



# **TORNADOES: A RISING RISK?**



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## 1 EXECUTIVE SUMMARY

**THE US EXPERIENCES MORE TORNADOES THAN ANY OTHER COUNTRY IN THE WORLD.** Every year an average of 1200 tornadoes kill up to 60 people, injure 1,500 and cause at least \$400m in economic damage in the US. 2011 was a record year for US tornado losses. Over 1600 tornadoes were reported, and it surpassed records for the greatest number of tornadoes for both a single month and for the greatest daily total. Total damages from the outbreaks exceeded \$25bn.

**ALTHOUGH THE REPORTING OF ANNUAL TORNADO EVENTS IS INCREASING THIS DOES NOT NECESSARILY MEAN TORNADOES ARE BECOMING MORE FREQUENT.** The number of tornado reports has increased by an average of 14 per year since the mid-50s. However, a large proportion of this can be attributed to population movement to rural areas and increased communication around and understanding of the nature of tornadoes.

**INCREASING EXPOSURE MEANS THAT AGGREGATE LOSSES FROM SEVERE WEATHER EVENTS ARE LIKELY TO INCREASE AND MODELLING THE RISK IS BECOMING MORE IMPORTANT.** As the process of urbanisation continues, the chances of a tornado hitting a densely populated area increase. This is already being shown in the increase in the number of billion dollar events. The rising capacity for potential losses, such as those seen in 2011, is leading to greater take up of tornado models.

**IN THE US, ANNUAL AGGREGATE LOSSES FROM SEVERE THUNDERSTORMS INCLUDING TORNADOES HAVE, ON AVERAGE, ACCOUNTED FOR MORE THAN HALF OF ALL CATASTROPHE LOSSES SINCE 1990.** The main insurance classes affected are property, motor and agriculture, with tornadoes primarily causing loss and damage to property. Wind and hail damage is covered by most homeowners' policies. Given that tornado damage is often localised in nature, insurers may wish to assess their retentions in a given development or community.

**LONG TERM AVERAGE LOSSES IN THE US FROM SEVERE THUNDERSTORMS INCLUDING TORNADOES ARE SIMILAR TO THOSE FROM HURRICANES.** Between 1980 and 2011, 43% of windstorm losses were attributable to severe thunderstorms compared with 50% for tropical cyclones.

**PREDICTION AND DETECTION OF TORNADOES IS DIFFICULT.** Although technology has made it increasingly possible to identify weather patterns which favour tornado formation, it remains difficult to predict exactly where and when a tornado will form, resulting in relatively short lead times.

**THE EL NIÑO AND LA NIÑA PHASES HAVE VARYING IMPACTS ON TORNADO ACTIVITY IN THE LONG TERM.** El Niño and La Niña can affect the location of highest tornado frequency in the US. In general, El Niño phases result in fewer thunderstorm and tornado outbreaks inland than during La Niña phases. The two devastating outbreaks of tornadoes in 2011 occurred during a La Niña phase.

**IT IS CURRENTLY DIFFICULT TO MAKE A LINK BETWEEN CLIMATE CHANGE AND TORNADO ACTIVITY.** While climate change may have a number of effects on atmospheric conditions favourable to tornado formation, the relatively short and unreliable record of tornado activity makes it difficult to determine a definite trend in tornado climatology. Climate models are currently unable to resolve small-scale phenomena such as tornadoes, and no models exist which can use climate model data to predict future tornado activity.

## 2 INTRODUCTION

Tornadoes create some of the strongest winds on earth and have the potential to cause significant damage if they cross a densely populated area.

Although tornadoes occur across the world, the US experiences more tornadoes than any other country. Tornadoes in the US are an annual phenomenon, every year, an average of 1,200 tornadoes kill at least 60 people, injure 1,500 more and cause over \$400m in damage.<sup>1</sup> This means that, apart from tropical cyclones, thunderstorms are the most important US severe weather hazard for the insurance industry. When examining data from the past few decades, aggregated losses show a rising trend, predominantly due to increasing exposure. A violent, long track tornado or severe hailstorm has the potential to cause a significant single loss if it passes through a built-up area and, as populations increase and migrate, this is becoming increasingly more likely.<sup>2</sup>

2011 was an unusually active and deadly year for tornadoes across the US, with over 1,600 tornadoes recorded across the country, more than any other year on record except for 2004.<sup>3</sup> 2011 was a record breaking year in terms of tornadoes, with the greatest number of tornadoes in a single month (758 in April) as well as the greatest daily total (200, 27 April).<sup>4</sup> Costs were high, with seven individual tornado and severe weather outbreaks recording damages that exceeded \$1bn. Total damage from the outbreaks is estimated to have exceeded \$28bn.<sup>5</sup> This figure represents the highest costs in terms of property damage from severe thunderstorms in a single year since records began.<sup>6</sup> The two 2011 events are among the top ten natural catastrophe losses for the US; in relative terms this amounts to almost half the loss inflicted by Hurricane Katrina in 2005 and five times that caused by Hurricane Irene in 2011.<sup>7</sup>

Due to the large losses and high frequency and severity of tornadoes, the 2011 season attracted much attention from the insurance and risk management industries, raising important questions about tornado risk. Among them, does the unusually active 2011 represent a trend of increasing tornado activity and is tornado risk changing? This report examines some of these questions with particular focus on severe thunderstorms and tornadoes in the US, where the largest losses are recorded.

## 3 THE NATURE OF TORNADOES

Tornadoes are the most violent of all atmospheric storms. A tornado is essentially a narrow, vortex of air that extends between the base of a thunderstorm and the ground. As wind is invisible, it is hard to see a tornado unless it forms a condensation funnel. A condensation funnel forms when moisture condenses out of humid air as the vortex intensifies and the air pressure inside it drops. To be classified as a tornado, the vortex must be in contact with both the ground and cloud base.<sup>8</sup>

Tornadoes are highly variable, and size doesn't necessarily correlate with strength. Large tornadoes can be weak, and some of the smallest funnels are the most destructive. Most tornadoes move from southwest to northeast, but tornadoes can move in any direction and can change their direction, sometimes suddenly. The average width of a tornado funnel is about 90 metres although widths of more than ten times this size have been recorded. Track length on average is just a few kilometres/miles, though the longest recorded track lengths have been more than 320 kilometres. The average speed of advance is 48kph but may vary from nearly stationary up to 113kph. The maximum possible wind speed on the edge of the funnel is estimated to exceed 480kph, this is the highest speed of all windstorm phenomena.<sup>9</sup> Such wind speeds have been observed by radars on a couple of occasions.

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### 3.1 HOW ARE TORNADOES FORMED?

Tornadoes form most commonly in conjunction with thunderstorms, and can accompany tropical storms and hurricanes as they move onto land. A tornado which forms over water is called a waterspout. If a waterspout moves onto land it can cause extensive damage to coastal areas.<sup>10</sup>

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Globally, tornadoes occur most often during the spring and summer in the mid-latitudes of both the northern and southern hemispheres.<sup>11</sup> However, there is still much that remains unknown about tornadoes. While it appears relatively easy to identify atmospheric conditions which produce thunderstorms and severe weather, only a limited set of conditions can lead to the most severe events and these are more difficult to forecast and identify.<sup>12</sup>

The main parameters that show some skill in discriminating between significant tornadic and non-tornadic environments include the height of the lifted condensation level (LCL) and measures of lower tropospheric wind shear. The environment is most favourable to the formation of tornadoes when the LCL height is low and the wind shear is large in the lowest kilometre above the ground.<sup>13</sup> Several key factors which increase the likelihood of a tornado forming have been identified. First, as tornadoes occur in association with thunderstorms, moisture must be present in the air and temperature should fall relatively rapidly with height. Relative magnitudes of moisture instability and lift (a mechanism by which air is forced to rise) modulate both the extent and intensity of thunderstorms, and therefore the likelihood of tornadoes.<sup>14</sup> While thunderstorms can generate tornadoes, it is important to note that only about 5% of thunderstorms become severe and only about 1% produce tornadoes.<sup>15</sup>

Tornadoes form during the most moist and violent storms. These conditions often occur at cold fronts where warm air is forced to rise quickly causing strong updrafts of air to come close to an unusually strong downdraft. The strong updrafts leave a low pressure area in the cloud and warmer air from below rushes in to replace the updraft and even out the pressure. This warm air further strengthens the updrafts and, as it streams up and in, this air twists the already soaring air into a spinning spiral.<sup>16</sup>

Research has shown that the majority of tornadoes are produced by a special type of thunderstorm known as a supercell.<sup>17</sup> Supercells contain a deep and persistent rotating updraft called a mesocyclone, which makes them unique from all other types of thunderstorm.<sup>18</sup> Supercell formation is possible when the wind speed and direction changes with height. This is known as vertical wind shear. When vertical wind shear is large, the likelihood of extra-tropical cyclones forming is increased, which can be seen as low-pressure systems on maps.<sup>19</sup> Vertical wind shear is notably enhanced during the spring when the temperature difference between the poles and the equator is large increasing the likelihood of tornado formation.<sup>20</sup>

However, it is important to note that not all rotating thunderstorms will produce tornadoes. In some instances, although thunderstorms form, the conditions necessary to spawn a tornado may not all coincide and this represents a real challenge for forecasters. The result is that understanding tornado formation is not currently an exact science and as such there is an element of uncertainty to all forecasts.<sup>21</sup>

### 3.2 TORNADO FORMATION

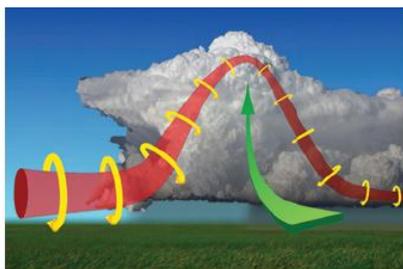
The diagram below gives a brief explanation of the birth of a tornado.

**Figure 1: The birth of a tornado**<sup>22</sup>

Before thunderstorms develop, winds change direction and increase in speed with altitude. This creates an invisible, horizontal spinning effect in the lower atmosphere.



Rising air within the thunderstorm updraft tilts the rotating air from horizontal to vertical.



An area of rotation, 3-10 kilometres wide, now extends through much of the storm. Most tornadoes form within this area of strong rotation.



