Natural Hazards and Disaster

Lab in Class 22: Tornadoes

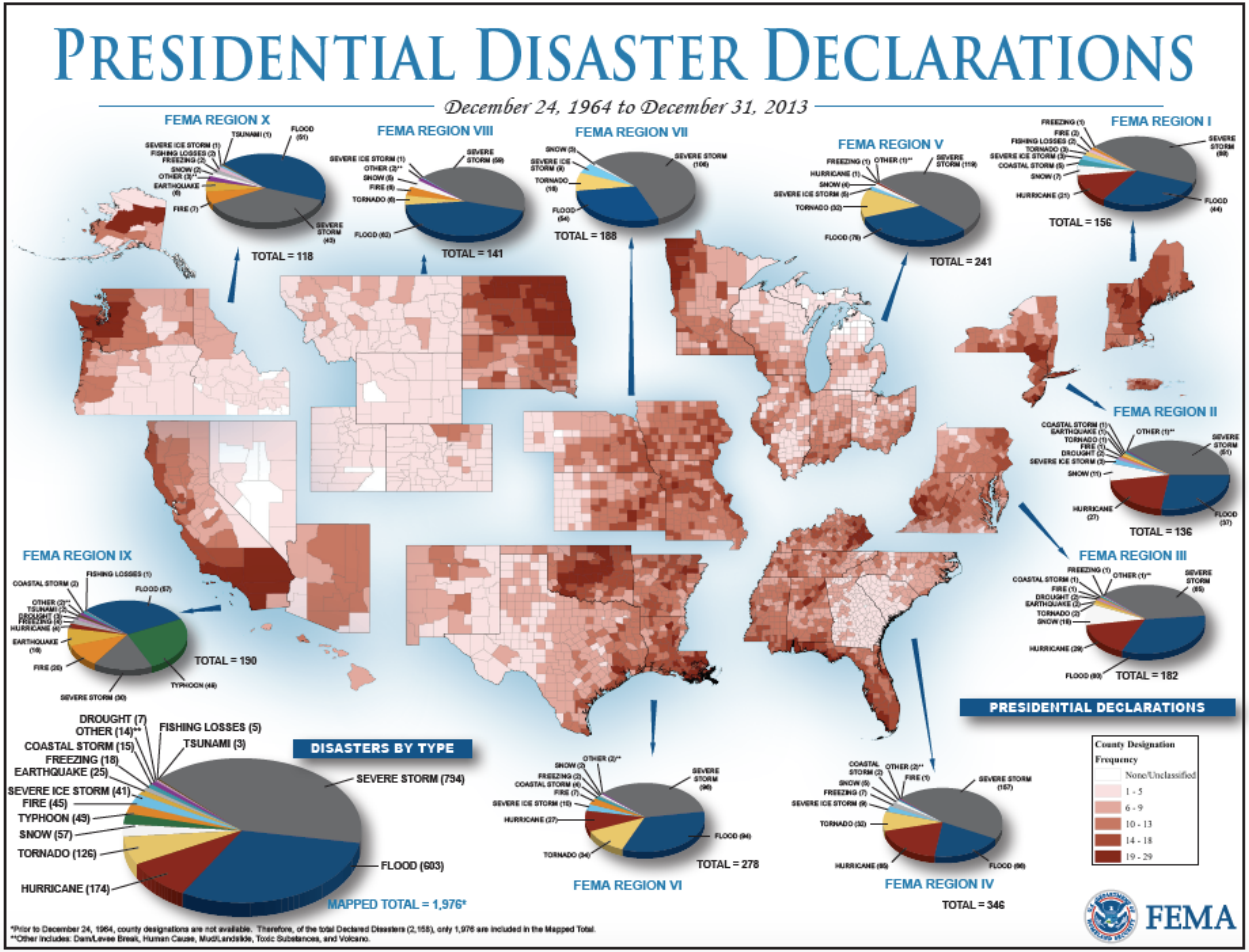
International Disasters

Between 1964 and 2014 there were almost 2,000 disaster declarations in the U.S.A. and thousands more disasters occurred around the world. Some of these events were exceptional in the number of fatalities caused:
2004 - Indian Ocean Tsunami caused 226,408 fatalities
2010 - Haitian earthquake, 222,570
2008 - Cyclone Nargis in Burma (Myanmar), 138,375
2008 - Sichuan earthquake in China, 87,476
2005 - earthquake in Nepal, 74,648
2010 - heatwave in Russia, 55,736

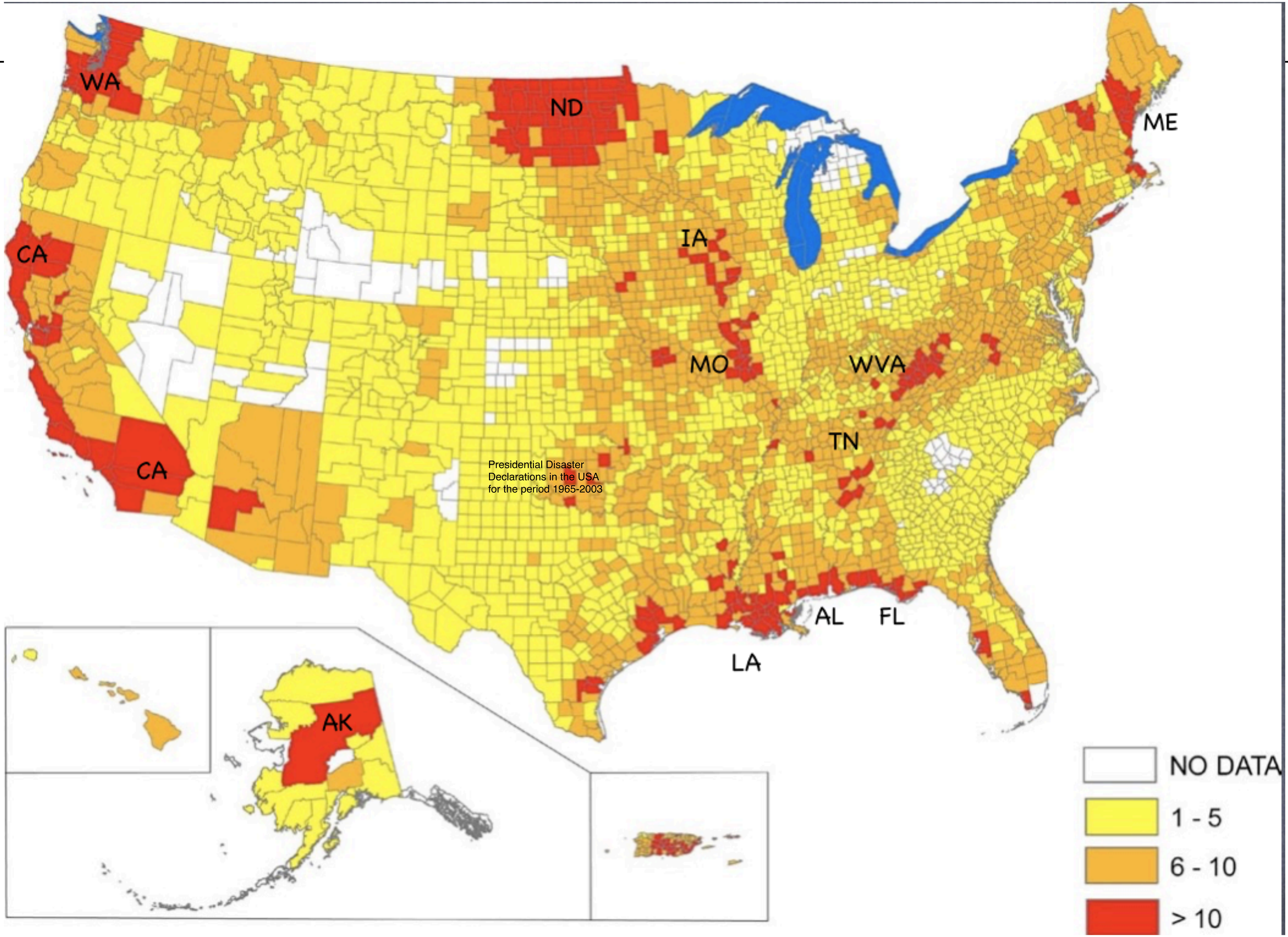
Several different organizations attempt to collect accurate and reproducible data on disasters, but for a variety of reasons the data from different sources never quite agree with one another. However, the general trends are consistent: natural disasters disproportionately affect the lives of people in the poorer areas of underdeveloped nations; flooding remains the most frequently reported disaster annually – both in the USA and internationally; and earthquakes cause the most fatalities per event, especially if earthquake-induced landslides and tsunamis are included. An example of recently compiled data on international natural disasters is in a 2014 report compiled by the International Federation of Red Cross and Red Crescent Societies, which summarizes data for 2013. By their analysis, 2013 had the lowest number of reported disasters related to natural hazards in a decade, totaling 337. The two worst natural disasters that year were Typhoon Haiyan in the Philippines, which caused 7,986 fatalities, and monsoon floods in India, which caused the deaths of 6,064 people.

See http://www.ifrc.org/world-disasters-report-2014/data. See also http://www.ifrc.org/world-disasters-report-2015.

U.S. Disasters



U.S. Disasters



EXERCISE: Natural Disasters in the USA
The map summarizes the Presidential Disaster Declarations for the period 1964 to 2013. The pie charts adjacent to each sub-region show the proportion of disasters caused by the different natural hazards. These maps are updated annually, but are always a year or two behind the current year. The map on the next slide (in mainly yellow colors) is a summary of disaster declarations for the period 1965-2003 and includes earthquakes, tsunamis, floods, hurricanes, landslides, volcanic eruptions, and wildfires, but does not break out the individual phenomena.

Examine and compare the two maps, and use them to answer the following questions:

A. Which have been the top 3 FEMA regions for disaster declarations for the entire period of
record (1964-2013)?
i. ____________________ ii. _________________________
iii. ____________________

B. Has the additional information for the period 2003 to 2013 made any significant change to the geographic distribution of declared disasters? It so, state specifically where you see any increase (or decrease) in disaster declarations.

C. With few exceptions, the disaster declarations are not equally distributed by county within the FEMA regions. Why does FEMA Region VIII show such a marked difference between counties on the western and southern areas and counties in the northeast of the region, when the most frequently reported disaster types for the Region are not very different to those of its neighboring region. Hint: sketch the Mississippi River and its major tributaries onto the 1965-2003 map.

D. The top two disaster types for all FEMA Regions are obvious from the pie charts on the 1964-2013 map. What are the next most reported disaster types, after Severe Storms and Floods, for (i) the eastern half of the country, and (ii) the northwest (Region X)?

i. 3rd most reported disaster type for Regions I, II and III

____

ii. 3rd most reported disaster type for Region X ____________________

E. Compare Regions IX and X. What are the main differences between the two regions in terms of (a) disaster type and (b) number and proportion of each disaster type, and why are there such differences?

F. California and Nevada are neighboring states, yet they have very different disaster declaration histories. What are some of the reasons why California has so many disasters and Nevada has so few?

EXERCISE: Tornado Disasters
See Chapter on Tornadoes

Although tornadoes can occur anywhere in the world, the vast majority of them occur annually in North America. The 3 maps on the next slide show tornado occurrences in 2014, 2015, and 2016 (but only up to mid-September 2016). Below each map is a histogram of tornado occurrences by date.

A. Compare the 2014 and 2015 maps and histograms. If you only had the data for these two years, and no other data, what would you infer about the most active time of year for tornadoes?

Apparent most active period for North American tornadoes

____

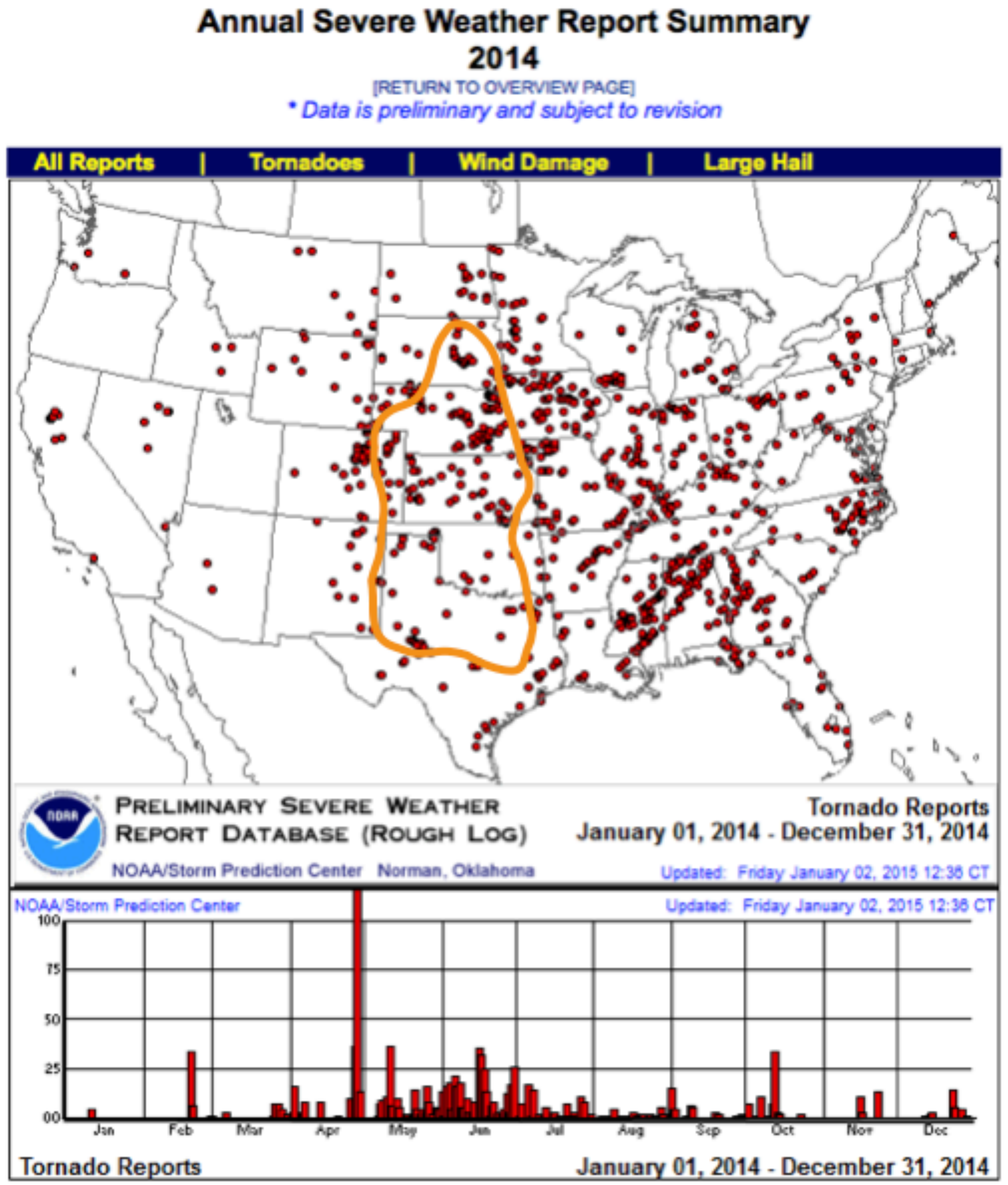
B. Now compare with the 2016 histogram. Did the same activity pattern as 2014/2015 hold true for 2016? What differences do you see?

C. The region known as ‘tornado alley’ is marked onto the 2014 and 2015 maps. From the distribution of tornados in the past 3 years, where would you consider the most active region(s) to be? Outline your own version of ‘tornado alley’ (or ‘alleys’ if you think there are more than one) onto the 2016 map.

D. Is there any US State that has not had a tornado in the past 3 years? If so, which?

____

Tornadoes


Annual Severe Weather Report Summary
2014
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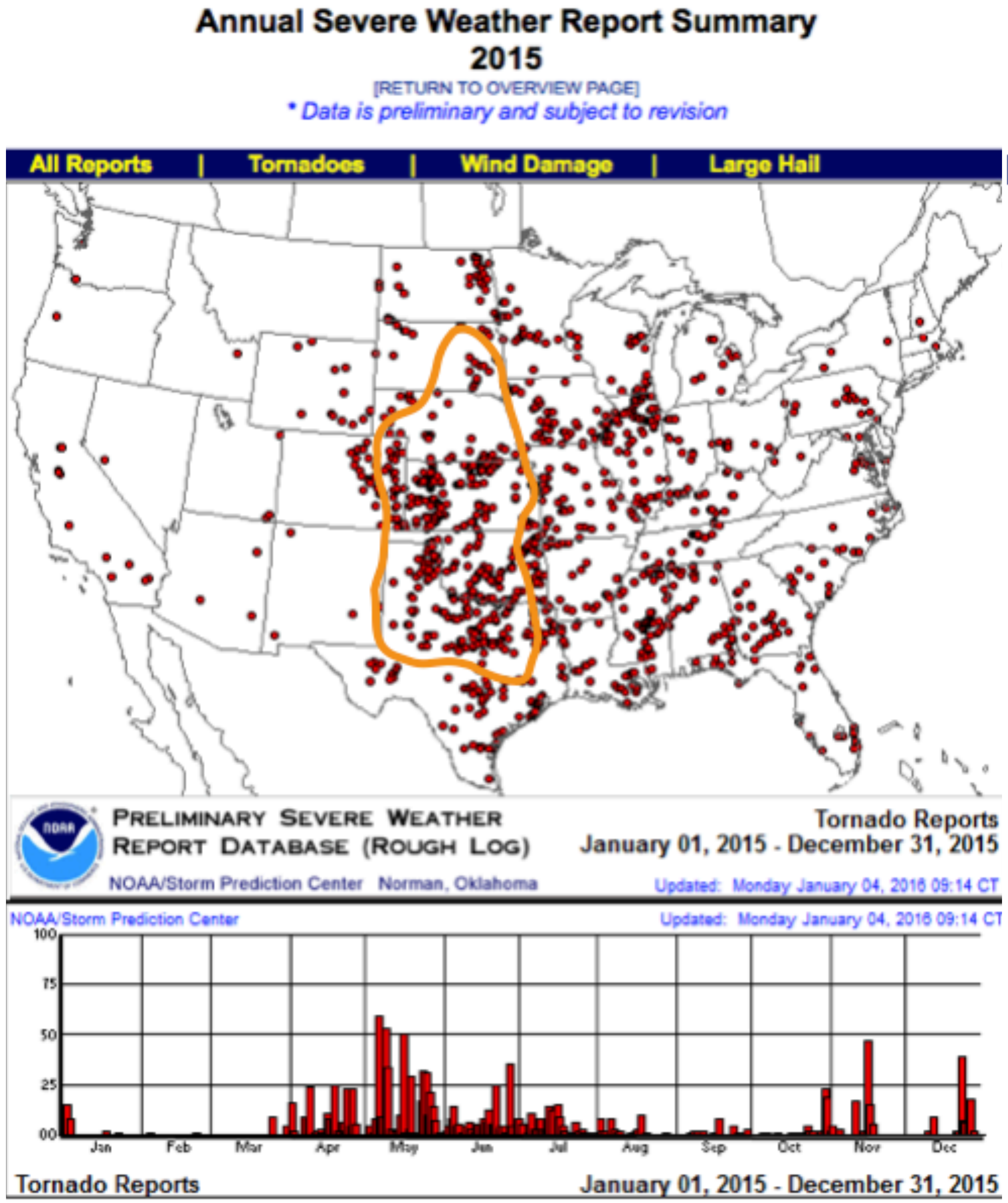
* Data is preliminary and subject to revision
All Reports | Tornadoes | Wind Damage | Large Hail
Preliminary Severe Weather Report Database (Rough Log)
Tornado Reports
January 01, 2014 - December 31, 2014
NOAA/Storm Prediction Center Norman, Oklahoma
Updated: Friday January 02, 2015 12:38 CT
Tornado Reports January 01, 2014 - December 31, 2014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2015
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All Reports | Tornadoes | Wind Damage | Large Hail
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Tornado Reports
January 01, 2015 - December 31, 2015
NOAA/Storm Prediction Center Norman, Oklahoma
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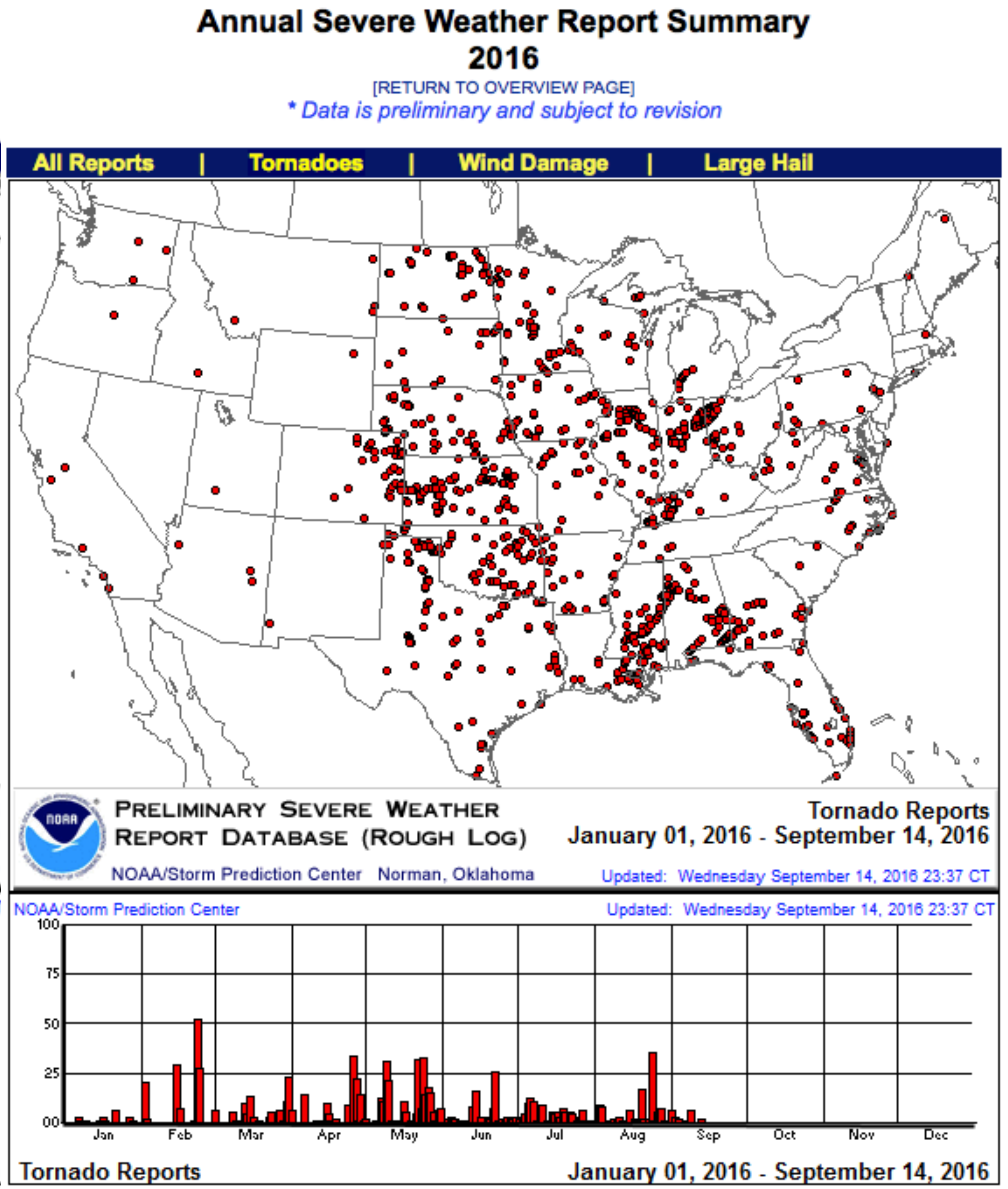
Tornado Reports January 01, 2015 - December 31, 2015


Annual Severe Weather Report Summary
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All Reports | Tornadoes | Wind Damage | Large Hail
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Tornado Reports
January 01, 2016 - September 14, 2016
NOAA/Storm Prediction Center Norman, Oklahoma
Updated: Wednesday September 14, 2016 23:37 CT
Tornado Reports January 01, 2016 - September 14, 2016

EXERCISE: Estimating a tornado’s EF scale

The four images on the next slide show some of the damage from a severe tornado outbreak in 1999.

In (a), a wood-framed home lost its roof, but its outer walls were left standing. Almost all surrounding trees were blown down. Rated as EF2

In (b), the tornado’s path though a mobile home park completely destroyed the mobile homes. Tree branches were stripped and some were blown down. Rated as EF2.

In (c), the wood-framed home was destroyed, but not scattered very far. Rated as EF3.

A. Assume that the roads in (d) are aligned north-south with south at lower right. Estimate the EF scale and corresponding wind speed range for the houses in each quadrant:
(i) West-southwest quadrant = EF___ Wind speeds in the range _____ to _____ km/h
(ii) West-northwest quadrant = EF___ Wind speeds in the range _____ to _____ km/h
(iii) Northwest quadrant = EF _______ Wind speeds in the range _____ to _____ km/h
(iv) Northeast quadrant = EF _______ Wind speeds in the range _____ to _____ km/h

B. Explain why the house at lower right was relatively unaffected when the other houses on the street were so severely damaged.

Tornadoes

a)

b)

c)

d)

Tornadoes

EXERCISE: What should you do in a tornado outbreak?

The National Institute for Safety (NIST) has issued an online resource help communities build resilience to tornadoes and other natural disasters.

https://www.nist.gov/topics/disaster-resilience/helping-build-nation-resilient-communities

As part of its own resilience planning, ODU has a tornado warning siren system in place.

