SEVERE LOCAL STORMS

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ABSTRACT

Severe weather associated with thunderstorms (tornadoes, hail, high winds, and flash floods) is reviewed with emphasis on the processes that are responsible. The basis for forecasting severe thunderstorms is reviewed. The parts of the world that are most vulnerable to various kinds of severe weather and the nature of the threats are described. The current state of the climatology of severe thunderstorms and problems and importance of improving climatological information are described. The lack of high-quality climatological information makes it very difficult to determine differences in event occurrence during different periods of the El Niño-Southern Oscillation (ENSO) in most of the world and almost impossible to detect changes associated with global climate change. It is argued, however, that the threats from severe thunderstorms are generally underestimated in many parts of the world.

In general, the effects of severe local storms are concentrated in a small number of events. Death tolls and damage in "average" years are typically smaller than the totals from individual events in other years. As a result, maintaining public awareness and preparedness activities is difficult since the threat of rare, extremely damaging events, is small at any individual location and time.

1. INTRODUCTION

Severe weather associated with thunderstorms affects almost all of the planet and represents a significant threat to life and property in many locations. The definition of what is considered "severe" depends on operational forecasting considerations that vary from country to country but, typically, includes phenomena such as tornadoes, large hail (usually of diameter at least approximately 2 cm), strong convective wind gusts (usually approximately 90 km hr^{-1} or more), and extremely heavy precipitation associated with flash floods (frequently 50 mm hr^{-1} at a single location). Criteria associated with heavy precipitation vary from country to country and, in some nations, even within regions. In the USA, for instance, flash flooding is not considered a severe thunderstorm event, and in Canada the objective definition of heavy precipitation is different in different regions.

Increasing population and increased dependence of society on complex infrastructure have led to an increased exposure and threat from severe local storms. This increased exposure has been counterbalanced by an increasing awareness of the threats and improved scientific understanding and technology that allows for better anticipation of the threats. These opposing forces make changes in the actual effects difficult to ascertain, especially in developing countries.

In this paper, we will briefly describe the nature of the various threats and areas of vulnerability and efforts to prepare for and forecast them. Because the greatest efforts to measure the occurrence of severe weather and forecast it have, historically, occurred in North America and particularly in the USA, the greatest focus will be on that geographic region. However, where possible, some indication of the threats in other areas will be given (e.g., Figure 1).

2. NATURE OF THREATS

2.1 TORNADOES

Tornadoes have been observed on every continent except Antarctica although they are most common in North America, particularly the Great Plains of the USA (Fujita, 1972, 1973; and see Altinger de Schwarzkopf and Rosso, 1982; Peterson, 1992; Dessens and Snow, 1989; Zixiu *et al.*, 1993; Dotzek *et al.*, 1998; Hanstrum *et al* 1998 for details of many individual countries.) Maps of events and threats ranging from worldwide (Figures 2 and 3) to continental (Figure 4) and for individual countries or regions (Figures 5-8) have been produced. Increased efforts to collect information about tornadoes in North America have led to an increase in the number of reports, with an average of 1 200-1 400 tornadoes reported annually in the USA in recent years, compared to only 600-700 just 50 years ago. Climatologies of tornado occurrence in the USA have identified the temporal and spatial structure of the threat (e.g., Kelly *et al.*, 1979; Brooks 1999) (Figure 9). Reported property damage, adjusted for inflation, has also increased in that time It is important to note that the number of strong and violent tornadoes reported has increased at a much slower rate and the annual death toll in the USA has dropped considerably during that time (Figure 10). While individual tornadoes producing 40 or more fatalities used to occur in the USA on an almost annual basis, none has occurred in the last 20 years. The decrease in fatalities has been the result of many factors, including improvements in our scientific understanding of the kinds of thunderstorms that produce the strongest tornadoes and the environmental conditions in which they form, improvements in the technology to detect tornadic storms, and an aggressive program to communicate information about weather conditions and preparedness (Doswell *et al.*, 1999).

Basic research over a period of nearly 40 years has improved our understanding of tornadic storms (Church *et al.*, 1993). In the early 1960s, Browning (1964) identified a class of storm now known as a supercell, which rotates throughout its depth (Rotunno, 1993). Almost all supercells produce some kind of severe weather and it is believed that almost all strong and violent tornadoes come from supercells (Doswell and Burgess, 1993). Investigations of radiosonde observations have identified characteristics of the environments in which tornadic storms form (e.g., Darkow, 1969; Schaefer and Livingston, 1988; Davies and Johns, 1993; Brooks *et al.*, 1994a). These characteristics can then be used to help in forecasting situations in which tornadoes are likely. Further, studies of the observations and numerical modelling of thunderstorms (e.g., Weisman and Klemp, 1982, 1984) have led to conceptual models of the formation of tornadoes (Doswell and Burgess, 1993; Brooks *et al.*, 1994b) that have focused attention on what information is important to consider in tornado forecasting and warning situations.