Source: NOAA, *Nature's Most Violent Storms*

## 4 MEASURING TORNADOES

Theoretically, the most accurate way to measure and rate tornadoes would be to measure their wind speed but, this is not possible in practice. Wind speed measurements for tornadoes are relatively rare; the probability of there being an in situ anemometer (a device used to measure wind speed) is quite small and strong tornadic winds leave little chance of it remaining intact.<sup>23</sup> As such, only a handful of anemometer measurements of tornado wind speeds exist. Whilst the creation of the WSR-88D Doppler Radar network has made remote sensing and forecasting of the parent thunderstorm's rotation more possible, physical limitations such as beam spreading and radar horizons, as well as their spatial and temporal sampling resolutions render the devices somewhat useless for measuring the rotation associated with the tornado itself, which precludes their use for rating tornado intensity.<sup>24</sup> Wind speed may occasionally be measured by mobile Doppler radars, which can be positioned close enough to the storm to resolve the rotation within the tornado itself. At present only around 20 of the 1000 tornadoes which are reported annually in the US are sampled by mobile Doppler radars.<sup>25</sup> This means that the use of wind speed as a sole method for rating tornado intensity is implausible and the best way to determine tornado intensity remains to assess the damage.<sup>26</sup>

### 4.1 THE FUJITA (F) SCALE

The Fujita scale for rating tornado intensity is based primarily on the damage that tornadoes inflict on "well-constructed" buildings. The scale was introduced in 1971 and updated in 1973 to take account of tornado path width/length. Shortly after the Fujita Scale was introduced as the rating system for tornadoes, the National Weather Service (NWS) launched a project to rate tornadoes retroactively. By reviewing photographs and newspaper articles, tornadoes from as early as 1950 were assigned an F scale rating. These ratings were used to compile the National Oceanic and Atmospheric Administration (NOAA) National Tornado Database which provided the first climatological data for tornadoes. Tetsuya Fujita of the University of Chicago, who introduced the scheme, carried out work to rate tornadoes from as early as 1916. The F scale rates tornado intensity from F0 (light damage) to F5 (very heavy damage). The rating is determined by the local NWS official, with contributions from engineers, by carrying out a ground and/or aerial survey. Ground-swirl patterns, radar tracking, eyewitness testimonies, media reports and damage imagery as well as photogrammetry/videogrammetry can contribute to the rating process.<sup>27</sup>

### 4.2 THE ENHANCED FUJITA (EF) SCALE

In 2007 following the 'Fujita Scale Forum' the scale was updated by the American National Weather Service. Engineers felt that the lack of calibration of the F scale's wind-speed-damage relationship was associated with over-estimates of the wind speeds for F3-F5 damage. They believed that much of the observed damage to frame houses caused by the strongest rated tornadoes could actually have been caused by F3 wind speeds.<sup>28</sup> The scale was adjusted and the Enhanced Fujita Scale was introduced on 1 February 2007. Whereas the F scale had been based on a single primary damage indicator, damage to a 'well-constructed' frame house, the EF scale took into account 28 different damage indicators. New tornado ratings would take account of the observed degree of damage to each of these indicators. Complete destruction of a typical frame house in the US was no longer sufficient to warrant an F5 rating.<sup>29</sup> The Enhanced Fujita Scale is summarised in the table below:<sup>30</sup>

**Table 1: The Enhanced Fujita Scale<sup>31</sup>**

EF Rating	Wind Speed	Damage
EFO	65-85mph, 105-137 km/h	Light damage: Peels surface off some roofs; some damage to gutters or siding; branches broken off trees; shallow-rooted trees pushed over.
EF1	86-110mph, 138-178 km/h	Moderate damage: Roofs severely stripped; mobile homes overturned or badly damaged; loss of exterior doors; windows and other glass broken.

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EF2	111-135mph, 179-218 km/h	Considerable damage: Roofs torn off well-constructed houses; foundations of frame homes shifted; mobile homes completely destroyed; large trees snapped or uprooted; light object missiles generated; cars lifted off ground.
EF3	136-165mph, 219-266 km/h	Severe damage: Entire stories of well-constructed houses destroyed; severe damage to large buildings such as shopping malls; trains overturned; trees debarked; heavy cars lifted off the ground and thrown; structures with weak foundations blown away some distance.
EF4	166-200mph, 267-322 km/h	Devastating damage: Well-constructed houses and whole frame houses completely levelled; cars thrown and small missiles generated.
EF5	>200mph, >322 km/h	Incredible damage: Strong frame houses levelled off foundation and swept away; auto-mobile sized missiles fly through the air in excess of 100m; steel reinforced concrete structure badly damaged; high-rise buildings have significant structural deformation.

*Source: Munich Re, 2012*

Around the same time that the F Scale was developed, the T Scale was devised in the UK by Dr G.T.Meaden, in order to categorise wind speeds of tornadoes. Indeed, where the T Scale differs to the F Scale is in the fact that it is based on windspeed (and directly linked to the Beaufort Scale), whereas the F Scale is based on damage alone. The scale ranges from T0 for extremely weak tornadoes to T11 for the most powerful known tornadoes.

Tornadoes can also be categorised as weak (F0 – F1), strong (F2 – F3) or violent (F4 – F5) depending on their estimated wind speed and damage caused. The most violent and potentially deadly tornadoes account for less than 1% of the total. The table below, which uses data from NOAA's Storm Prediction Centre, demonstrates the relationship between tornado intensity, frequency and death toll.

**Table 2: Tornado Rating**<sup>32</sup>

Weak	Strong	Violent
88% of all tornadoes	11% of all tornadoes	Less than 1% of all tornadoes
Less than 5% of tornado deaths	Nearly 30% of tornado deaths	70% of tornado deaths
Lifetime 1 – 10+ minutes	May last 20 minutes or longer	Can exceed 1 hour
Winds less than 110 mph	Winds 111-165 mph	Winds greater than 166mph
Produces EF0 or EF1 damage	Produces EF2 or EF3 damage	Produces EF4-EF5 damage

*Source: NOAA, Nature's Most Violent Storms*

### 4.3 ISSUES WITH TORNADO MEASURING

The biggest problem with the original F scale was that it was based on a single damage indicator: a “well-constructed” wood frame house. This was limiting: the term “well-constructed” is ambiguous and the scale failed to present a valid rating system for tornadoes which did not strike populated areas with this type of structure. It was extremely difficult to allocate a rating using the original F scale to tornadoes which only passed through uninhabited areas of vegetation.

Additionally, rating damage is itself not a scientific process. The absence of reliable wind speed measurements requires a reliance on human judgement, yet assigning a rating from damage surveying is complicated by the relationship between wind speed and damage. The absence of standard structures and building practices in many tornado hit areas has made assigning an F scale, and therefore inferred wind speed rating post-tornado, more difficult. Rarely, an engineered structure will be within the damage path of a tornado and this can provide, to a degree, a useful source of calibration for the damage-wind speed relationship. If, for example, a building has been designed specifically to resist wind speeds of X, in the event the building fails then the wind speeds must have exceeded X. However, it is rare for such engineered

structures to encounter a tornado and, in the event of complete destruction they manage to provide only a lower bound to the wind speed. Furthermore, the F scale rating to the maximum observed damage along the tornado track and therefore provides no information about any variation in intensity along the tornado's path.<sup>33</sup>

The hard boundaries of the Fujita scale represent another weakness. For example, a 253kph wind speed produces F2-type damage, whereas a 254kph wind speed produces F3-type damage. This is obviously an implausible way to interpret damage – a given instance of damage might be produced by a range of wind speeds which could encompass more than one F scale category.<sup>34</sup>

The introduction of the Enhanced Fujita scale offered some improvement in terms of damage indicators but it too has many of the same limitations. It is important to note that other factors besides wind speed will contribute to the levels of damage: for example, the length of time that the structure is subjected to the tornadic winds, flying debris impacting a structure and changing the damage response to a given wind speed, the orientation of the structure and the presence of other nearby structures may influence the level of damage caused. These features are not captured by the F and EF scale rating system.

## 5 WHERE TORNADOES OCCUR

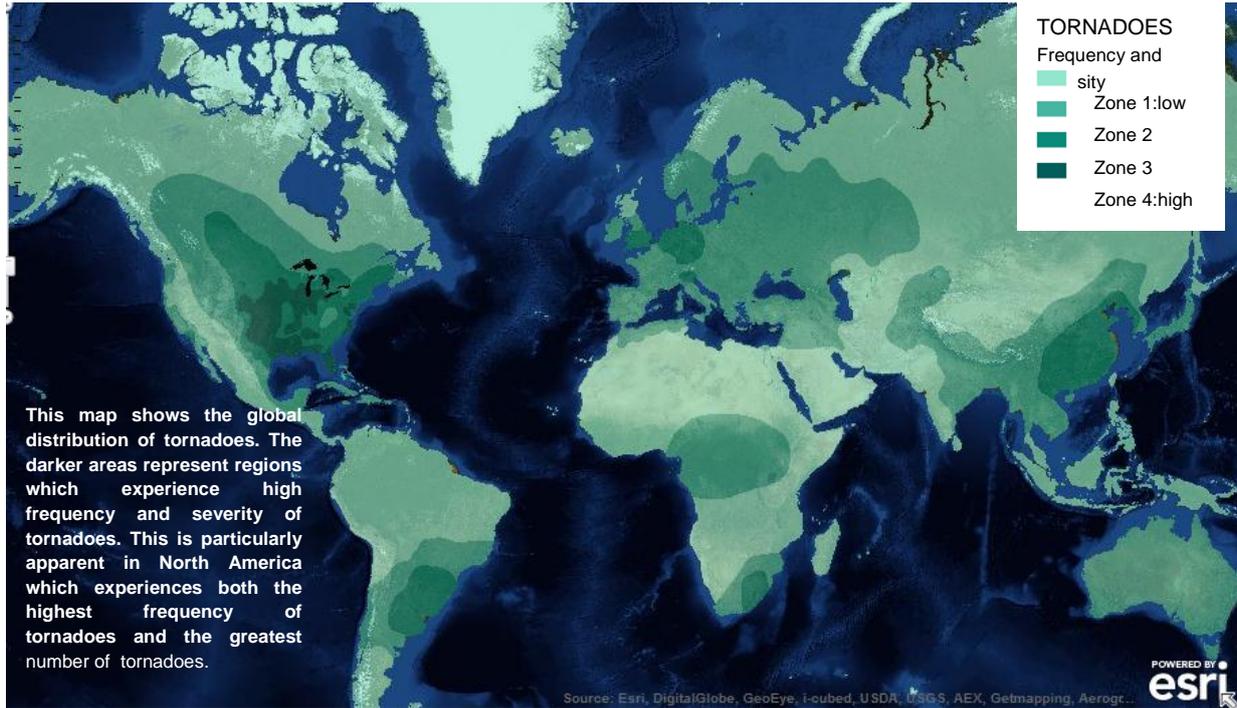
Tornadoes have been reported on all continents except Antarctica. They are most common on continents in the mid-latitudes (between 20° and 60° N and S), where they are frequently associated with thunderstorms which develop in regions where cold polar air meets warm tropical air.<sup>35</sup>

Calculating which country has the most tornadoes per year depends on how this measurement is defined. The UK has the most tornadoes per land size. On average, about 33 tornadoes are reported annually, most of them weak. In absolute numbers, the US has the most tornadoes by far (more than 1,000 per year have been reported every year since 1990). The US also has the most violent tornadoes (about ten to 20 per year). Tornadoes of this intensity are very infrequent outside the US. Canada reports the second largest number of tornadoes (about 80 to 100 annually). Russia may have many tornadoes, but reports are not available to quantify their occurrence. About 20 tornadoes are reported in Australia each year, though the actual number is probably much higher. For most if not all countries, many storms occur in uninhabited areas, and so any tornadoes they produce are undocumented.<sup>36</sup>

Records of tornado occurrences in many areas are fragmentary, making estimates of global tornado frequency difficult. According to insurance records, tornadoes have caused losses in Europe, India, Japan, South Africa and Australia. Infrequent but, nevertheless, deadly tornadoes have occurred in a number of other countries, including Bangladesh, China, and Argentina. Reports of tornadoes from either the Arctic and the equatorial tropics are few and far between.<sup>37</sup>