Have you (or someone in your group) heard the siren?

If so, where were you at the time and how easy or difficult was it to hear the announcement, if there was one?

What would you do if you were in class, or crossing campus, or in the neighborhood, and a tornado warning occurred?

What would you recommend to ODU to further improve its tornado warning system.

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- Basics: What, Where, When
- Strength

Class 22: Tornadoes continued, Ice Storms, Meteotsunamis
- Origin
- Warnings and Preparedness
- Characteristics
- Cases
- In the Media

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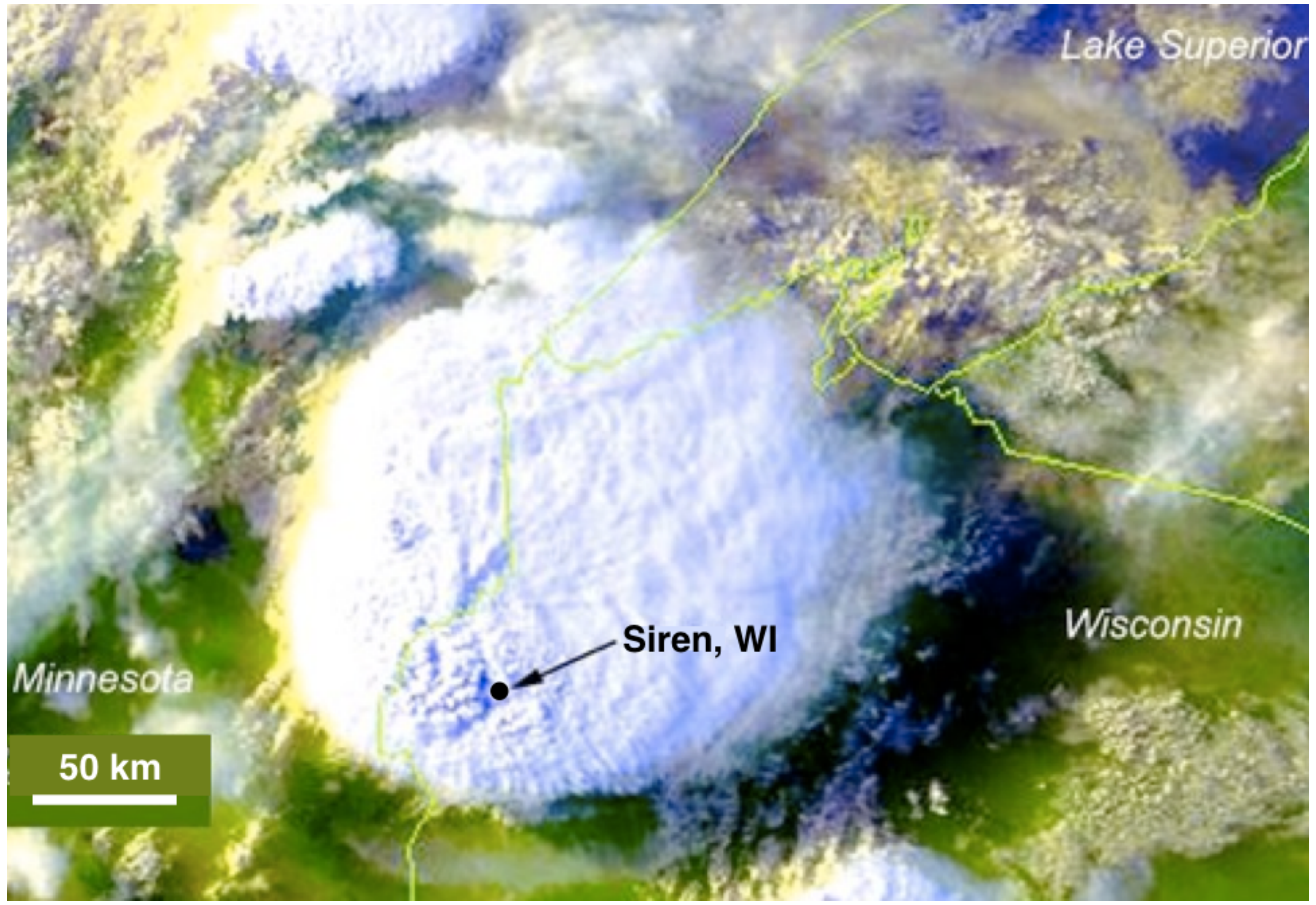
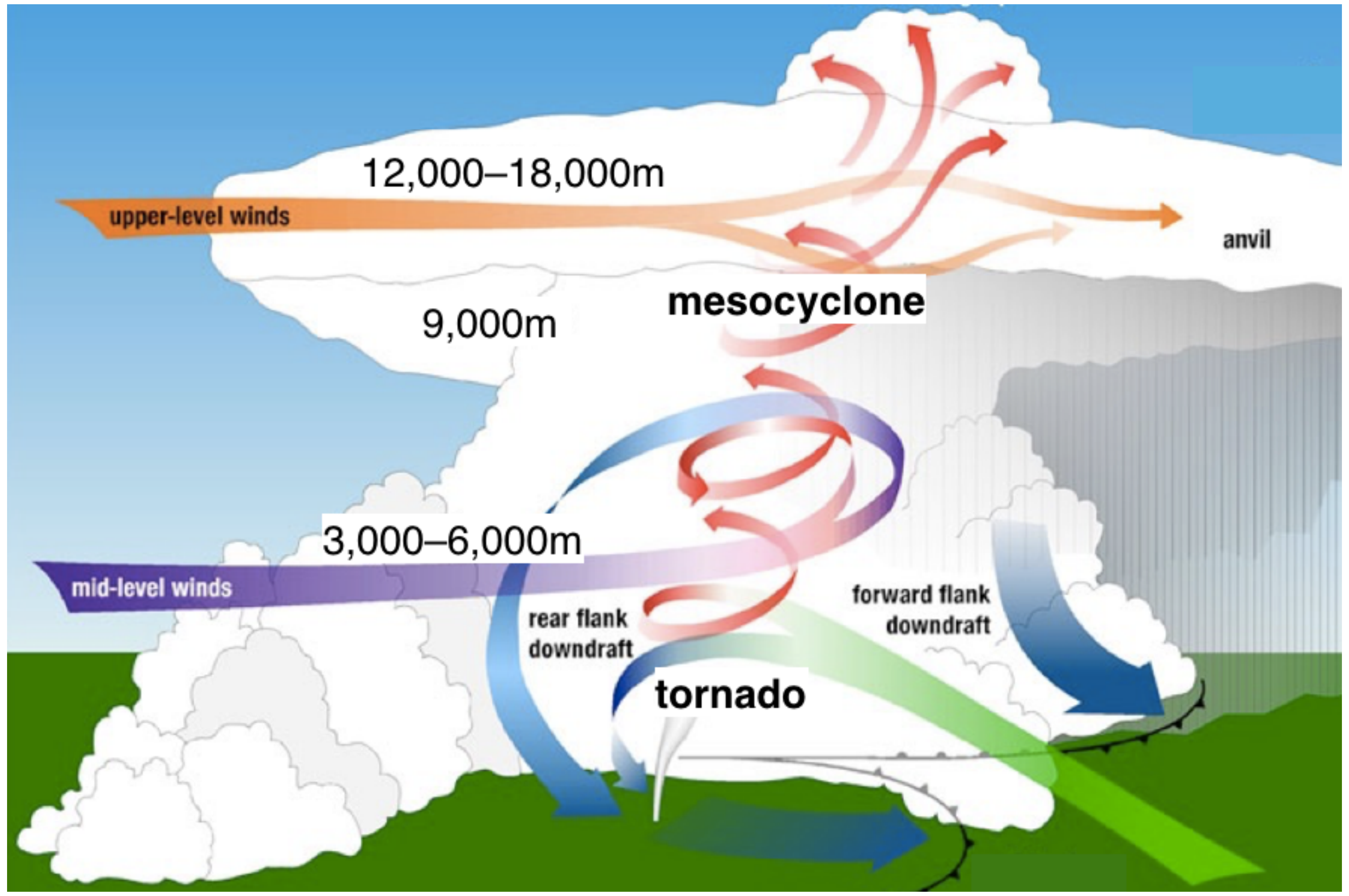
Tornadoes: Origin

Tornadoes commonly occur in supercell thunderstorms, also known as mesocyclones.

Severe thunderstorms occur when buoyant, warm air rises rapidly upward by convection into the cooler troposphere forming cumulus clouds. A mesocyclone, commonly called a supercell, occurs when the entire thunderstorm rotates due to a strong, continuously rotating updraft. Supercells are usually 2-10 km wide, although they can be much wider.
Tornadoes can also occur under other atmospheric conditions, but they are most commonly formed in mesocyclones, which create the potential for tornado formation through strong downdrafts, both in their forward flank – where a shelf cloud (also called anvil cloud) spreads out and generates heavy rain – and, more often, in the downdraft at the trailing edge of the storm. The violent tornado that devastated Tuscaloosa, AL, on April 27, 2011, was generated in the trading edge of a supercell thunderstorm.

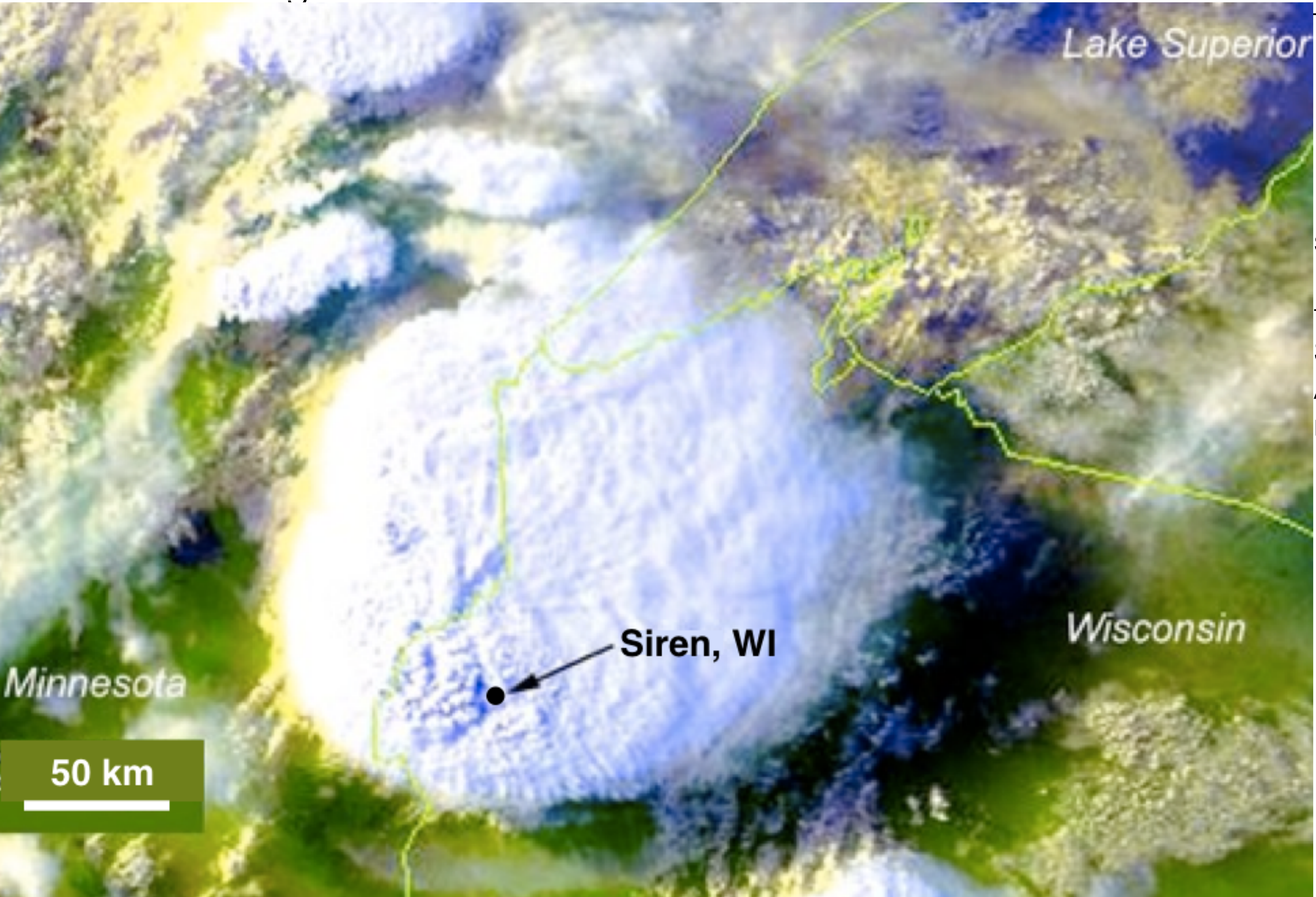


NOAA satellite imagery of a supercell storm on June 19, 2001 that spawned a fatal tornado touchdown in Siren, Wisconsin. In North America, supercells usually rotate counterclockwise.



Warm air updrafts (red) and strong, cold air downdrafts (blue) in a rotating mesocyclone (also called a supercell) create ideal conditions for tornados.

Tornadoes: Origin



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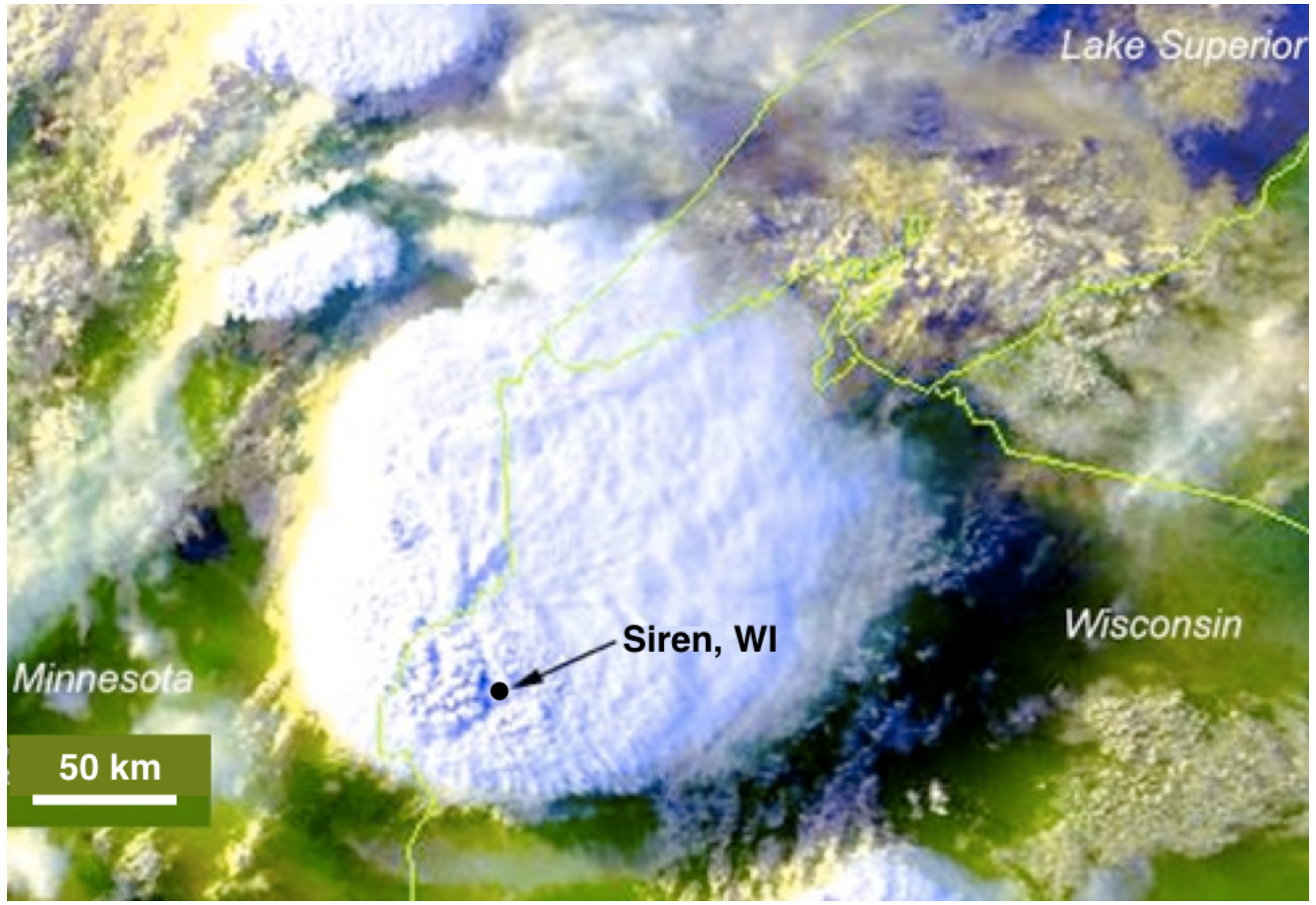

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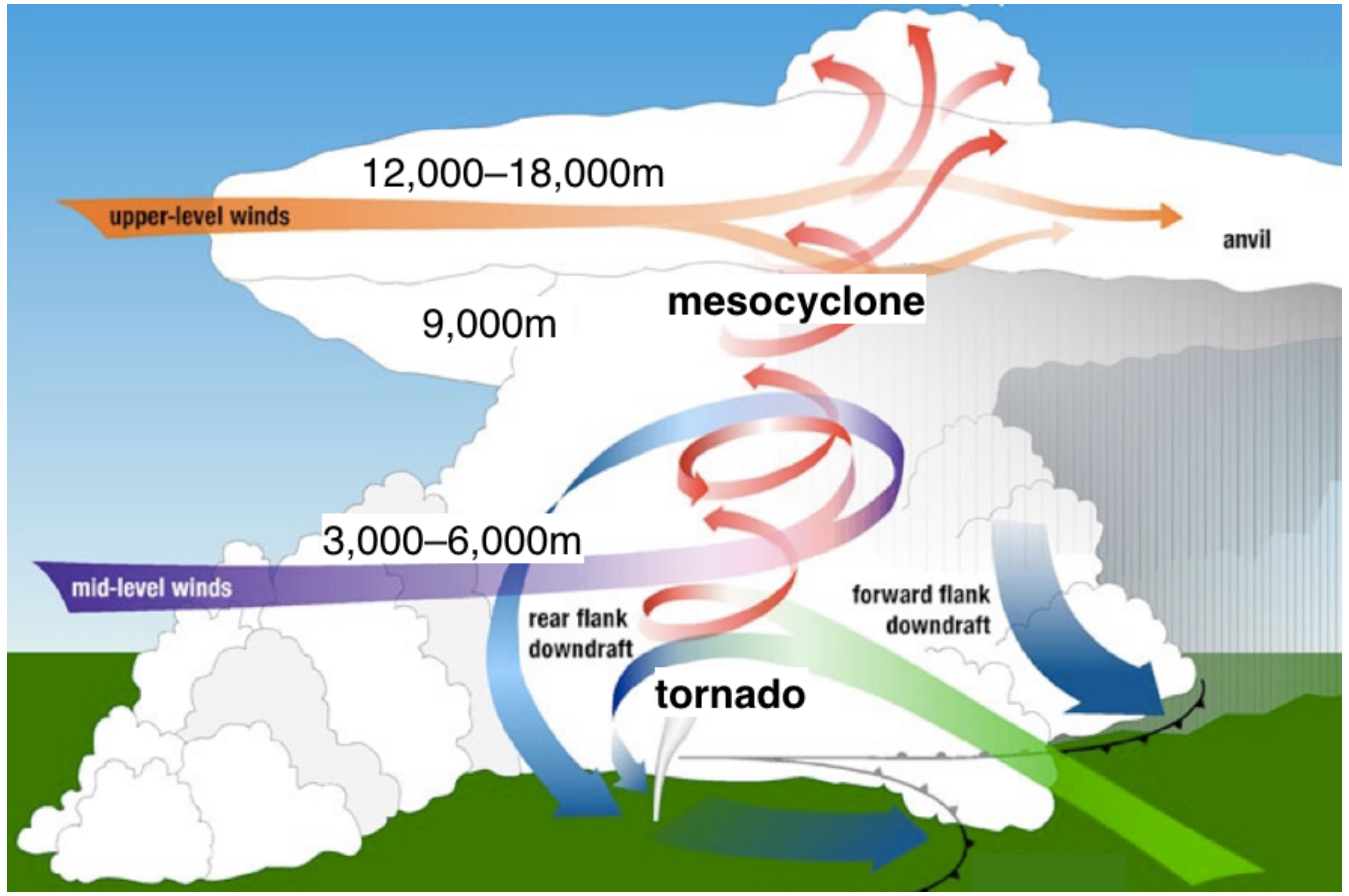

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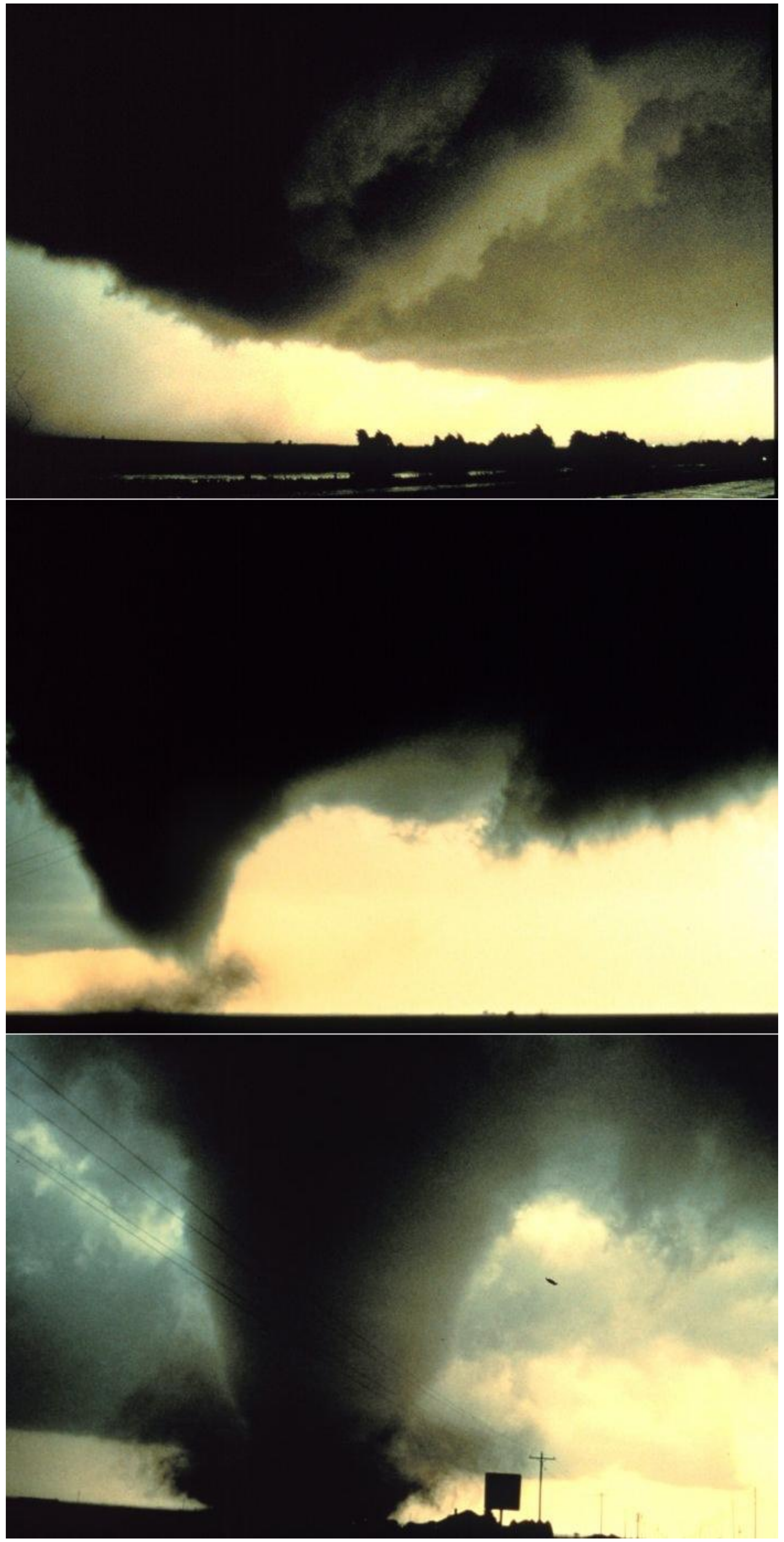
Tornadoes: Origin

Most tornadoes from supercells follow a recognizable life cycle. That begins when increasing rainfall drags with it an area of quickly descending air known as the rear flank downdraft (RFD). This downdraft accelerates as it approaches the ground, and drags the supercell's rotating mesocyclone towards the ground with it.

