even in nearby regions within the USA, and especially so outside the USA. For two of the most intense (F5) tornadoes of 1990, one hit a small town in "Tornado Alley" – Hesston, Kansas on 13 March; the other struck a small town outside of the region of highest frequency – Plainfield, Illinois on 28 August. I believe it not to be simply bad luck that Plainfield had nearly 30 fatalities and good luck that Hesston had none. Brooks et al. (2003b) have pointed out that of the 21 tornadoes in the period 1980–1999 that produced 10 or more fatalities, only two of them occurred in "Tornado Alley" and both were extremely intense (F5) tornadoes hitting major metropolitan areas (near Wichita, Kansas on 26 April 1991, and Oklahoma City on 3 May 1999), producing vast damage swaths. Preparation, both by the population as a whole and by the meteorological infrastruction can indeed make an important difference in the outcome of an event where a strong tornado strikes a populated area. Without those preparations, the two aforementioned tornadoes in "Tornado Alley" likely would have caused many more fatalities (Brooks and Doswell, 2002).

To the extent it is perceived that important tornado events occur only in some parts of the USA, when tornadoes occur elsewhere, the affected population can have little idea how to respond properly, even if a warning is issued 30 min in advance. Compounding this situation, local meteorological services can be similarly unaware of the reality that the threat of significant tornadoes in their area of responsibility is non-vanishing, albeit lower than in the tornado frequency maxima of the USA. Hence, in locations of low tornado annual frequency, warnings likely will *not* be issued even a few minutes in advance of an approaching tornadic storm; indeed, no infrastructure for severe convective storm warning may even exist in most tornado-prone parts of the world outside of North America. Without that infrastructure, forecasters have little chance even to recognize quickly that a tornado event is underway, until after the event is over.

If it is perceived that tornadoes are unlikely, the whole infrastructure for dealing with them is likely either to be absent or to be ineffective. This perception can become a self-fulfilling prophecy, because outside of North America, official records of tornado events generally have not been created and maintained. The occasional tornadoes that do occur are not recorded and, hence, fade from the collective memory rather quickly. This reinforces the misconception that tornadoes don't occur outside of North America. Therefore, when such tornadoes happen, they likely will strike with little or no warning and if strong enough and affect a populated area, a local disaster can be the result. Nevertheless, given the long time between recurrences, lessons learned from such isolated events can be forgotten.

3 Climatology of severe convective storms in the USA

The unique physical geography of the USA is the primary factor in making it the part of the world with the highest frequency of severe convective storms. The high, mostly arid terrain of the Rocky Mountains provides a source for elevated high lapse rates, which can be readily superimposed on a poleward stream of moist low-level air that has become enriched with moisture over warm tropical oceans and the relatively shallow Gulf of Mexico. This provides a vertical temperature and moisture profile with considerable convective available potential energy. Further, there is no topographic barrier to the passage of poleward-moving and equatorward-moving air masses over the Plains region east of the Rocky Mountains, which therefore are often visited by cold and warm frontal baroclinic zones, with the attendant vertical wind shear that promotes supercell forms of deep convection (Browning, 1964; Weisman and Klemp, 1982, 1984). Herein, most of my attention will be to the most intense reports of severe convective weather – tornadoes rated F2 intensity or higher on the so-called Fujita scale, convective winds >65 knots (∼33 m s^{-1}), and hailstones with diameters >2 inches (∼ 5 cm), collectively referred to herein as "significant" reports – producing the frequency maps in Fig. 3. Observe that significant tornadoes are much less frequent than nontornadic significant severe weather. The highest annual frequencies for all three major types of significant severe convective weather are in the Central Plains region that is sometimes referred to colloquially as "Tornado Alley". Outside of this region, all these significant events are notably less frequent. It is likely that most significant reports are associated with supercell thunderstorms (Rasmussen and Blanchard, 1998; Thompson et al., 2003). Detailed discussions of these severe weather distributions can be found in Brooks et al. (2003b) and Doswell et al. (2005). Generally, the region of high event frequency for all these severe weather phenomena is in the southern states bordering the Gulf of Mexico in the early spring, and moves poleward into the summer, returning equatorward in the fall. The spring maximum in activity is generally larger than the secondary peak in the fall (Doswell and Bosart, 2001). Peak frequency of severe events during the diurnal cycle is late in the afternoon, around 1–3 h before sunset, local time. Within the regions of peak frequency, events generally follow these seasonal and diurnal tendencies, although exceptions occur. Outside of the regions of high spatial frequency, the events are much less reliably predictable in terms of seasonal or diurnal probability (Brooks et al., 2003b).