The majority of Southern Hemisphere tornadoes are reported in Australia. Many such reports come from New South Wales, where there were 173 reported tornadoes between 1901 and 1966. Additionally, South Africa and Argentina both reported 191 tornadoes between 1930 and 1979.<sup>38</sup> Due to tornado formation being largely down to the speed and directional shear of the wind with height, tornadoes in the Southern Hemisphere almost always rotate clockwise ie the opposite to their Northern Hemisphere counterparts.<sup>39</sup>

Figure 2: Global Distribution of Frequency and Severity of Tornadoes<sup>40</sup>



Source: Munich Re, NATHAN, Natural Hazards Assessment Network

## 6 THE US

Tornadoes occur more frequently in the US than anywhere else, due to a geographical quirk. Cool dry air descending from Canada gets funneled eastward by the Rocky Mountains. The high desert terrain of the Rocky Mountain plateau is ideal for generating high lapse rates, which are transported east of the continental divide.<sup>i</sup> Over the Great Plains, the air meets low-level moisture travelling northward from its source over the warm tropical waters of the Caribbean and the Gulf of Mexico.<sup>41</sup> Although fewer than 1% of thunderstorms in the US spawn tornadoes this still amounts to an average of over 1000 tornadoes per year.<sup>42</sup>

### 6.1 WHERE IN THE USA?

Tornadoes have been documented in every US state at least once since 1950, although some regions experience tornadoes much more frequently than others. For example, states such as Alaska, Rhode Island and Vermont have experienced very few tornadoes throughout history, whilst others such as Oklahoma experience over 50 per year, and in Texas the annual average is over 100.<sup>43</sup> Obviously, states have different land sizes. Considered on a per unit area basis, the state which has the highest number of tornadoes is Florida. Florida experiences a high number of tornadoes due to its high frequency of thunderstorms, when tropical systems move ashore the convective storms in the rain bands often produce tornadoes. Most of the tornadoes in Florida are weak tornadoes of EF0 or EF1 intensity.<sup>44</sup> A number of Florida's tornadoes occur along the edge of hurricanes that strike the state. The highest total number of strong tornadoes is in Texas, however on a per unit area basis it is higher in Oklahoma, which experiences the highest number of strong tornadoes per unit area.<sup>45</sup>

<sup>i</sup> The lapse rate can be defined as the rate of change in temperature observed while moving upward through the Earth's atmosphere

Nearly a third of all average annual reported tornadoes occur in the states of Texas, Oklahoma, Kansas and Nebraska, these states are found in the area termed 'Tornado Alley' ideally situated for the formation of supercell thunderstorms which may spawn tornadoes.<sup>46</sup> Cold, dry, polar air masses from the northwest converge with moist, warm, tropical air masses from the Gulf of Mexico causing strong convective activity over the relatively level topography. If vertical wind shear is great enough, the formation of supercells may well occur.<sup>47</sup> The Gulf Coast area has an area nicknamed "Dixie Alley" where frequency of tornadoes tends to be higher later in the year [and early in the year e.g. February-April].<sup>48</sup> Figure 3 shows the sources of the different air masses and the location of Tornado Alley. Figure 4 shows that the annual number of tornado reports is correspondingly higher in this area.

Figure 3: Tornado Alley Tornado Formation<sup>49</sup>

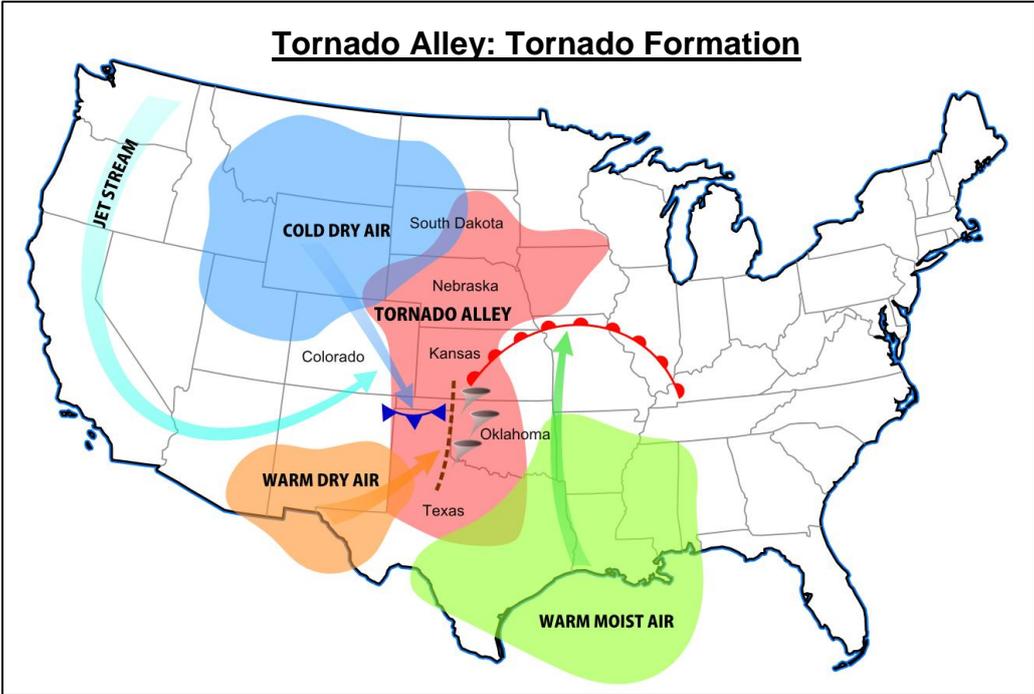
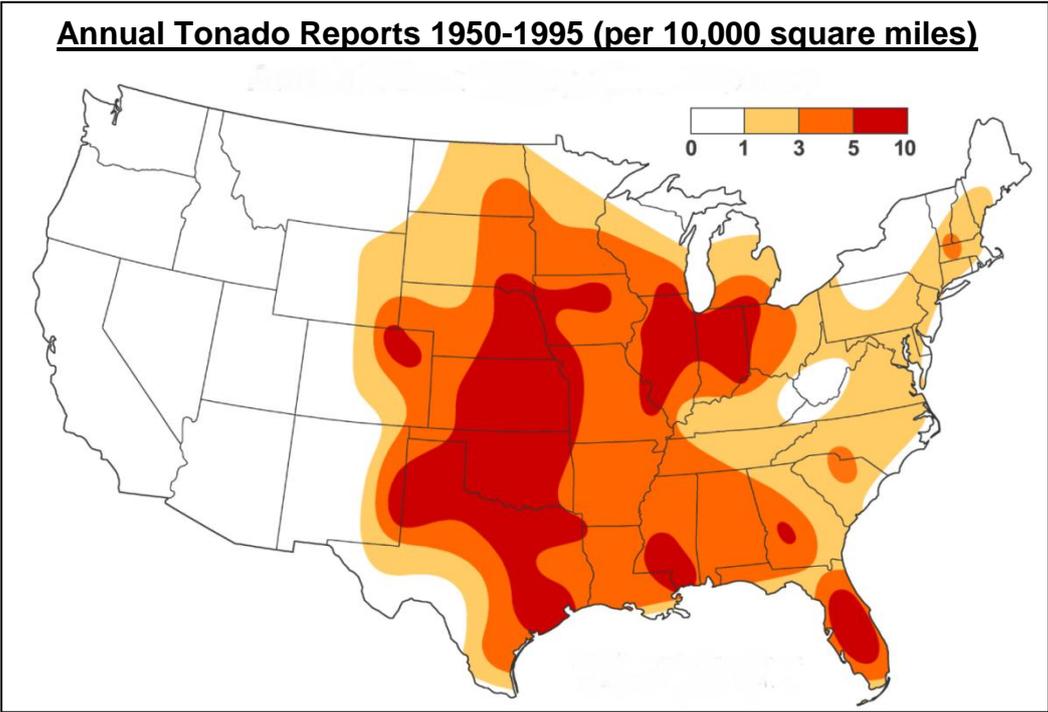


Figure 4: Annual Tornado Reports 1950-1995<sup>50</sup>

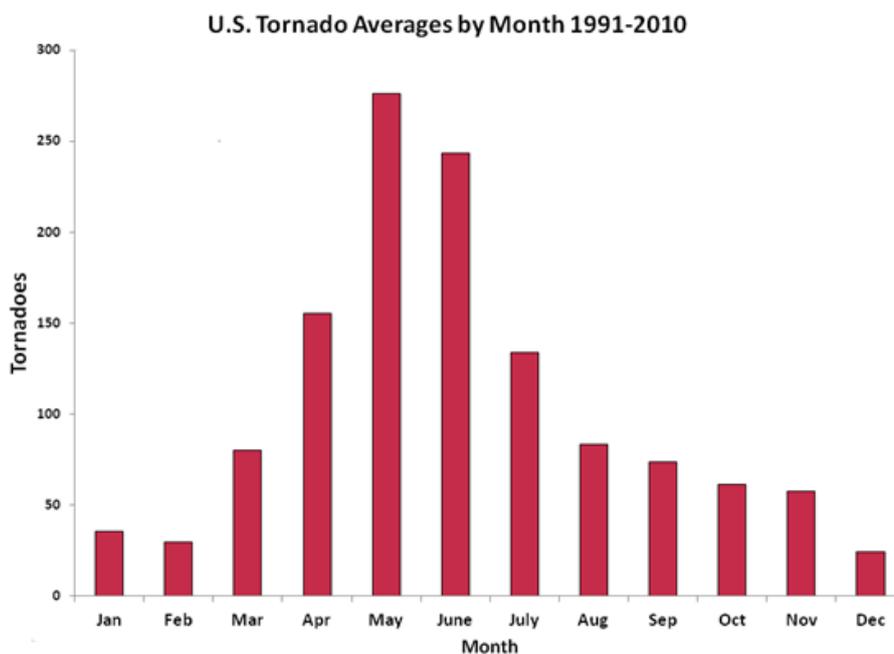


6.2 WHEN TORNADOES OCCUR IN THE US

Although favourable conditions for tornadoes in the US can occur at any time, they are most common in the spring and least common in winter. Spring is a transitional period for the climate which means there are more chances of cooler air meeting with warmer air, resulting in more thunderstorms. Increased solar heating warms the ground rapidly in the spring, resulting in larger lapse rates which can intensify spring extra-tropical cyclones (ETCs). “Tornado season” varies by location. In southern states, the tornado season typically lasts from March to May, in the Southern Plains it lasts from May to early June and in the Northern Plains, Northern states and upper Midwest, peak season is in June or July.<sup>51</sup> Tornadoes may also be spawned by land falling tropical cyclones along the Gulf or southeast coasts, which usually occur in late summer and autumn. These tornadoes occur most frequently ahead and to the right of the hurricane’s path as vertical wind shear is at its greatest here. This partly explains the relatively high frequency of tornadoes in Florida.<sup>52,53</sup>

Figure 5 shows the average number of tornadoes by month. Although some general trends can be identified, notable outbreaks of tornadoes have been recorded in the US during every month. In December 1991 a notable tornado struck McLean County, Illinois causing \$0.25m in property damage.<sup>54</sup> The following November, a series of winter tornadoes hit the state of Indiana, causing over \$12m in damage.<sup>55</sup> More recently, the ‘Super Tuesday’ outbreak of 2008 occurred in February. Across two days, 84 tornadoes occurred, some of which hit populated areas including the Memphis metropolitan area in Jackson, Tennessee.<sup>56</sup> These occurrences demonstrate that notable tornado outbreaks can and do occur outside of ‘tornado season’.