The use of radar and, in particular, deployment of operational Doppler radars, allowing for the estimation of winds within thunderstorms, has led to large improvements in warnings for tornadoes in the USA. Identification of significant features in radar reflectivity and velocity patterns, associated with tornadic thunderstorms, provides operational weather forecasters with guidance about storms that are likely to produce tornadoes (Burgess and Lemon, 1990). Lead times for warnings for tornadoes have increased from an average of almost zero to more than ten minutes during the last decade.

Preparedness efforts have grown in the USA since 1925. Studies of the effects of tornadoes on structures and human beings have led to general safety advice about the construction of tornado-resistant structures and where people should go in case of the approach of a tornado. (The basic advice can be summarized as "getting as low as possible in as small a room as possible in the center of a well-built building, with as many solid walls between people and the tornado as possible"). Storm "spotters" are trained to identify important features of potentially tornadic thunderstorms and communicate that information to civil defence and National Weather Service personnel (Doswell *et al.*, 1999). Warnings of tornadic storms are communicated via special weather radios, broadcast media and in many areas, via civil defence sirens.

The results of these efforts can be seen in the effects of the 3 May 1999 Oklahoma City area tornado. It destroyed more homes (perhaps up to 8 000) than any tornado in US history and may well have produced the largest area of violent tornado damage in a heavily populated region ever recorded. Despite that, only 38 fatalities were associated directly with the tornado. When the long-term changes in death rates due to tornadoes and the relationship between property damage and fatalities are considered, estimates can be made of the number of fatalities that would have occurred in the absence of improvements in the overall system. Both techniques [use of historical death rates (Figure 11) and damage/death relationships (Figure 12)] yield estimates of more than 600

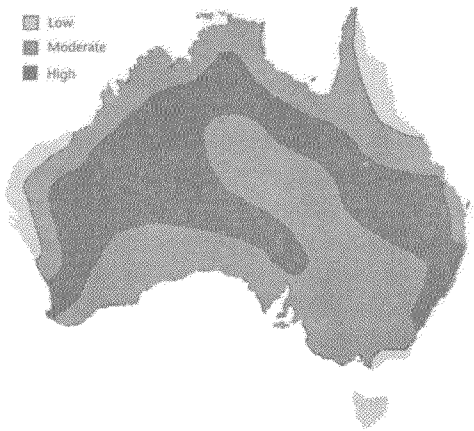


Figure 1. General description of overall severe weather threat in Australia (Australian Bureau of Meteorology).

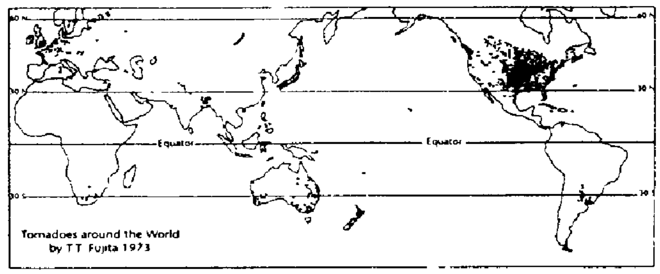


Figure 2: Reported tornado locations around the world (Fujita, 1973).

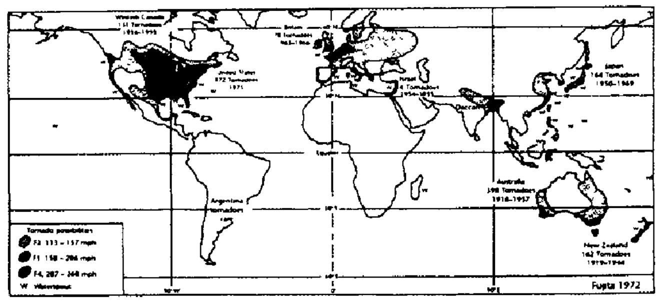


Figure 3: Estimate of maximum tornado damage around the world (Fujita, 1972).