Heavy convective rainfalls are also most often observed east of the Rocky Mountains (Brooks and Stensrud, 2000), but they are not so confined to the Central Plains, especially during the warm season (Fig. 4). These events are not primarily associated with supercells, although some supercell storms do produce torrential rainfalls (Smith et al., 2001). Rather, most heavy convective rainfalls are from multicell thunderstorms, often associated with the so-called "training" of cells (Doswell et al., 1996) and these storms can arise in a variety of environments. Orographic ascent clearly plays a role in many rainstorms occurring over complex terrain, as well (see Douglas et al., 1993; Maddox et al., 1978, 1980; Doswell et al., 1996). Convectively-driven flash flood-producing rainfalls are strongly dependent on the hydrological setting in which the rainfall occurs. Therefore, flash flood climatology is not described only by rainfall distributions, complicating the issue of predicting them. By definition,

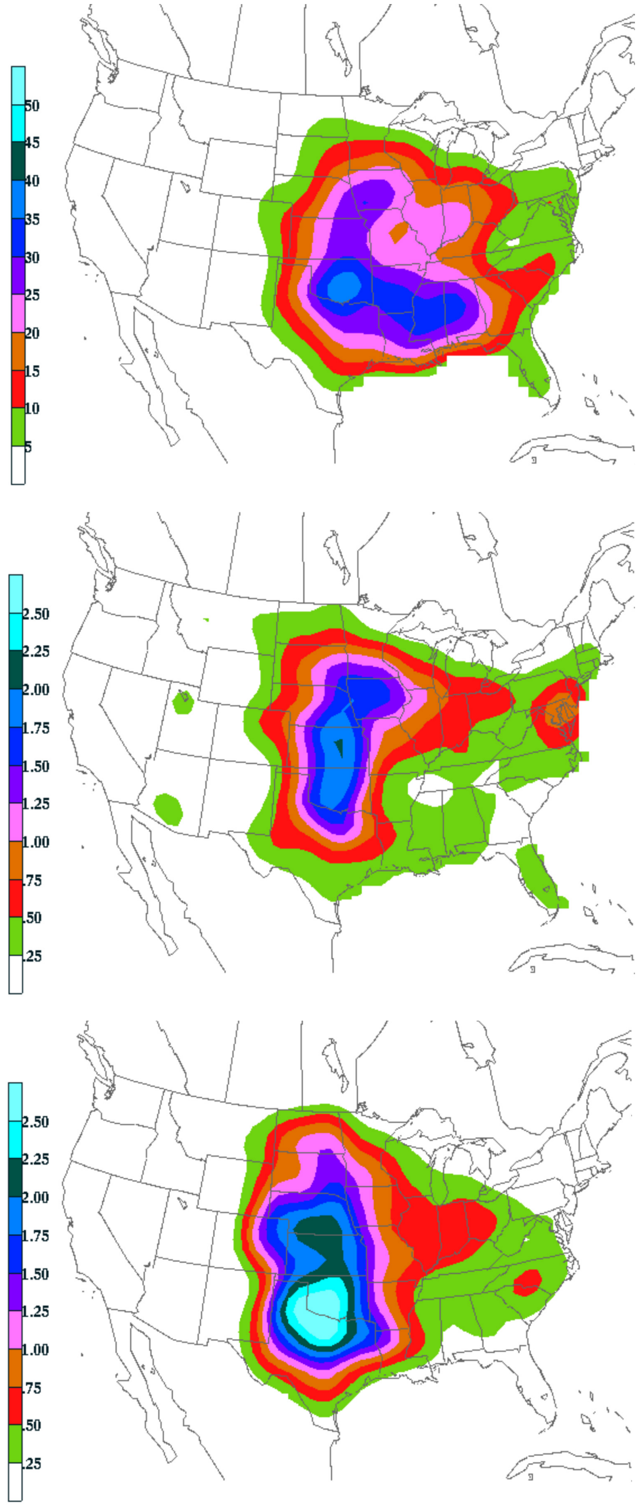

Fig. 3. (a, Top) Frequency of significant (see text for description) tornado touchdown days per century within 25 mi (∼40 km) of a point, based on tornado reports from 1980–1994; **(b, Middle)** frequency of significant convective wind event days per year (note the change in frequency scale) based on data for the same period; **(c, Bottom)** frequency of significant hail event days per year based on data the same period. Source: http://www.nssl.noaa.gov/hazard/totalthreat.html.