Figure 5: US Tornado Averages by Month 1991-2010<sup>57</sup>



Source: NOAA

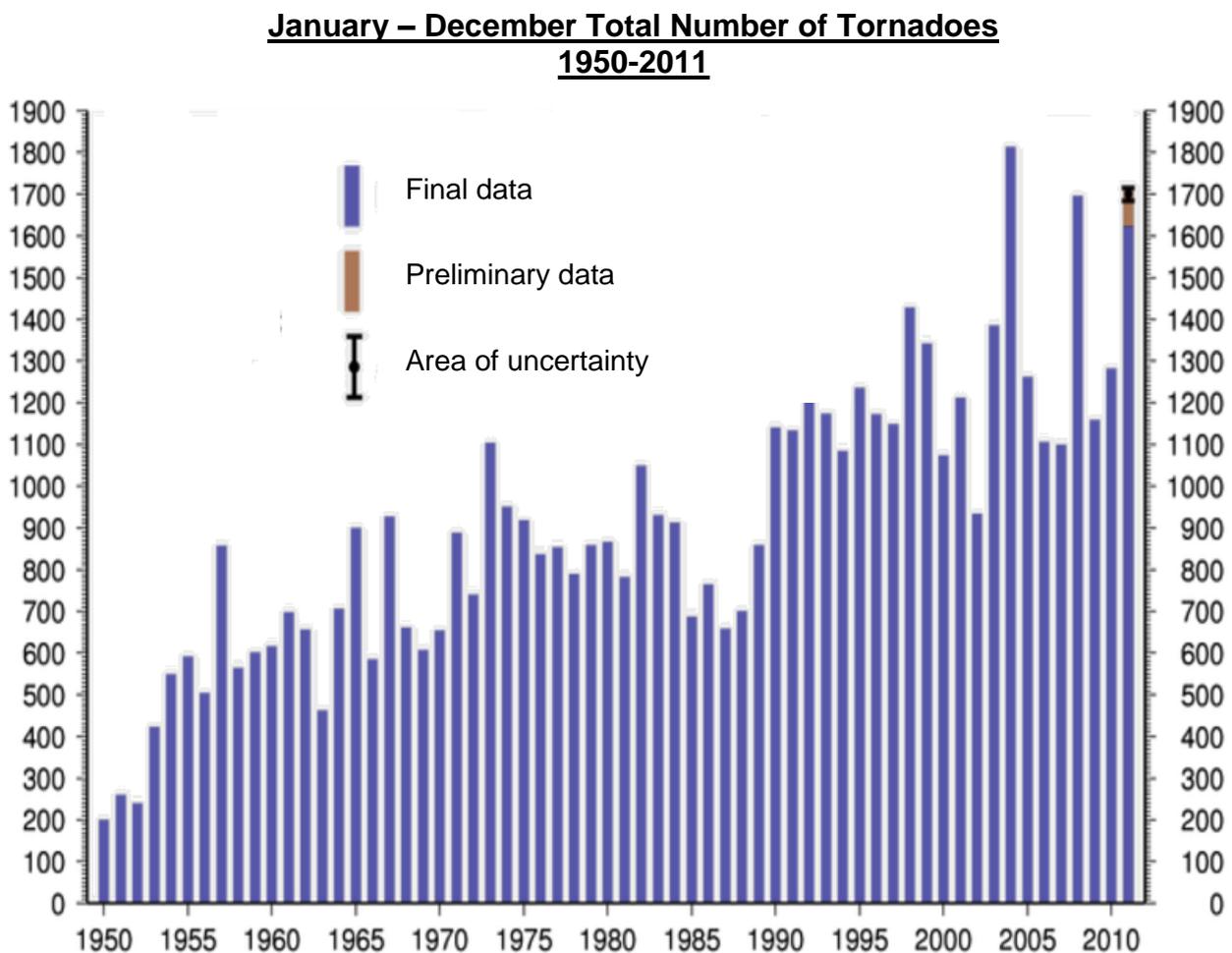
As well as particular months, particular times of day are also more likely to experience tornadoes. In the US, severe thunderstorms capable of forming tornadoes usually form when temperatures are at their highest in the afternoon and early evening hours.<sup>58</sup> Tornadoes which occur during the night can pose a greater threat as people are likely to receive ample warning.

## 7 FREQUENCY AND SEVERITY

### 7.1 FREQUENCY

The number of tornadoes can vary from year to year and what makes tornadoes more frequent in one year than another is not yet understood, nor predictable. Whilst a quick look at statistics will show that the number of tornadoes being reported in the US has been steadily increasing over the past half century (see Figure 6), it is important to consider the influence of other factors that may affect the reported frequency of tornadoes. The graph below shows the annual tornado count from 1950–2011, demonstrating a clear trend of increasing tornado reports. In the 1960s, the annual average reports in the US were around 650 (Figure 6), whilst today they average over 1000. Since the mid 1950s tornado reports have increased on average by 14 a year, taken alone however this figure means little and socio-economic factors provide a better explanation for this trend than meteorological ones.<sup>59</sup>

Figure 6: January – December Total Number of Tornadoes 1950-2011<sup>60</sup>



Source: NOAA

### 7.2 DIFFICULTIES IN DETERMINING TRENDS

Tornado record keeping has a relatively short history (official reporting and collection of data only began in the 1950s) which means that attempting an analysis of long-term trends is difficult. Additionally, maintaining record keeping consistency for climatological studies has not been a major priority for surveyors, with recording of tornadoes used more for verification of forecasting purposes.<sup>61</sup> As previously noted, it is extremely difficult to measure and record tornadoes using wind speed and, as such, reporting relies on

human verification. Although with guidance (e.g. the Fujita Scale) human records of tornadoes can help to standardise reports, they may still be prone to exaggeration and different interpretations of damage intensities. The reliance on the presence of a human observer has also meant that some tornadoes have gone unreported,<sup>62</sup> While tornado records can be examined as far back as 1950, tornadoes from 1950-1970 were rated retrogressively using photographs and newspaper reports, while those from 2007 were rated using the enhanced version of the Fujita scale; leading to obvious inconsistencies. The US is very much an exception in having a ~60 year tornado record. Indeed, in most other countries (besides Canada and some European countries) there is no systematic documentation of tornadoes, other than of those that cause great damage or loss of life.

One reason for the increasing number of tornado reports is due to the geographical dispersion of people. The link between increasing population growth and number of reported tornadoes is arguably not entirely coincidental. As populations have increased, so has urban sprawl, and fewer areas remain completely unpopulated. In turn, the organisation of 'storm spotter' networks, community education and awareness programs has increased and improved, making those who might encounter tornadoes in the suburbs and exurbs more weather-aware. These factors, as well as advances in technology such as the Doppler radar, can all be seen as influences on increased tornado reporting.<sup>63</sup>

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### 7.3 INFLUENCE OF CLIMATIC FACTORS

Although effects may not be observable for individual tornado seasons (especially during weak El Niño Southern Oscillations episodes), when long term trends are examined natural climate variability, such as El Niño and La Niña phases, can be seen to have an effect on severe thunderstorm activity in North America.<sup>64</sup> El Niño is characterised by unusually warm temperatures in the equatorial Pacific, and La Niña by unusually cool temperatures in the same region.<sup>65</sup>

La Niña phases tend to be characterised by an anomalously strong jet stream over North America.<sup>66</sup> The associated extra-tropical storms help to move cold air masses from the northwest to the southern parts of the Great Plains.<sup>67</sup> When these masses encounter the warm and moist air masses from the Gulf of Mexico, intense thunderstorms occur which have the potential to spawn tornadoes; this happens especially in late winter and spring. A stronger jet stream also enhances vertical wind shear, which is favourable for severe thunderstorm formation. The effects of La Niña on tornado activity are felt mostly by the area that extends from Louisiana, Mississippi, Alabama and Georgia in the south to the Great Lakes in the north. Enhanced levels of vertical wind shear mean that it is more likely that long-lived supercell storms will form. During a strong La Niña phase, Tornado Alley, the region frequently hit by significant tornadoes, extends eastwards. Notable examples of tornadoes occurring during a La Niña phase are the 1974 Super Outbreak as well as the two outbreaks of 2011.<sup>68</sup>

By contrast, El Niño phases can be associated with more frequent tornadoes in the southern US. During such a phase, the jet stream in winter and spring is, in general diverted to the south. During El Niño the areas close to the Gulf Coast and in Florida are most affected, there are on average fewer thunderstorm and tornado outbreaks inland.<sup>69</sup>

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### 7.4 SEVERITY

Tornadoes not only vary in frequency but also severity. Table 3 demonstrates that, whilst there has been an increase in the frequency of all reported tornadoes, this has not been coupled with an increase in the number of strong to violent tornadoes. The vast majority of tornadoes reported are considered weak, and the increase in tornado reporting has mainly been an increase in the number of reports of weak tornadoes. Indeed tornado reports over the last 50 years indicate that the US experiences an average of 800 weak, 173 strong and nine violent tornadoes annually.<sup>70</sup> Figure 7 shows a graphical representation of these trends.

**Table 3: Tornado Reports<sup>71</sup>**

F Rating	1970-1979	1980-1989	1990-1999	2002-2011
F0	274	331	739	816
F1	343	334	331	376
F2	188	124	109	108
F3	50	33	38	31
F4	14	9	9	7
F5	3	1	1	1
TOTAL	872	832	1227	1339
F2 AND ABOVE	255	167	157	147