Figure 4 Reported locations of tornadoes in Europe from the end of World War I until 1980 (Peterson, 1982)

Figure 5: Reported number of days with tornadoes in China by province from 1971-1991. Numbers in parentheses are number of days with hail during period. (Zixiu *et al*, 1993)

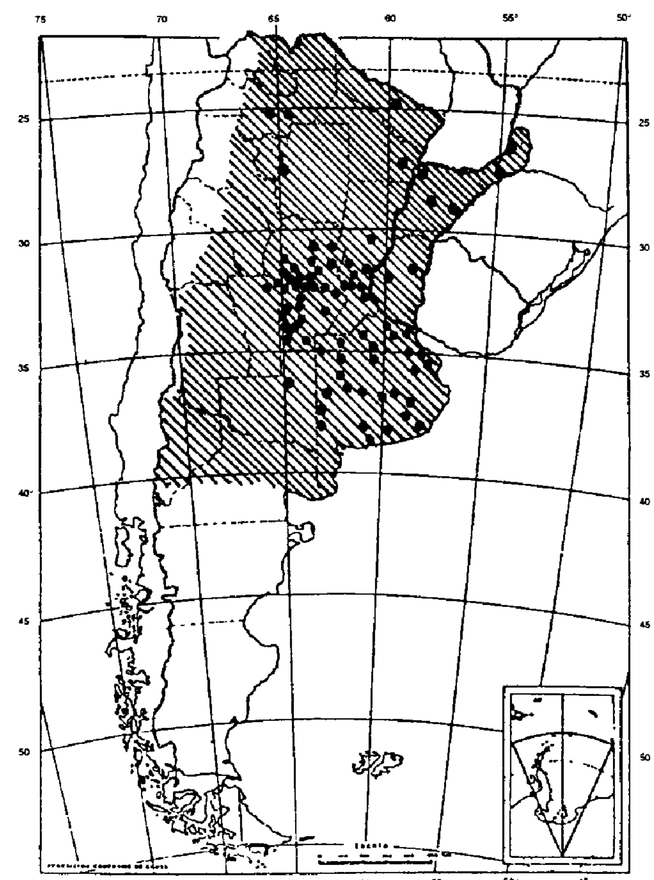
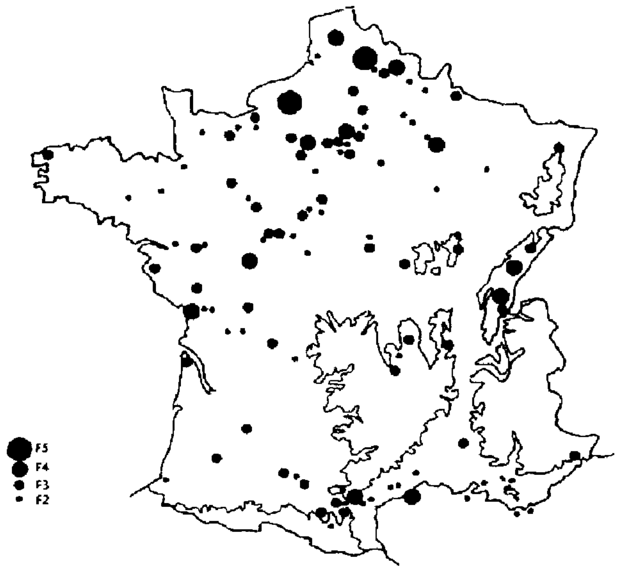


Figure 6: Reported locations of tornadoes in Argentina from 1930-1979 (Altinger and Schwarzkopf and Rosso, 1982)



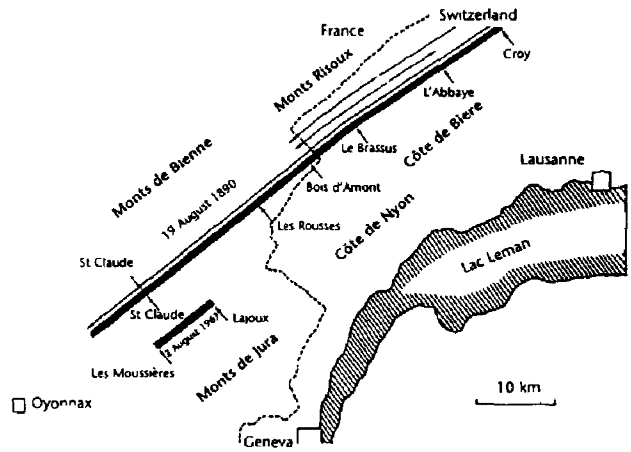


Figure 8: Approximate damage paths of tornadoes north of Geneva, Switzerland from 1680-1989 (Dessens and Snow, 1993)

Figure 7: Reported locations of significant tornadoes in France from 1680-1989 by damage evaluated according to the Fujita scale (Dessens and Snow, 1993).

fatalities in the Oklahoma City event for a pre-warning/preparedness-era tornado similar to the one that occurred in May (Doswell *et al.* 1999). In particular, there were no fatalities between the ages of 4 and 24 (Figure 13). Given the long-term record of deaths by age in tornadoes, the probability of zero deaths in that age group is approximately 1 in 5 000. It seems likely that education about safety in schools has been very successful in preparing young people to know what to do in threatening weather situations in that area of the USA.

