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Atmospheric Research 67–68 (2003) 135–152

ATMOSPHERIC RESEARCH

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Societal impacts of severe thunderstorms and tornadoes: lessons learned and implications for Europe

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Accepted 28 March 2003

Abstract

It is well known that the United States has the greatest number of severe thunderstorms and tornadoes of any nation worldwide. Therefore, in the United States, a substantial infrastructure has evolved in response to the numerous natural hazards (not limited to severe thunderstorms and tornadoes) in an effort to reduce the societal impacts of these hazards. In addition to keeping records of the events, there are state and national programs (public and private) to help reduce the economic and social impacts on local communities that might otherwise have to prepare for severe storms and rebuild using only the limited local resources. This paper reviews the basics of the infrastructure that has been developed to deal with severe thunderstorms and tornadoes, and describes its history briefly, as well as considering some of its successes and problems.

Although the American system should not be used as a simple template for Europe, it does need to be considered as Europe begins to address how to deal with the unique character of European severe storm hazards. Given that severe thunderstorm and tornado event frequencies are generally lower in Europe, as well as the smaller areas of individual European nations, each country has a correspondingly low annual event frequency, especially for the rare "high end" events that have the potential create major disasters. Collectively, however, the severe weather threat is almost certainly larger for Europe as a whole than most Europeans realize. Any decision concerning the phenomena that will be considered "severe weather" in Europe needs to be made in a purely European context. It is suggested that severe weather is best dealt with as the pan-European hazard it truly represents. Pan-European severe weather forecasting and research centers are proposed and issues that will need to be confronted are reviewed.

Keywords: Societal impact; Thunderstorms; Tornadoes

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doi:10.1016/S0169-8095(03)00048-6

1. Introduction

The issue of societal impacts of weather is not typically discussed in the meteorological literature. In a very real sense, societal impacts can be viewed as well outside the traditional subject matter of scientific journals. Meteorological journals and meteorologists themselves naturally tend to be focused on the *meteorology*, which certainly is challenging enough for anyone. Nevertheless, experience with severe convective storms in the United States, which has the highest frequency of severe convective storms of any country on Earth, has suggested that this traditional lack of interest in societal impact can be detrimental in a number of ways.

First, it is important for weather forecasters to understand that even if they could issue perfect forecasts, the *value* of those forecasts (see Murphy, 1993) would be trivial if the users of those forecasts fail to understand them or to know how to make use of the information. Weather forecasting is arguably the most important application of the science of meteorology, but its value can only be realized if forecasters are aware of the needs of the forecast users. No forecasting service that is insensitive to the needs of its users can ever know if the forecasts actually have real value.

Another issue concerns the funding of research. Societies have many urgent needs and scientific research is only one of many competitors for the resources of a society. In Third World economies, owing to their limited size, only a small fraction of their resources can be used for sponsoring scientific research. In times of crisis, research resources are usually pushed down any nation's priority list. If meteorologists believe that their research is important to society, they must accept some responsibility for showing that their work is at least potentially valuable enough to society to be worth the investment sought from that society. Once again, we are led to the acceptance that an understanding of societal impacts of weather is an issue few research meteorologists can afford to overlook.

Finally, the impacts of weather on society are complex and typically highly nonlinear. It is generally the case that similar weather events do not inevitably have equal impacts from case to case. The impacts depend on who and what is in the way of the weather, and how the time-space evolution of the weather interacts with human society. In order to understand this, meteorologists need to collaborate with other disciplines, since a complete understanding of the process depends on knowledge that meteorologists generally do not have (e.g., engineering, psychology, economics, etc.).

In what follows, I am going to focus on severe thunderstorms, and primarily on the tornado problem. In large part, this is due to my specific scientific interests, rather than because the tornado is uniformly of importance around the world. This begins in Section 2 with a broad description of the tornado problem in the United States. Included is a brief summary of the tornado climatology, including long-term trends in casualties and damage, followed by a description of the existing infrastructure for dealing with tornadoes. Section 3 then considers some issues that confront us in attempting to mitigate both casualties and damage. In Section 4, a discussion of what the lessons learned in the United States might mean in the context of Europe is provided.

2. Dealing with the tornado hazard in the United States

Although the distribution of tornadoes in the United States (e.g., Fig. 1) is known only imperfectly, it certainly is the case that tornadoes in the United States pose a significant threat to society. Over the course of a year, on the order of 1000 tornadoes are reported. Note that Fig. 1 shows only the distribution of the ‘‘touchdown’’ points for tornadoes and does not account for the actual area affected by each tornado. Moreover, the raw data used to construct Fig. 1 have been considerably smoothed.[1] Fig. 2 shows a comparable map but only for the most violent tornadoes [those rated F4–F5 on the Fujita (1971) scale]. It can be seen that violent tornadoes are quite rare events, even in the United States, and even in those locations with the highest frequency. For the areas with the highest frequency, it is possible for a given location to not experience a violent tornado directly for more than 1000 years.

The data used to create these maps are known to have many flaws and problems (e.g., Kelly et al., 1978; Doswell and Burgess, 1988), not the least of which is the large areas on the Plains of the United States that have quite low population densities, such that a small event in space-time like a tornado can easily be missed, despite the efforts of volunteer storm spotters (Doswell et al., 1999) and the growing numbers of storm chasers, who follow storms recreationally. Therefore, even in the United States, the true climatology of severe thunderstorms and tornadoes is not known, and the actual number of tornadoes could be as much as a factor of 2 larger than what is reported.