**Figure 7: Number of Tornado Reports by Intensity<sup>72</sup>**

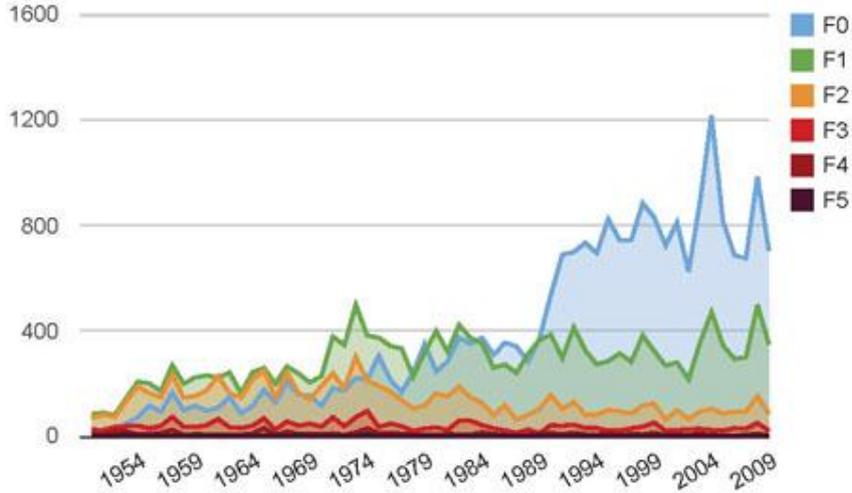
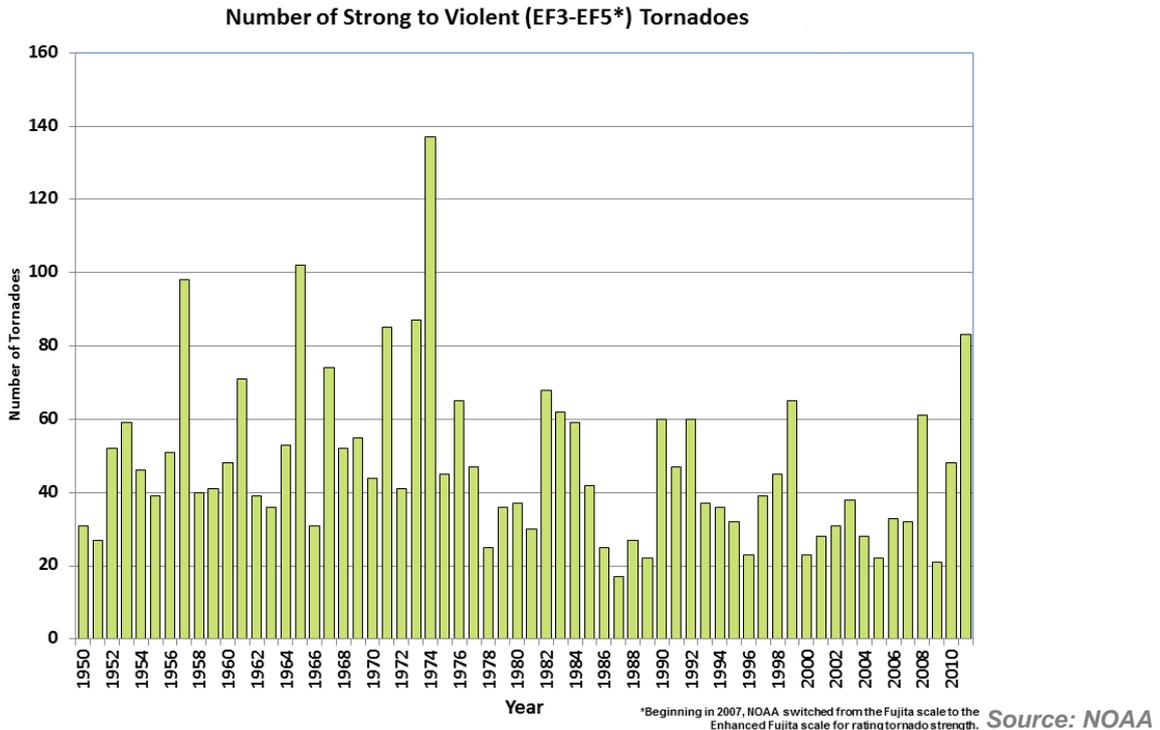


Figure 8 indicates that the increase in reporting has mainly been for F0-F1 tornadoes by showing little noticeable trend in the number of strong to violent tornadoes being reported in the last 60 years, suggesting little evidence from the available record that tornadoes are becoming more severe.

**Figure 8: Number of Strong to Violent Tornadoes<sup>73</sup>**



In total the US has seen over 50 F5 and EF5 tornadoes since records began in 1950.<sup>74</sup> The probability of a high intensity (violent) tornado forming may, however, differ by geographical location. Due to the meeting of air masses, Tornado Alley experiences a high frequency of strong thunderstorms capable of spawning a tornado. The higher frequency of tornadoes here makes it more likely that a violent tornado will form. States with the highest recorded number of F5 and EF5 tornadoes (since record keeping began in 1950) tend to be found in Tornado Alley: Alabama has the highest number with seven recorded, whilst Iowa, Kansas, Oklahoma and Texas have each experienced six of the highest rated tornadoes.<sup>75</sup> Such high intensity storms can record winds of over 322kph and may stay on the ground for over an hour causing significant damage.

## 8 TORNADOES AND CLIMATE CHANGE

While socio-economic factors can explain, to a large extent, the increasing number of recorded tornadoes and tornado losses, there has been some debate as to the possible influence of climate change.

Whilst it is easy to determine the weather characteristics (atmospheric conditions) which can produce tornadoes, it is more difficult to determine long term climate trends for tornado activity.

There are some difficulties in historical data collection and in its accuracy, including under-reporting and over-estimating intensity, which make any long term tornado records unreliable. Inconsistencies in the reporting criteria for tornadoes as well as improvements in technologies used to observe tornadoes have made development of long term climatologies for such weather events almost impossible.<sup>76</sup> The climate is changing, but these changes have to be observed over periods of decades. The record of severe weather events in the US, although the best of its kind in the world, remains compromised by reporting and rating errors and non-meteorological factors such as increased population making it difficult to identify from the data how climate change might influence the occurrence of major tornado outbreaks.<sup>77</sup> According to the National Science and Technology Council's 'Scientific Assessment of the Effects of Global Change on the US', "Trends in extreme weather events that occur at small spatial scales-such as tornadoes, cannot be determined at the present time due to insufficient evidence."<sup>78</sup> Tornadoes occur on the time scale of seconds and minutes, and a space scale of fractions of a mile across. Climate trends can take many years, decades, or even millennia to be distinguished from natural variability.<sup>79</sup>

While these issues highlight the difficulty in gathering sufficient, reliable data to analyse, another issue is the inability of current climate models to resolve individual thunderstorms.<sup>80</sup> Severe weather events occur on small spatial scales (a few km) that are well below the horizontal resolution of almost all currently available climate models (spatial scales of 10 – 50 km).<sup>81</sup> As a result, climate modelling is incapable of analysing the existence of climate driven changes in frequency and intensity of small scale weather events.<sup>82</sup>

However, by looking at the long term trends in large scale meteorological conditions that are favourable for the formation of severe thunderstorms, it may be possible to make a few projections.<sup>83</sup> These projections provide a mixed message. It is likely that some atmospheric conditions conducive to tornadoes will increase with climate change while others may decrease, placing limitations on any conclusion as to whether severe thunderstorm activity will increase or decrease.<sup>84</sup> Indeed, the IPCC's recent report on climate change adaptation confirmed the low confidence in projections of small-scale phenomena such as tornadoes, because competing physical processes may affect future trends, and tornadoes are not simulated by climate models<sup>85</sup>.

A report published in 2008 by the US Global Change and Research Program, overseen by the White House Office of Science and Technology Policy, found that increasing levels of green-house gases in the atmosphere could lead to an increase in severe storm conditions.<sup>86</sup> The main meteorological conditions which favour the formation of severe thunderstorms are Convective Available Potential Energy (CAPE) and vertical wind shear. CAPE measures energy in the atmosphere which is available for convection. It is directly related to maximum potential vertical speed within an updraft: higher values indicate greater potential for severe weather.<sup>87</sup> Generally, the more water vapour present within warm air found at low atmospheric levels,

the higher the CAPE.<sup>88</sup> It is estimated that an increase of 1°C in air temperature, can increase the capacity of the atmosphere to hold water vapour by 7%. This has been reflected in long term humidity trends in the US. Examining data for the period of 1973-2003 a clear increase in humidity can be observed, demonstrating clear correlation with increase in air temperature most likely driven by anthropogenic warming.<sup>89</sup> Continued global warming, increasing temperature and humidity levels are therefore likely to coincide with increased levels of CAPE.<sup>90</sup>

Whilst climate change can be seen to contribute to an increase in CAPE, at the same time, continued warming could lead to a decrease in vertical wind shear, another important parameter for severe thunderstorm formation. Climate model simulations project that warming would occur in northern polar regions, which would reduce the temperature differential between the pole and the equator. This would be likely to lead to a decrease in vertical wind shear and extra-tropical cyclone intensity which would make the formation of the supercell thunderstorms which spawn tornadoes less likely.<sup>91</sup>

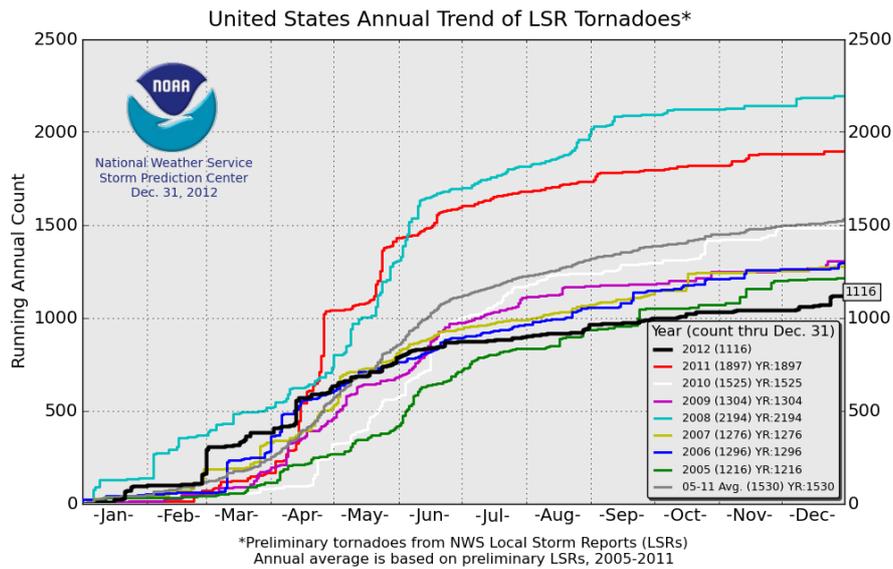
It is difficult, therefore, to project a meaningful trend in the combination of atmospheric conditions required for severe thunderstorm and tornado formation. While regions that have experienced peak tornado occurrence may see reductions due to weakened vertical wind shear, these reductions could well be offset by increasing CAPE which could increase occurrence.<sup>92</sup> The areas affected may also shift in location, areas which currently have the highest occurrence of tornadoes could move polewards as a result of shifting peak wind shear. These factors leave forecasting open to a large element of uncertainty, and even if trends can be detected in favourable factors, these do not necessarily guarantee tornadoes. Tornado formation is dependent not only on large scale meteorological conditions coming together but also on day-to-day patterns and minute-to-minute local weather.<sup>93</sup> This means that the future regarding tornado outbreaks and activity remains largely unknown and unpredictable. Weather forecasts and climate models are unable to definitively predict a tornado more than a few minutes in advance nor can they make projections on the effects of climate change on tornado numbers and intensities.<sup>94</sup>

The anomalously high activity of the 2011 tornado season ignited the debate on the effect of climate change on tornado activity. However, experienced meteorologists are keen to dispel any link at this time. Experts have emphasised that there is 'no evidence' that the events of spring 2011 are 'meteorologically unprecedented'.<sup>95</sup> The similarities between the outbreak on 27 April 2011, which affected southern, midwestern and northeastern states and the 'super' outbreak of April 1974 demonstrate that the atmospheric conditions particularly favourable for the formation of tornadoes have been present in the past and are likely to be present again in the future. These events are better seen as weather events; just as one extremely hot day in summer is not an indication of rising temperatures, so an increase in tornadoes in one year does not necessarily imply anything about the long term average.<sup>96</sup>

Referring to the tornado outbreaks of 2011, Joshua Wurman, the lead tornado researcher and president of the Center for Severe Weather Research, said "If we started seeing this every year, we'd say that this is a climate change. But we're not seeing that." Rather than a climactic shift, he believes the 2011 tornado season is really just 'bad luck'.<sup>97</sup>

The 2012 tornado season reiterates these points. Harold Brooks of NOAA, examined inflation adjusted tornado reports between 1954 and 2012. He found that the median tornado count for the period 15 April-21 July was 850. This figure represents approximately two thirds of the annual average number of reported tornadoes in the US. In 2012 this period saw fewer than 300 recorded tornadoes ie 2012 experienced over 40% fewer tornadoes than the average for this period. In comparison the 2011 season has the second highest number of tornadoes in this period (over 1100) across the whole record. In the last two years the US has therefore experienced seasons with numbers of tornadoes at the extreme high and low ends of the observed distribution<sup>98</sup>. The graph below from the SPC shows the seasonal variability in tornado trends.