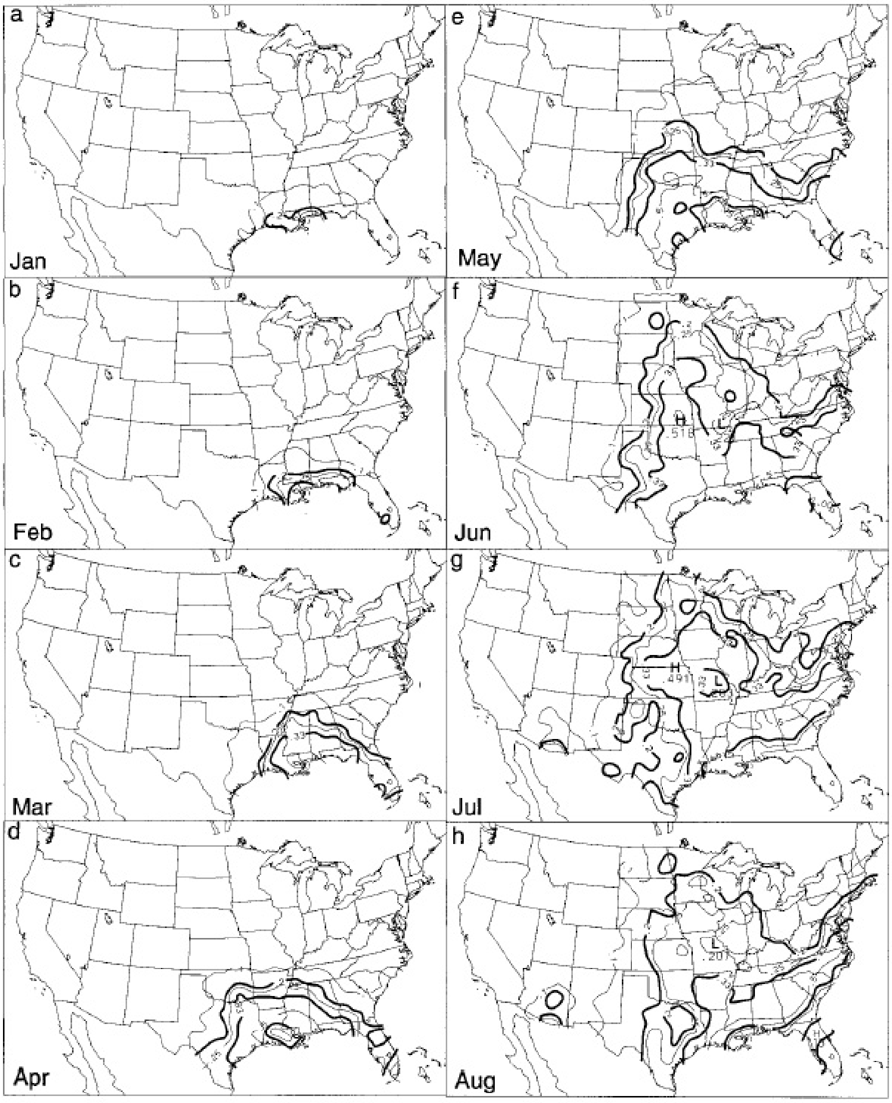

Fig. 4. Frequency (events year^{-1}) of 1 inch (25.4 mm) h^{-1} or larger rainfall totals for each month, objectively analyzed to a regular grid from the hourly precipitation stations. Contour intervals of 0.1, 0.2, 0.25, 0.33, 0.5, 0.66, 0.75, and 1.0 events year^{-1}. From Brooks and Stensrud (2000).

flash floods are distinguished from riverine floods by their small space and time scales – flash floods generally occur in small catchments, often beginning even before the cessation of the rainfall that produces them. Riverine floods are somewhat less likely to produce fatalities, since the time available for a response to rising water is longer than for flash floods, but the area affected can be quite large, with extensive long-term impacts (Barry, 1998).