When considering the long-term trends in tornado fatalities in the United States, it is useful to normalize by the total population (Fig. 3). There are at least two notable aspects of this. First, the annual variability in fatalities is large—the obvious explanation for this is that deaths result from the interaction of a tornado with a populated area. When tornadoes are confined to open regions (by far the largest fraction of the area of any country, including the United States), few, if any, fatalities result. When tornadoes strike in heavily populated areas, many casualties can occur so the normalized fatality figures reflect the apparently random interaction between tornadoes and the population. The other striking aspect of this figure is the notable change in the fatality rate beginning roughly in 1925. The exact reasons for this are not known—see Doswell et al. (1999) for a discussion—but probably are related to such factors as communication (telephones, radio, television, etc.) and the growth in awareness of what it takes to reduce casualties.

The preceding suggests that the fatality rate should be a function of the damage produced by a tornado. To test this, the fatality rate per unit of population and per unit of inflation-adjusted damage was calculated for a selection of tornadoes. The selection process began with finding all tornadoes causing 44 or more fatalities, then finding all those tornadoes that produced at least $50,000 worth of damage (in inflation-adjusted 1997 US$) (Fig. 4). Highlighted on the figure are two noteworthy events: the infamous ‘‘Tri-State’’ tornado of 18 March 1925 (nearly 700 deaths) and the Wichita Falls, TX, event of 10 April 1979 (44 deaths). These famous events fall very near the regression lines in their respective eras (to be described below). Even in these results for the most

[1] A description of the data and the processing used to create this and other figures can be found at: http://www.nssl.noaa.gov/hazard/data.html.

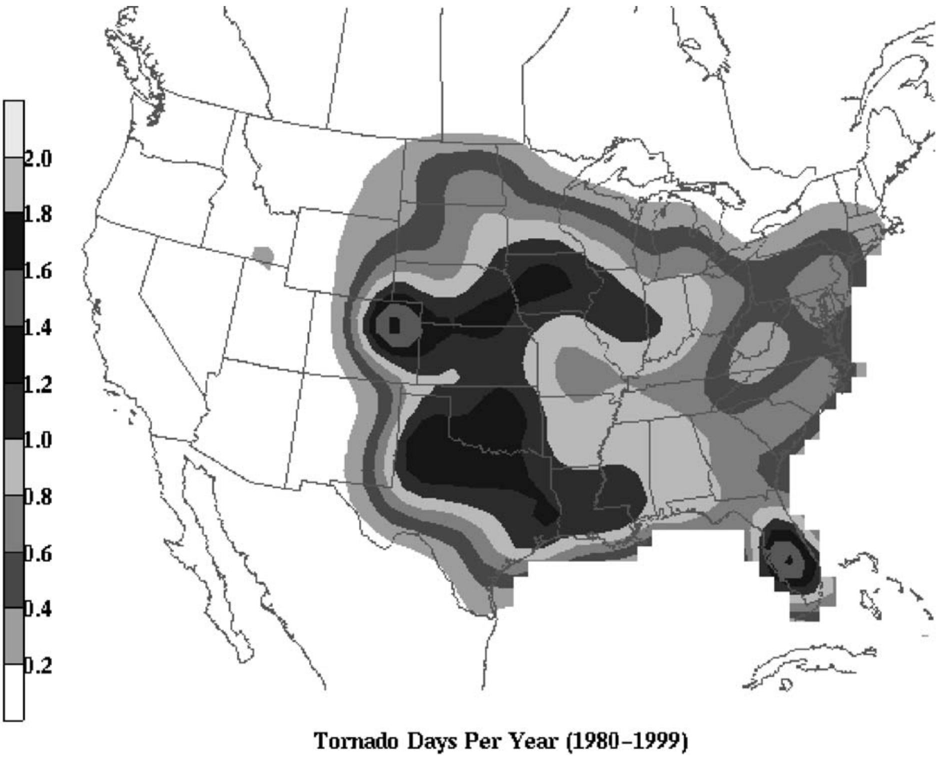

Fig. 1. Smoothed distribution of tornado touchdown points in terms of tornado days within 25 miles of a given point (i.e., days on which one or more tornadoes are reported within that distance of a point) using the record of all tornadoes, regardless of intensity during the period 1980–1999.

important tornadic events, there is considerable scatter, but of interest is the clear indication of a time trend and an important change in the normalized fatality rate. The trend has been shown by Brooks and Doswell (2001b) to be related to a steady growth in the "wealth" in the United States. However, a most important change is seen in 1953, which not coincidentally is the first full year of severe thunderstorm and tornado forecasting in the United States. That the break occurs sometime in the year 1953 has been demonstrated to be statistically significant (Brooks and Doswell, 2001b). What this implies it that since 1953, it currently takes considerably *more* damage (on average) to produce a tornado-related fatality in a major tornado event than it did before the National Weather Service (NWS) tornado, and severe thunderstorm forecast and warning service was begun.

Also included in the figure is an event which did *not* actually qualify for the data set because it did not cause the required number of fatalities[2]—that for Saragosa, TX in 1987. This event was the result of a violent tornado striking a small, unincorporated village.

[2] Although fewer than 44 people were killed, there were 30 fatalities in a village with a population of only 428 (7% of the population).