The rarity of tornadoes in other regions of the world does not mean that the effects are small when events occur there. Landfalling tropical cyclones often produce tornadoes (McCaul, 1993; Zixiu *et al.*, 1993). Historically, devastating tornadoes have struck Europe approximately once every 20 years (Wegener, 1917; van Everdingen, 1925; Peterson, 1982; Dessens and Snow, 1989, 1993). In the last 20 years, individual tornadoes with hundreds of fatalities have occurred in Russia, northeast of Moscow, and in Bangladesh. It is perhaps significant that the largest events have produced fatalities of the same order of magnitude as the largest death tolls in US history and the "pre-warning/preparedness-era" Oklahoma City tornado. While it seems that strong and violent tornadoes are much less common in other parts of the world compared to the USA, it also appears likely that

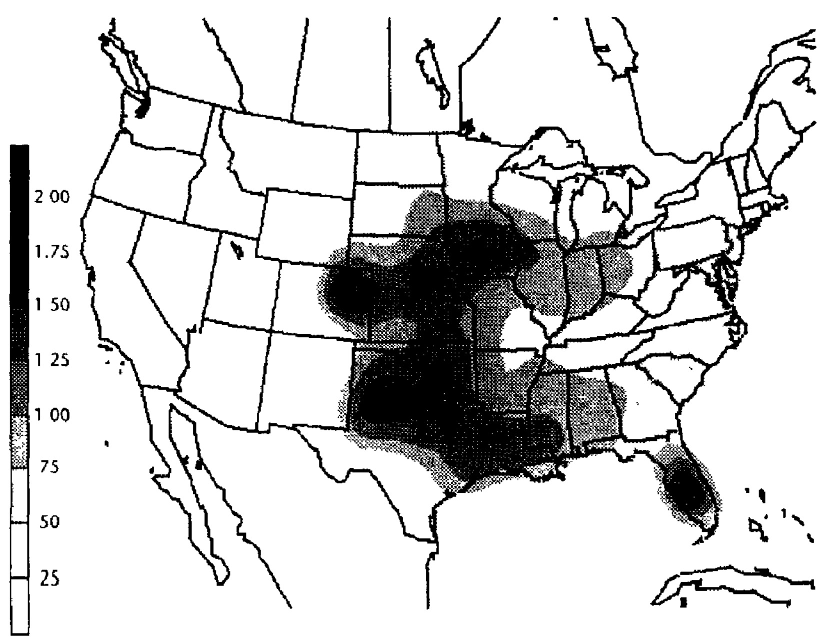


Figure 9: The mean number of days per year with a tornado touching down within 40 km of any location in the United States based on data from 1980-1994 (Brooks, 1999)

Figure 10: Mean annual number of tornadoes reported in the USA by damage rating per decade since 1920. A simple statistical model estimating the 'true' number of tornadoes expected per year is given in the thick black line (model). For comparison, the distribution of tornadoes in Argentina per 100 years is included. (Based on data of Altinger de Schwarzkopf and Rosso (1982) for 1930-1979