In addition to these hazards, lightning is also a threat from convective storms. However, lightning casualties are typically singular (Curran et al., 2000) – they occur more or less randomly and in small numbers in any given event, unlike tornadoes or flash floods. Because almost any thunderstorm can produce casualties and damage from lightning ground strikes, whether it is otherwise severe or not, the lightning hazard is present whenever thunderstorms are present. It is virtually impossible to predict which lightning ground strikes will cause casualties and/or damage, however. Thus, this topic will not be considered further herein.

What makes the threats occurring in association with severe convection unique compared to other geophysical hazards is their relatively small space and time scales. There are two distinctly different temporal perspectives for considering societal responses to these hazards – one climatological and the other associated with the weather itself. The climatology just reviewed in brief gives some indications about where and when such events are most likely. Populations most at risk in terms of climatological frequency might be fairly well-motivated to make preparation for dealing with these events, whereas populations residing in areas of relatively low frequency might choose to do little, if any, preparation.

An important difference between geological hazards and those hazards associated with severe convection is that the probability of an intense weather event remains finite even far from the climatologically-favored times and locations. It is quite possible for major tornadoes to occur in places where they are not frequent. One example of this is the violent (F4) tornado that struck Worcester, Massachusetts on 9 June 1953, resulting in nearly 100 fatalities and considerable damage. Recall that in regions where the frequency is low, it is common for the level of preparation by most residents to be minimal. Long-term "forecasts" based on observed climatological frequencies can give some idea of the return period for major events, but if that return period is long enough, it is typical for residents (and even weather forecasters) to believe that the events are so unlikely as to not warrant making any preparations. That complacency is predictably going to lead eventually to a disaster, but it might be a long time (more than one human lifetime) between successive disasters. In regions of high frequency, a societal infrastructure can be developed to meet the perceived threat and mitigate casualties and even damage, at least to some extent.

Once convective storms are imminent or underway, it is possible to provide short-term forecasts for severe weather. These forecasts are at most on the order of a few days in advance, with the time- and space-specificity increasing as the time before the event decreases (see Ostby, 1992). That is, a day or so in advance, it is possible only to provide indications of enhanced threat of severe convection over broad regions, whereas once storms are underway, it becomes possible to specify which specific locations are likely to be in the path of the most dangerous storms and give an estimate of the approximate time those towns might be affected by the storm. Given the relatively short *lead time* (i.e. the time between the forecast and the event) once the event is underway, which can be on the order of a few minutes for some tornadoes, it is not possible to mitigate damage to any significant extent, but lives can be spared if precautions are taken. This generally requires planning, which once again must take place well *before* the event. This, in turn, requires that the planners have decided it to be in their best interest to develop a response plan in the unlikely event that a hazardous convective storm will threaten them. It is not difficult or costly to formulate a plan, even for an event as unlikely as a major tornado.

To put the chances for a major tornado in quantitative terms, consider Fig. 3a – for locations near the peak frequency in the USA (central Oklahoma), the observed climatological frequency of having one or more significant tornadoes touch down within 40 km of a point during a day is about 50 days per century, or about 0.5 days per year, corresponding to a 50% annual probability. It is no accident that the Oklahoma City area has been hit more often than any other city in the USA, since it comprises a large, sprawling metroplex right in the peak frequency area. What is the probability that a given one km^2 area within that 40 km radius would actually experience a significant tornado (as exemplified in Fig. 5)? Let us assume that *if* a significant tornado touches down within 40 km of a point (i.e. within a circle

Fig. 5. View of a tornado that struck the small community of Union City, Oklahoma on 24 May 1973. This tornado caused one fatality and was rated F4. Some tornado damage on the periphery of the tornado's path can be seen in the foreground. Photograph © 1973 C. Doswell.