Figure 9: United States Annual Trend of LSR Tornadoes<sup>99</sup>



Source: SPC, NOAA

## 9 LOSSES

### 9.1 INCREASING EXPOSURE

The majority of damage caused by tornadoes comes from wind-induced forces tearing structures apart. When high-speed air flows over a building's roof and around its corners it produces forces which pull upward and outward. Once windows or doors in the building break, air is able to rush in pushing upward on the roof and outward on the walls. These forces are powerful and often a building can be torn apart so quickly it appears as if it has exploded. As a result property damage in a violent tornado's path can be severe.<sup>100</sup> However, it is not just high severity tornadoes that have the potential to cause damage. Large losses may be recorded from relatively low-severity tornadoes. The single F2 tornado that cut a narrow path across Atlanta in March 2008, for example, caused an estimated \$340m of damage in less than 20 minutes.<sup>101</sup>

A major factor which has influenced tornado losses is increasing exposure of property. In a major outbreak, violent tornadoes can be anomalously long lived and have wide damage paths, affecting large areas. As populations have grown and spread into previously uninhabited areas, the chances of this occurring have increased. It has been estimated that a major tornado outbreak in which tornadoes strike large metropolitan areas occurs only about once every 20 years or so.<sup>102</sup> However as densely populated suburbs which surround cities continue to grow, the chances of tornadoes hitting an urban or suburban region increases. In turn, it is likely that property damage claims for tornado damage will become more expensive as the values at risk grow.

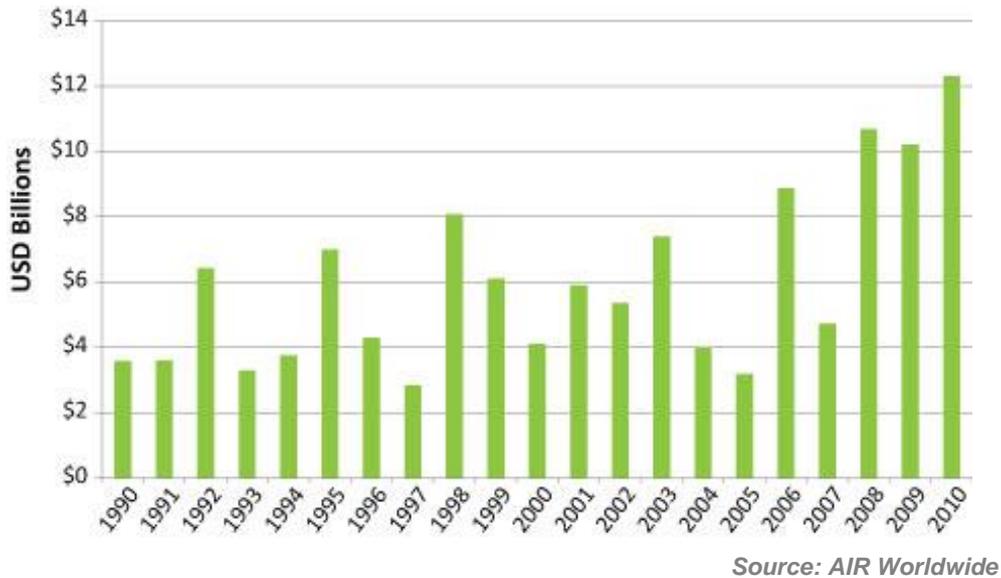
### 9.2 PREDICTING THE LOSSES

Modelling insured losses from tornadoes is difficult. Wind-speed measurements are often not available for the hundreds of tornadoes that occur annually. Tornado damage is often localised; in some cases one side of a street may remain completely intact whilst the other is completely destroyed. Although, general trends can be identified in terms of frequency and severity of tornadoes for different states, it is extremely difficult to predict the exact locations where tornadoes will make landfall. Whilst vast areas are vulnerable to tornadoes, only a small area and number of people will be severely affected each year. Due to these factors, insurers often invest little in tornado modelling in comparison to hurricanes and earthquakes<sup>103</sup>.

However, costs seem to be increasing. In the US, annual aggregate losses from severe thunderstorms have, on average, accounted for more than half of all insured catastrophe losses since 1990. Billion dollar losses are becoming more frequent. For example, both 2008 and 2009 saw three severe thunderstorm events which cost over \$1bn, whilst the record breaking 2011 cost the insurance industry over \$25bn.<sup>104</sup> It is clear that damage costs from thunderstorm events are increasing and this is a trend that is likely to continue; the result has been costly for the insurance industry and has had a significant effect on many insurers' bottom lines.<sup>105</sup>

Figure 10 below shows an upward long-term trend for aggregate annual losses.

**Figure 10: Aggregate Annual Severe Weather Losses<sup>106</sup>**



NB: The above AIR graph includes losses from hail and straight-line wind as well as from tornadoes

### 9.3 INJURIES AND FATALITIES

On average tornadoes in the US cause 80 deaths and injure a further 1,500 people.<sup>107</sup> Since records began warning systems have improved and NOAA attribute most tornado-related deaths to people failing to adhere to instructions on what to do in the event of a tornado. The number of people who are not warned has decreased with improvements in technology and, in turn, the number of deaths per year has decreased. The number of deaths resulting from tornadoes was generally lower for the last quarter of the 20th century than previously. Tornadoes recording over 100 deaths occurred only twice in the period between 1975 and 2000 compared with 54 times between 1875 and 1974. From 1916 to 1998 the average number of deaths per year was much higher than it is today at 150 per year. Between 1953 and 1998, the figure decreases to 88, demonstrating that deaths from tornadoes were much higher in the first part of the century.<sup>108</sup>

### 9.4 MOBILE HOMES

People living in mobile homes make up a disproportionate number of fatalities caused by tornadoes. Since 1975 the National Weather Service has measured fatalities by location. They examine the number of deaths that occur in mobile homes, permanent homes, other buildings, vehicles and outdoors. From 1976 to 1980, 24% of tornado deaths were in mobile homes; this percentage increased to 34% between 1986 and 1990 and to 50% from 1996-2000.<sup>109</sup> NOAA estimates that one third of all tornado fatalities occur in mobile homes and that people living in mobile homes are 23 times more likely to be killed by a tornado than those

in permanent houses.<sup>110</sup> Since 1950 mobile homes as a proportion of total housing in the US have increased. Using data taken from the decennial census carried out by the Census Bureau it can be inferred that ten times the amount of people lived in mobile homes in 1990 compared with 1950.<sup>111</sup> Notably a large increase in the number of mobile homes has been seen in southeastern US, an area prone to tornadoes. This is of special concern as a number of tornadoes have been known to occur in this area over night when getting messages to people proves particularly difficult. Examples include the night time tornadoes in Orlando, Florida (1998) and Camilla, Georgia (2000). As mobile homes have less wind resistant construction they may fail to provide adequate protection during a tornado event. In April 1991, a tornado with a 74 km path hit the town of Andover in Kansas, 84 homes and 14 businesses were destroyed by the tornado but with no fatalities and only minor injuries. However the tornado proceeded to sweep through a mobile home park where it destroyed over 80% of homes. The park had a shelter where over 200 residents took cover. However, some people decided to stay in their mobile homes, which led to 13 fatalities.<sup>112</sup>



**Figure 11:**<sup>113</sup> The Golden Spur Mobile Home Park was almost completely destroyed in the April 1991 tornado. (reprinted with permission of the Wichita Eagle)

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## 9.5 RECENT LOSSES

Recent years have seen some of the most costly tornado losses in history, including the Super Tuesday outbreak in 2008 and the record breaking outbreaks of 2011.

### 9.5.1 Super Tuesday Tornado Outbreak, 5-6 February 2008

The beginning of 2008 was unusually active in terms of tornadoes. The month of January saw the second highest number of tornadoes recorded since records began, whilst the beginning of February also saw a higher than average frequency of tornadoes.<sup>114</sup>

The tornado outbreak of February 2008, dubbed Super Tuesday because many states were holding primary elections that day, culminated in 87 tornadoes touching down in nine states, causing 57 fatalities over a 12 hour period.<sup>115</sup> In terms of fatalities this was the second highest recorded tally for a February outbreak since records began in the 1950s. The outbreak saw five recorded EF4 tornadoes, two in both Tennessee and Alabama and one in Arkansas along with five EF3 and 15 EF2 Tornadoes.<sup>116</sup> In Arkansas a notable EF4 tornado touched down with a continuous damage path of 196km, the longest recorded in the state since 1950. Another notable tornado from the outbreak was the EF3 tornado in Tennessee. The tornado had a 82km damage path crossing over areas just north west of Nashville and causing 22 deaths. At the time this

was the deadliest single tornado since November 2005.<sup>117</sup> Among the areas damaged was a shopping mall in Memphis and Jackson where buildings belonging to Union University were damaged. Here, an EF4 tornado passed through the middle of the campus, tearing the roof off the main academic hall and destroying over 80% of the student dormitories. The tornado served as an example that construction can make a considerable difference to damage in the face of tornadic winds. Many of the wood frame dormitories experienced damage exceeding 90%, those with concrete-block side walls fared slightly better, whilst two masonry academic buildings experienced damage restricted to their roofs.<sup>118</sup> In total insurers were left with a bill from the outbreak totalling close to \$1bn.<sup>119</sup>



**Figure 12:**<sup>120</sup> The picture of the left shows the complete destruction of the wood frame Jelks dormitory, whilst the masonry academic building, Jennings hall (right) experienced damage only to the roof. (Source: AIR Worldwide)

NOAA identified certain key demographic and social factors which contributed to the losses:<sup>121</sup>

- 63% of fatalities occurred in manufactured homes
- The majority of fatalities occurred at night
- The majority of areas affected by tornadoes were heavily forested
- Many reported that February was not a month that they perceived to be the ‘tornado season’

Thus, despite the Storm Prediction Centre monitoring the storms six days prior to the event, and ultimately issuing a high risk convective outlook for the large portion of the impacted area on the morning of Tuesday 5 February, the outbreak still proved deadly.

### 9.5.2 The 2011 tornado season

2011 was also an unusual and costly year in terms of tornado activity. During the spring and summer of 2011 there were seven individual tornado and severe weather outbreaks which resulted in damages exceeding \$1bn. Total damage from the outbreaks amounted to \$28bn, the highest cost of property damage from severe weather outbreaks in a single year since record keeping began (in 1950). During the year, six EF5 tornadoes were recorded by the National Weather Service, this ties with 1974 as the most EF5 tornadoes in a year. Fatalities totalling 551 were the highest for the 62 year period of records.<sup>122</sup> The unusually active spring, coupled with the fact that tornadoes hit populated areas led to the extensive property damage and loss of life.