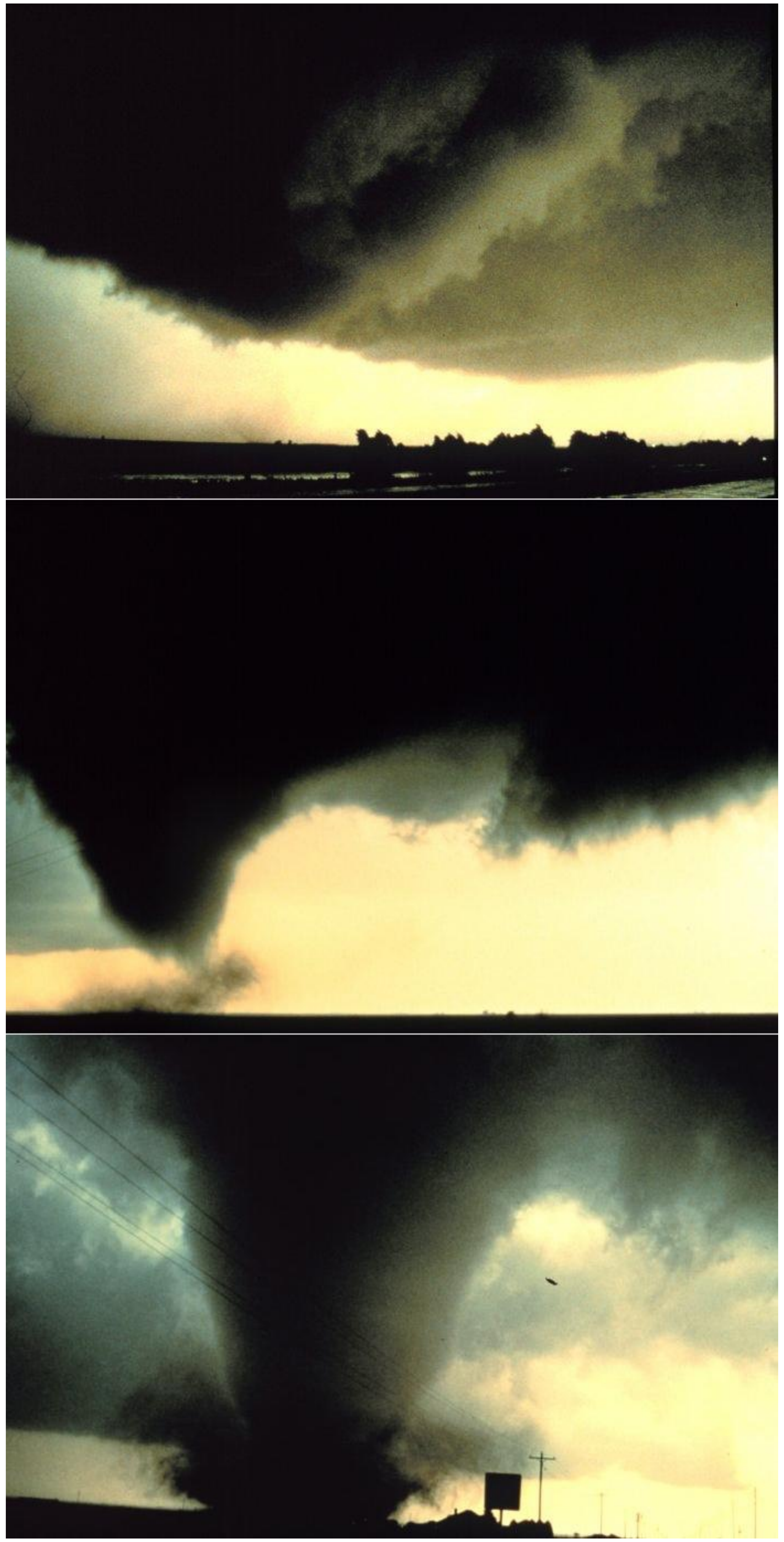
Formation: As the mesocyclone lowers below the cloud base, it begins to take in cool, moist air from the downdraft region of the storm. The convergence of warm air in the updraft and cool air causes a rotating wall to form. The RFD also focuses the mesocyclone's base, causing it to draw air from a smaller and smaller area on the ground. As the updraft intensifies, it creates an area of low pressure at the surface. This pulls the focused mesocyclone down, in the form of a visible condensation funnel. As the funnel descends, the RFD also reaches the ground, fanning outward and creating a gust front that can cause severe damage a considerable distance from the tornado. Usually, the funnel cloud begins causing damage on the ground (becoming a tornado) within a few minutes of the RFD reaching the ground.



A sequence of images showing the birth of a tornado. First, the rotating cloud base lowers. This lowering becomes a funnel, which continues descending while winds build near the surface, kicking up dust and debris and causing damage. As the pressure continues to drop, the visible funnel extends to the ground. This tornado, near Dimmitt, Texas was one of the best-observed violent tornadoes in history. http://www.photolib.noaa.gov/nssl/tornado3.html

Tornadoes: Origin

Maturity: Initially, the tornado has a good source of warm, moist air flowing inward to power it, and it grows until it reaches the "mature stage". This can last anywhere from a few minutes to more than an hour, and during that time a tornado often causes the most damage, and in rare cases can be more than 1.6 km across. The low pressured atmosphere at the base of the tornado is essential to the endurance of the system. Meanwhile, the RFD, now an area of cool surface winds, begins to wrap around the tornado, cutting off the inflow of warm air which previously fed the tornado.



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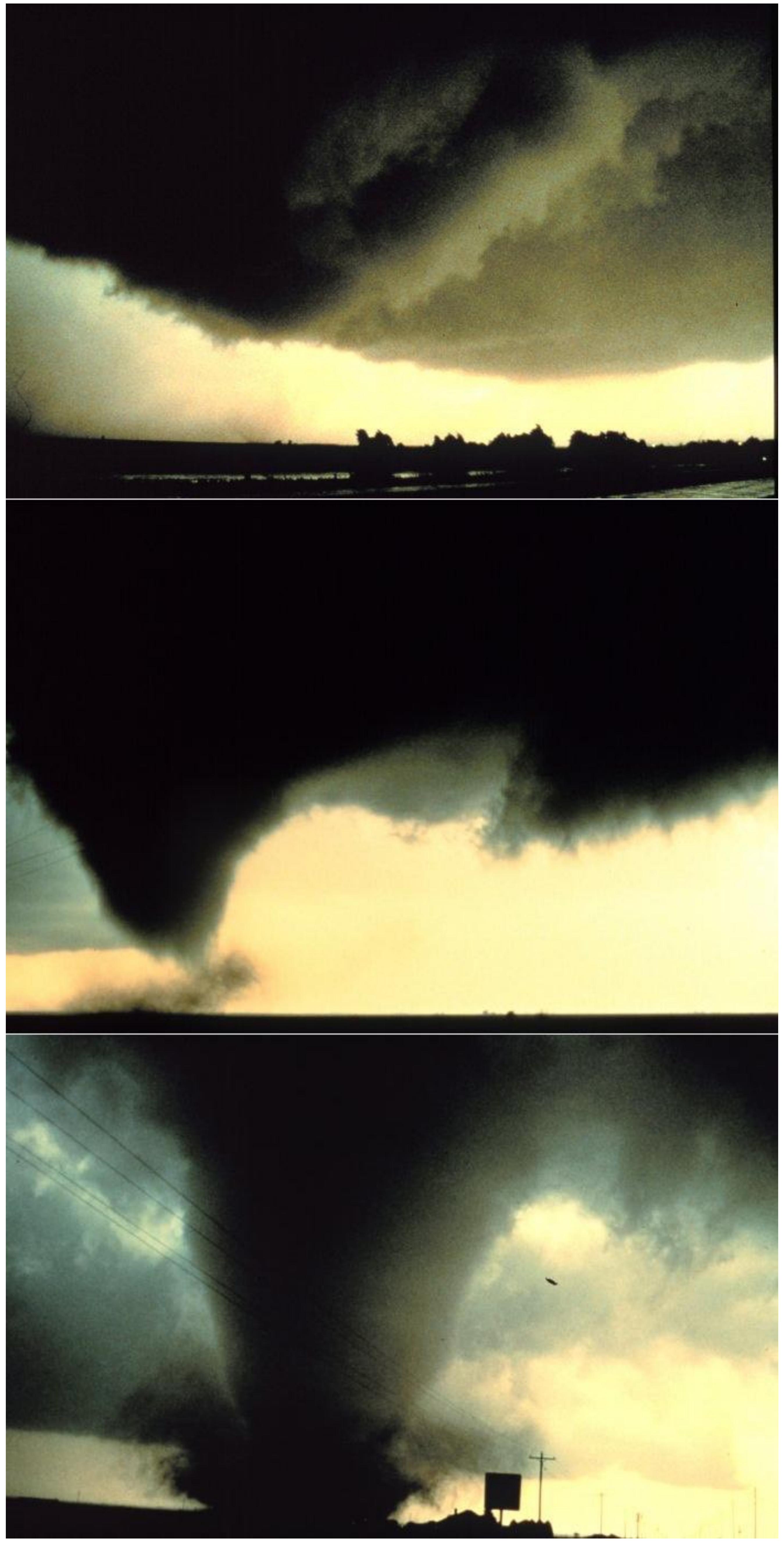
Tornadoes: Origin

Dissipation: As the RFD completely wraps around and chokes off the tornado's air supply, the vortex begins to weaken, and become thin and rope-like. This is the "dissipating stage", often lasting no more than a few minutes, after which the tornado ends. During this stage the shape of the tornado becomes highly influenced by the winds of the parent storm, and can be blown into fantastic patterns. Even though the tornado is dissipating, it is still capable of causing damage. The storm is contracting into a rope-like tube and, due to conservation of angular momentum, winds can increase at this point. As the tornado enters the dissipating stage, its associated mesocyclone often weakens as well, as the rear flank downdraft cuts off the inflow powering it. Sometimes, in intense supercells, tornadoes can develop cyclically. As the first mesocyclone and associated tornado dissipate, the storm's inflow may be concentrated into a new area closer to the center of the storm and possibly feed a new mesocyclone. If a new mesocyclone develops, the cycle may start again, producing one or more new tornadoes. Occasionally, the old (occluded) mesocyclone and the new mesocyclone produce a tornado at the same time.



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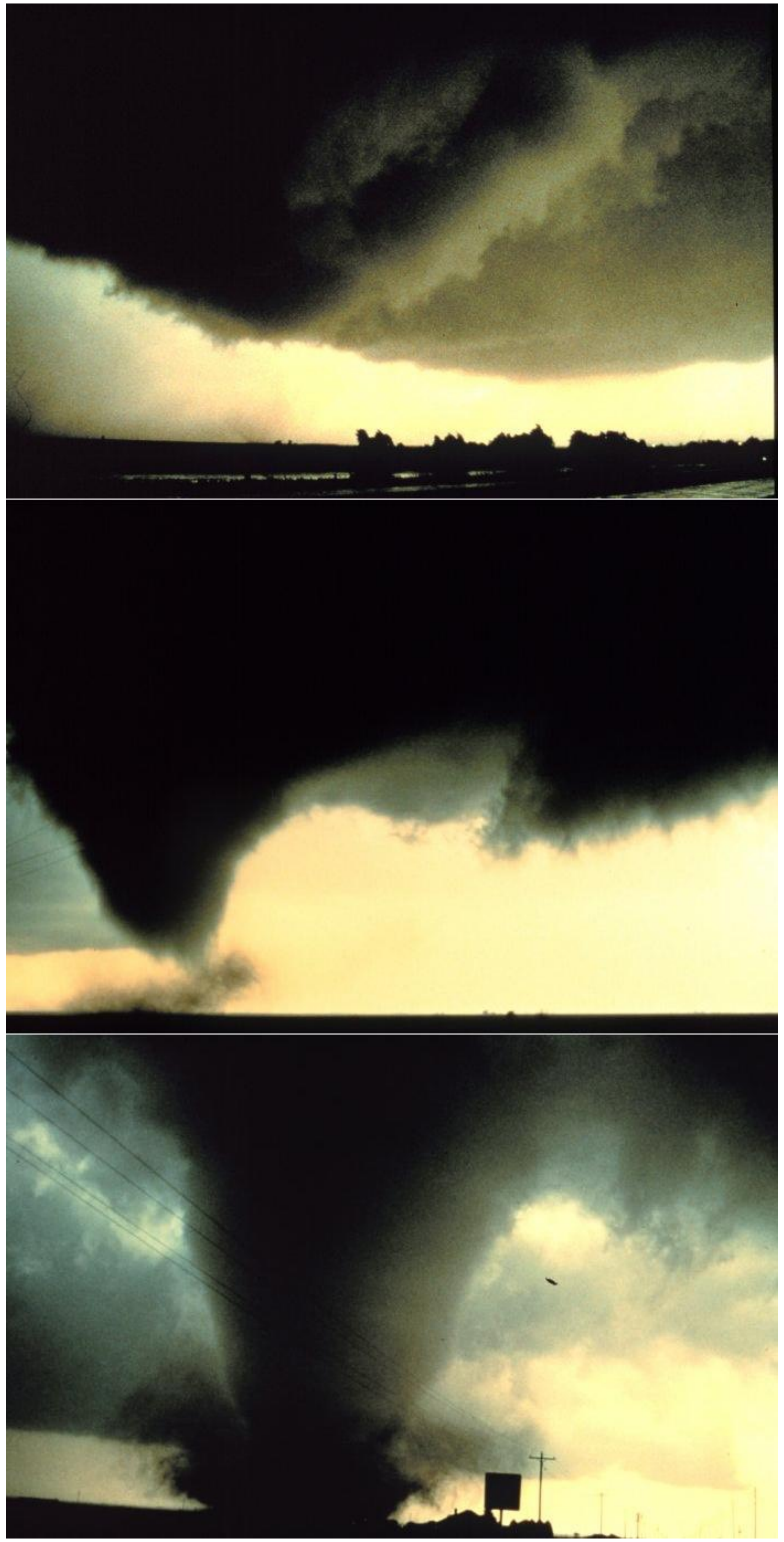
Tornadoes: Origin

Although this lifecycle is a widely accepted theory for the formation and development of most tornadoes, it does not explain the formation of smaller tornadoes, such as landspouts, long-lived tornadoes, or tornadoes with multiple vortices. These each have different mechanisms which influence their development.



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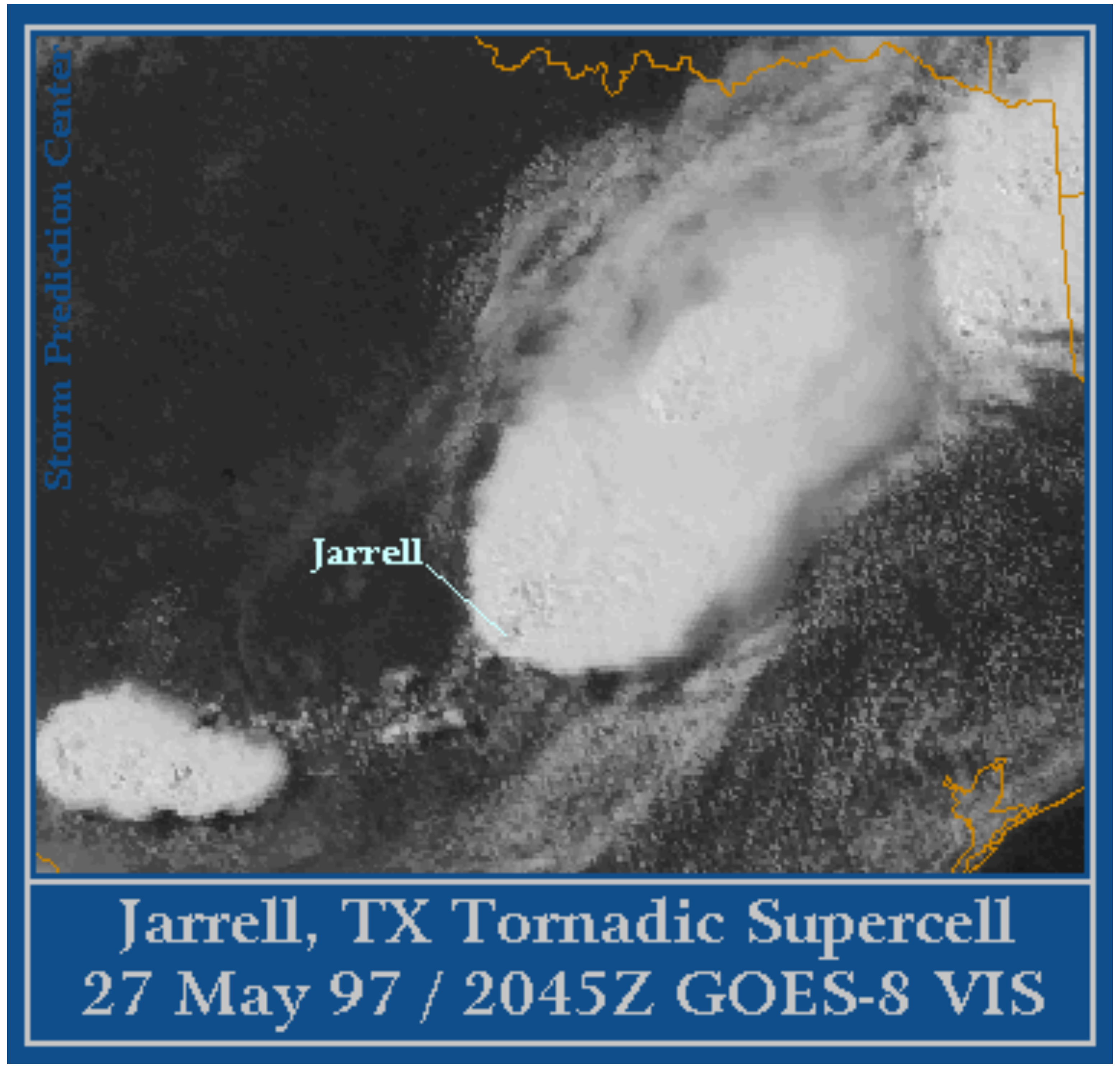
Precursors to Tornado Formation

High levels of convective available potential energy (CAPE) occur in severe thunderstorms and are often predictors of tornadic activity.

The rapid upward air movement in thunderstorms generates **convective available potential energy** (CAPE), which is measured in joules or kilojoules per kilogram of air (J/kg or kJ/kg). A high CAPE value (>2500 J/kg) means strong and rapid updrafts and also downdrafts, caused by rain or hail. Supercells, which favor tornado formation, often occur in regions of high CAPE value.

Two hours before a tornado outbreak in Oklahoma on May 3 1999, the CAPE value in a supercell near Oklahoma City was 5.89 kJ/kg. CAPE values of 5.5 kJ/kg were recorded just before an EF5 tornado hit Greensburg, Kansas on May 4, 2007. Even if the overall CAPE value in the storm's area is not extremely high, tornadoes can form if locally high CAPE values occur in the lowest 1 to 3 km of air beneath a thunderstorm's cloud base.



NASA GOES-8 satellite image of supercell over Jarrell, TX on May 27, 1997. The CAPE value was estimated as 7 kJ/kg just before the tornado struck.

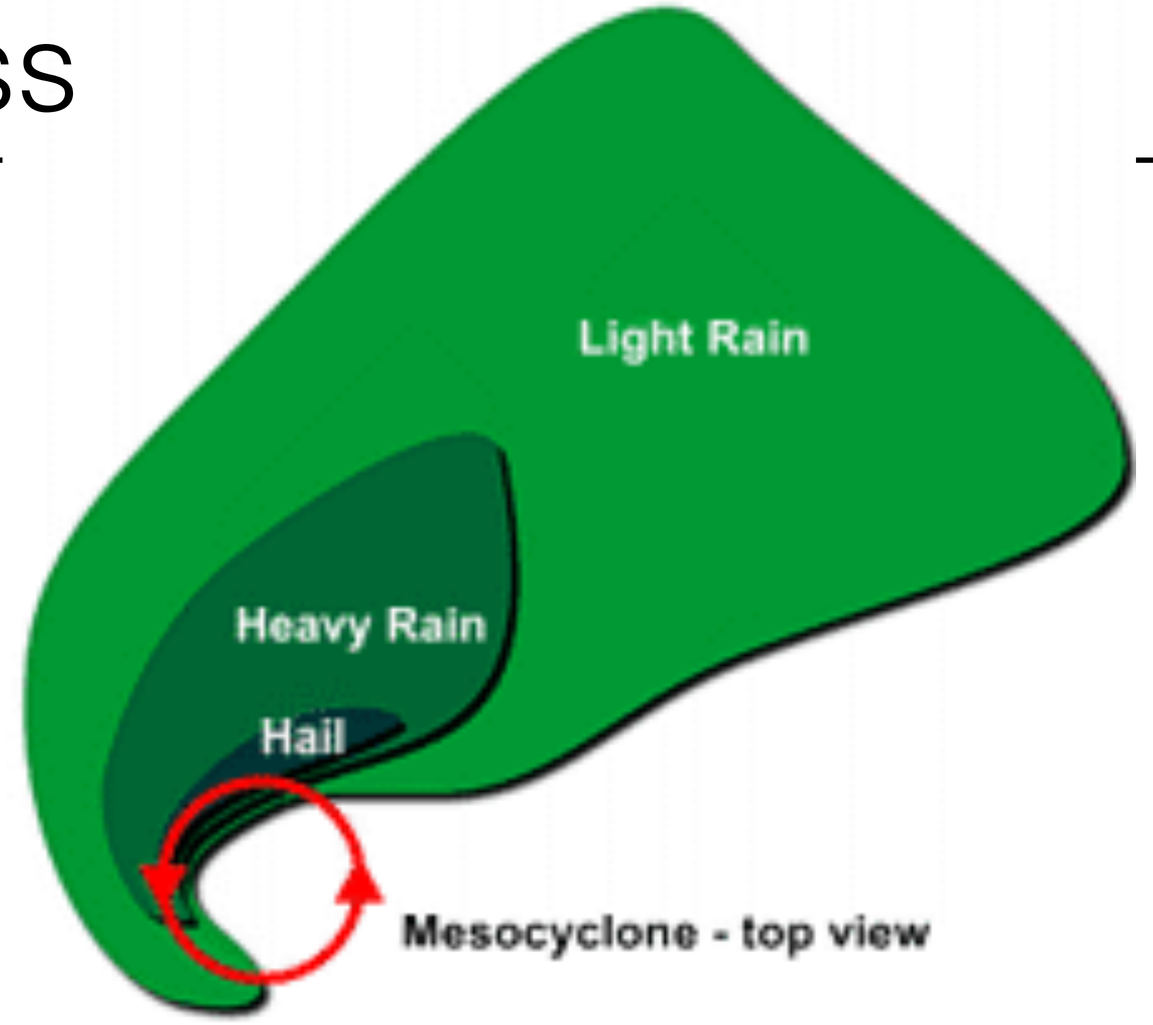
EF5 tornado touches down near Jarrell, TX, on May 27, 1997, causing 27 human fatalities and the death of more than 300 cattle.