with an area of about 5000 km^2), on the average, its swath of damage might affect about 5 km^2 of that region (a generous estimate). Thus, even in cases where a tornado is known to have touched down within a radius of 40 km, the probability of that tornado hitting a *particular* area of 1 km^2 within that circle is only about 5/5000, or 0.1%. Thus, the annual probability of having a significant tornado hit the particular one km^2 area where you live is down to 0.5/1000=0.05% per year. Generally speaking, the strongest winds within the path of a tornado affect about 10% of the damage area, or less. Thus, the annual probability that same area will experience the most intense winds of a significant tornado is about 0.005% per year, or less. Even for the most tornado-prone region within the most tornado-prone nation in the world, this is a *rare* event for any particular location. Making the assumption that the annual probabilities of experiencing a significant tornado event are statistically independent from year to year, it can be shown that with this annual probability, you could live in that 1 km^2 area for about 150 years (approximately two human lifetimes) before the probability of experiencing the strongest winds in a significant tornado reaches 50%. Outside of the peak frequency locations, of course, the numbers are much lower (at Worcester, Massachusetts, for example, the annual frequency is less than one-tenth that for Oklahoma City). People who are actually struck by significant tornadoes are extraordinarily unlucky, but if the entire area of the USA is considered, the probability that a 1 km^2 area *somewhere* in the USA is going to be hit by the strongest winds of a significant tornado is indistinguishable from unity – it is virtually a *certainty* that at least one area that size will have such an experience every year in the USA.

To conclude this section, it should be observed that the climatological record of severe convective weather is far from perfect, even in the USA. Some of the issues associated with the data used to construct Fig. 3 are discussed in Brooks et al. (2003b) and Doswell et al. (2005). Outside of the USA, the climatological record of severe convective storms is almost nonexistent. This is an important issue for understanding and dealing appropriately with the hazards posed by such storms. Figure 2, for example, shows a downward trend in fatalities beginning in 1925 and continuing to the present, as discussed in Doswell et al. (1999). The actual reasons for this trend have not been shown conclusively, but it can be surmised that they are a response by society to the recognition of the threat posed by tornadoes and to the idea that something could be done to mitigate tornado-caused fatalities. Doswell et al. (1999) and Brooks and Doswell (2001) have shown that there is also a noticeable reduction in the fatality rates associated with *major* tornado events that likely can be attributed to the forecasts and warnings provided by the National Weather Service (NWS). It also appears the new technology has maintained the relatively low death toll from tornadoes, despite an increasing population at risk (Simmons and Sutter, 2005). This leads me to the topic of the next section – the system by which society responds to the hazards posed by severe convection in the USA.

4 Infrastructure for severe convective storms in the USA

There are two basic themes for this discussion. First, the meteorological infrastructure that has developed; a history of which will be reviewed briefly and then its basic structure will be described. The second theme includes all the non-meteorological elements for dealing with the hazards.

4.1 Meteorological infrastructure

The first attempts to develop forecasts for severe convective storms and tornadoes, in particular, began in the 1880s by John Park Finley (Galway, 1985a, b). As Galway has described, however, Finley fell out of favor with his superiors and severe storm forecasting was discontinued in the USA until after World War II. On 25 March 1948, the first successful tornado forecast of the modern era was issued by Air Force officers E. J. Fawbush and R. C. Miller (see Miller and Crisp, 1999a). This led first to the formation of a centralized office for forecasting severe convective storms for the military (Miller and Crisp, 1999b) and then ultimately to a centralized office dedicated to severe storms forcasting in the NWS (at the time known as the US Weather Bureau) in March of 1952, now known as the Storm Prediction Center, or SPC (Corfidi, 1999). While these developments were underway, the local offices of the NWS were attempting to provide some short-term warnings for severe storms and, especially, for tornadoes using radar and storm spotters (Doswell et al., 1999).

The infrastructure for forecasting severe convective storms has been evolving ever since these programs began, but the essence of the system has remained essentially unchanged in its basic structure. It has three parts (Ostby, 1992): convective outlooks issued by the SPC for periods of a few days in advance, severe thunderstorm and tornado watches issued by the SPC for periods of up to a few hours in advance, and warnings issued by local offices for periods of up to about 30 min in advance. The convective outlooks are scheduled at regular times each day, to facilitate planning by local forecast offices and other local preparedness operations (see the next section). Watches and warnings are not scheduled, but rather are issued as needed.