#### 9.5.2.1 April

April was a particularly active month. In total 748 tornadoes were reported, which is more than any other month in history. The tornado outbreak in the last part of April 2011 was the result of a powerful extra-tropical cyclone which developed over the southern plains and moved eastward across the Ohio River Valley.<sup>123</sup> 305 tornadoes were recorded during the outbreak between 08:00 on 27 April and on 28 April 2011. This figure easily surpassed the previous record of 148 tornadoes recorded in an outbreak that happened between 3 April and 4 April 1974.<sup>124</sup> Northern Alabama was particularly affected by the events.

The city of Tuscaloosa which is situated on the suburbs of Birmingham, Alabama was hit by a F4 tornado which stayed on the ground for over 113km and reached a maximum width of 2.5km. This tornado represented the largest single cause of insured loss of the outbreak and caused over 60 fatalities.<sup>125</sup> Between April 22 and 28, 23 states were affected by tornadoes and altogether the April tornadoes caused over 300 casualties. Experts have pointed out that whilst none of the individual weather elements (a strong jet stream and persistent frontal feature) that created the outbreak are unusual, it is rare that all the risk factors come together optimally in the same place at the same time.<sup>126</sup>

Most weather-related losses are covered by homeowners and commercial insurance policies. The 2011 April super outbreak of tornadoes resulted in an estimated \$7.3bn in insured damage, the largest insured loss event caused by a thunderstorm outbreak<sup>127</sup>

### 9.5.2.2 May

2011 experienced another major tornado outbreak in May. Although the first 15 days of the month saw the fewest recorded tornadoes for the previous 25 years, the lapse rates, moisture and shear conditions in the latter half of the month were similar to those observed in April. Major tornadoes occurred from 20 – 27 May as a series of low pressure systems triggered waves of severe thunderstorms which stretched from Texas to the Mid-Atlantic States. 250 tornadoes occurred including three F4 and two F5 events.<sup>128</sup> At least 178 fatalities were recorded as a result of the outbreak.<sup>129</sup> Overall insured losses were \$6.9bn.<sup>130</sup> Much of the loss occurred as a result of a single event: a tornado which originated near the Kansas-Missouri state line and rapidly intensified as it moved eastward over densely populated Joplin on 22 May. At its greatest intensity the tornado reached F5 and had a maximum width of 2km. It is estimated that up to a quarter of the building stock was destroyed.<sup>131</sup> Estimated overall losses from the Joplin tornado exceed US\$3bn and direct casualties amounted to 158.<sup>132</sup>

Whilst the conditions which were present prior to the formation of the two tornado outbreaks in April and May 2011 were similar, the outbreaks manifested themselves in different ways. The 27 April outbreak is notable because of the large number of long-track, strong to violent tornadoes whilst the 22 May Joplin Tornado stands out as the only US single tornado to have produced more than 100 fatalities in over 50 years. Although meteorological events may share certain similarities, this highlights the fact that every meteorological event is unique in detail and has important repercussions for tornado reporting and research.

## 10 RISK MITIGATION

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### 10.1 WHAT CAN BE DONE?

When a tornado hits, little can be done to prevent damage to structures which fall within its path. Mobile homes are particularly vulnerable to damage, their light construction means they begin to come apart at relatively low wind speeds. They also fuel tornadoes with debris due to their easy destruction. Even in weak tornadoes mobile homes provide a risky form of shelter and as a result some cities such as those in Minnesota have installed mandates for shelters in mobile home parks.<sup>133</sup> While little can be done to protect mobile homes, certain building practices could help to mitigate damage from weaker tornadoes to permanent homes. Securely fastening the roof of the building to the walls and securing the walls to the foundations may help reduce damage to structures especially from lower rated tornadoes.

Protecting property against tornadoes is expensive. No official building codes exist for areas prone to tornadoes as they do for certain areas which are prone to other hazards such as earthquakes. This is largely due to the return period (the interval between two events in a given location). Tornadoes affect very small areas (of order 250-270 km<sup>2</sup> annually) and the likelihood of two tornadoes occurring in exactly the same place is very small – return periods may be thousands of years.<sup>134</sup> It has been estimated that the chances of

a particular building in Tornado Alley being hit by a tornado in a given year are only one in 5000, and in turn the chances of this tornado being of magnitude F4 or F5 are even lower.<sup>135</sup>

In practice, a number of cities have implemented the international building code which includes 'Wichita'; an amendment which requires buildings to be built to withstand 145kph 'straight line' (i.e. non-tornadic) winds. Home owners may also chose to build a storm shelter which is designed to withstand 322kph winds. In some participating states money is available from the Federal Emergency Management Agency (FEMA) for households to build a storm shelter. FEMA has estimated the cost of constructing a safe home inside a new home/small business at somewhere between \$6,500 and \$8,500.<sup>136</sup> Due to this relatively high cost, and the large return period of tornado losses in a particular location, it is not deemed cost effective to implement mandatory shelters in homes across Tornado Alley.

According to Donald Griffin, Vice President of personal lines at the Property Casualty Insurers Association of America: "Because tornadoes can occur rapidly and with little warning, advanced preparation is very important. We encourage consumers to know the warning signals used in their community and be prepared to take cover when alerted".<sup>137</sup>

## 10.2 PREDICTION AND DETECTION

In the US, the National Weather Service (NWS) issues official national tornado forecasts. Individual tornado warnings will be given by local NWS offices, whilst the Storm Prediction Centre (SPC) will issue tornado watches, general severe weather outlooks and mesoscale discussions, which are updates to local forecasters in a region where a severe weather threat is emerging. Very few other nations have a specific tornado watch and warning service in place.<sup>138</sup>

The improvement of tornado forecasting remains problematic, meaning tornadoes remain deadly and somewhat unpredictable. This is reflected in the relatively low average lead times (ie the time between issuance of a warning and occurrence of the tornado) of just ten-15 minutes.<sup>139</sup> As discussed earlier, a very low percentage of thunderstorms spawn tornadoes and it can be difficult to predict the instances when this will occur. Long term forecasting for tornadoes is not currently possible because there are too many small-scale variables involved in tornado formations which occur and change rapidly and, as such, cannot be measured reliably or modelled weeks or months in advance.<sup>140</sup> Although scientists can detect the conditions necessary for the formation of tornadoes in the atmosphere, predicting when and where a tornado will strike is not an exact science.

Using data from weather forecast models, it is relatively easy to identify areas that may be favourable for the development of severe storms several days in advance. Essentially these are areas where cool dry air at middle levels in the troposphere is superimposed over a layer of moist, conditionally unstable air near the surface. Forecasters can readily identify these regions of instability and assess the expected wind profiles in these regions. Observing systems such as vertically pointing radars (wind profilers), radiosondes (weather balloons) and imaging systems on satellites which can measure winds at various levels in the atmosphere have helped give forecasters up to seven hours' notice of the existence of favourable tornado conditions. Once these conditions have been identified, forecasters will issue a tornado watch to the public then, once a tornado has been spotted either visually or via a weather radar a tornado warning will be issued.<sup>141</sup>

### 10.2.1 Monitoring Equipment

Forecasters at the National Weather Service use many devices to aid them in the prediction and detection of tornadoes. Advances in modern technology and the capability of weather forecast models have supported their work. Using imagery from satellite sensors and radars, scientists are able to monitor the development of strong thunderstorms. Scientists can monitor the progress and evolution of a storm and form estimates of its intensity. Sequences of radar data show the speed and direction of movement of a storm, from which its likely future path can be inferred. In the past, forecasters had to infer the onset of rotation within a storms updraft, as radars were only able to provide intensity levels of rainfall. This was done using circumstantial

evidence, for example monitoring when a ‘hook echo’ formed.<sup>ii</sup> However relying on such predictions led to volatile results due to the subjectivity of the inferences; false alarms were common and where a warning was given it was often at very short notice. The situation has, however, improved with the introduction of new technology such as the Doppler radar. Between 1992 and 1996 a network of advanced Doppler radars was implemented in the US known as NEXRAD.<sup>142</sup> A Doppler radar works by using a mechanical rotating dish which sends out pulses of microwave radiation, a small fraction of which is reflected or scattered by clouds, raindrops and hail.<sup>143</sup> These radars go beyond providing precipitation intensity readings from within a storm and utilise what is known as the Doppler principle in order to sense winds within thunderstorms. Microwaves reflect off particles carried along by the wind including raindrops in order to determine the wind speed within the storm.<sup>144</sup> Doppler radars can measure the atmosphere in the direction horizontally towards or away from the radar (the radial velocity).<sup>145</sup> Certain patterns (‘signatures’) in the radial velocity data can indicate the presence of storm rotation, which may be a precursor to tornado formation.<sup>146</sup>

However, despite representing an improvement to previous radar technologies, there remain some problems with Doppler radars. At the time of writing, most operational radars take at least five minutes to do a 360° scan of the sky meaning information can only be updated at five minute intervals.<sup>147</sup> This is a problem because many tornadoes can develop and intensify extremely quickly. Harold Brooks of the National Severe Storm Laboratory (NSSL) noted that ‘five minutes can be a long time in tornado world’ and speaking about the deadly Joplin Tornado of 2011, which wasn’t violent until just about the time it hit the town’s hospital, Brooks said ‘even when you’re in the field there are times when you’re surprised by the event and how fast it started.’<sup>148</sup> The rapid development and evolution of tornadoes limits the accuracy even of very short-term forecasts.

### 10.2.2 Future Forecasting

Average trends suggest that further increases in lead time will be difficult to achieve using the current system which relies on a warn-on-detection approach using NWS Doppler radars.<sup>149</sup> Work is currently being carried out by the NSSL with particular focus on improving radar technology. David Stensrud, head of the Warn-on-Forecast programme at NOAA, is looking to try and shorten radar sweep time down to one minute by replacing rotating disks with flat electronic panels which sample the sky electronically. The intention is that these panels will be able to focus on particular areas of the sky where tornado formation is most likely and retrieve information at intervals of 20 seconds. Stensrud aims to improve observations of storms before they become severe in order to improve warning times.<sup>150</sup> Although this will mark an improvement in radar sensing, and hopefully tornado prediction, it is likely this technology will not be ready for operational use for about ten years.

## 11 RISK TRANSFER

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### 11.1 MODELLING EFFORTS

Despite tornado frequency and the magnitude of potential losses, many insurers treat severe thunderstorm events simply as a cost of doing business. Insurers heavily exposed to severe thunderstorms, who actively model hurricanes and earthquakes, often make little or no investment in modelling tornado peril, which arguably contributes significantly to volatility in financial results.<sup>151</sup> The increase in aggregate losses from tornadoes each year, as the quantity and value of property exposed to the risk increase, means that tornado losses are increasing in value. The extraordinarily active year of 2011 highlights this fact.