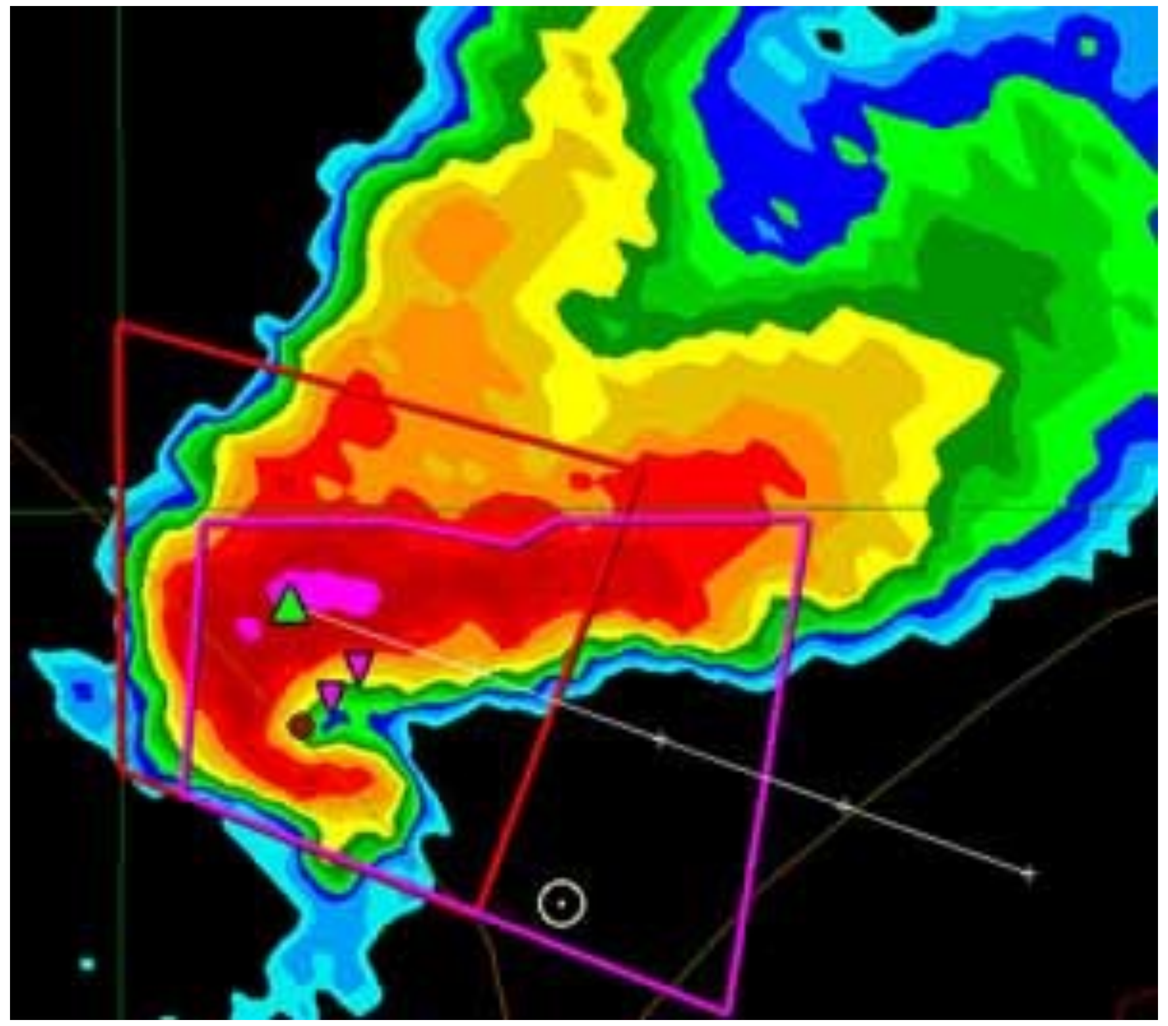
Tornadoes: Warnings and Preparedness

Tornado Warning Signs

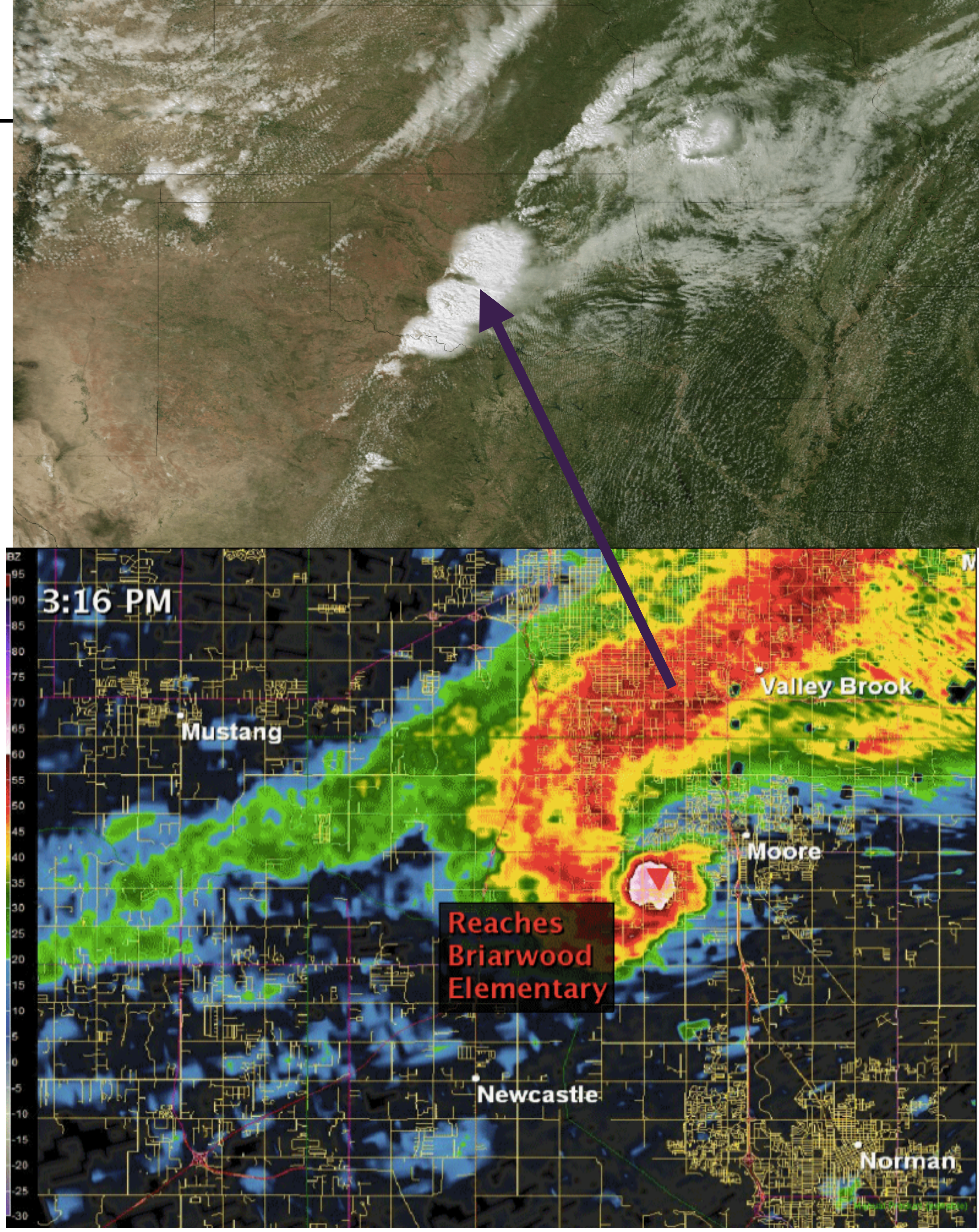
A strong indicator of an impending tornado is a hook-shaped cloud pattern around a mesocyclone.

The exact timing and position of a potential tornado touchdown during a severe thunderstorm is difficult to predict. Areas of high wind shear and high moisture content that have increasing CAPE values beyond 1000 J/kg are always cause for concern, and mesocyclones (supercells) are most likely to develop at the trailing edge of a such storm systems. Where satellite radar imagery of the rotating cloud tops shows a hook-like structure, this is a sure sign of a mesocyclone that has the potential to produce tornadoes. Meteorologists can watch a tell-tale hook structure as it develops by monitoring rainfall intensity and real-time cloud top reflectivity, which increases markedly above a mesocyclone, using geostationary satellites. Tornado watch and warning notices are then transmitted over the emergency broadcast system.





Top: Schematic view from above of hookshaped cloud (green) indicating a supercell (mesocyclone) with the potential for tornado formation. Bottom: Radar image of an actual mesocyclone hook. Red and pink colors indicate areas of highest rain intensity.



Top: Satellite image of three mesocyclones on May 20, 2013 over eastern Oklahoma. Bottom: Radar image of the supercell that spawned the EF5 tornado at Moore City, OK on May 20, 2013. Red triangle indicates the tornado's position at 3:16 p.m. that day.

Tornadoes: Warnings and Preparedness

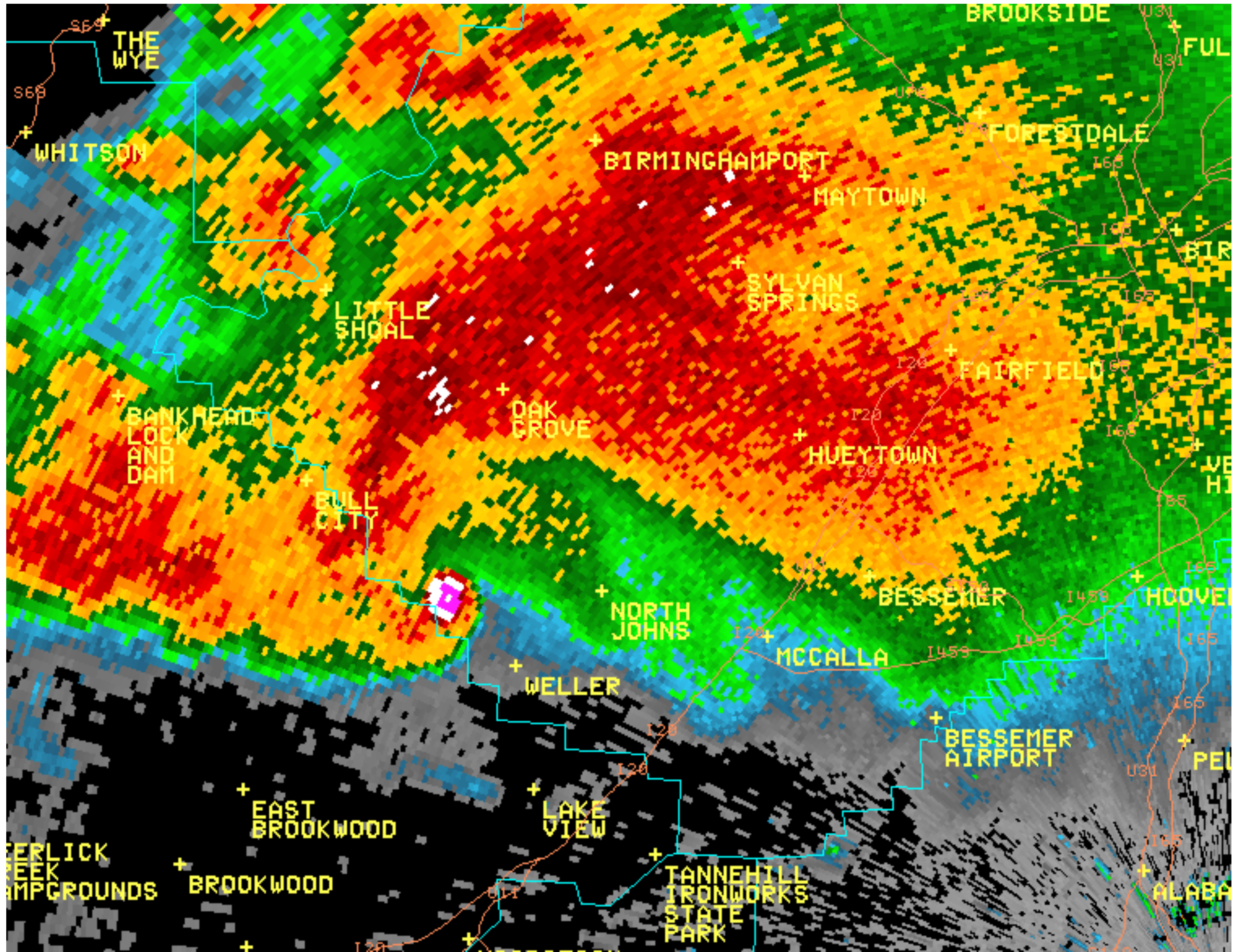
Measuring Tornadoes

Tornado chasing is not recommended!!

Despite all the imagery and after-the-fact reports that are available about tornadoes, there is still much that remains unexplained regarding their formation and their internal structure. Scientists at NOAA's National Severe Storms Laboratory (NSSL) in Norman, OK, work to develop more accurate forecasts of severe weather conditions, including supercells. One of their goals is to provide longer lead-times for emergency broadcasts when a tornado is imminent.

Much of our scientific knowledge about supercells and tornadoes has been obtained from aircraft that were flown into the storms – a highly dangerous exercise even for very experienced pilots – and from satellites. Since 2010, it has been possible to use unmanned aerial vehicles to directly measure windspeed, humidity, temperature, etc. within tornadoes and highly advanced radar systems have been recently developed. Data from these modern remote systems are far more precise (and far less dangerous to obtain!) than those obtained by manually operated vehicles, either airborne or on the ground.

NOAA's National Severe Storms Laboratory has a Multifunction Phased Array Radar system to replace aircraft surveillance of severe weather, including supercell formation.



NASA radar image of cloud heights around a supercell on April 27, 2011 over Birmingham, Alabama. The EF4 tornado caused 65 fatalities and 1500 injuries.

Tornadoes: Warnings and Preparedness

Tornado Mitigation

Tornadoes sirens and storm shelters save lives.

U.S. National Weather Service forecasters are trained to look out for weather conditions that are likely to produce a tornado. If mesocyclone conditions occur, they will issue a Tornado Watch notice over the emergency broadcast system. A tornado watch means that a tornado is possible and citizens should be prepared with emergency supplies at the ready and a safe place identified in which to shelter if necessary.
A Tornado Warning means that a tornado has either been sighted in the immediate area or is strongly indicated by radar and there is imminent danger to life and property. Tornado sirens will sound in tornado-prone parts of the U.S.A. When a warning is issued it is vital to take immediate action by avoiding windows and moving to an interior room on the lowest floor of a sturdy building. Many municipalities in regions where tornadoes are frequent offer communal tornado shelters and some homeowners build their own. Avoiding flying debris will be a major concern for anyone outdoors or in a vehicle or mobile home.

National Weather Service tornado warning for Blaine County, Montana, on June 19, 2016.

Typical tornado shelter signs.

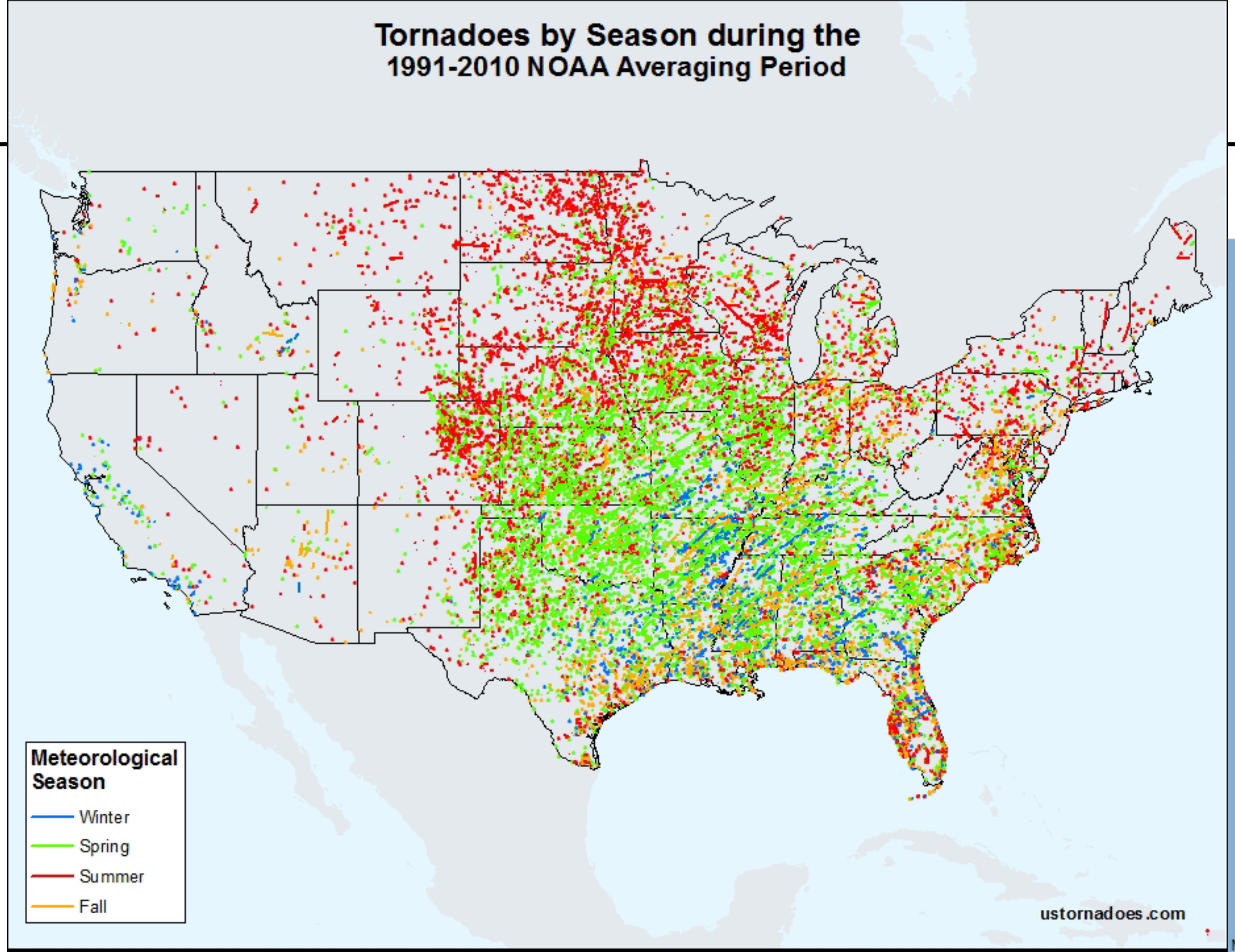
Left: Schematic home tornado shelter. Right: Surface view of a home tornado shelter in Dallas, TX.

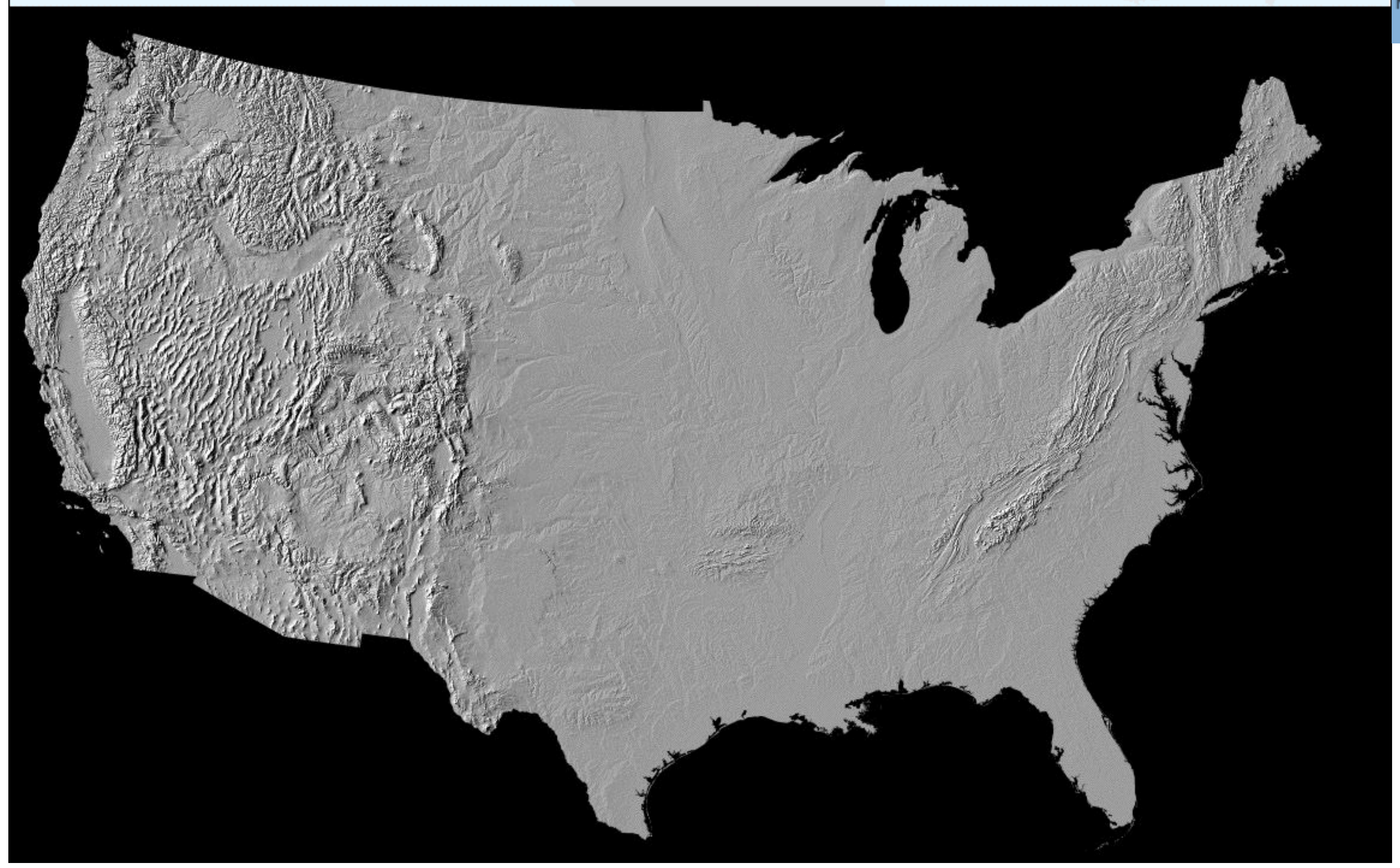
Tornadoes: Characteristics

Tornado Season In The U.S.A.

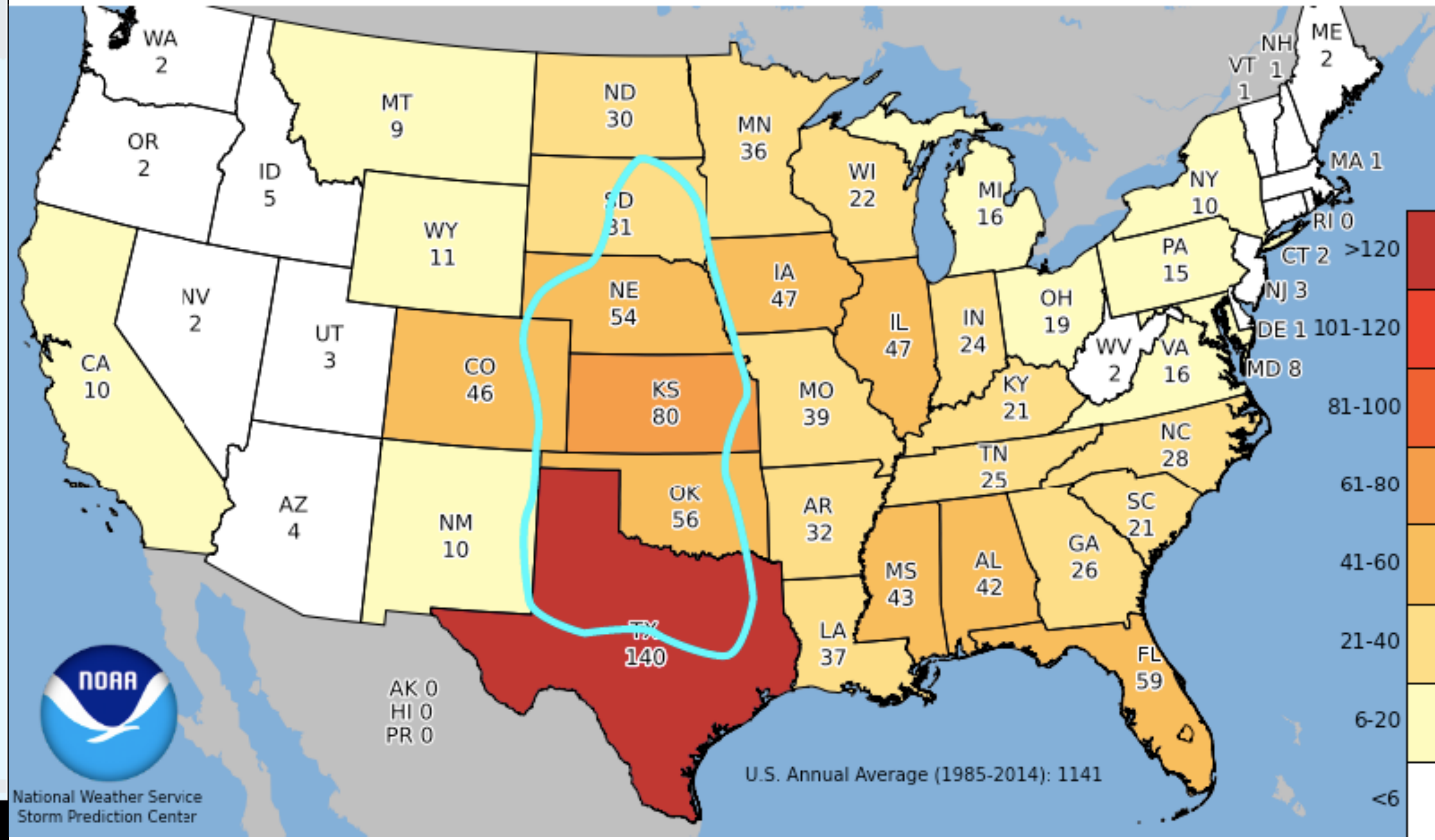
Tornadoes can occur at any time of year, but are
more frequent in Spring in U.S.A.'s plains regions.

Defining a tornado 'season' can be misleading, as they can and do occur at any time of the year in almost any part of the country. However, they are most prevalent in the southern, central, and southeastern states from early March to June, and somewhat more likely in the more northerly midwestern states in the summer months.
Comparison of tornado concentrations with the general topography of North America shows their concentration in the lower-elevation plains regions. The state of Texas averages by far the most tornadoes per year, and together with Kansas, Oklahoma, Nebraska, and South Dakota, forms part of "Tornado Alley," a region that has a high incidence of annual tornadoes. Oklahoma City holds the record for the most tornadoes to hit a city, with at least 160 since first records in 1890, although nearly 40 of these were relatively minor F0 or EF0 tornadoes.





Top: Location of tornadoes in the U.S.A. for the period 1991-2010, color-coded by season. Compare tornado concentrations with shaded relief map (bottom).



Average annual number of tornadoes in the U.S.A. by state, using data from 1985–2014. The so called Tornado Alley region is outlined in cyan.