This system has been reasonably successful in the sense that its introduction is associated with evidence of a reduction in fatality rates since it began (Doswell et al., 1999). The value of a centralized office for issuing outlooks and watches is that the forecasters typically work enough cases each year to gain effective experience at severe convective storms forecasting, owing the their national area of responsibility. In the local offices, it would take many years to work as many forecast shifts with important severe weather events as SPC forecasters deal with in one year. This centralized guidance is then a sort of "safety net" for the local offices, which have many duties other than severe storms forecasting. See Moller (2001) for a review of forecasting severe storms from the perspective of a local office, whereas Johns and Doswell (1992) and Doswell et al. (1993) have reviewed the elements of the SPC forecasting operations.

4.2 Non-meteorological infrastructure

Given that severe convective storms annually account for the majority of the total financial losses from weather hazards in the USA (except for the occasional years when major hurricane impacts exceed the losses from severe convection), society in the USA has been forced to develop means for coping with these hazards before, during, and even well after the event. Before the event, a number of emergency management groups at the Federal, state, and local level provide information to the public about how to prepare for various natural hazards. They also serve to coordinate their respective governmental responses to a developing hazard. Many (not *all*) communities and enterprises, such as schools, hospitals and nursing homes, as well as manufacturing plants and other businesses, have designated emergency managers (EMs), as well, who have the responsibility of preparing and planning for the possibility of hazards such as fire and severe weather. Most EMs also deal with hazards *not* associated with the weather: hazardous chemical spills, terrorist threats, and so forth. If warnings are issued by the NWS, it is EMs who alert the people and groups for which they are responsible and who oversee any responses to the hazards. The extent to which EMs are trained and prepared to respond properly to the hazards posed by severe convection is unknown, in general. As of this writing, to my knowledge, there is no mandated Federal or state program for supporting EMs with training for severe convective weather (see Morris et al., 2002, however). In many communities, there is some sort of emergency operations center (EOC), from which the community's EM coordinates activities, such as issuing tornado warnings for the local community by blowing sirens, or other designated activities. The EOC is also involved in coordinating first responses after the disaster has occurred – including the local police and fire departments, and beginning the process of clean-up, as well as restoring water, power, telephone, Internet, and gas services, if necessary.

Storm spotter training has become an important component of the NWS program for preparing communities for severe storms (Doswell et al., 1999) and the so-called integrated warning system (IWS – which includes the NWS as well as EMs and the broadcast media) and such training is conducted annually in most states. Many state and local governments conduct severe storm awareness programs in late winter or early spring, primarily in the most tornado-prone parts of the USA. Spotters are local volunteers and report to the local EMs to serve their communities, not typically to the NWS. Reports from spotters are relayed from the EOC to the NWS, however. The IWS generally works rather effectively (see McCarthy, 2002 for an example), although there have been occasions when the partnership is rather more adversarial than it should be.

In the 19th century, if a major city was hit by a disastrous tornado (as was St. Louis, Missouri on 22 May 1896, resulting in what might be the most damaging tornado in the history of the USA – see Table 3 in Brooks and Doswell, 2001), the cost for recovery was borne mostly by the local economy. Since then, it has become commonplace for this cost to be supported by the nation's economy as a whole, through Federal, state, and local disaster relief assistance and by commercial insurance. For significant events, the President of the USA can designate an affected region a "disaster area," making victims (without insurance) eligible for low-interest loans and other aid to assist in their recovery. This happens for weather-related events several times annually in the USA. There is some controversy about how this is being done (see Steinberg, 2000), but Presidential disaster declarations are a major source of support for affected communities. Life and health insurance also defrays at least part of the societal impacts associated with injuries and fatalities. Typical homeowner's insurance covers most severe convective storm events, except for floods. Separate policies for flood insurance can be purchased and may be required in some communities where homes have been built in flood-prone areas. Insurance spreads the cost for natural hazard disasters over the whole set of company policy holders. Some controversy is associated with this practice with regard to flood insurance, as it essentially promotes the reconstruction and restoration of homes in flood-prone areas at the expense of other policyholders not living in such vulnerable places. After major flooding events, land-use policies are often the subject of bitter debates.