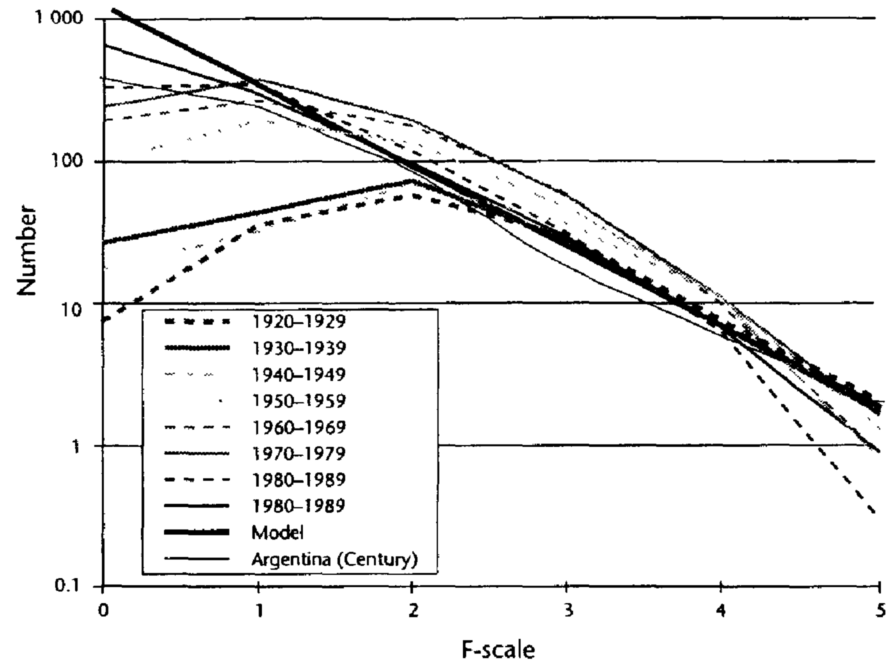


Figure 11: Annual death rates from tornadoes per million people in the USA from 1880 to the end of June 1999 on a logarithmic scale. Raw data shown by the dots, with light (linear fit) smoothing of data shown by the flowing thick median line. The dotted lines indicate 10th and 90th percentiles of annual death rates since 1925. The blank circles show death rates for residents of mobile homes since 1985 and the filled circles represent permanent homes.

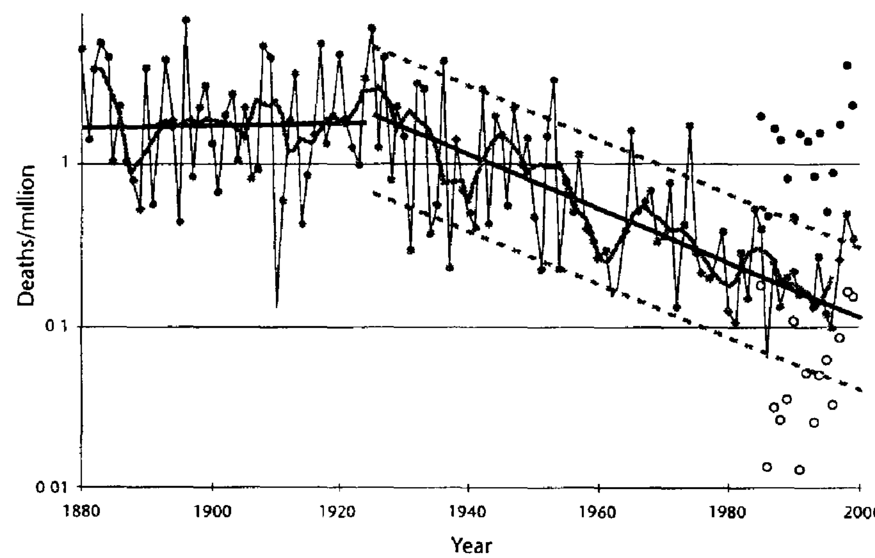
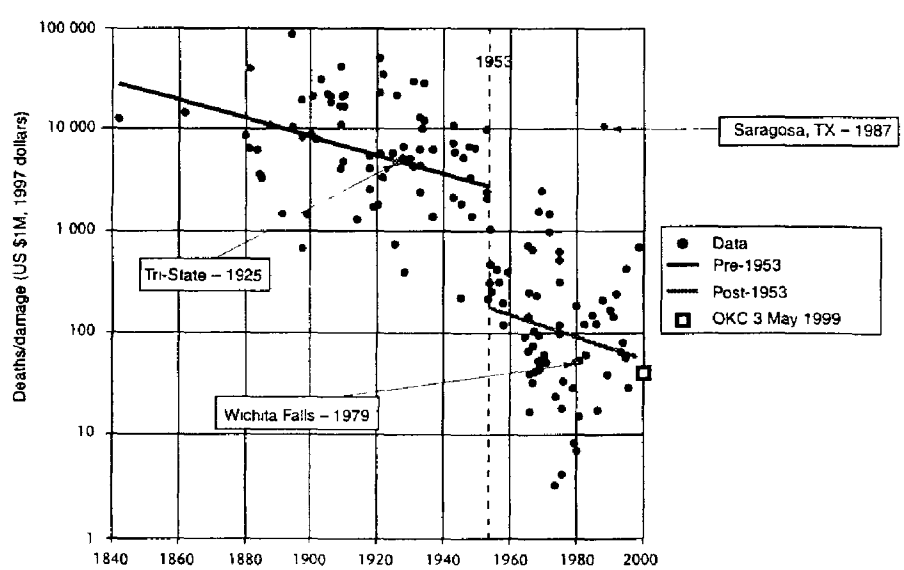