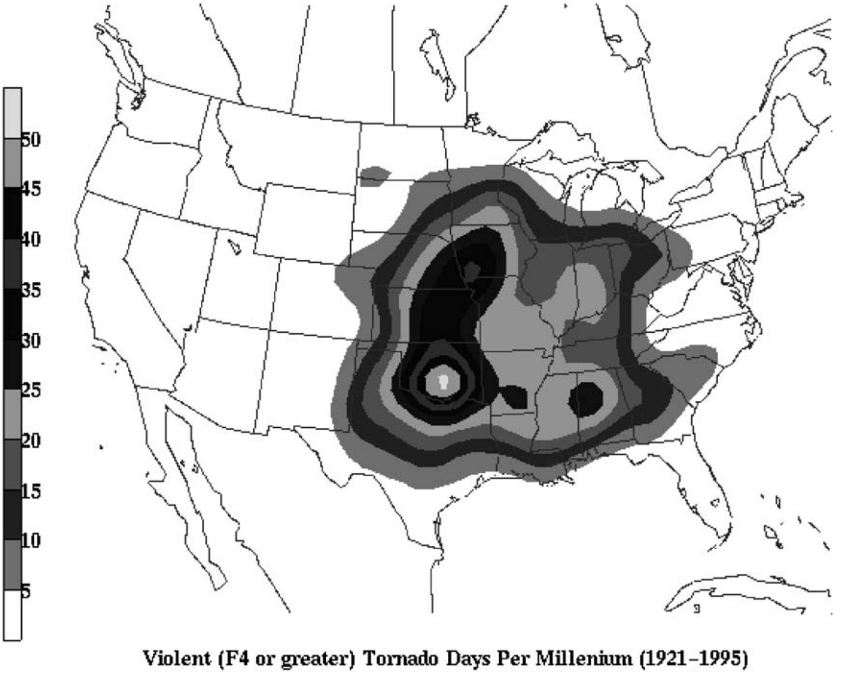

Fig. 2. As in Fig. 1, except only for violent tornadoes, using the record of tornadoes during the period 1921–1995. Note the change in the scale.

Owing to a number of factors discussed by Aguirre et al. (1991), even though a warning was issued by the NWS for this storm, most of the villagers simply did not hear that warning. In effect, this small town was poorly prepared to deal with tornadoes and the result was an event that is much more representative of the pre-1953 era than of 1987. The lack of appropriate infrastructure in this town meant a much greater loss of life than typically occurs in the modern (post-1953) era.

There is also considerable interannual variation in *economic* losses owing to tornadoes (Fig. 5) from year to year.[3] Again, the simplest explanation for the variability is the apparently random chance of a major tornado event striking a populated area. "Significant" tornadoes (F2 and greater) only comprise about 1/3 of all tornadoes, and violent tornadoes (recall, F4 and greater) account for only on the order of a few percent. Large economic losses in a year tend to occur when a violent tornado strikes a major population center, which does not happen every year, even in the United States.

The economic losses due to tornadoes (and other severe thunderstorm hazards) are spread over the nation, rather than being concentrated locally, especially through the medium of insurance, but also through direct and indirect Federal government disaster

[3] During this period, the peak damage year (1974) was associated with the so-called "Superoutbreak" of tornadoes on 3–4 April involving 148 tornadoes, several of which struck population centers.

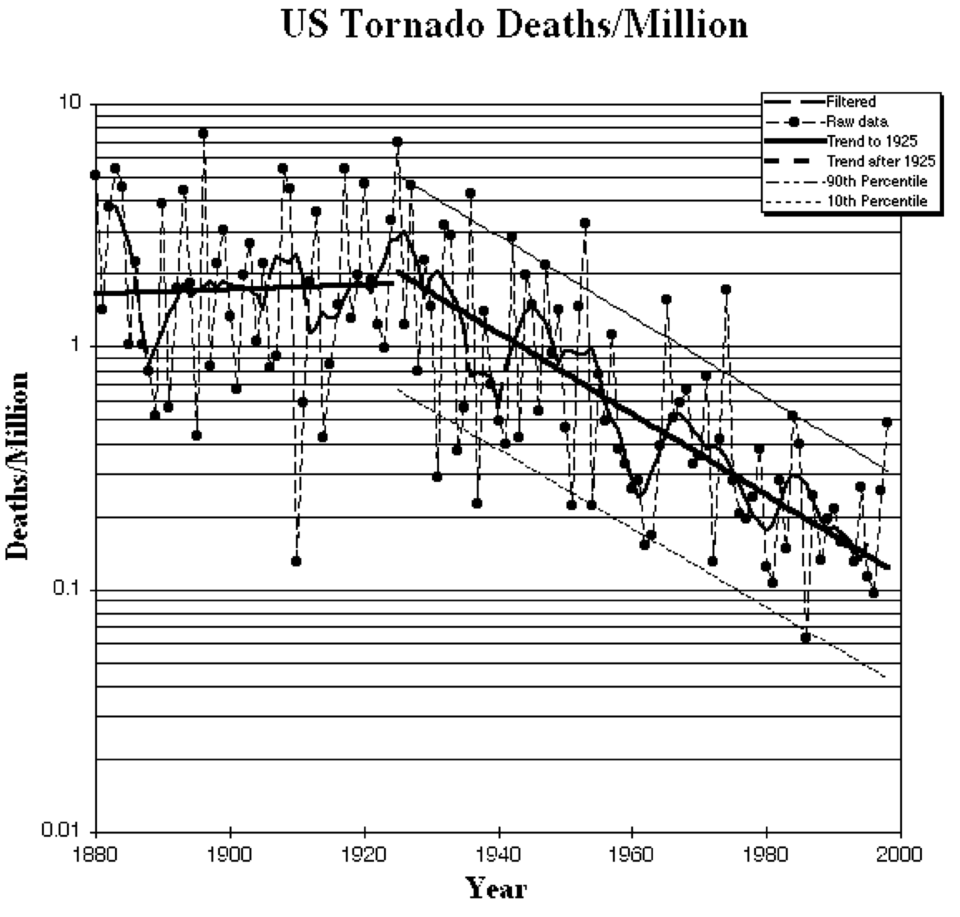

Fig. 3. The annual fatality rate, normalized by population, expressed as the number of deaths per million of United States population, for the period 1880–1999. Regression lines are shown for the period 1880–1925, and the period 1926–1999. Also shown are the 10th and 90th percentiles for 1926–1999 regression line. The sold line shows the raw data after the application of a smoother consisting of a 3-point median filter followed by a 5-point moving average (after Doswell et al., 1999).

relief. The infrastructure that permits this has evolved in a primarily ad hoc way over the course of time in response to the hazards posed by tornadoes (and other phenomena, of course).