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- In the Media

Natural Hazards and Disaster

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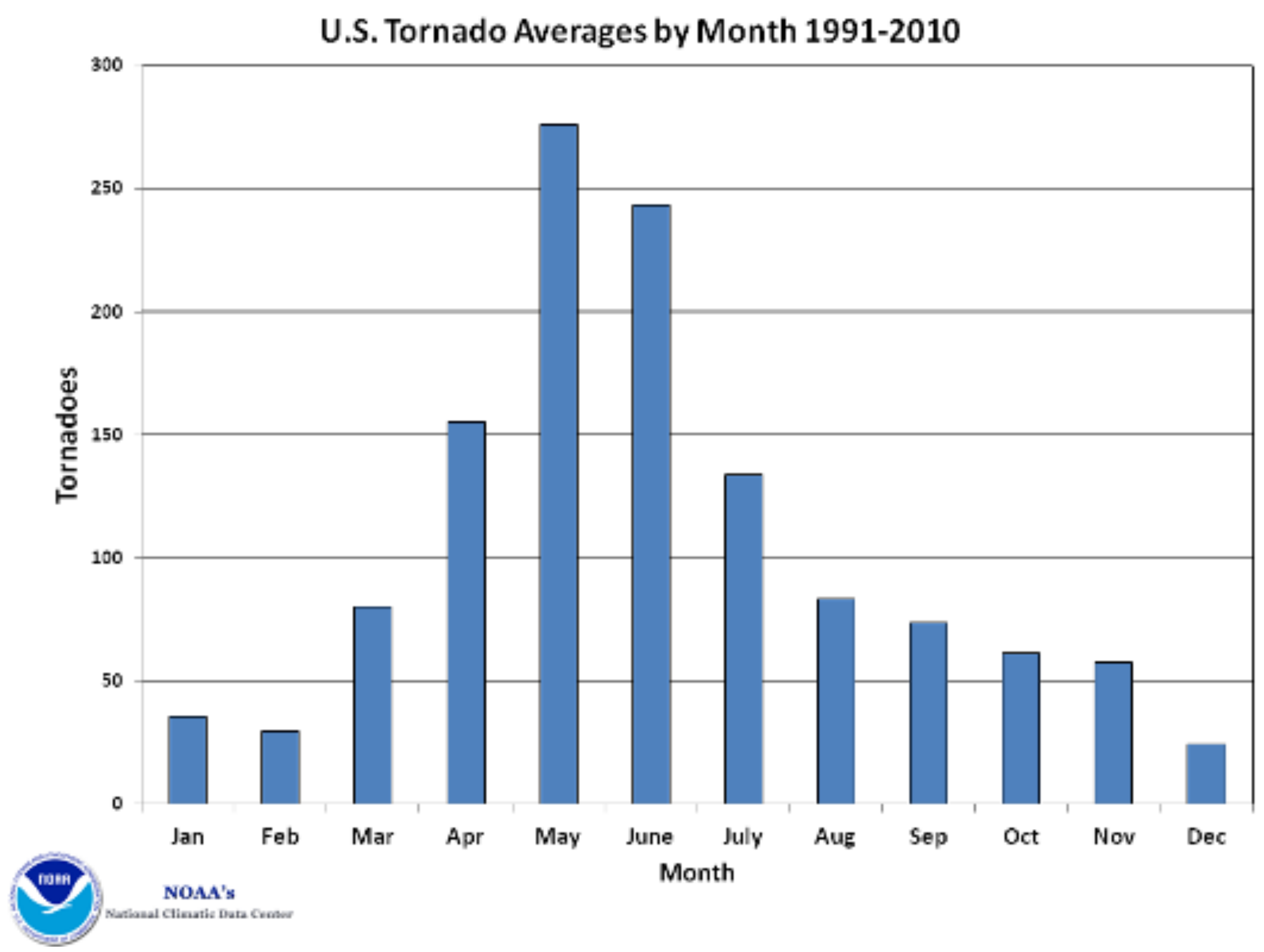
Tornadoes: Characteristics

U.S. Tornadoes In Fall

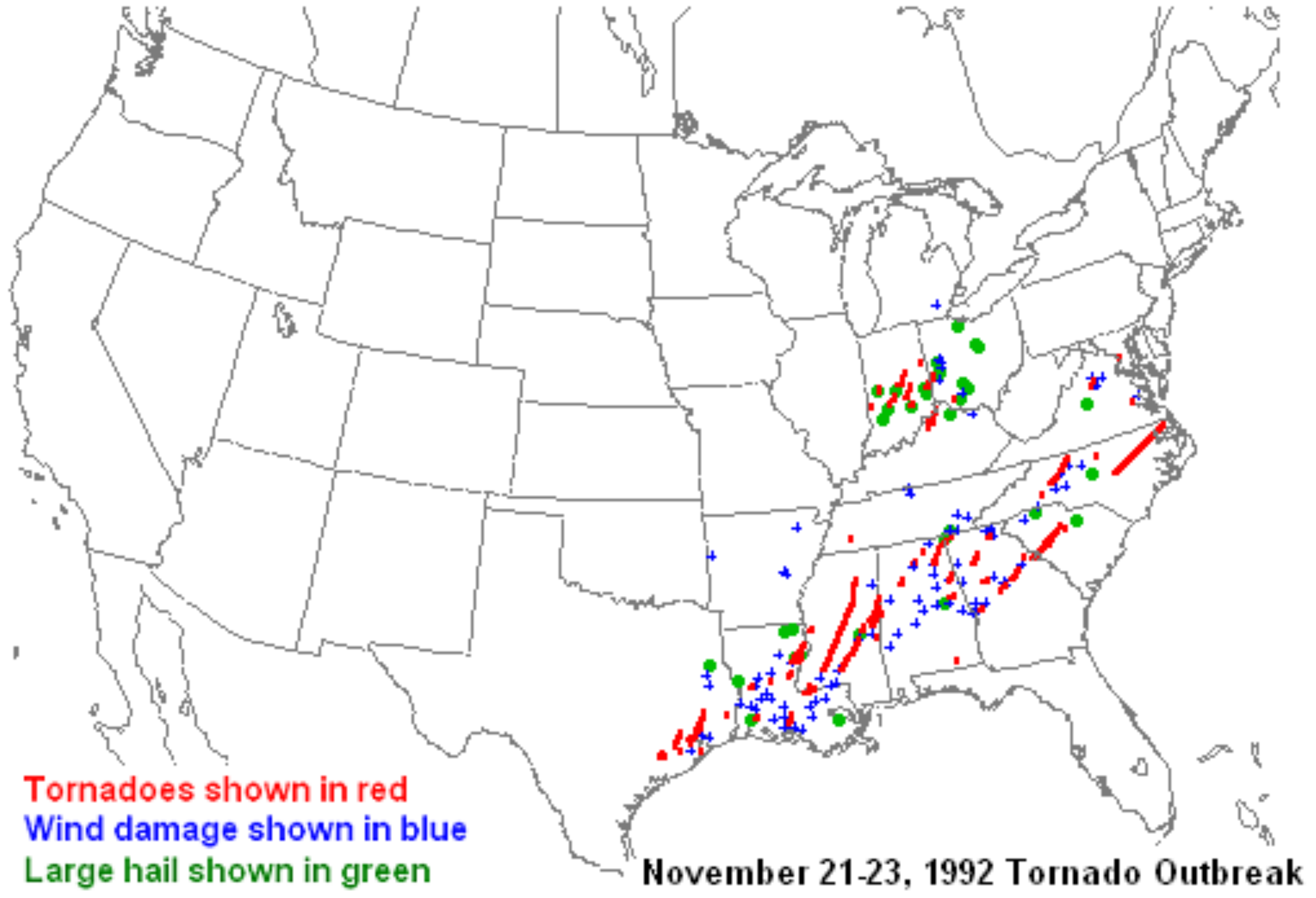
Most tornadoes in southeastern U.S.A. occur in spring, but severe outbreaks have occurred in fall .

Although spring and early summer are by far the most active tornado seasons in the southern U.S.A., the October through January period has produced several significant tornado outbreaks. An outbreak of 94 tornadoes was generated on November 21–23, 1992 when an unseasonably warm air mass over southeast U.S.A. encountered a low pressure area from the west. At least two EF4 tornadoes hit Mississippi, causing 15 out of a total of 26 fatalities.

On December 26, 2015, a severe storm system that extended from southern Texas to Alabama, spawned at least 9 tornadoes that caused at least 43 fatalities as they moved across the country. The cities of Rowlett and Garland, suburbs of Dallas, TX, were among the worst regions affected, with 11 fatalities and more than 1,000 homes and businesses destroyed by an EF3 tornado that became locally EF4.



Average number of U.S. tornadoes by month between 1991 and 2010.



Torrnado tracks for November 21–23, 1992.

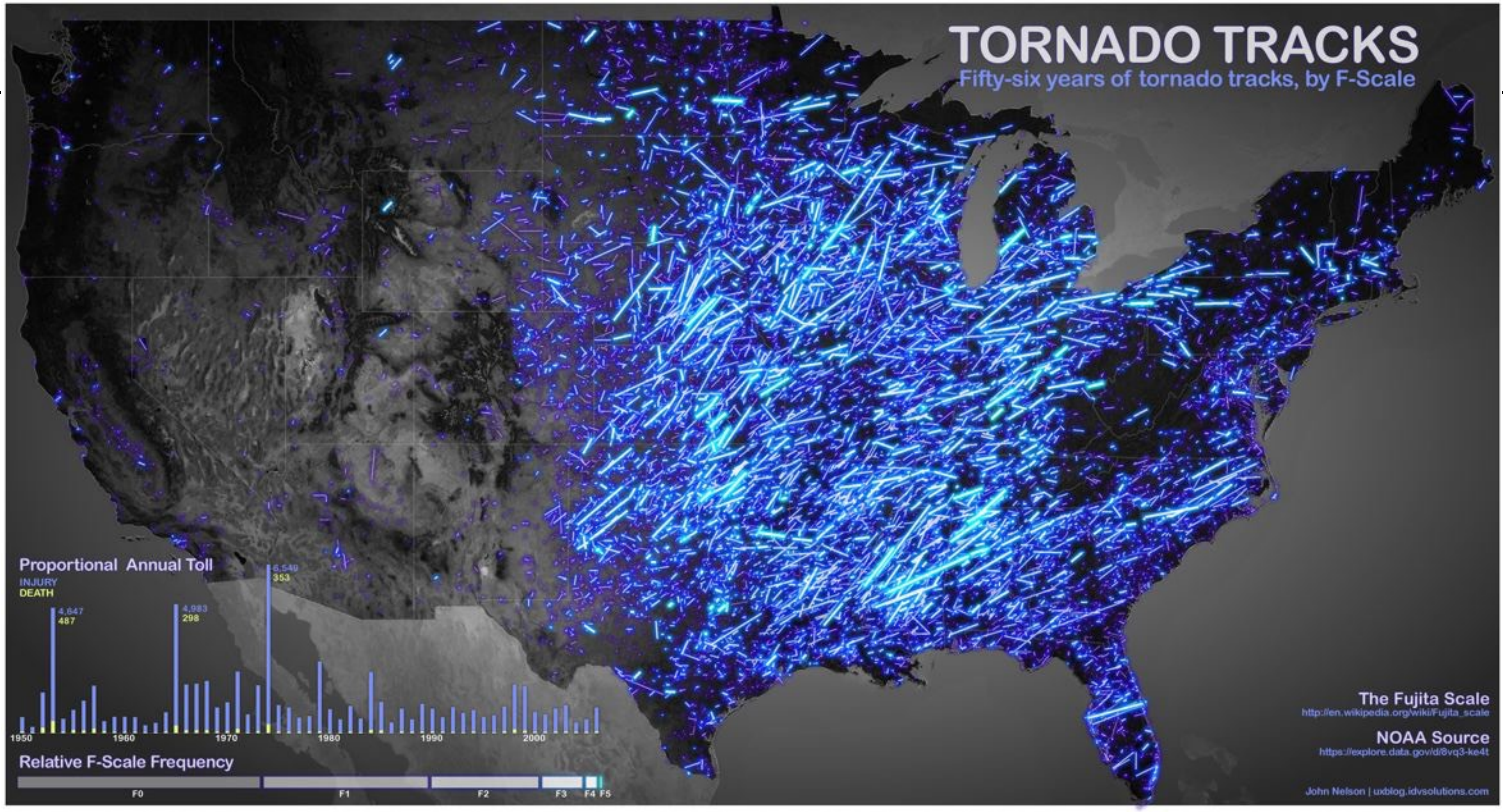
Left: Damage caused by an EF4 tornado (seen at right) in Rowlett, TX on December 26, 2015

Tornadoes: Characteristics

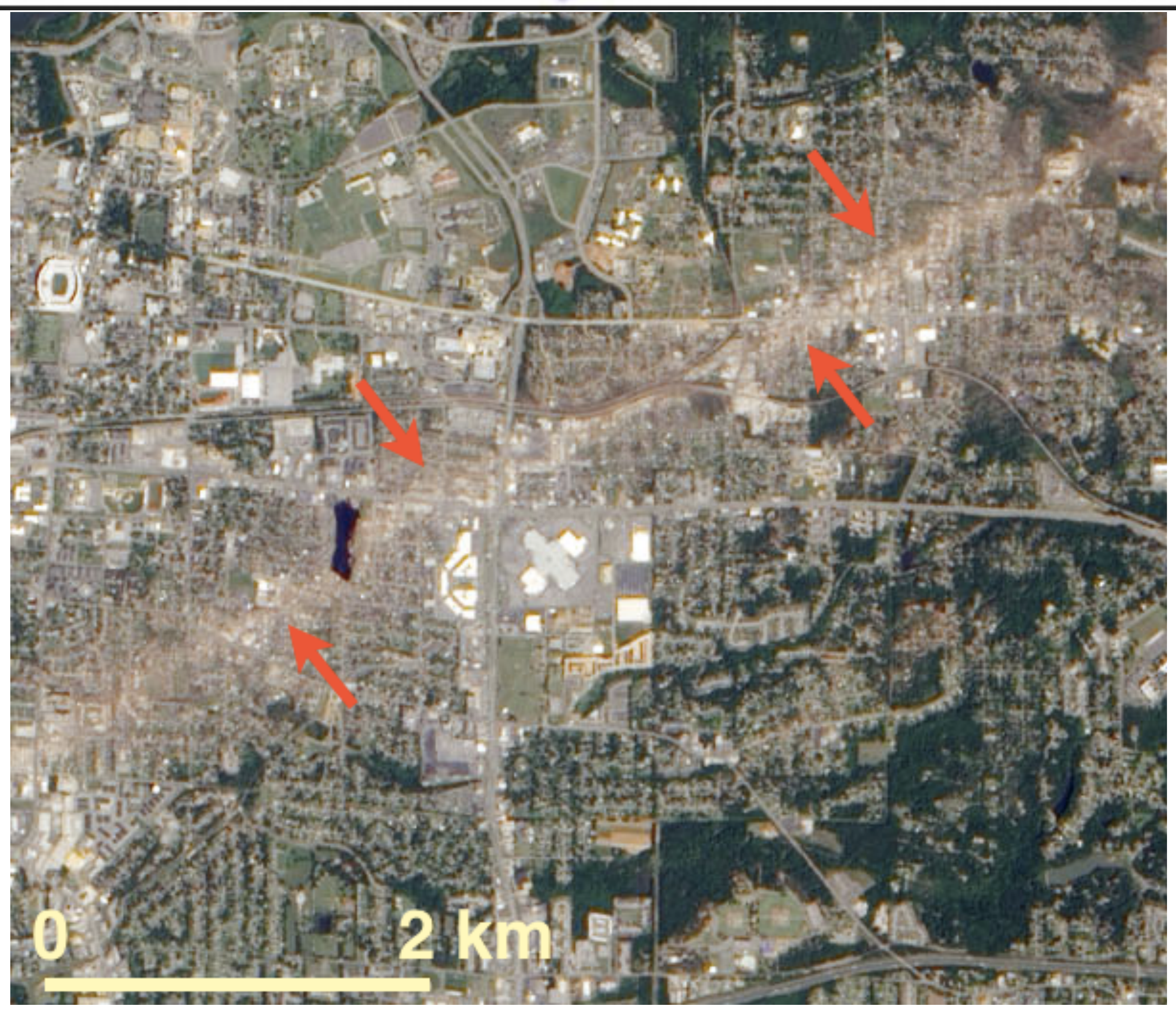
Tornado Tracks

Tornadoes leave their tracks as linear damage scars that can be clearly seen from the air.

Tornadoes in North American follow a remarkably consistent direction on average, from southwest to northeast, along the eastern boundaries between cold, dry northern air and warm, moist air from the southern Gulf states. Although some tornadoes do follow less predictable directions on a local scale, the majority track in the same general direction. However, this does not mean the wind direction in a tornado touchdown will necessarily be from southwest to northeast: tornado winds follow a circular path at ground level!
Damage tracks caused by EF3 and higher strength tornadoes are often visible from the air, especially when they cross a city, and some are even visible from space. The scars left on forested areas may last for decades, which allows researchers to map out the older tracks. Tracks of recent tornadoes are recorded by satellite and ground-level social media as the storms progress.



Cumulative tornado track map from 1950–2007, highlighted according to F-scale. Lightest blue lines are tracks of historical EF5 tornadoes.



Aerial view of visible damage caused by EF4 tornado's track across Tuscaloosa, AL, on April 27, 2011.

Tornadoes: Characteristics

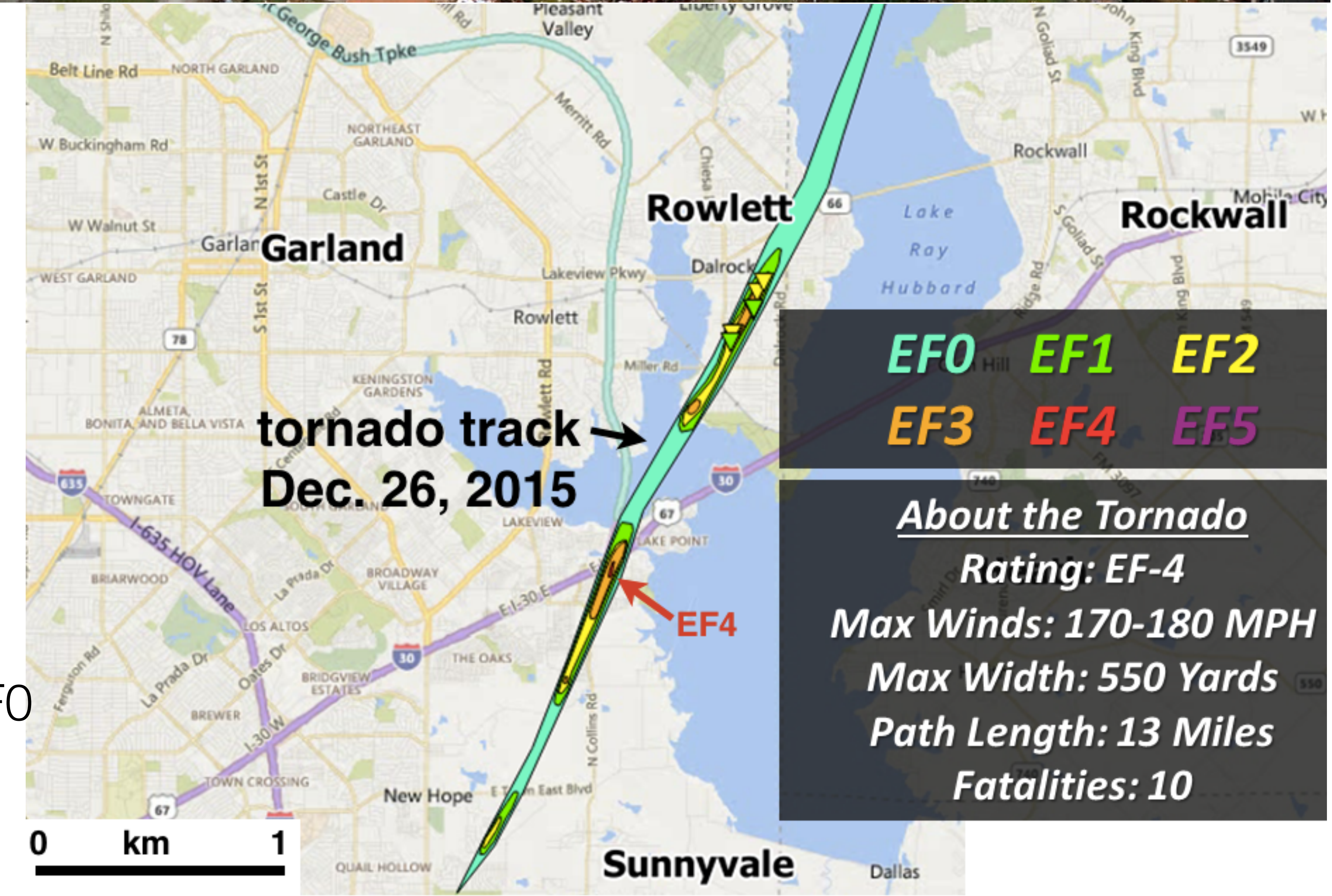
Variation In Tornado Intensity

A tornado's intensity can vary greatly; its EF number is based on greatest observed damage.

Like the majority of tornadoes, the one that struck Rowlett, TX, on December 26, 2015 varied significantly in damage intensity as it moved along its track with wind speeds in constant fluctuation. Initially touching down as an EF0, it three times reached EF3 level and each time dropped back to an EF0 as its energy was used up by frictional resistance on the ground. The tornado did attain EF4 strength for one relatively brief period along its track, and therefore was given an overall assignment of EF4. Similarly, the EF5 Moore City, OK, tornado in 2013 caused EF5 level of damage along just 1.7% of its track.

Tornadoes are often described as 'skipping', but by definition a tornado remains in contact with the ground. However, multiple vortices often develop from the same supercell, which can give the appearance of a single tornado having skipped over some areas along the storm's path.

Aerial view December 27, 2015 of damage in Rowlett, TX, from the previous evening's tornado.



The Rowlett tornado of December 27, 2015 varied in intensity from EF0 to EF3 along its track and only locally reached EF4.

Tornadoes: Characteristics

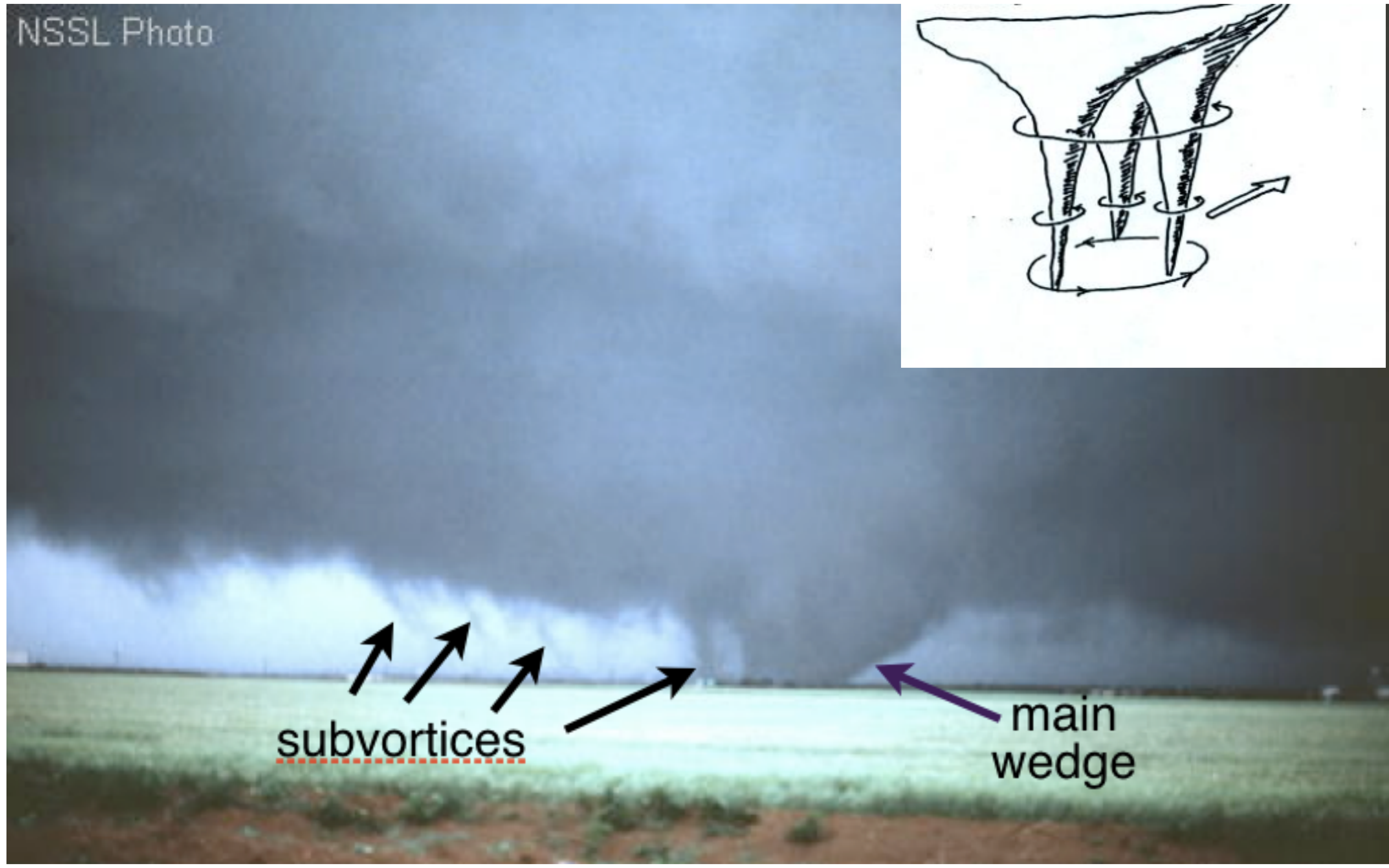
Multiple Vortex Tornadoes

Many large tornadoes contain short-lived multiple subvortices that add to the overall damage caused.