Figure 12: Rates of deaths in major US tornadoes per millions of dollars of damage (inflation-adjusted) since 1840. Linear fits to data in period before (after) 1953, when warning and preparedness activities began, shown by the darker (lighter) line. The black square shows the 3 May 1999 Oklahoma city tornado (adapted from Doswell *et al.*, 1999)



tornadoes are vastly underreported in the rest of the world. The prime evidence for this is that the majority of reported tornadoes in many parts of the world are fatality-producing events or are especially newsworthy (such as the 1998 tornado in Umtata, South Africa, while the South African President was visiting the town). This situation is similar to that in the USA in the mid-19th century when only approximately 25 tornadoes per year were reported. In some parts of Europe, such as Finland (J. Tettinen, personal communication), tornadoes were almost never reported until the last few years, when increased public attention has led to increased reporting.

2.2 HAIL

The exact definition of the nature of severe hail is troublesome. For some agricultural interests during certain periods of the year, even 1 cm diameter hail may be devastating. For urban areas, it may take much larger hail, say 4 cm in diameter, to cause problems The distribution of regions prone to these levels of threat is very different. The smaller limit occurs in much of the temperate world during the warm season (Figure 14). Larger hail is typically limited to the central part of North America (Kelly *et al.*, 1985) and regions near major mountain ranges in the rest of the world (e.g , the Himalayas and Alps [Houze *et al.*, 1993]). It has been suggested that extremely large hail is much more likely in supercell thunderstorms than in "ordinary" thunderstorms (Rasmussen and Blanchard, 1998). This is consistent with the observed distribution of tornadoes, presumably associated with supercells, in the central part of the USA. The lack of a relationship when hail of any size is considered has been pointed out for China by Zixiu *et al.* (1993). They show that the frequency of hail is maximized in the high plateau regions of western China (Figure 15), while tornadoes are more common in the eastern part of the country, particularly in the Yangtze River valley (Figure 5). The high plateaus and other regions downwind of mountains may produce large hail because of the steep tropospheric lapse rates that develop as air comes over mountains.

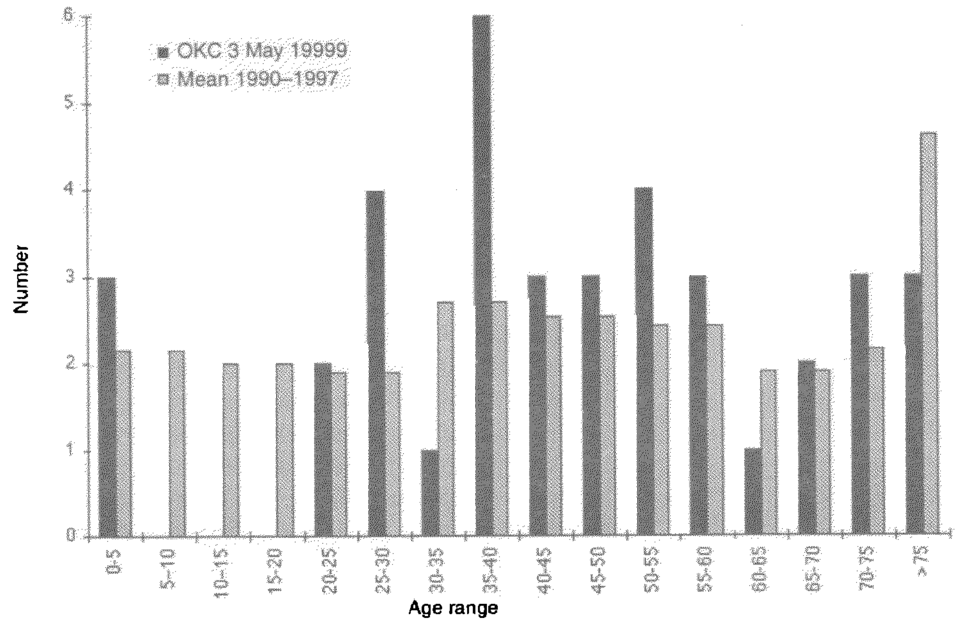
Unfortunately, observations of hail have not been consistent through the years. In the USA, the number of reports of severe hail (approximately 2 cm or larger) has increased by an order of magnitude in the past 30 years. Most of the increase has been in the smaller end of the severe range. As a result, attempts to develop a climatology based on the reports face significant challenges. Researchers are faced with the dilemma of having small sample sizes or an non-homogeneous record (Figure 16, Brooks, 1999). Efforts to use insurance losses are complicated by the issue of what causes the losses (agricultural vs. urban interests) and the temporal non-homogeneity of the insured base. Nevertheless, in the last 15 years, extremely large losses (greater than US $500 million) have been associated with hailstorms in areas such as Munich in Germany, and Denver (Colorado) and the Dallas-Fort Worth region (Texas) in the USA.