Tornadoes no longer produce the casualty figures that they once did, and it has been asserted here and elsewhere (e.g., Doswell et al., 1999) that the reduced fatality rate is the result of a number of factors. On the other hand, the economic losses owing to tornadoes are growing, for reasons to be discussed in Section 3. There can be no doubt that tornadoes are an important hazard in the United States, as evidenced by the recent devastating tornado outbreak that struck Oklahoma and Kansas on 3 May 1999 (see Brooks and Doswell, 2002; Doswell and Brooks, 2002). What has been done to mitigate the tornado hazard in the United States?

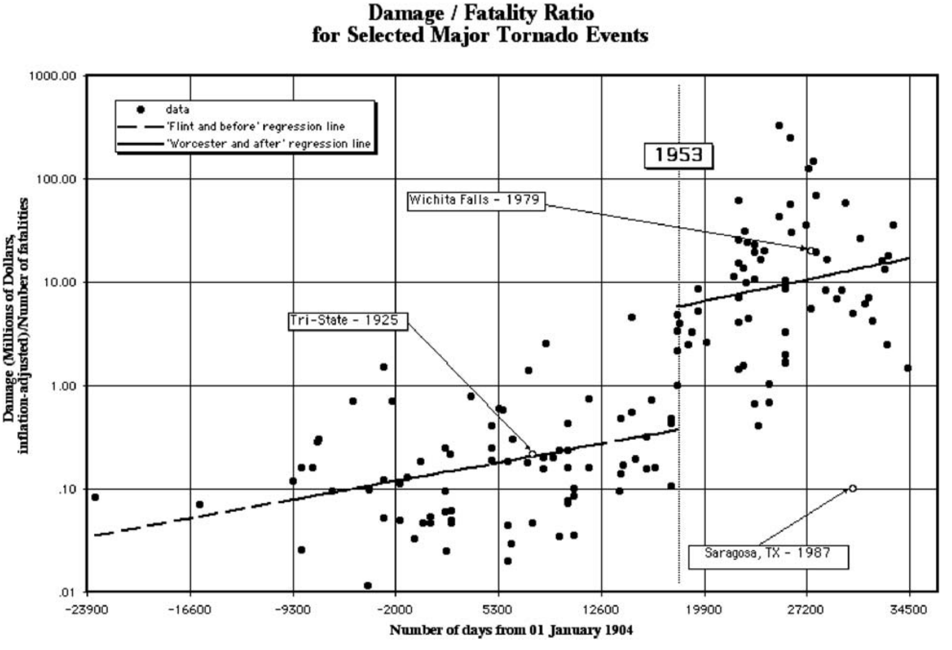

Fig. 4. Damage to fatalities ratio for selected "major" tornado events (see text for description) during the period 1880–1997, Regression lines fit the data from 1880 to 8 June 1953 (the date of the Flint, MI tornado) and from 9 June 1953 (the date of the Worcester, MA tornado) to 1997. Data points are filled circles, except for noteworthy events (see text for discussion), which are open circles. Damage amounts have been adjusted to 1997 US$ using the Consumer Price Index.

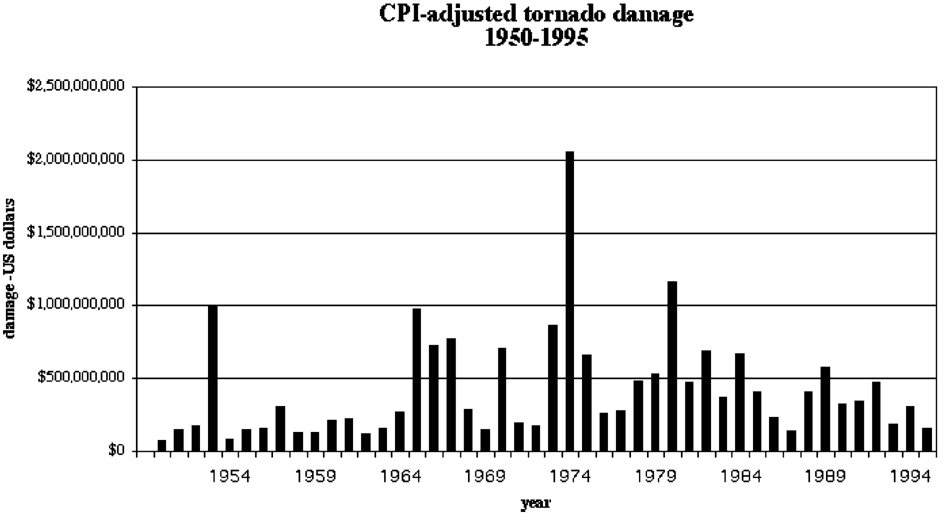

Fig. 5. Consumer Price Index (CPI)-adjusted damage, in 1997 United States dollars, from tornadoes in the United States for the period 1950–1995.

Tornado forecasting services by the NWS began partway through 1952 and continue to the present day, as described by Ostby (1992). The Storm Prediction Center (SPC) is the NWS agency associated with tornado forecasting over the range from a few hours to a few days. At the *local* forecast office level, which currently comprises more than 110 local offices across the nation, severe thunderstorm and tornado warnings are produced (covering the forecast time range from tens of minutes to few hours). These local NWS offices are responsible for recruiting and training volunteer storm ‘‘spotters’’ from surrounding communities, whose primary duty is to watch for and report threatening weather at it approaches their communities (Doswell et al., 1999). The local communities are ultimately responsible for their own protection from weather hazards—the NWS warnings are for areas larger than specific communities, although particular locations might be mentioned as being in the path of a threatening storm.

To a large extent, the official forecasts and warnings are produced by the NWS, but dissemination is largely by means of the media, primarily television weather broadcasts. Some tailored warnings for specific users are provided by the private sector (see, e.g., Smith, 2002), but the severe weather warnings for the public are the responsibility of the NWS and transmitted to the users by television (and other media). That this partnership can be successful has been shown dramatically during the 3 May 1999 outbreak of severe storms (see Andra et al., 2002). It is certainly the case that, on the whole, this partnership between the NWS and the broadcast media works and is an important part the reasons for the observed decline in the tornado fatality rate.