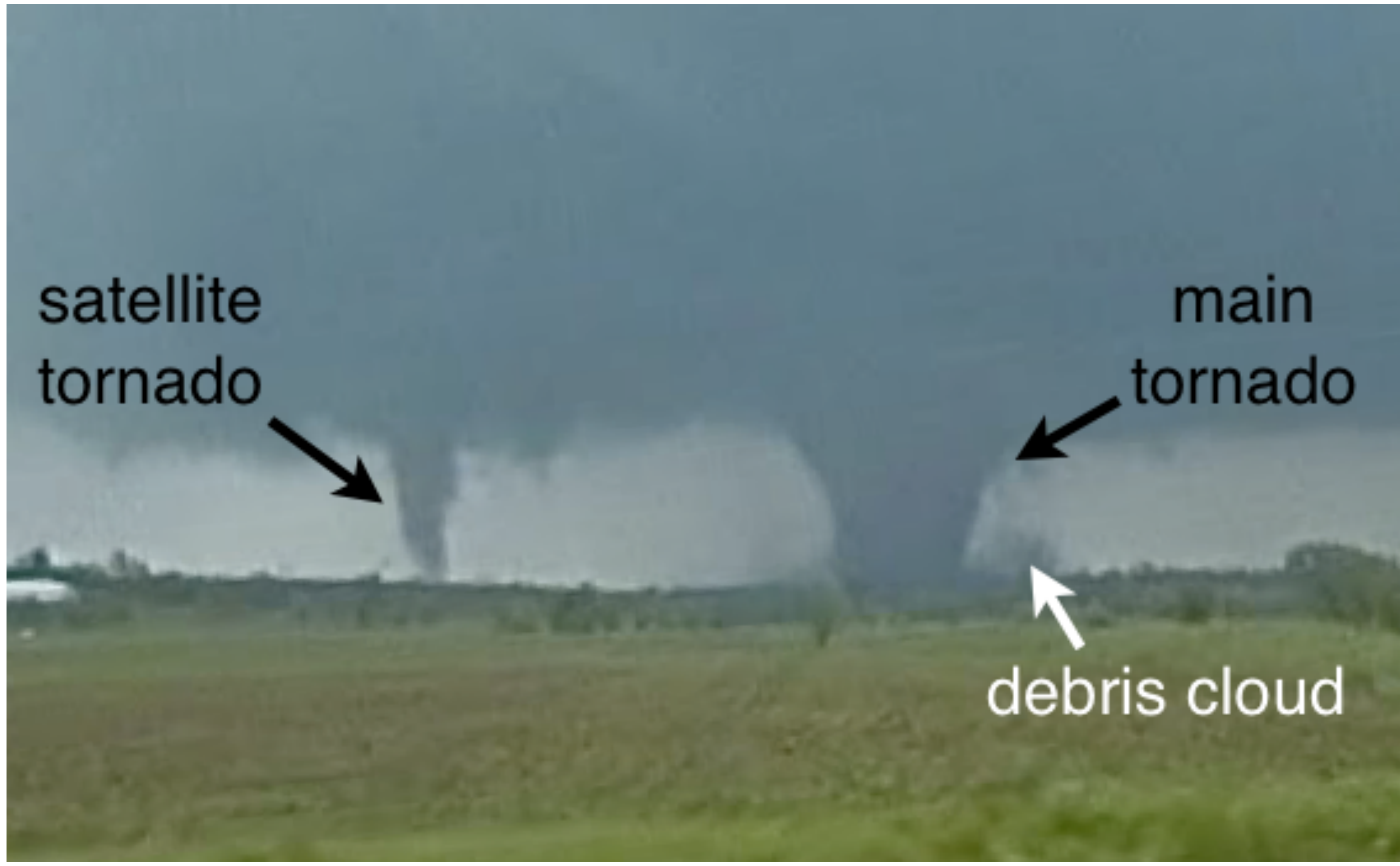
Subvortices, also called suction vortices, form when a downdraft in the main tornado's center touches ground and disturbs the structure of the spinning wind column. Each subvortex is itself a rapidly rotating wind column that orbits the central tornado, locally adding up to 160km/h to the ground-level windspeed. Groups of two to several narrow subvortices often occur just outside the central region of very strong tornadoes. They are often not visible in the rotating cloud and debris of the main tornado and do not usually last for more than a minute or so, but they create local zones of extreme damage adjacent to the main tornado's path.

A satellite tornado is a completely separate tornado that forms in the same supercell as a larger and very strong tornado. Satellite tornados are often drawn into, and may be seen to merge with, the vortex of the larger tornado.

Several subvortices are visible in this view of a large tornado near Altus, OK, onMay 11, 1982. Inset: Schematic of 3 subvortices within a large tornado.



A satellite tornado photographed adjacent to a larger tornado in Oklahoma on May 3, 1999. The larger tornado is much closer to the camera, as shown by the clearly visible debris cloud at its base.



Tornadoes: Characteristics

Tornado Width

Tornadoes range in width from slender rope tornadoes to broad wedge-shaped tornadoes.

The average width of a tornado's path on the ground is said to be about 90 m, but "average" is misleading, as the damage zone's width varies significantly along a single tornado's path. Very narrow 'rope' tornadoes, do tend to remain narrow for their entire duration and even though the twisting column of air bends and sways as it moves, it usually creates a relatively narrow, although still intense, damage path. At the other extreme are broad 'wedge' (also sometimes called 'funnel') tornadoes that create wide damage paths. A deadly EF3 tornado that hit just south of El Reno, OK, on May 31, 2013, created a damage path 4.2 km wide at its maximum width. Other tornados that have caused over 4 km-wide damage paths include an EF4 tornado in northern Oklahoma in 1999, an EF4 in Nebraska, on May 22, 2004, and an EF3 in Edmonson, Texas, on May 31, 1968.

A narrow 'rope' tornado with a dirt and debris cloud at its base as it moves across farmland.

An extremely wide EF3 wedge tornado near El Reno, OK, on May 31, 2013.

The wedge tornado in the figure above just missed El Reno, OK, on May 31, 2013, but killed several people, including 3 tornado researchers. At its maximum, the damage path was 4.2 km wide.

Tornadoes: Characteristics

Tornado Speed

A tornado's internal wind speed and forward motion speed are not related, but both affect the degree of damage caused.

Tornado wind speeds are not the same as tornado forward motion speeds. For example, an EF5 tornado by definition has internal wind speeds of >322 km/h, but its forward motion can be anywhere from 15 km/h or less, to 110 km/h or more. The more slowly a tornado moves forward, the more damage its winds are capable of inflicting. Narrow rope tornadoes tend to travel quickly, but they can still cause major damage with high internal wind speeds. Large wedge tornadoes often move forward quite slowly, inflicting massive damage as they go. The Jarrell, TX, EF5 tornado of May 27, 1997 was a slow moving wedge tornado; the Joplin, MO, EF4 tornado of May 22, 2011, crawled across the city at 16 km/h; and a wedge tornado in northern Nebraska in June 2014 became almost stationary at one point along its path. However, there are many exceptions to these generalities. An EF5 tornado that struck Hackleburg, AL, on April 27, 2011 travelled at 110 km/h or more along much of its track.

Extremely slow-moving wedge tornado near Coleridge, Nebraska, appeared to hover in place for almost an hour on June 17, 2014.

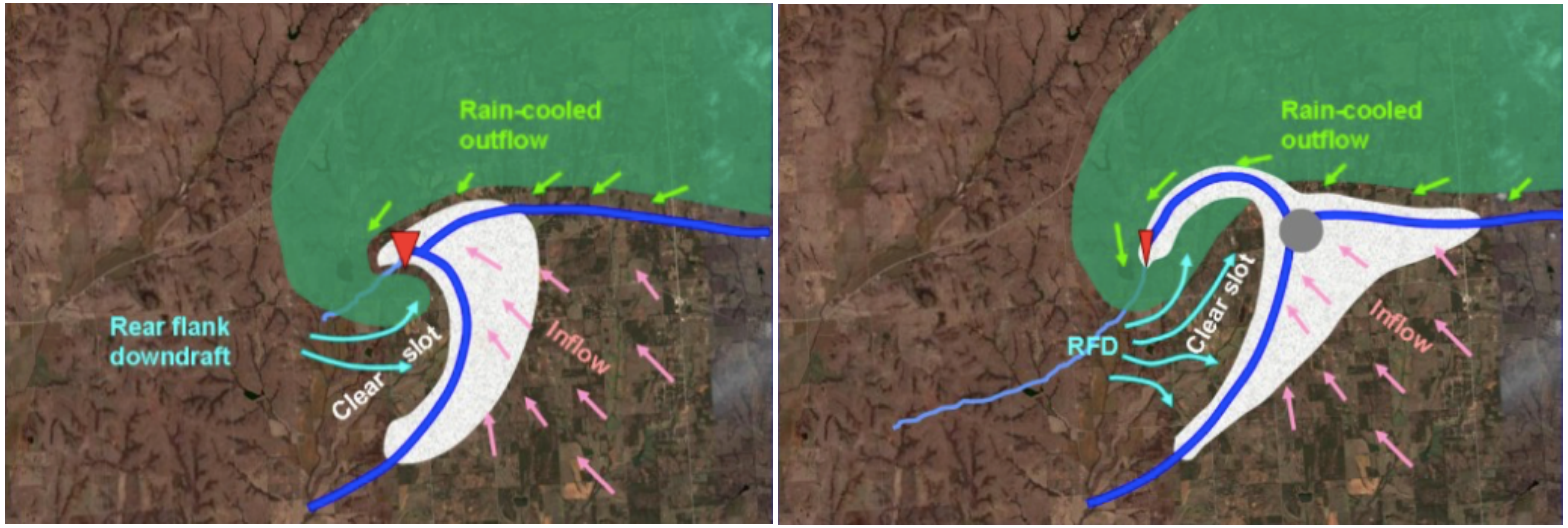
Destroyed Wrangler denim factory in Hackleburg, AL, from an EF5 tornado on April 27, 2011.

Tornadoes: Characteristics

Dying Tornadoes

Tornadoes die out when their energy has been expended through frictional contact or a when a rear flank downdraft cuts off the air inflow.

Tornadoes do not last forever, fortunately. Much of its energy is lost through frictional contact with the ground and any large structures along its path. Also, as the storm continues, rain-cooled air becomes mingled with the downdraft of air at the rear of the vortex (rear flank downdraft; RFD) and eventually cuts off the inflow of warm air that gives the tornado its energy.
As the spinning column of air slows down, the tornado's base lifts off the ground. The central updraft loses its strength, causing the funnel to tilt as it rises and is absorbed into the mesocyclone. Occasionally, however, a strong, narrow vortex remains for a while resulting in a so-called 'ropeout' stage, in which a slender, sinuous, and still dangerous rope tornado may remain until it lifts off the ground, becomes a rope funnel cloud), and eventually dissipates.



Left: Mature stage of tornado (red inverted triangle). Warm air inflow (pink arrows) and a rear flank downdraft (cyan arrows) sustain the vortex circulation. Right: Dissipation stage of tornado. Rear flank downdraft (RFD) and rain-cooled air cut off the inflow of warm air to the vortex.

Typical sinuous shape of rope funnel cloud during rope-out stage of tornado dissipation. Heavy rain at edge of mesocyclone visible on right of image.

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Tornadoes: Cases

Washington, IL, November 2013

Very large thunderstorm systems may produce several, or even many, individual supercells.

On Sunday evening November 17, 2013, a severe thunderstorm system consisting of several individual supercells spawned more than 70 tornadoes across Illinois, Iowa, Indiana, Michigan, Missouri, Ohio, and Wisconsin. This unusually severe tornado outbreak for so late in the year lasted for over 10 hours. Tornado tracks extended for 75 km, with hundreds of buildings destroyed and at least 8 fatalities. The supercells occurred along the edge of a cold front, where high levels of low-level atmospheric moisture and high wind shear created high CAPE values. One of the most heavily impacted areas was Washington, Illinois where a high EF4 tornado crossed a large suburban subdivision. Although it followed the main storm system on its overall northeasterly path, the tornado locally changed its direction several times, which is not unusual for tornado tracks.

Path taken by EF-4 tornado through a housing development in Washington, Illinois, U.S.A. on November 17, 2013.

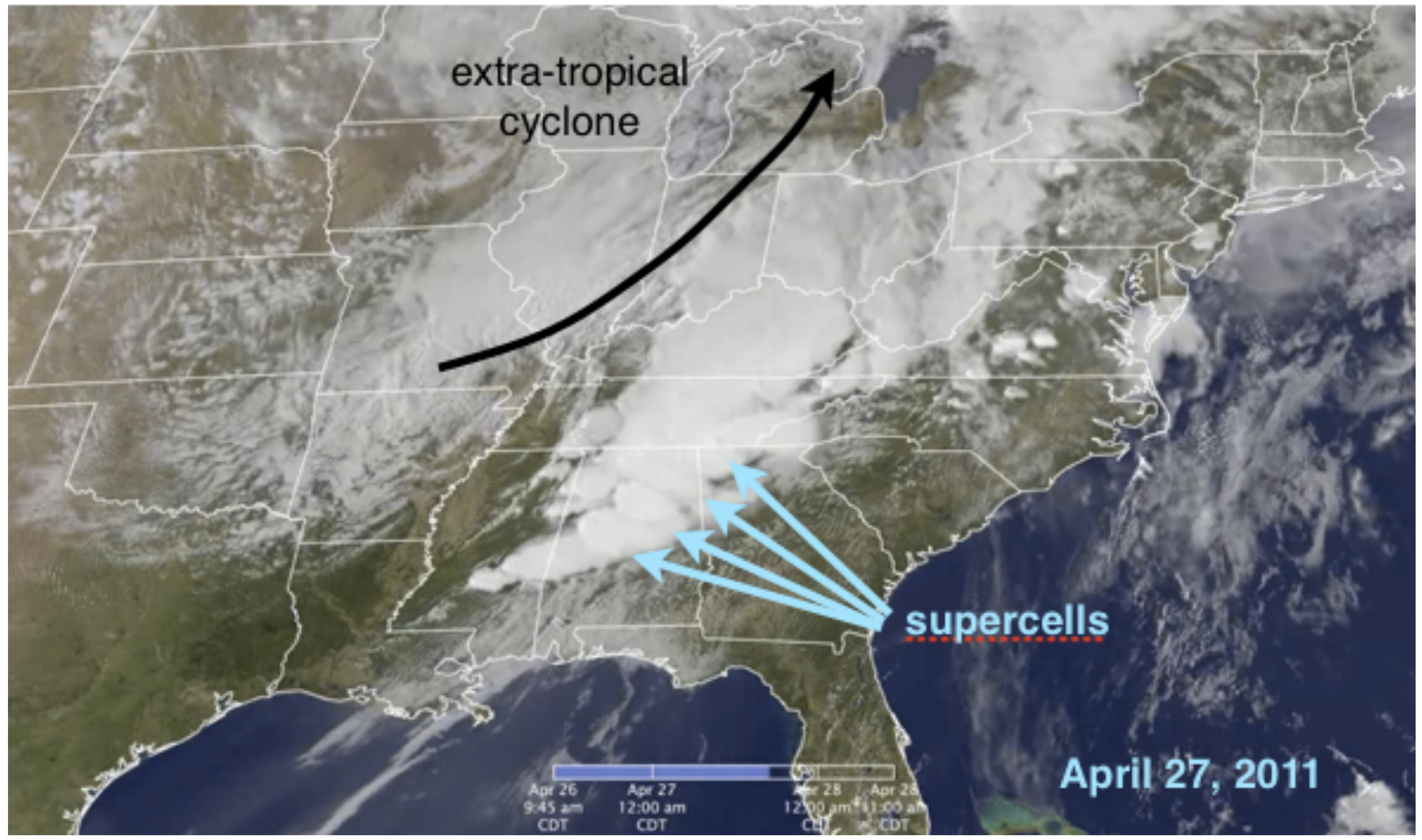
Total destruction of homes caused by an EF4 tornado in Washington, IL, on November 17, 2013.

Tornadoes: Cases

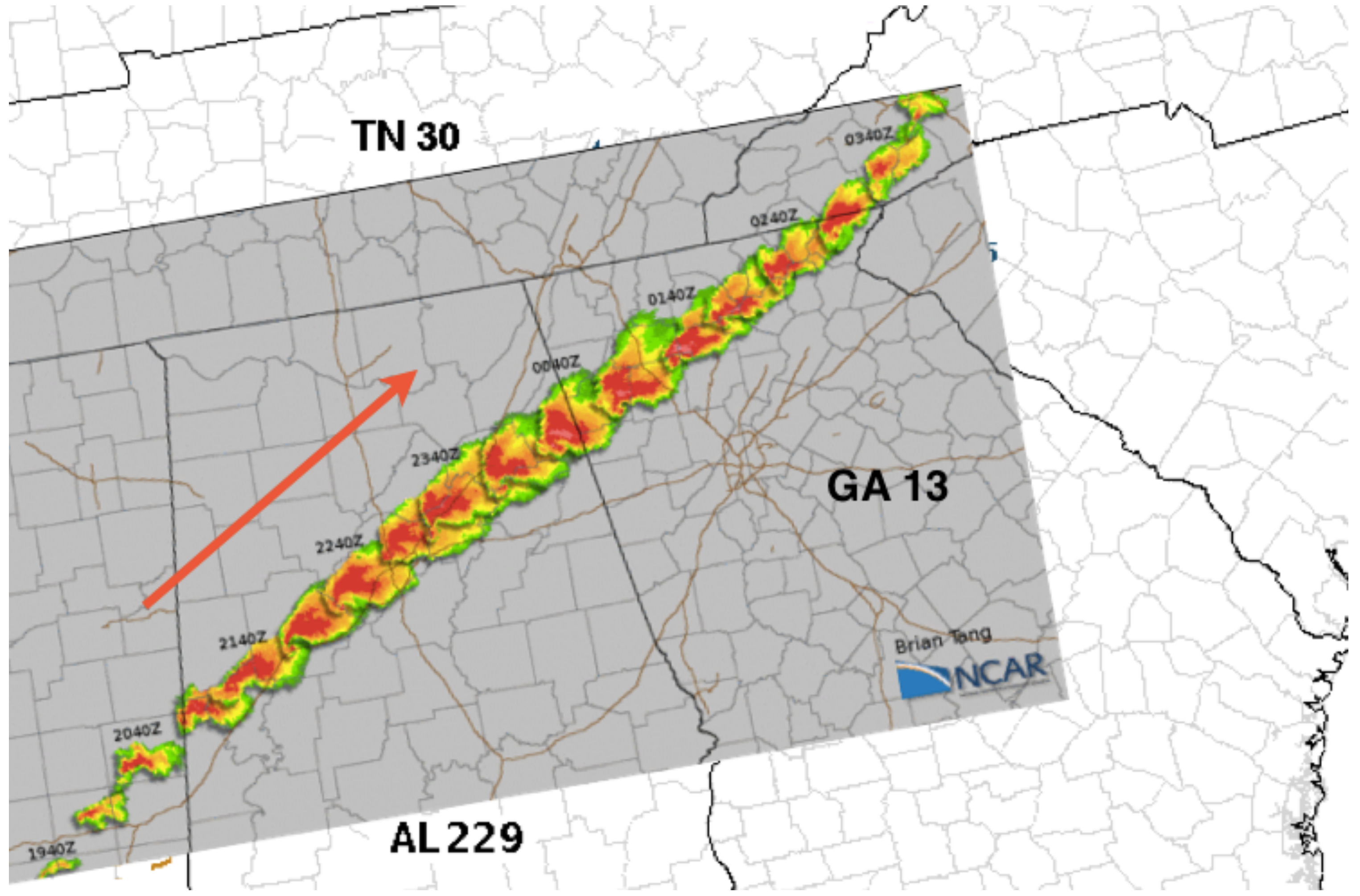
April 2011 Super Outbreak

A record number of tornadoes touched down in southeast U.S.A. over a 4-day period in April 2011.

A supercell storm may produce several tornadoes, depending on its size and CAPE value. On April 25, 2011 a large extratropical cyclone developed over south-central U.S.A., generating several supercells that moved across the southeastern U.S.A. and into northeastern states over the next 4 days. CAPE values of around 3000 J/kg were recorded from some supercells. A record number of 363 tornadoes over the 4 days of the storm, with 219 in one 24-hour period, resulted in the designation of Super Outbreak – only the second such designation in U.S. history.
The worst day was on April 27, when 4 EF5, and 11 EF4 tornadoes hit (Fig. W16c), destroying several hundred well-built homes, as well as schools and businesses, and causing 324 fatalities. The deadliest of the individual EF5 tornadoes took a 212 km-path through northern Alabama and Tennessee, causing 72 fatalities as it passed.



Supercells over southeastern U.S.A. on April, 27, 2011 spawned 219 tornadoes, causing 324 fatalities.



Radar montage of one supercell track (storm traveling in direction of arrow) on April 27, 2011. Colors indicate rainfall in mm/hr (red: >40 mm/hr). Death toll from tornadoes in each state noted.

Date	Total	EF0	EF1	EF2	EF3	EF4	EF5	Deaths	Injuries
April 25	42	17	20	4	1	0	0	4	--
April 26	55	31	19	4	1	0	0	0	--
April 27	219	68*	81	36	19	11	4	317	2000+
April 28	47	18	23	5	1	0	0	3	--
Total	363	134*	143	49	22	11	4	324	2000+

Tornado data for April 2011 Super Outbreak

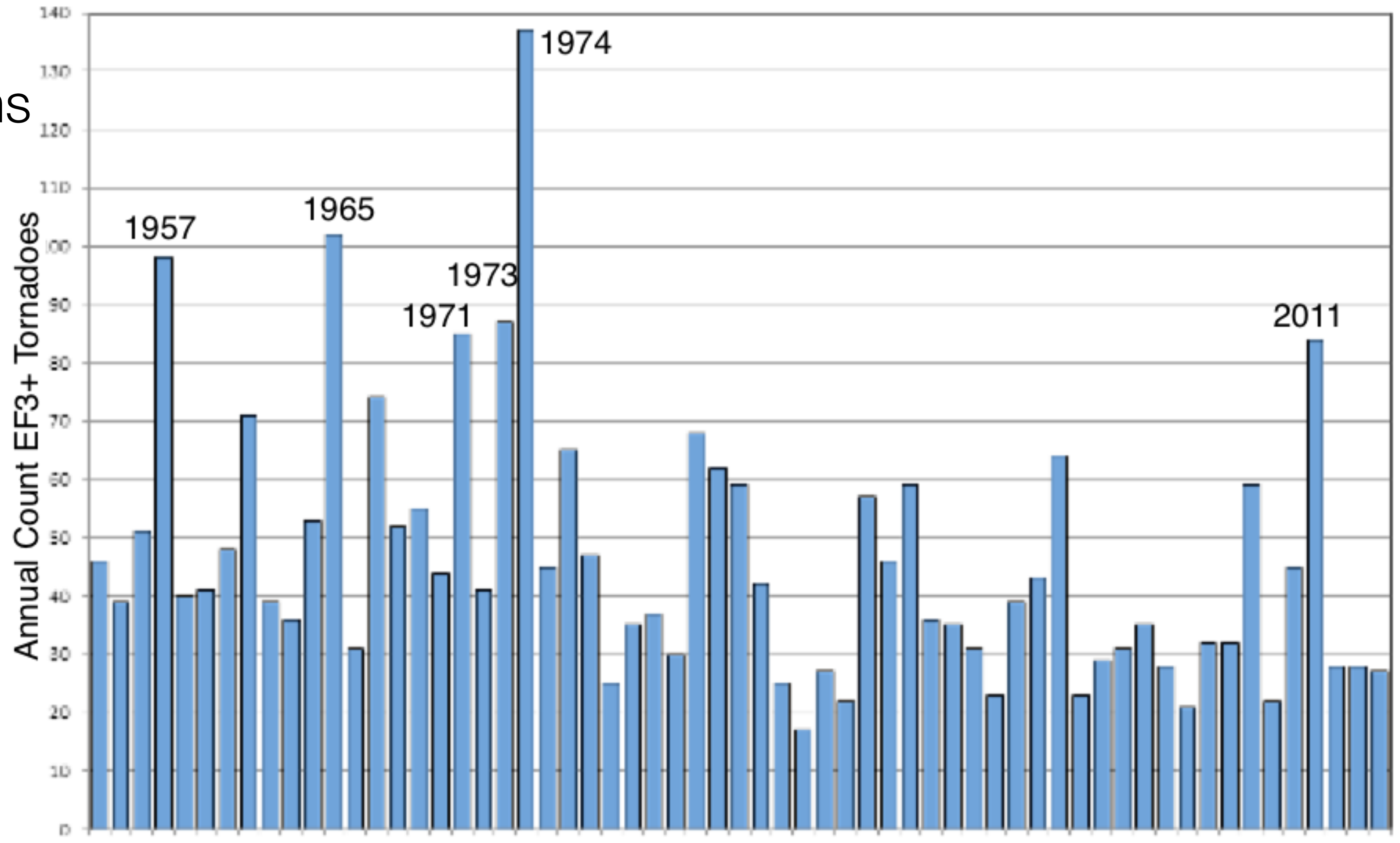
Tornadoes: Cases

The 1974 Super Outbreak

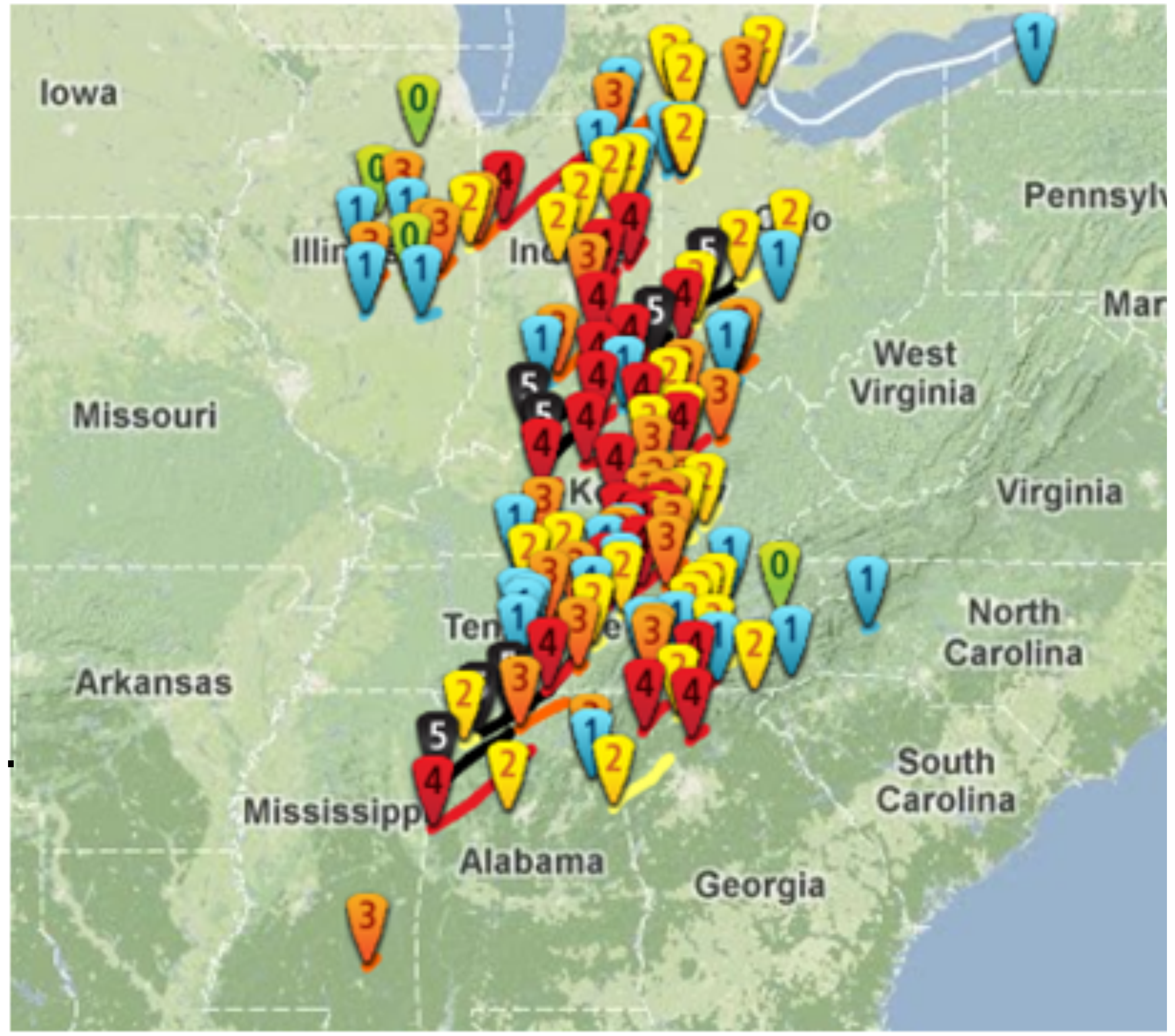
A Super Outbreak is one in which there is an exceptional number of tornadoes in one day.