2.3 DAMAGING CONVECTIVE WIND GUSTS

Strong winds associated with thunderstorms are a common feature. Little has been done to document their climatological occurrence (Figure 17) until recent years (e.g., Kelly *et al.*, 1985, Johns and Hirt, 1987, Brooks, 1999) although they are almost certainly the most common severe weather event. Damaging straight-line thunderstorm wind gusts are usually associated with cold air outflow as the downdraft reaches the ground Fujita and Byers (1977) were the first to use the term downburst to describe very strong wind gusts produced by thunderstorms. Factors that influence the generation of damaging wind gusts at the surface include: negative buoyancy enhanced by evaporative cooling within unsaturated air, precipitation loading within the downdraft, and downward transfer of horizontal momentum by the downdraft (e.g., Kamburova and Ludlam, 1966). Again, aspects of these processes are dependent on stormscale microphysics including drop size distribution and liquid water content per unit volume, which cannot be determined from standard observing systems.

Strong winds can occur in a variety of situations (for reviews, see Doswell, 1994 and Wakimoto, 1998). They can be associated with small, short-lived downdrafts and even when they are relatively weak (say less than 25 m s^{-1}), they can be

Figure 13. Number of deaths by 5-year age bins on 3 May 1999 during the Oklahoma City tornado and mean number of deaths expected for number of fatalities in tornado (based on all tornadoes) in the USA from 1990-1997.



a significant hazard to aviation (Fujita and Byers, 1977; Fujita and Caracena, 1977; Caracena *et al.*, 1989). Considerable effort has been expended in the last twenty years to decrease commercial aircraft accidents due to thunderstorm downdrafts. Radar detection and education of the aviation industry about the threats seems to have limited the number of accidents in the last decade, after several occurred from the early 1970s through the mid-1980s.

Brooks and Doswell (1993) modelled numerically a situation in which a supercell thunderstorm can produce a relatively wide (10–20 km), long (50–100 km) swath of extremely high winds (50 m s^{-1}). The winds occur in association with high-precipitation supercells (Moller *et al.*, 1990) when the storm-relative flow at mid-levels is very weak. Such storms have been observed (Cummine *et al.* 1992; Smith 1993; Conway *et al.*, 1996) and have caused significant damage over areas up to 2000 km^2.

Even larger areas can be affected by high winds when organized systems of thunderstorms occur. In the USA, widespread convective wind events are sometimes referred to as *derechos* (Johns and Hirt, 1987). They occur in association with mesoscale convective systems, which are composed of a number of individual thunderstorms. Often, they are arranged as a squall line, producing a wide area of high winds with new convective cells initiated on the leading edge of the outflow from earlier cells. The system may maintain itself for many hours, provided sufficient low-level moisture and mid-level unstable air can be found as the system moves along.

2.4 FLASH FLOODS

Flash floods are the most widespread severe local storm phenomenon associated with large loss of life. They occur all over the world (e.g., Sénési *et al.*, 1996; Li *et al.*, 1997; Bauer-Messmer *et al.*, 1997; Doswell *et al.*, 1998), especially in regions of complex terrain. They are the most difficult to forecast, in part because they involve both meteorological and hydrological aspects (Maddox *et al.*, 1978, 1979; Doswell *et al*, 1996). Determining their effects is complicated further by interactions with people and buildings (Petersen *et al.*, 1999). If a flash flood occurs in a location where it doesn't impact societal structures, it is unlikely to be reported. On the other hand, relatively minor precipitation events may produce significant flooding if antecedent conditions exacerbate the flooding, as occurred in the Shadyside, Ohio flood of 1990 with saturated soils (Doswell *et al*, 1996) or in the Buffalo Creek, Colorado flood of 1996 when a forest fire cleared vegetation from the area a couple of months before the rain event.