It is not precisely known what are the total costs associated with weather disasters like tornadoes. There are hidden societal costs that are not accounted for in the figures typically provided for the *direct* damage estimates associated with the costs attributable to storm damage. Examples of these indirect costs include loss of productivity, loss of business for companies affected by the event, losses associated with departure of residents and businesses from the affected area after the event, loss of income from sales and taxes while businesses are being repaired, and so on. There may also be hidden *benefits* from these disasters, as well, such as increased revenue for companies doing the clean-up and repair, new jobs created by the clean-up, the business advantages of having new buildings and facilities after obsolete infrastructure has been damaged and removed (usually covered by insurance), the positive impacts of people and businesses that left from storm-affected communities arriving in their new communities, and the benefits of moving away from vulnerable locations. A truly comprehensive economic analysis of weather-related disasters has never been done, to the best of my knowledge.

When housing units are rendered uninhabitable by a weather event, shelter must be provided for the survivors until more permanent housing can be found, and they need food and water. A variety of Federal, state, and local government agencies, as well as nongovernmental groups of all sorts, provide this relatively short-term support for survivors. The Federal Emergency Management Agency (FEMA) is responsible for coordinating the numerous activities associated with this short-term response to disasters, including post-event surveys to gather new information to assist in preparing for subsequent events (see Doswell and Brooks, 2002). FEMA also offers considerable financial support for the victims in the short term.

Psychological damage often results from natural disasters and can persist for years – this is now widely recognized as "post-traumatic stress disorder" and can have serious impacts on some individuals. Recognition of this has led to the creation of relief agencies, typically non-Federal, for helping people cope with the lingering after-effects of experiencing a disastrous event. Some of these are available from state and local agencies, and some are offered by religious groups or other charitable services.

Inevitably, there are victims irrevocably affected psychologically, physically, or economically, by natural hazard-related disasters. They may become permanently dependent on various long-term relief agencies, both governmental and non-governmental. Some businesses and Federal facilities (such as the closure of Homestead Air Force Base in Florida, after Hurricane Andrew in 1995) are permanently closed or reduced in capacity, which can have long-term impacts on their communities. I know of no systematic efforts to address this for storm victims.

5 Discussion

Meteorological forecasts and warnings have their greatest-value when the users of the information contained within them

- receive the information,
- understand the information, including its uncertainties,
- know what to do based on that information, and

– take the appropriate action.

Even in the unlikely situation that the forecasts are *perfect*, if one or more of these elements breaks down for some or all of the users, the forecasts may have little value for them. Among many other things, this means that meteorological agencies need to provide users with a proper awareness of the risks, as well as making clear what uncertainties are associated with their forecast products. When it comes to severe convective storms, it is not possible to be absolutely confident in any forecast or warning, and it is essentially not being responsible to their users for forecasts to be offered without uncertainty statements accompanying them (Pielke 1999).

Moreover, meteorological agencies should recognize their own limitations in helping users develop an understanding of the forecasts and warnings; meteorologists are not generally familiar with the diverse disciplines needed to develop optimal relationships with their users: psychology, economics, sociology, and so forth. Thus, any meteorological infrastructure for severe weather hazards should be fundamentally interlaced with diverse related disciplines. This is not the case generally, even in the USA, but it is an ideal toward which all societies should be moving.

Ultimately, every society must decide on how best to allocate its resources, weighing all the factors that affect that society. This allocation properly should at least consider the risks and consequences associated with the inevitable geophysical hazards, including severe convection. The optimum time to prepare for severe storms is long *before* a disaster occurs, not afterward. Although it is not necessarily appropriate for forecasters to take on the tasks of outreach to their user communities, the forecast agencies should develop comprehensive plans and have staffing to be effective in helping users to get value from the products (e.g. short-term forecasts and climatological hazard assessments) those agencies make available.