In addition to forecast and warning operations, the Federal government has established the National Severe Storms Laboratory (NSSL) to provide a research component to the meteorological response. Further, the National Science Foundation underwrites research in the academic community, a part of which is devoted to severe thunderstorms and tornadoes. These are infrastructure components that form the backbone of the meteorological response.

However, this is not the end of the story. Meteorology and the parts of the infrastructure routinely connected with meteorology are only *part* of the societal response to the hazards posed by tornadoes. The insurance industry provides a way for the public to absorb the losses associated with severe storms and tornadoes. Homeowners and businesses typically are covered by insurance from most storm-related losses; flood insurance is separate. That is, homeowner’s insurance does not cover flood-related losses.

For losses not covered by insurance, the Federal government can, at the discretion of the President and Congress, provide disaster assistance for major events, which might include low-interest loans as well as outright financial payments. Like insurance, this spreads the cost for disaster recovery over the nation as a whole, rather than forcing local communities to bear the burden alone. The political aspects of this are not without controversy (see, e.g., Steinberg, 2000; Platt, 1999), but this particular mechanism is presently a large part of the American infrastructure associated with disaster recovery.

There are many local, state, regional, and national organizations, both public and private, that can be mobilized in the event of a disaster. The variety of hazards (meteorological and nonmeteorological) in the United States has driven the development of a whole ‘‘culture’’ related to hazard response and mitigation that spans this wide range of agencies and groups. These organizations provide many different services to an effected area: short-term food, clothing, water, and shelter for those who have immediate needs as a result of the event, medical services for the injured, recovery and burial of fatalities, clean-up equipment and personnel, psychological counseling for those in the disaster area, long-term social services to assist those who have been displaced from their jobs by the disaster, teams providing assistance to those who are applying for disaster relief, and so on. In effect, disaster recovery from all types of hazards has been associated with a proliferation of specialized services to the victims, as a way to minimize the impact of these hazards, among which are severe thunderstorms and tornadoes. Arguably the foremost of the disaster recovery agencies is the Federal Emergency Management Agency (FEMA), which is tasked with coordination of the recovery as well as with providing assistance to victims. FEMA also coordinates post-event surveys of various sorts, including an assessment of building performance (e.g., BPAT, 1999).

Relative to the gross domestic product of the nation, of course, the losses from tornadoes are but a tiny amount. Nevertheless, when such intense damage as that produced by a violent tornado occurs to a community (Fig. 6), it can be a major disaster locally. It is only through the development of a wide range of services that the impact on any given community can be shared by the nation. Tornadoes exemplify the sort of local event that would be an enormous burden on a community but from which a large, wealthy *nation* can recover readily. It is of some interest to note that the city of St. Louis, MO, *refused* Federal assistance after the tornado disaster of 1896 (Brooks and Doswell, 2002), so as recently as the end of the 19th century, the infrastructure I have described was not yet in place. It is likely that the tornado disasters of the 1920s in the United States, including the famous

Fig. 6. Tornado damage from the violent tornado that struck in the Oklahoma City metropolitan area on 3 May 1999.

"Tri-State" tornado of 18 March 1925, were responsible for the recognition that more national infrastructure was needed to respond to the tornado threat. The development of the awareness that something *could* be done may have initiated the decline in the fatality rate in 1925 that continues to the present day. Only by sharing the costs collectively can the nation mitigate the devastating local impacts. Among the many mechanisms for dealing with hazardous weather, the meteorological component and its contributions can sometimes be difficult to assess, because those contributions are "negative"—that is, forecasts are valuable in terms of lives *not* lost, injuries *not* sustained, and perhaps even damages *not* incurred. We will explore this latter theme in the next section.

3. Issues with defining and dealing with the tornado hazard

In the United States, the growth of population and other societal trends are increasing the tornado hazard, even as the fatality figures decline. This apparent paradox is the result of a number of factors, and this section is devoted to addressing those factors.

The most obvious fact about the tornado hazard is that even in the nation with the highest tornado frequency in the world, tornadoes are rare events in any one place. In the 19th century and for the first few decades of the 20th century, the United States was primarily agricultural, with the population relatively widely dispersed and primarily engaged in outdoor employment. With the growth of industry following the American Civil War and accelerating into the 20th century, a vast movement of the populace off the farm and into urban, indoor employment was begun. As cities grew, the population was increasingly concentrated, rather than dispersed. This concentration of the population meant that any given tornado was less likely to strike humans, but if one actually did hit a population center, the *conditional* risk of fatalities actually increased.[4]

Another aspect of this societal tendency is that, by the present date, cities are prone to "urban sprawl" in the United States, which still has a much lower overall population density than most of Europe. The availability of open space means that cities can expand outward, with a large fraction of the growth in response to increasing population being in single-family homes in suburban communities, rather than concentrated in major cities and multi-family residences. Neighboring major cities are merging into giant "megalopolitan" areas along the highway corridors that connect them. This is already apparent along, for instance, the Boston–New York City–Washington, DC corridor sometimes referred to as "BosNYWash." This trend is also evident along the interstate highways in parts of the tornado-prone areas of the Plains. For instance, development is focusing along Interstate-35 between Oklahoma City and the Dallas–Fort Worth "Metroplex" such that less and less of that Interstate-35 corridor is without development as time passes. It is not hard to envision a day when "OKC–DFW" becomes another megalopolis. This has the effect of increasing the population at risk.