Great loss of life has been associated with flash flooding, even in developed nations. Recently, a campground in Biescas in the Spanish Pyrenees was flooded

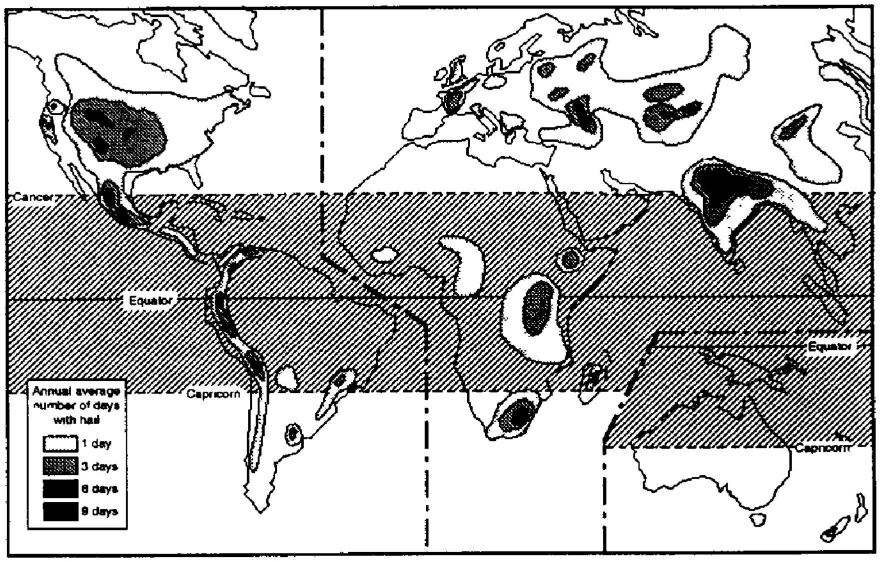


Figure 14. Number of days with hail per year around the world. Hatched region indicates tropics.
(Adapted from Munich Re, 1984)

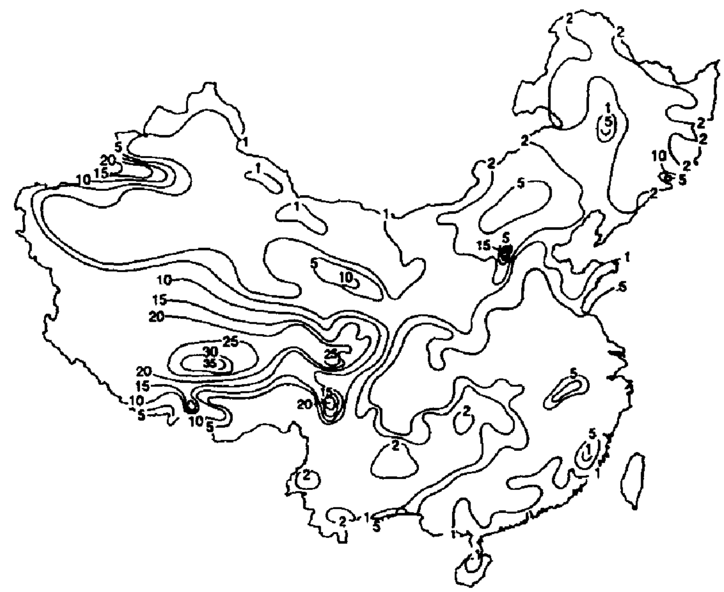


Figure 15. Number of days with hail per year in China.
(Zixiu *et al.*, 1993).

and caused more than 80 deaths. In 1998, 11 hikers were killed by a flash flood in a "slot canyon" in northern Arizona when rain from a storm tens of km away from the canyon was funnelled into the canyon. The three biggest convective-weather death toll single events in the USA (with the exception of aircraft crashes) in the last 40 years have all been flash floods (235 fatalities in Rapid City, South Dakota in 1973, 145 fatalities in Big Thompson Canyon, Colorado in 1976, and 77 fatalities in Johnstown, Pennsylvania in 1977). Death tolls in developing countries are frequently difficult to estimate.

Flash floods are distinguished from riparine floods by the extremely rapid rate of rise of river levels. While riparine floods may have river stages rising by tens of cm per day, flash floods are associated with river stages rising by tens of cm per hour or, in extreme cases, per minute. Because of their very small basins, small streams can produce flash floods as they can carry up to 100 times their normal capacity in such floods. Even in the USA, this can cause problems in operational practice since these small basins may not be mapped as well as larger basins, particularly for comparison to radar estimates of precipitation. As a result, forecasters may be unaware of the nature of the threat even if accurate estimates of rainfall are available

Detection of heavy precipitation is also complicated. Direct estimates from radar can be complicated by the presence of hail (e.g., Zrnic *et al.*, 1993) or by intervening