Although the April 2011 Super Outbreak now holds the record for the most tornadoes generated in a 24-hour period, a Super Outbreak in 1974 still holds the record for the total number of EF3 and higher-rated tornadoes, and April 3, 1974 holds the record for the number of severe EF4 and EF5 tornadoes in one 18-hour period. Of the 148 tornadoes that occurred across 13 states on April 3 and 4, 1974, on a path covering 4,000 km from Alabama to the Great Lakes region, 23 were EF4 and 7 were EF5 tornadoes. By the time the storm system had dissipated, almost 5,500 people had been injured and 330 killed, with northern Alabama suffering the worst number of fatalities. An excellent summary of the 1974 Super Outbreak is available at https://en.wikipedia.org/wiki/1974_Super_Outbreak

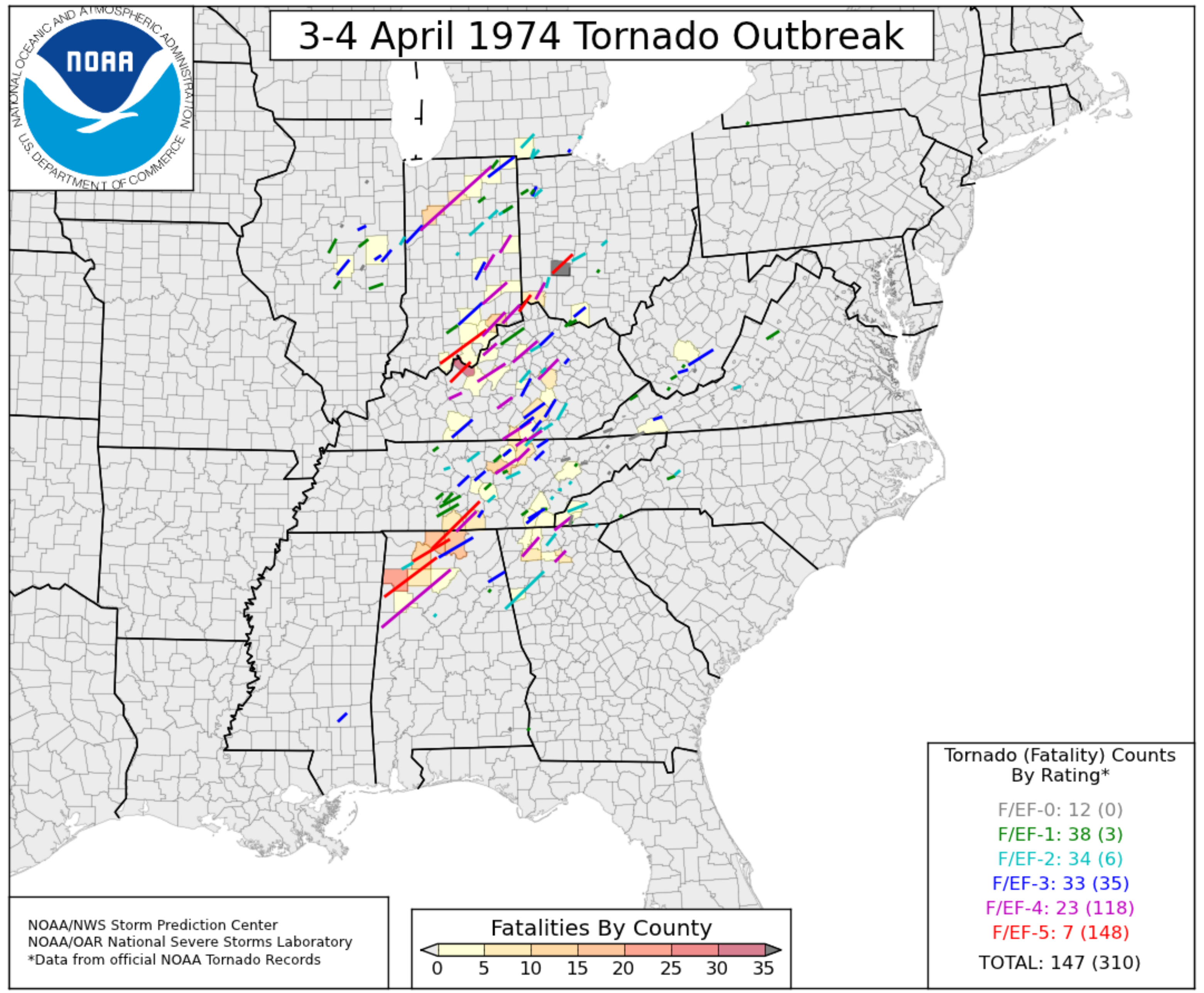
Annual count of EF3 and higher tornado touchdowns in the U.S.A. from 1954 to 2014.



April 3rd



April 4th



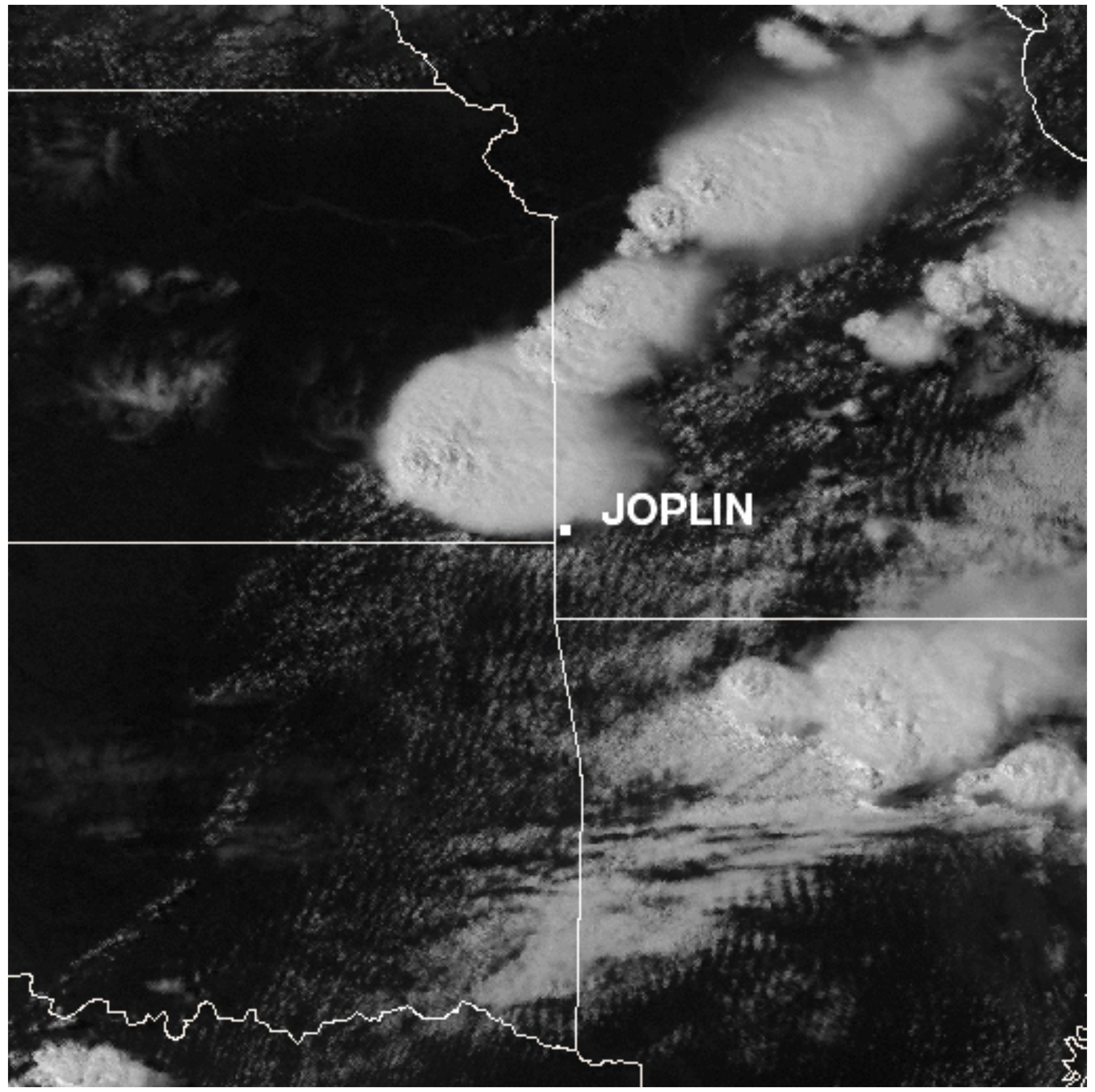
Tornado touchdowns in the eastern U.S.A. on April 3, 1974. Left: Number/color indicates EF rating. Right: Tornado tracks for April 3 and 4, 1974: blue = EF3; magenta = EF4; red = EF5.

Tornadoes: Cases

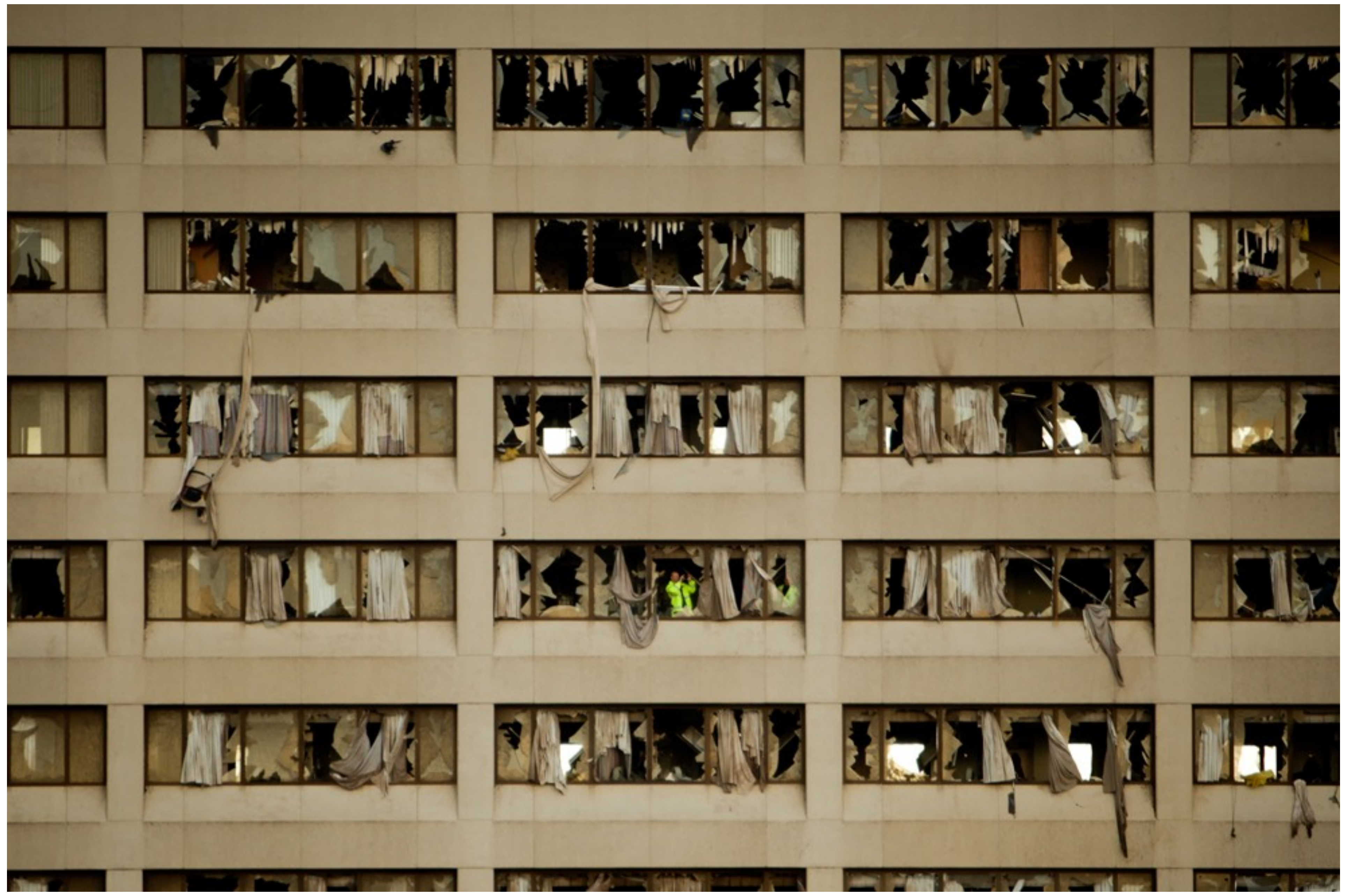
Joplin, MO, May 22, 2011

An EF5 tornado generated by a supercell caused massive destruction to the city of Joplin, MO.

A series of severe storms with supercells moved across central U.S.A., from Texas to Minnesota, on May 22, 2011, spawning numerous tornado outbreaks. An EF5 tornado from one supercell that originated in southeast Kanas approached the western edge of Joplin, Missouri, a city of approximately 50,000 people. A tornado warning was issued by the local weather bureau 17 minutes before the tornado hit.
The tornado travelled 10 km across the entire city of Joplin, with winds of over 300 km/h. It destroyed approximately 4,000 homes, injured over 1,000 people, and caused more than 160 fatalities, making it one of the 10 deadliest tornadoes in U.S. history. The local hospital was one of many buildings that were severely damaged by the tornado. As a result, the newly built Mercy Hospital in Joplin has been constructed to withstand any future large tornado.



Animation composite of satellite imagery of mesocyclone clouds and rainfall on May 22, 2011 over Joplin, MO. Data from NASA's Tropical Rainfall Measuring Mission satellite shows heaviest rain (red >40mm/hr), associated with strong downdrafts.



Rescuers (in green) search for survivors and injured patients of St. John's Regional Medical Center, Joplin, MO, after an EF5 tornado on May 22, 2011.

Tornadoes: Cases

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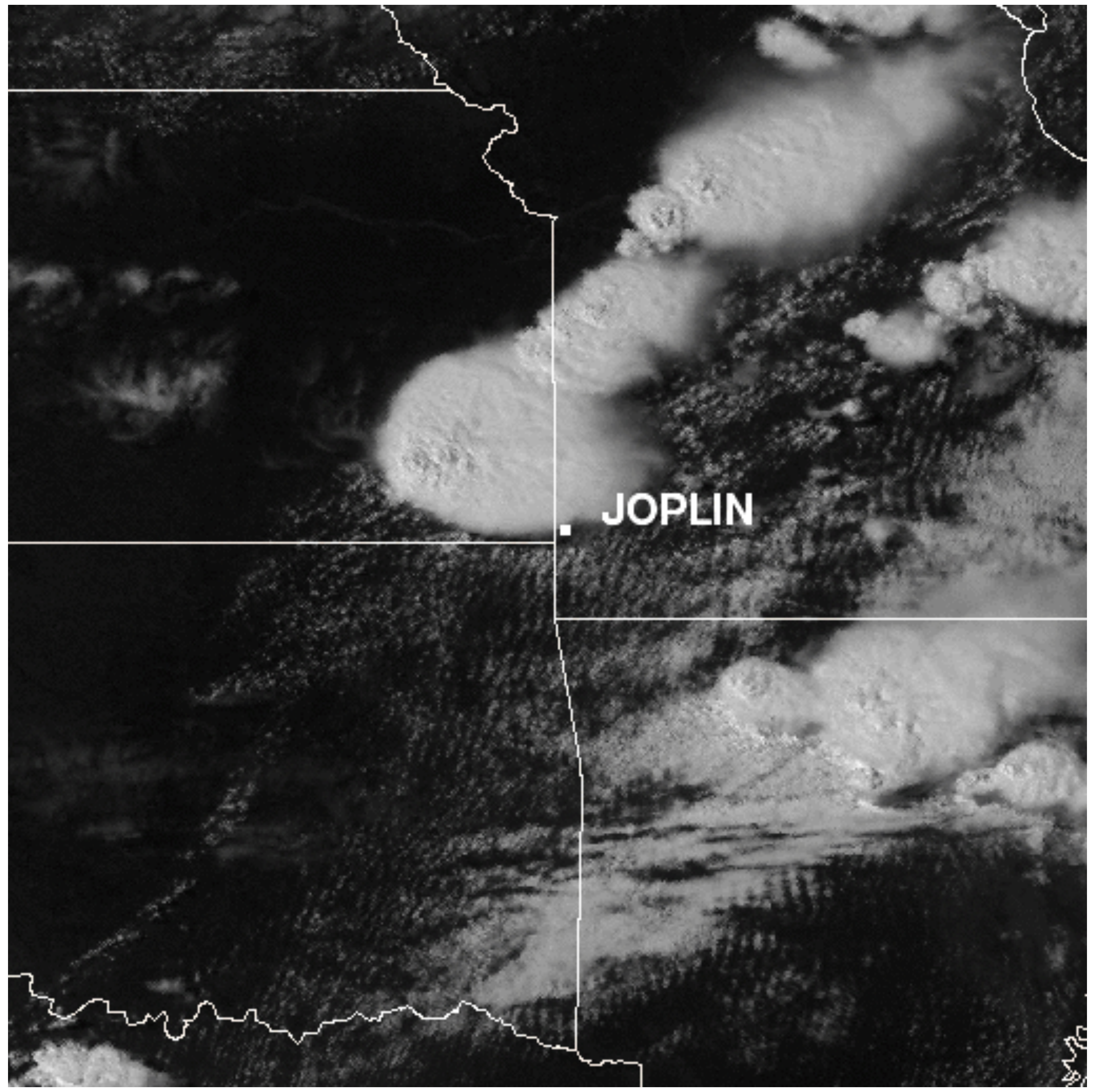

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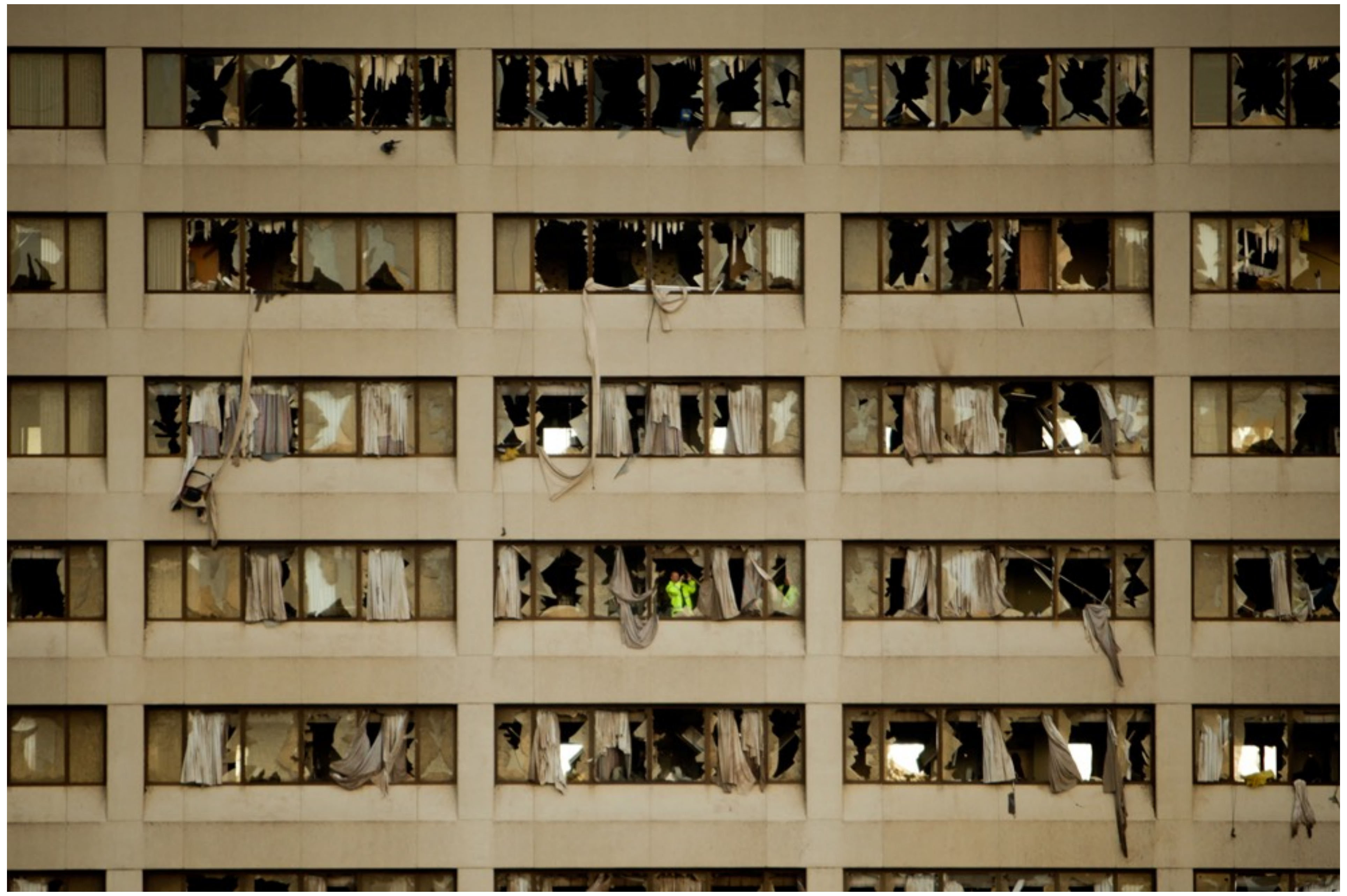


Rescuers (in green) search for survivors and injured patients of St. John's Regional Medical Center, Joplin, MO, after an EF5 tornado on May 22, 2011.