As the cost of housing increases, it is becoming ever more difficult for Americans to purchase their own single-family home. This means that for many Americans, the "manufactured home" is increasingly an attractive, low-cost alternative to standard "site-

[4] That is, conditional on the occurrence of a tornado striking that particular location.

built'' homes. Unfortunately, manufactured homes are much less safe than site-built homes during a tornado (BPAT, 1999; Brooks and Doswell, 2002). There is some evidence that the growth in the fraction of Americans living in mobile homes may be causing the decades-long decline in the normalized fatality rate to level off (Brooks and Doswell, 2002).

Moreover, Americans are quite willing and able to move about the nation in search of employment opportunities and other goals. Most Americans do not now live in the city where they were born, and may have moved numerous times. This mobility means that many Americans are unaware of the details of the climatology of their current residence. Since tornadoes are rare in any one place, and since the memory of past events depends on having people around who remember the past in that area, this mobility means that most of the residents in any given location have little or no direct memory of important past weather events in that location. As an example, there was a killer tornado that struck near Gainesville, GA on 20 March 1998, in the early morning hours. During an investigation of this event, we learned that a local emergency official was unaware ''that the weather could ever get that bad in Gainesville'' (H. Brooks, 1998, personal communication). Apparently, the memory of the last tornado in the United States to produce 200 or more fatalities (203) that struck Gainesville on 16 April 1936 was not retained in the collective memory of Gainesville emergency managers.

Although the infrastructure for dealing with tornado hazards in the United States is the most comprehensive of any in the world, there are still some barriers to a completely satisfactory response to tornado hazards. First of all, as suggested in Fig. 1, the hazard varies substantially around the nation. To exemplify this, consider Fig. 7; the average annual frequency of significant (recall, F2 and stronger) tornadoes in the Philadelphia, PA area is much lower than in the vicinity of Norman, OK, but it is significant that the distributions are very different. The distribution of tornadoes during the year near Philadelphia is relatively flat, whereas that near Norman is notably narrow. Moreover, the value near Norman is high only for a relatively short period of the year. This means that there is a very clear ''tornado season'' in central Oklahoma, and indeed over much of the Plains west of the Mississippi River (Brooks et al., in press), whereas in most of the rest of the United States, the ''tornado season'' is much less clearly defined. Over the Plains, then, it is possible to have a reasonably focused period of enhanced vigilance, outside of which the threat of tornadoes is much reduced (although certainly not to zero!). In many other places in the United States, however, the average overall threat is low and, except for deep winter in the north (and deep summer in the south), the hazard remains more or less constant at that relatively low level. If the overall hazard is low, this tends to foster an attitude that says, ''It can't happen here!''—at the same time that the actual hazard is not *zero*. The prevalence of a denial of the threat, combined with a nonvanishing probability of a significant tornado, is a formula for having a significant tornado strike with little or no preparation. It can be difficult to convince those living outside of the so-called ''Tornado Alley'' (Brooks et al., in press) that they need to be prepared for tornadoes.

Further, with the growth of the meteorological response to the tornado hazard, it has become common for many within the public to believe that their safety is solely the responsibility of someone within government. It is not uncommon for tornado disasters to be followed by media interviews in which members of the public are quoted as saying ''It

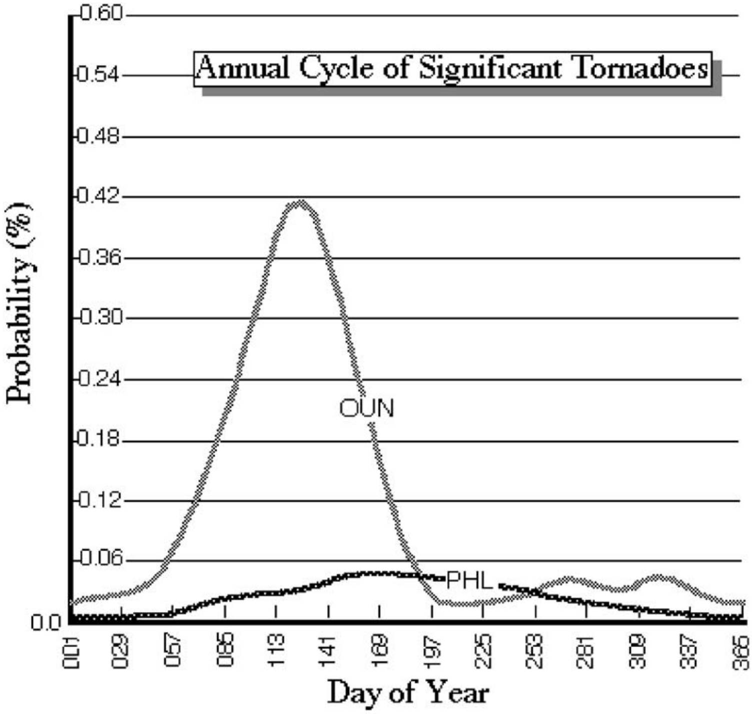

Fig. 7. Annual cycles of significant tornadoes (F2 and greater) for points near Philadelphia, PA (PHL) and Norman, OK (OUN), in terms of the probability of a significant tornado day within 25 miles of that point.

struck without warning!" even when NWS warnings were, in fact, issued. It seems that some people do not want to accept responsibility for seeking information pertinent to their own safety—rather, it seems they expect to be notified personally!

This situation may in some sense be related to the *success* of the tornado and NWS severe thunderstorm forecasts and warnings. This not to say, however, that the existing meteorological infrastructure for dealing with the tornado hazard in the United States is perfect. This infrastructure was not created according to some overarching plan, on the basis of careful studies into what would be the most effective system. On the contrary, the history of severe thunderstorm and tornado forecasting (Galway, 1989) make it clear that the system was begun when political demand for it arose, and then ad hoc solutions, put together in order to respond to that political pressure, eventually solidified into the existing system. If it were possible to create a new meteorological infrastructure for dealing with tornadoes on the basis of a systematic study of what would be the most effective system, the result might differ in important ways from the existing structure. Such a careful study would have to include much more than a meteorological perspective, however. Carefully executed surveys, done with the involvement of psychologists, geographers, and sociologists (who are experienced at doing such surveys), would be a critical component that is presently lacking. Getting weather information to as many users as possible, in terms they can understand and know how to use, is something meteorologists do not generally know very much about. Further, the implementation of any new meteorological infrastructure would need to be preceded by a massive public education exercise, to familiarize everyone with what the new products are, what they mean, and how they can be put to use. Any new meteorological infrastructure would also need to be designed in close coordination with *all* the components of the total infrastructure (see below) for coping with tornado hazards.