The system for coping with severe convective weather hazards in the USA has arisen in a primarily ad hoc fashion. If we were able to start all over again, it might be useful to review the whole system in detail from top to bottom and consider alternative approaches. On the other hand, it could be argued that for the most part, the system works reasonably well and there may not be much we can do that would be substantially better. The costs associated with revising the system might be so large as to overwhelm any benefits associated with a drastically revised infrastructure. In order to accomplish a thorough review of the system, a collaboration among many different disciplines would be needed: economists, geographers, meteorologists, hydrologists, psychologists, engineers, sociologists, and so on. Moreover, given the diverse and complex interactions within the whole society, representatives from first responders (notably, police and fire departments), EMs, governmental officials at all levels, utility operators (power, telephone, Internet, gas, etc.), insurance companies, construction companies, communication media, and other interested parties would need to be involved. It is safe to assume than any such discussions would be prolonged and could be characterized by controversy arising from competing self-interests among the participants. The main benefit to such an interdisciplinary planning process is that it would be possible to account for most of the interlocking requirements and thereby develop an efficient and effective system. Without actually doing this planning exercise, however, it is hard to be certain in advance if the benefits would outweigh the time and resources expended.

It is my perception that *outside* of the USA, however, there is relatively little *meteorological* infrastructure in place for dealing with severe convective storms. Thus, wherever it is intended to develop such infrastructure, a multidisciplinary process would be extremely useful. Although every nation has at least some infrastructure in place for coping with diverse hazards, the perception that severe convection is primarily an issue only for the USA is widespread. Most national weather agencies outside of North America have at most only a token program aimed at severe convective storms, and there is scant attention paid to such events in the media, except perhaps on the rare occasions when a significant event happens to have a noticeable societal impact. Severe convective storms, especially tornadoes, are much more likely in Europe, for instance, than most Europeans realize. There have been major tornado disasters in Europe during the historical past, from European Russia all the way to the United Kingdom and the Iberian Peninsula, and from the Arctic Circle to the Mediterranean Sea. Major severe convective storm disasters *will* happen again. It is just a matter of time. Therefore, my hope is that a broad, *pan-European* perspective for a meteorological infrastructure will develop (see Doswell, 2003) – this is because no single nation in Europe has a notably high frequency of severe convective storms, although Europe *collectively* experiences on the order of 300 tornadoes annually (Dotzek, 2003). Moreover, development of separate meteorological infrastructures within each nation would be unnecessarily costly and could infringe on the natural operating domain of the various national forecasting services. Ultimately, the weather is not concerned with arbitrary geopolitical boundaries, and to that extent, societal responses to the weather should to look beyond those boundaries, as well.

What is true for Europe is also true for other regions around the world. The challenge of developing a global understanding of the distribution of severe convective events is magnified by a widespread absence of organized efforts to collect and archive reports of severe convective events outside of North America. Without a reasonably accurate knowledge of the frequency of severe convective storm events, it can be difficult to make the decision to go ahead with preparations. Recently, efforts have begun to use what is known about the environmental conditions that favor the development of severe convection to produce a global "synthetic climatology" of severe convective storms (Brooks et al., 2003a). It is known via anecdotal evidence that there are several regions around the world – the plains of Argentina, South Africa, and Australia, for instance – where significant tornadoes occur relatively frequently. In those locations, population densities are low enough to suggest that a substantial underreporting of tornadoes has been the rule. Bangladesh has a history of high casualty figures attributed to tornadoes, as well, although it is unclear that all of the major events were indeed truly caused by tornadoes.

Anywhere around the world, wherever there is an initiative to respond to the hazards posed by severe convective storms, it is my hope that those involved in planning for the creation of meteorological and societal infrastructure for dealing with the hazards posed by severe convection would take the time to review the system in the USA carefully. I also hope they will be very cautious in picking and choosing which parts of that system can be duplicated and which parts need alteration to fit the local requirements. It would be foolish simply to copy the system in the USA without first considering whether or not the various components can work effectively with the existing *nonmeteorological* response systems available in the local area. It would be similarly foolish to try to develop that infrastructure independently, without first reviewing the experiences in the USA. Development of practical (affordable) societal responses to the hazards posed by severe convection can mitigate the impacts of these storms and make a large contribution to their respective societies. But this is necessarily a multidisciplinary program that should not be driven primarily by politicians, the media, or as a hasty response to a recent disaster. The way to develop a *practical* system is likely to require considerable effort, but the long-term benefits are almost certain to outweigh the resources expended in a multidisciplinary effort.

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