Annual aggregated thunderstorm losses are less volatile than those from tropical cyclones. Whilst a major hurricane in a given year can cause damage which greatly surpasses annual losses from thunderstorms,

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<sup>ii</sup> A hook echo is a hook shaped region on the edge of the storm that wraps around the updraft.

long term severe thunderstorm losses (including tornadoes) are comparable to those from tropical cyclones. Between 1980 and 2011, 43% of windstorm losses were attributable to severe thunderstorms compared with 50% for tropical cyclones.<sup>152</sup>

Recent growing population density in some of the areas at highest risk from severe thunderstorms has led to increased exposure to tornadoes. Oklahoma City, for example, saw a 15% increase in population from 2000-2010.<sup>153</sup> The number of properties has increased as areas exposed to tornadoes become more urban. Billion dollar losses are becoming increasingly common, and it is becoming more important to try to model tornado risks in order to determine exposure. There is limited availability of reliable historical data on frequency and intensity of severe storms. Records are only available for a relatively short time span for directly observed and rated tornadoes, making risk modelling more difficult. In 2010, two severe thunderstorm outbreaks cost over \$2bn, while aggregate losses approached \$13bn. Records were broken in 2011 with two occurrences of losses of more than \$6bn each. With losses this great, some insurers are transitioning from treating severe storm losses as a cost of doing business to incorporating sophisticated modelling techniques to provide a complete view of their risk.<sup>154</sup>

Catastrophe models are provided by modelling companies including AIR, RMS and EQECAT, with some incorporating tornado risk into a three peril model: Tornadoes, Hail and Straight Line Wind. Models which rely completely on historical catalogues can be biased due to under or over reporting of events. CAT Models therefore incorporate other factors such as weather observation, historical damage surveys and industry claims.<sup>155</sup> By using simulated footprints of each peril and a high degree of spatial resolution, average annual losses can be calculated for any location, enabling a user to be site specific. This allows single location underwriting analysis.<sup>156</sup>

The uptake of CAT Modelling for tornado risk has been slow in the past as insurers have considered tornadoes a cost of doing business in the US; one of the modelling companies commented that their models were not in wide use by its insurance clients before last year. However, the increasing capacity for potential losses, as seen in 2011, is beginning to increase the use of modelling for tornado risk.<sup>157</sup> Modelling may become an increasing concern for reinsurers who might be affected by the largest tornado losses.

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## 11.2 TORNADO AND HAIL

Another peril which results from severe thunderstorms is hail. It is estimated that hail causes at least \$1bn dollars in damage to crops and property every year in the US.<sup>158</sup> In April 2001, Kansas City experienced a hail storm which caused over \$1.5bn in damage.<sup>159</sup>

Hail forms when small ice particles in a cloud encounter super-cooled water droplets (liquid water at temperatures well below 32°F (0°C)), which freeze on contact. This process usually occurs where strong updrafts are present. Eventually the growing ice particles fall as hail. Particularly large hail can occur in supercell thunderstorms, due to their very strong updrafts. The occurrence of large hail may therefore show some correlation with the occurrence of tornadoes, which are also sometimes produced by the same supercell storms. With eastward- or northeast-ward moving supercells, hail can often be seen immediately north of a tornado track. However, the presence of hail certainly doesn't guarantee there will be a tornado. Conversely, its absence does not mean there is no tornado risk.

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## 11.3 INSURANCE IMPLICATIONS

### 11.3.1 Property

Tornadoes primarily cause loss and damage to property. In the US, wind and hail damage to property is covered as standard by the majority of homeowners policies.

The majority of property insurance policies will provide coverage for losses resulting from tornadoes however hazards which may accompany tornadoes may be covered differently. Damage from flash flooding which may accompany tornadoes is not covered.<sup>160</sup> Homeowners and small businesses can purchase cover for

flash floods up to a specific amount under the National Flood Insurance Program, designed to provide an insurance alternative to disaster assistance.<sup>161</sup> Coverage for fire and lightning is standard and losses from these perils when accompanying tornadoes can be significant: between 2006 and 2010 losses averaged \$1bn a year.<sup>162</sup> Coverage will usually include buildings and contents under homeowners' policies; however, windstorm deductibles may apply, especially in areas that are prone to thunderstorm activity.

The majority of property policies offer coverage for losses resulting from hail, this is often on a named peril basis. This means hail must be defined in the policy as a covered peril.<sup>163</sup> Hail can cause extensive damage to roofs as well as superficial damage to property; this can cause creeping claims costs following severe thunderstorms. Small superficial claims from hail aggregated together can amount to millions in losses. As a result, some insurers have changed their cover from a replacement cost basis to actual cash or agreed value and may exclude coverage for purely cosmetic roof damage.<sup>164</sup>

Although the 2011 loss total can arguably be treated as an anomaly, due to the unusually high frequency of activity, even when adjusted for inflation there is a long term trend of increasing market losses caused by tornadoes, hail, straight line winds and flash floods over the last 30 years. A large proportion of this is undoubtedly due to increasing exposure and the rise in the value of property exposed. Continuing population growth and urban and suburban sprawling has increased the likelihood that a storm will occur in areas where there is property. These trends are likely to continue and thus those insuring against tornadoes and similar perils could continue to see a rise in claims<sup>165</sup> Following the Tuscaloosa and Joplin tornadoes, small and large property and casualty insurers saw a significant erosion of earnings, leading to poor results for the industry overall, but particularly in the homeowners section and losses for reinsurers.<sup>166</sup>

Due to the localised nature of tornado losses, it is important that insurers consider managing their portfolio to diversify their exposure. For example, insurers may wish to limit their exposure within a given development or community or, alternatively, they may wish to increase their reinsurance program. Insurers may also wish to look at building construction, and balance their book against structures more prone to wind damage.<sup>167</sup> In certain areas insurers have introduced mandatory percentage wind deductibles or have begun to follow more restrictive underwriting guidelines which may exclude outbuildings and other structures.<sup>168</sup>

### 11.3.2 Motor

On average one fifth of losses occurring from perils accompanying thunderstorms such as winds, hail and flash floods have been in automobile insurance lines. Comprehensive automobile insurance policies will include coverage for damage caused by windstorm or hail.<sup>169</sup>

### 11.3.3 Agriculture

Another area which may experience losses from wind and hail damage is agriculture. Multi-peril crop insurance (MPCI) covers agricultural losses caused by severe weather hazards. Due to the localised and significant losses to crops caused by hail, farmers can take out crop hail insurance to cover a particular field for a specific amount against such a localised loss. Crop hail insurance covers damage caused by hail to crops at an individual site, whereas MPCI covers the overall yield for the crop on the farm. Liability under both policies has more than doubled since 2001. Annual average losses for hail under MPCI policies from 2001 to 2010 were \$325m with comparable losses (\$310m) for crop hail insurance.<sup>170</sup> There is clear correlation between the states with the highest levels of crop hail insurance and Tornado Alley. 70 per cent of crop hail insurance is concentrated in seven states: Illinois, Iowa, Kansas, Minnesota, Nebraska, North Dakota and Texas the case is similar for MPCI states.<sup>171</sup>

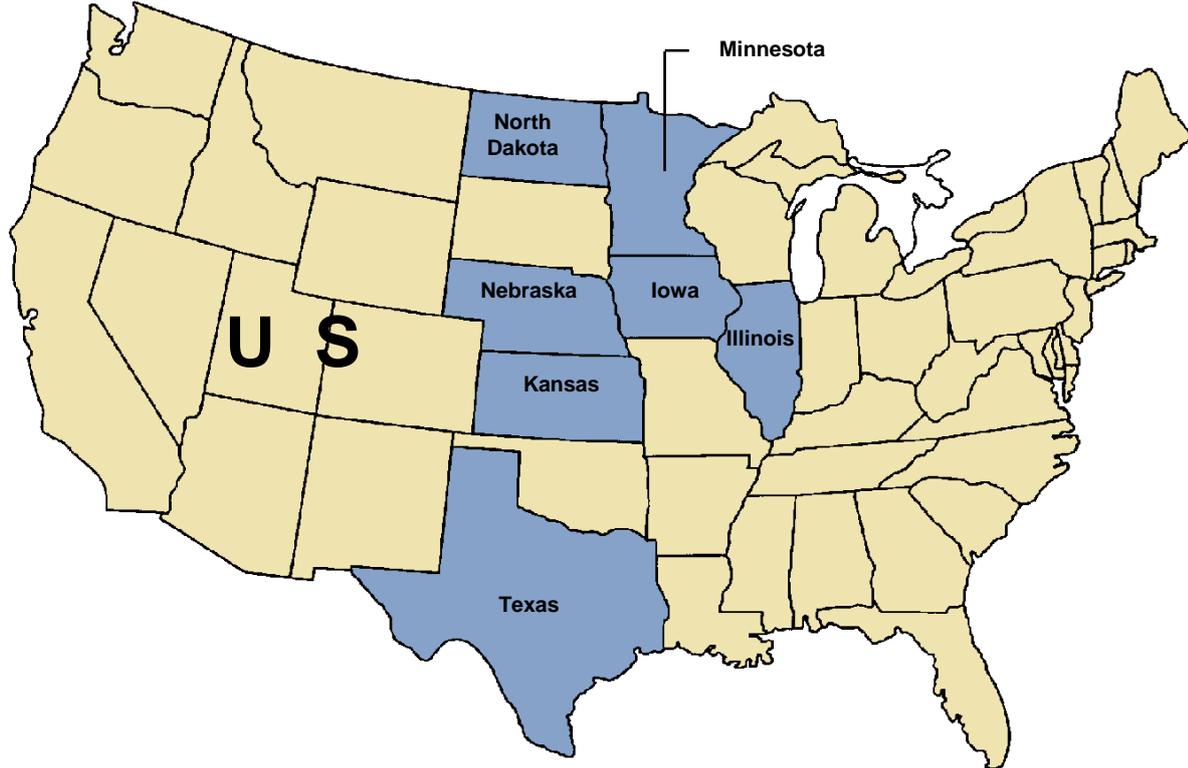


Figure 14: Map showing main crop hail states<sup>172</sup>

## 12 CONCLUSION

There is much about tornadoes which remains unknown. Whilst significant improvements have been made in the prediction and detection of tornadoes due to advances in science, technology and observational techniques it still remains difficult to predict exactly when a tornado will occur. Thus, although atmospheric conditions which may increase the likelihood of a tornado have become more easily identifiable, tornado prediction is not yet an exact science. Continued work by the NSSL, NOAA and other research centres aims to increase prediction techniques.

Tornado records underreport tornado numbers and changes in classification of tornado strengths adds further uncertainty, which makes determination of trends in tornado frequency and severity more difficult. Even in the US detailed records only exist back to 1950. The number of officially recorded tornadoes has risen; which can mainly be attributed to better reporting, tracking and more people, homes and infrastructures in the path of a tornado. Despite the anomalous 2011 season there is no trend in the number of strong to violent tornadoes between 1950 and 2012, evidence that the number of high intensity events has not increased over that period.

Although the number of violent tornado losses may not be increasing, insured losses are. There is a clear trend of increasing annual aggregate losses to the insurance market and billion dollar losses are becoming more common. As exposure continues to increase, tornadoes represent a more serious threat to the insurance industry. An active tornado season hitting populated areas could result in high damages and it is important that insurers consider modelling and managing potential exposure.

While the effects of climate change are not yet clearly observable on tornado activity, it is likely that changing temperatures will affect some of the atmospheric conditions which are favourable to tornado formation. It is important to bear in mind these possible effects when considering the future of tornado risk.

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