A continuing problem is that "the public" is a vague description of the users of weather information. The public is not some monolithic group with equal needs, capabilities, and interests; rather, it is very diverse. Meteorologists should be seeking to convey weather information to the public, not to dictate their actions. As noted by Murphy (1993), users of weather information inevitably vary considerably in their actions relative to some given weather situation. User decisions are based on factors unique to specific users that will always remain unknown to public-sector meteorologists, so providers of weather information should not be making decisions about what actions users should take. Within the public sector, at least, it will never be possible to make decisions for all users; private sector services can be tailored to the needs of specific users, of course. Public sector meteorologist should provide useful and valuable *meteorological* information, and allow users to make their own decisions based on that input, in combination with all the other factors affecting their individual decisions.

To achieve this end, meteorologists must strive to provide users with useful information about the *uncertainty* in the forecast and warning products (Pielke, 1999).[5] The natural language of uncertainty at least among forecasters is in terms of *probability* (Sanders, 1963) even though it is possible that probabilistic statements would cause difficulty for many users. Nevertheless, it has already been acknowledged that *failing* to convey uncertainty information is to deny users of weather products the full range of weather knowledge meteorologists can provide. It is not yet known how best to convey forecast uncertainty to users, but learning this needs to be a goal for the future.

It is not obvious how practical it might be to attempt to mitigate damage from tornadoes. Contrary to popular opinion, homes *can* be built so as to resist the winds of a tornado. This is because within any tornado, the wind speed is very far from uniform, and the most intense winds of even a violent tornado are typically confined to only a small fraction (a few percent) of the total path area. Moreover, only a few percent of all tornadoes ever reach violent intensity, so most structures affected by a tornado experience intensity levels of F3 or less. This means that strengthening the structural integrity of homes could indeed result in reduced damage (see BPAT, 1999).[6] The challenge is that there are *economic* issues tied to the task of enhancing structural integrity on a national scale. Increasing structural integrity cannot be done inexpensively except for *new* construction—retrofitting enhanced structural integrity on existing homes can be prohibitively expensive. Any effort to mitigate tornado damage nationally would have to take the long-range perspective (on the order of many decades) of mandating the use of enhanced structural features primarily for *new* construction, eventually attaining a high percentage of buildings nationally only after a long period of transition. The extent to which this is practical or even desirable is open to question.

[5] This paper can be found at: http://www.esig.ucar.edu/redriver/text.html.

[6] This publication can be found at: http://www.fema.gov/mit/bpat/bpat012.htm.

It is disturbing to note how few homes, even in the most tornado-prone areas of the United States, have tornado shelters. No doubt this is related to the cost of shelter installation (see Merrell et al., 2002). The addition of shelters can be relatively inexpensive in new construction, but again is relatively expensive for installation in existing homes. Many businesses and public facilities do not have adequate shelters, nor adequate action plans to protect the occupants in the event of a tornado. This is especially important for manufactured home parks (and also for recreational vehicle parks), owing to the increased threat for the occupants in such structures. In spite of abundant evidence that shelters are effective at protecting their occupants, it appears that the relative rarity of tornado events, even in the areas of highest frequency, has led many American to choose not to have shelters.

Finally, it is useful to review the complex infrastructure associated with the tornado hazard. Meteorologists in the United States are generally aware of the meteorological side of this infrastructure: the NWS has its Storm Prediction Center and its suite of products (notably, the severe thunderstorm and tornado watches), as well as the local forecast offices throughout the nation (who produce the warnings and do spotter training). However, there are many other components that interact with the NWS: private sector forecasters, the media and media forecasters, governmental emergency management agencies, public and private agencies for dealing with post-disaster situations, the politicians (who must provide the resource support to make services available), and even research scientists of all sorts, as well as structural engineers. In order for any infrastructure to be effective in dealing with hazards like tornadoes, *all* of these components must be *partners*, not strangers, competitors, or enemies. Creating and updating an effective infrastructure to cope with tornadoes depends critically on forging and maintaining good working relationships among all these components of an effective system. In the United States, the actual nature of these relationships can vary widely from place to place, ranging from close partnerships to outright hostility and everywhere in between. To the extent that positive relations among all these components have not been created and maintained everywhere, the infrastructure in the United States is still not yet a perfect model of effectiveness and efficiency.

4. Implications for Europe

There can be no doubt that the unique geography of North America favors severe thunderstorms and tornadoes, especially in the central Plains area, resulting in a national average for the United States of about 1000 tornadoes reported annually, as well as many nontornadic storms per year that produce extensive damage from large hail (5 cm and larger) and/or strong winds (exceeding 30 m s^{-1}). Although the frequency of such events in any single European nation is much lower than that of the United States, there is mounting evidence that suggests Europe collectively might experience as many as 300 or more tornadoes annually (N. Dotzek, 2002, personal communication). Unlike in the United States, European nations have no institutionalized process of gathering and archiving reports of severe thunderstorm and tornado events, perhaps owing to the perception that such storms are too rare to merit such a commitment. Unfortunately, this has become a self-fulfilling prophecy. Even though devastating severe thunderstorms (e.g., Heimann and Kurz, 1985) and tornadoes (e.g., Dessens and Snow, 1989) occur virtually every year *somewhere* in Europe, as of this writing, there remains no formal, *institutional* responsibility in virtually any European nation for even maintaining an archive of such events. Records of severe thunderstorms and tornadoes in Europe traditionally have been kept by a few interested individuals, not governmental agencies or even private sector firms (with the possible exception of insurance companies, who generally regard such data as proprietary). An obvious conclusion is that severe thunderstorms and tornadoes are much more common in Europe than most Europeans realize (Brooks and Doswell, 2001a). The perception that such storms do not happen in Europe also manifests itself in the nearly complete absence of any infrastructure (meteorological or otherwise) specifically to cope with severe thunderstorm and tornado hazards. Eastern Europe appears to be even less inclined to maintain severe thunderstorm and tornado event archives than is Western Europe.

At least since World War II, severe thunderstorm and tornado forecasting and research have come to be dominated by the United States. No doubt this is related to the greater extent of the problem for the United States as a nation, but also to the perception that something needs to be *done* concerning the problem. Although the American infrastructure for dealing with severe weather is much more extensive, it should not be viewed as a simple prototype to be imposed on Europe. In part, this conclusion is due to the ad hoc nature of its evolution. Since Europe is considering developing new infrastructures, it is important to recall that if forced to start over, the infrastructure we in the United States would create might be very different from the existing system for dealing with tornadoes and severe thunderstorms. In addition to this, however, is the observation that the character of the "severe weather" problem in Europe is not the same as in the United States. Hail and flooding are much more important events in Europe than tornadoes; also, mesoscale windstorms embedded within extratropical cyclones are arguably within the purview of any new "severe storm" infrastructure of Europe, whereas in the United States, such events are not severe *thunderstorms* and so are addressed by means of a different infrastructure. Other issues could be mentioned, but the main point I want to make is that any proposed European system for dealing with "severe storms" should not be modeled simply on the existing structures within the United States.

One very important issue arises in Europe owing to the relatively rarity of extreme weather events. Given the fact that "Europe" comprises a collection of nations that individually have relatively small areas, the frequency of "severe weather" (however that might be defined) is necessarily going to be low in any one nation. This means that the impact of those events is going to be perceived to be low for any single nation, certainly less than that for any single average-sized state on the Plains of the United States. This makes the development of individual *national* infrastructures for forecasting and researching these events (i.e., the *meteorological* infrastructure) a relatively large investment for any European nation; such an investment might be politically difficult to justify, and especially if each nation were required to develop its *own* complete severe storm infrastructure. This would be costly and largely redundant, with the added burden of trying to coordinate the forecasts (and research) for storms that cross (or even approach) national boundaries. The storms, of course, know nothing of geopolitical boundaries.

Forecasters in individual nations would have infrequent opportunities to gain experience with severe storm events within their national borders, so their forecasting expertise would be slow to develop.[7]

Therefore, I propose that at least one important lesson from the experience in the United States is that a *pan-European approach* to severe storms is a critically important goal to develop and institutionalize. That is, the forecasting and research associated with European severe weather is most logically done in pan-European agencies comparable to the Storm Prediction Center and the National Severe Storms Laboratory, respectively. Moreover, the forecasting and research agencies should be co-located, as they currently are in the United States, to encourage as much interaction between them as possible.

No doubt there are important political and cultural barriers to the establishment of pan-European forecasting and research centers. Nevertheless, the establishment of the European Center for Medium-Range Weather Forecasting (ECMWF) and the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) set clear precedents for a pan-European meteorological perspective. Some meteorological issues clearly demand multinational cooperation by their very nature. Forecasting and research into severe weather seems rather clearly to me to be such an issue. I believe that Europe would be best served if they choose to draw inspiration from these existing precedents (e.g., ECMWF and EUMETSAT) and to overcome the geopolitical barriers to the creation of viable pan-European severe weather forecasting and research agencies.

I hasten to point out that the presence of the SPC in the United States does not diminish in any way the critical role served by local NWS forecast offices. In the same way, a pan-European severe weather forecasting agency need not usurp any of the important missions of the national and regional forecasting services across Europe. Instead, like the SPC, such an agency would provide expert severe weather forecasting services to create a critically important "safety net" of guidance products in support of the national and regional forecasting services throughout Europe. Given that such an agency would have only to concern itself with the specific severe weather events under its charter, it would serve essentially to *support* all the national and regional forecast services, whose attention is often dispersed among a wide diversity of weather forecasting responsibilities (e.g., aviation weather, agricultural forecasts, routine public forecasts, interacting with the public, etc.). National and regional services would still maintain and perhaps even expand their close working relationships with their users if a pan-European severe weather forecasting agency could be established.

Finally, I want to emphasize that the opportunity to create new infrastructure to meet uniquely European requirements represents an important challenge to the European meteorological community. By being aware of the American example, it is possible to avoid at least some of the mistakes made during the largely ad hoc development of the American system. Goals will need to be established with which every participating nation can agree, at least in principle. Hopefully, one of those goals will be the creation of a pan-

[7] In my experience, it takes several years for forecasters in the SPC to develop enough experience to be proficient, in an agency where they deal with severe thunderstorms and/or tornadoes on more than half of the days in a year.

European way of dealing with meteorological events that, after all, do not recognize geopolitical boundaries.

Given the goals, then, it is *possible* for decisions to be made about that infrastructure that can be based on a careful study of what will be the most effective way to accomplish the chosen goals. These decisions surely will require some careful (and perhaps lengthy) consideration. It is my hope that decisions about infrastructure will not be made hastily, but rather with due care. I also hope that careful decisions will indeed be made as rapidly as possible. The natural evolution of bureaucracies means that early decisions usually become hardened into inflexible regulations far more easily than most participants expect. Inflexibility can be a serious obstacle slowing or even preventing the necessary evolution of the infrastructure as experience grows and scientific knowledge increases.

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