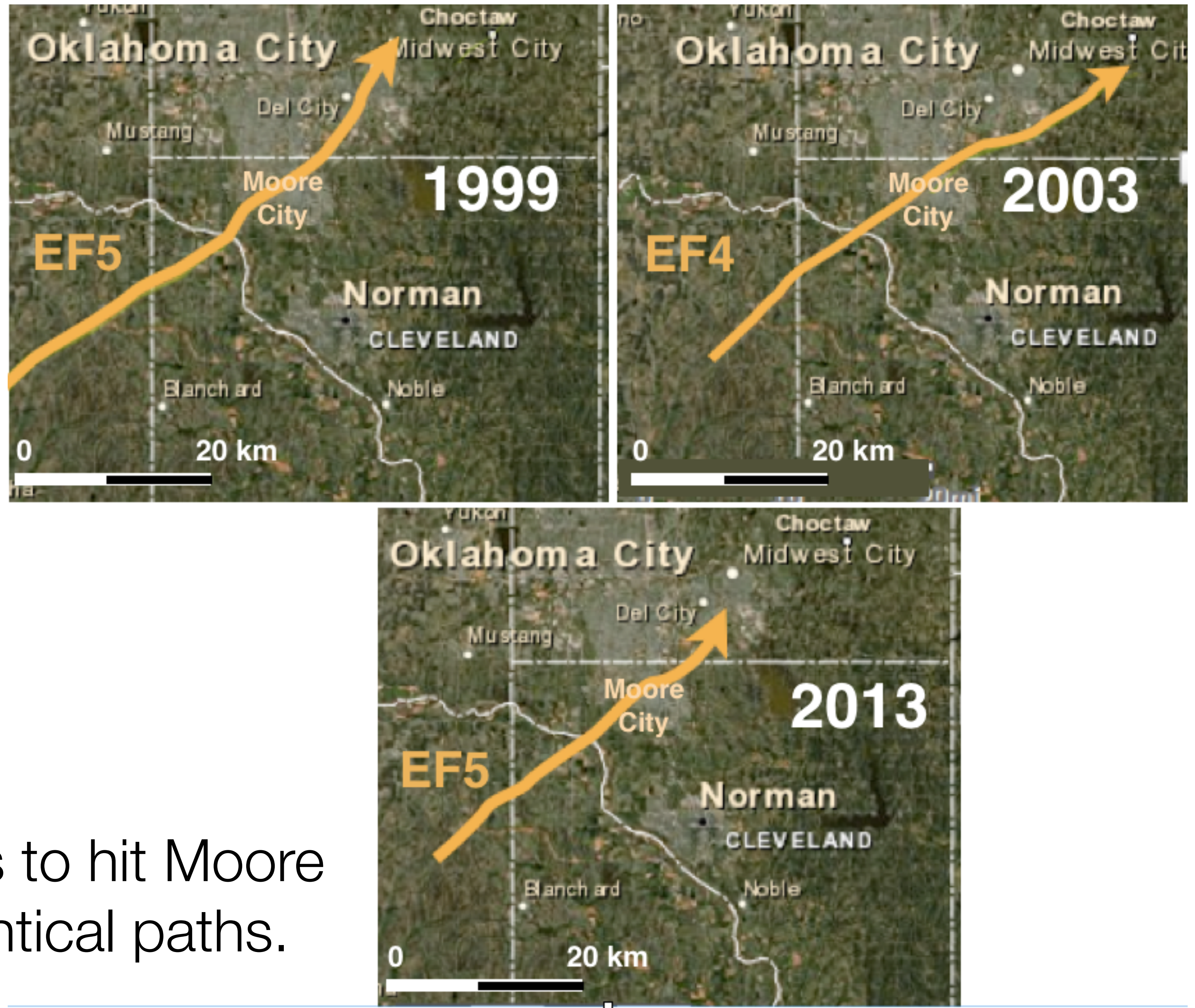
Tornadoes: Cases

Moore, OK, May 20, 2013

EF4 and EF5 tornadoes have more than once taken a path through Moore City, OK.

On May 20, 2013, a tornado of intensity EF4 touched down southwest of Oklahoma City, its strength intensifying to EF5 as it travelled eastnortheast across Moore City, on the south side of the metropolis. The tornado lasted for 50 minutes, inflicting EF4 and greater damage to suburban areas along its 22 km-long path. Two schools and over 300 homes were destroyed and 24 fatalities recorded, including 7 schoolchildren who were killed by collapsing walls.
Moore City has seen at least ten other F4 (or EF4) tornadoes in the past 100 years, as well as another EF5 on May 3, 1999, which was one of more than 60 tornadoes to hit central Oklahoma on the same afternoon. That EF5 tornado lasted for 1 hour and 25 minutes and caused more than 40 fatalities as it destroyed 1,800 homes, damaged a further 2,500, and inflicted injuries on more than 580 people along its 60 km-long path.

Aerial view of part of Moore City before (top) and after (below) the EF5 tornado of May 20, 2013.



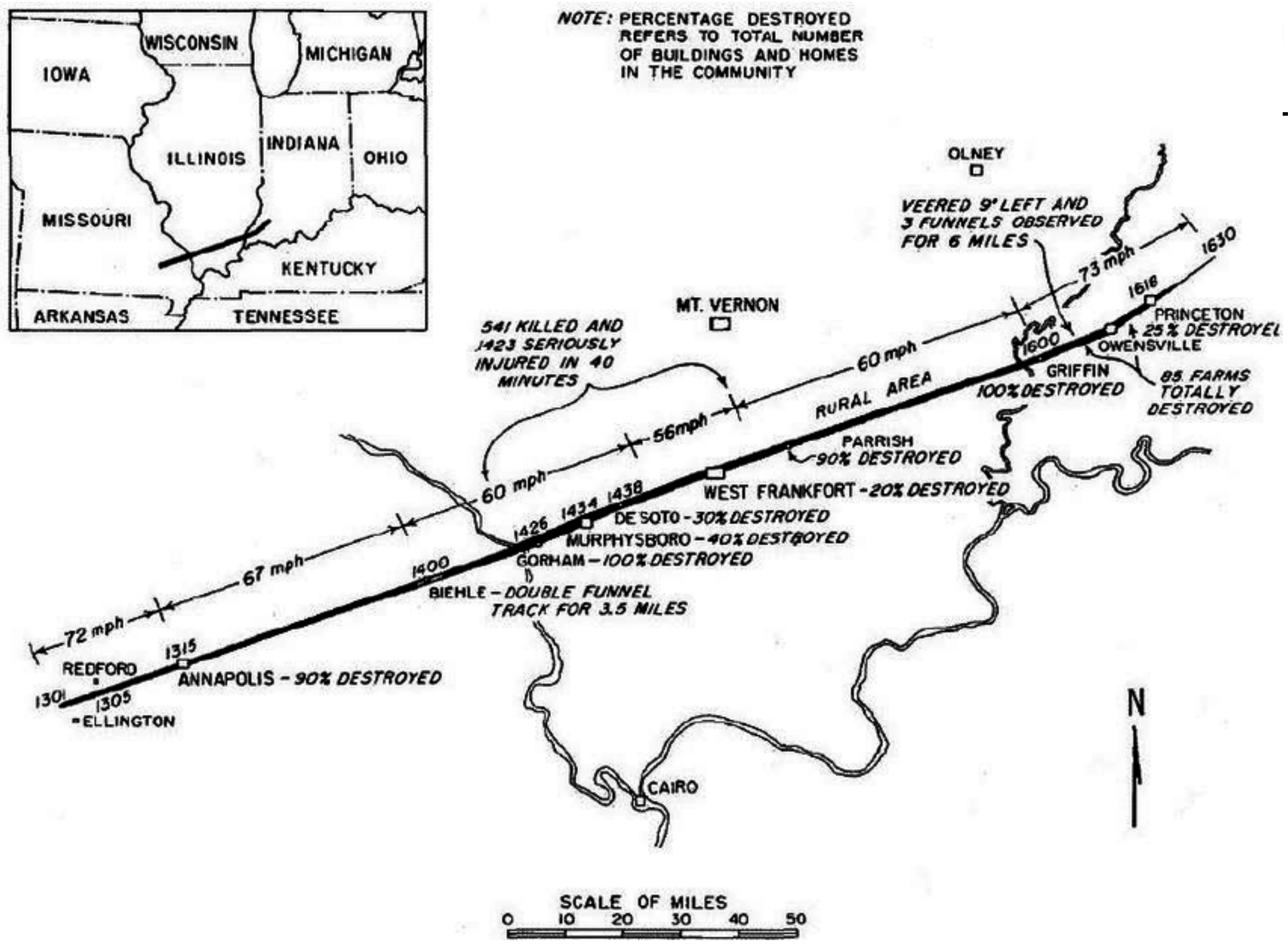
Three of the most severe tornadoes to hit Moore City, OK, travelled along almost identical paths.

Tornadoes: Cases

Tri-States Tornado, 1925

The deadliest single tornado in U.S. history remains the March 18, 1925, Tri-States Tornado.

Many tornadoes and tornado outbreaks can claim to hold a record, such as the longest, widest, fastest, most costly, etc. However, the the Tri-States tornado of March 18, 1925 holds the record as the deadliest single tornado in U.S. history. Part of a severe outbreak across Missouri, Illinois, and Indiana on March 18, 1925, the tornado first developed at 1:00 pm near Ellington, Missouri and apparently did not dissipate until 4:30 pm, having travelled on a 350 km-track to Petersburg, Indiana. Later assigned the value of EF5, the Tri-States tornado killed 695 people and injured at least 2,000.
Some researchers have questioned whether this really was a single, exceptionally long-lived vortex; there was no radar imagery in those days to verify this assumption. It is possible that the Tri-States tornado was really a series of tornadoes generated from supercells as part of a Super Outbreak.



Track of the Tri-States tornado of March 18, 1925, with percentage of buildings destroyed. Inset shows the tornado's track across the three U.S. states.

Photo courtesy of the Jackson County Historical Society in Murphysboro, Illinois.

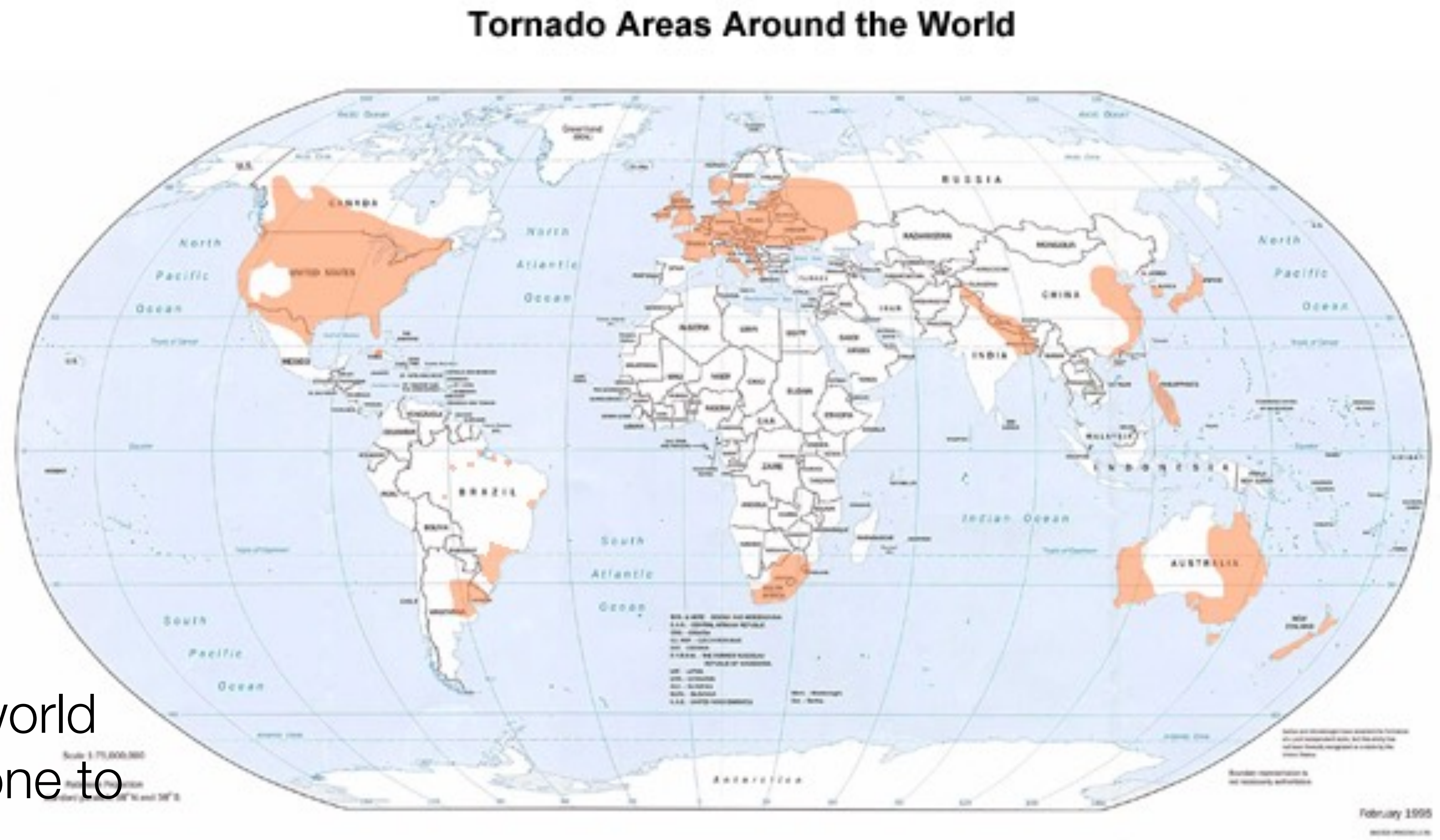
Devastation caused in Murphysboro, Illinois, by the Tri-States tornado of March 18, 1925. Southern Illinois was the worst-affected area.

Tornadoes: Cases

Bangladesh Tornadoes

Tornadoes in Bangladesh often cause extreme destruction due to poorly constructed buildings.

Bangladesh is one of many regions in the world where tornadoes regularly occur, yet it suffers exceptionally high numbers of fatalities. The seasonal monsoon winds that bring summer rain to Bangladesh and east India are frequently preceded in Spring, and occasionally followed in Fall, by unstable weather conditions that generate severe thunderstorms and tornadoes. On April 26, 1989, the most deadly tornado in recent world history occurred in central Bangladesh, killing approximately 1,300 people and leaving 80,000 homeless. Other severe tornado outbreaks in Bangladesh that resulted in over 600 fatalities include April 14, 1969 (923 fatalities), April 17, 1973 (681), and May 13, 1996 (750).
Two major factors contribute to the high death toll from these and other tornadoes that cause major damage, but would be assigned relatively low EF values: poor-quality building construction in poorer rural regions; and the lack of modern equipment for adequate forecasting, monitoring, and provision of warnings about impending tornado conditions.



Localities around the world that are particularly prone to tornadoes.

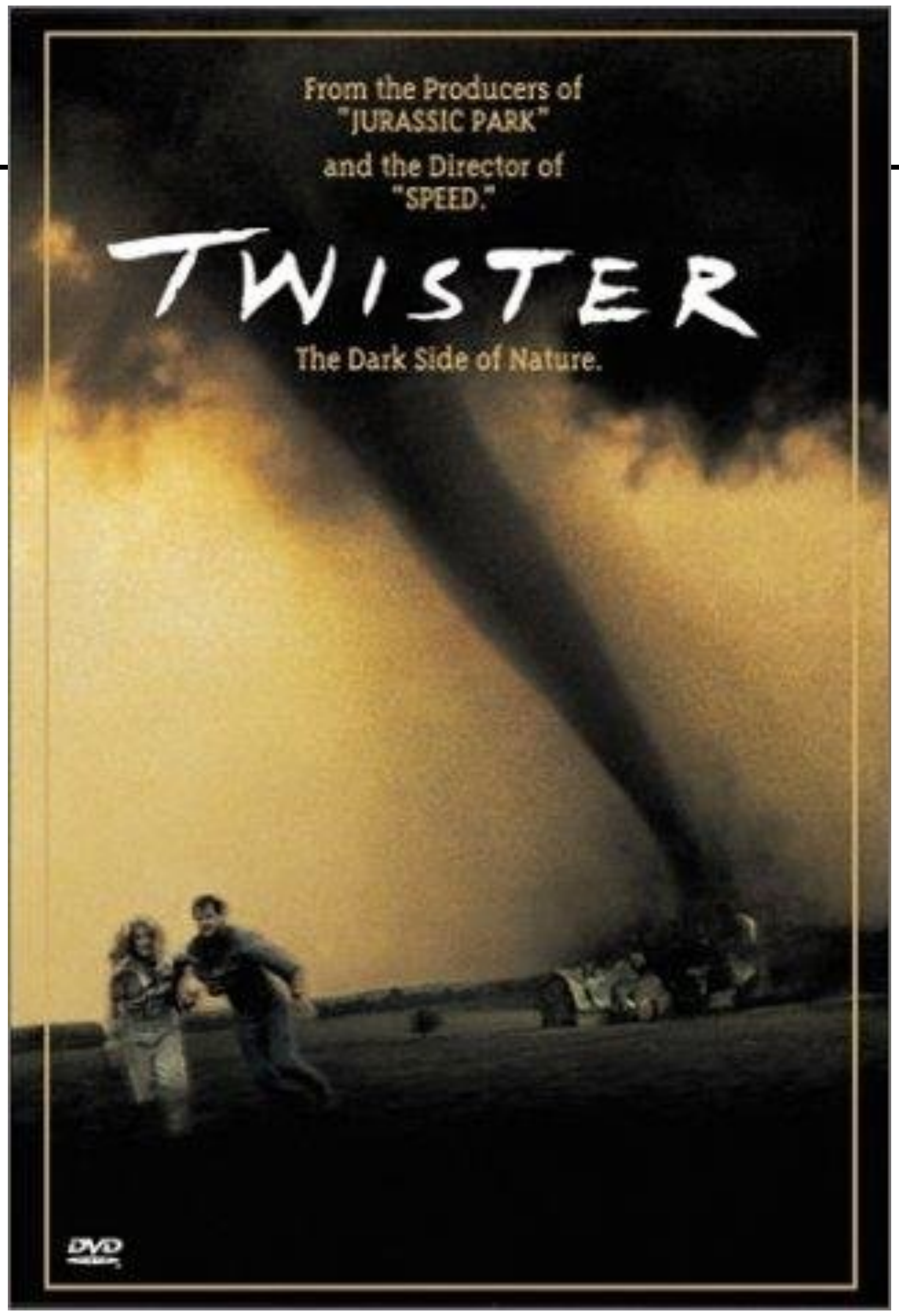
Devastation of a Bangladesh village from a tornado on March 22, 2013 that destroyed 25 villages.

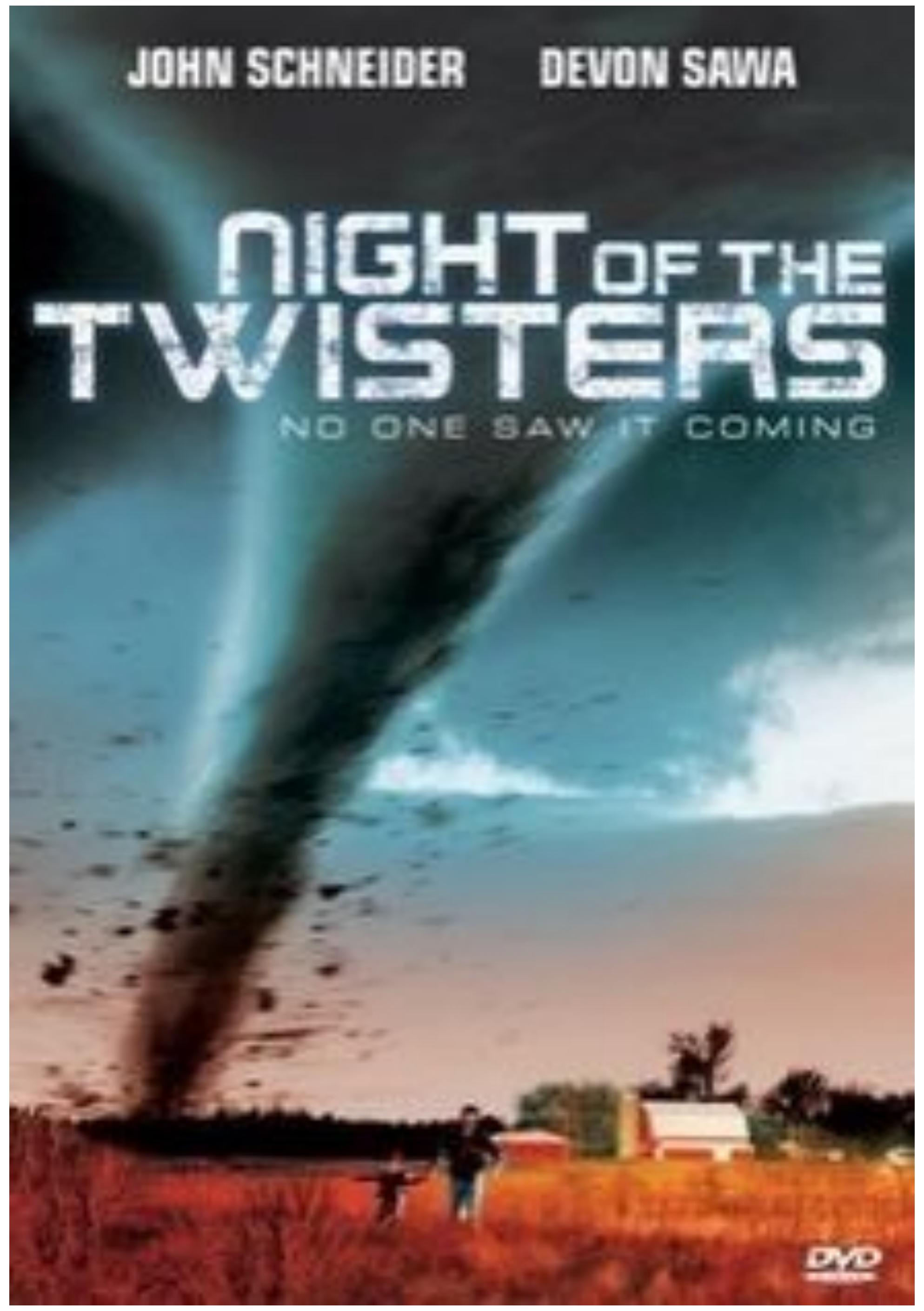
Tornadoes: In the media

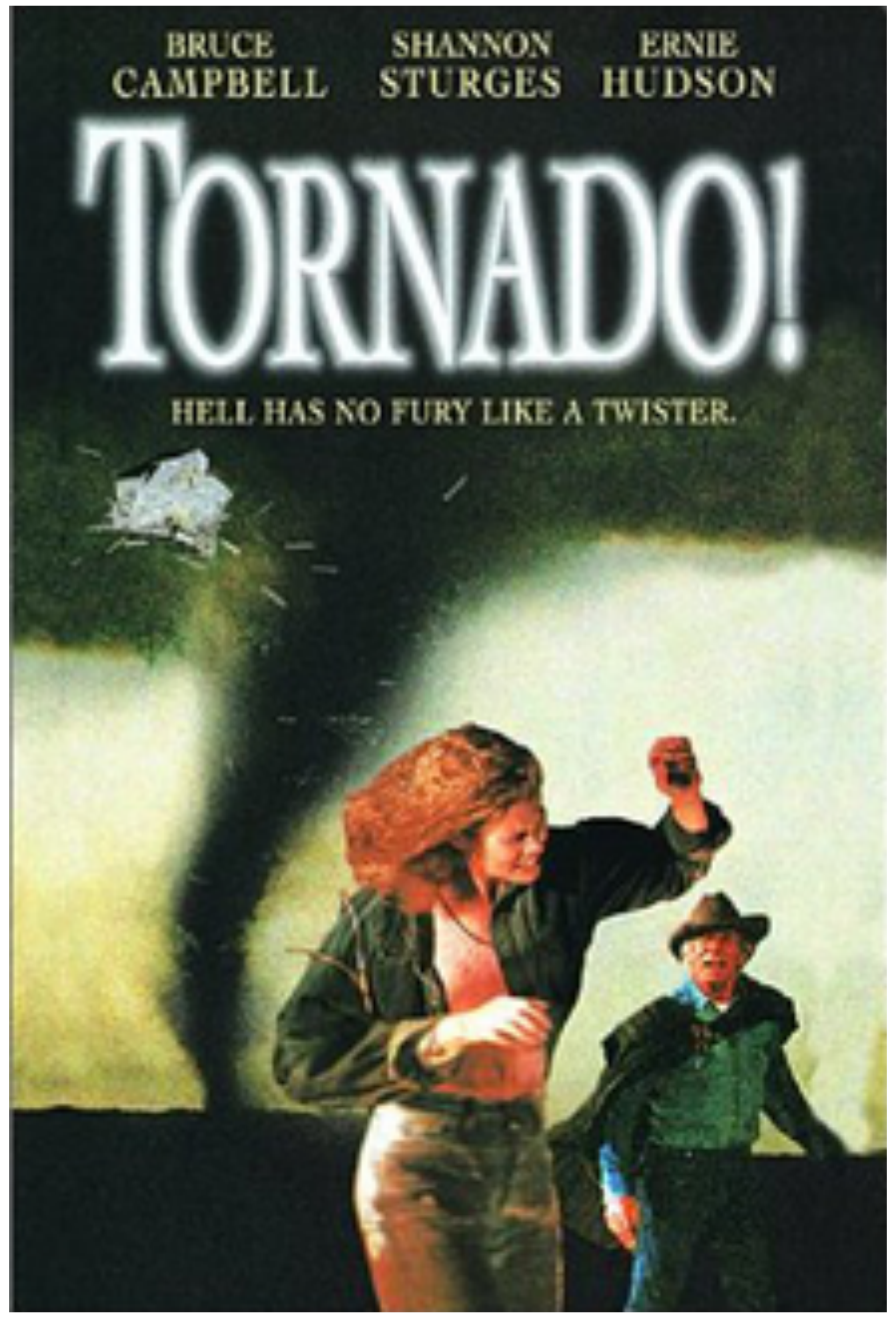
Tornadoes In The Media

Not everything you see in movies is real!

Big-screen and TV movies about tornadoes are always popular as the storms provide good material for the special effects experts. Some of these productions are based on actual events, such as Twister (1996) and Tornado (1996), which both used the National Severe Storm Laboratory's real-life work with a TOtable Tornado Observatory (TOTO) and their Verification of the Origins of Rotation in Tornadoes Experiment (VORTEX) in 1994 and 1995. VORTEX deployed 18 vehicles with customized equipment to measure and monitor the full life cycle of a tornado.
Other media representations of tornadoes are a little thin on facts, but social media uploads of actual tornadoes are becoming common. The variety of shapes and sizes of tornadoes is certainly extraordinary and awe-inspriring, but be aware that certain sites may contain imagery that has been seriously altered.







Movie posters for *Twister* (1996) and *Into the Storm* (2014), and the 1996 TV movies *Night of the Twisters* and *Tornado*.

Natural Hazards and Disaster

Class 22: Ice Storms, Meteotsunamis

- Freezing Rain
- Meteotsunamies

Natural Hazards and Disaster

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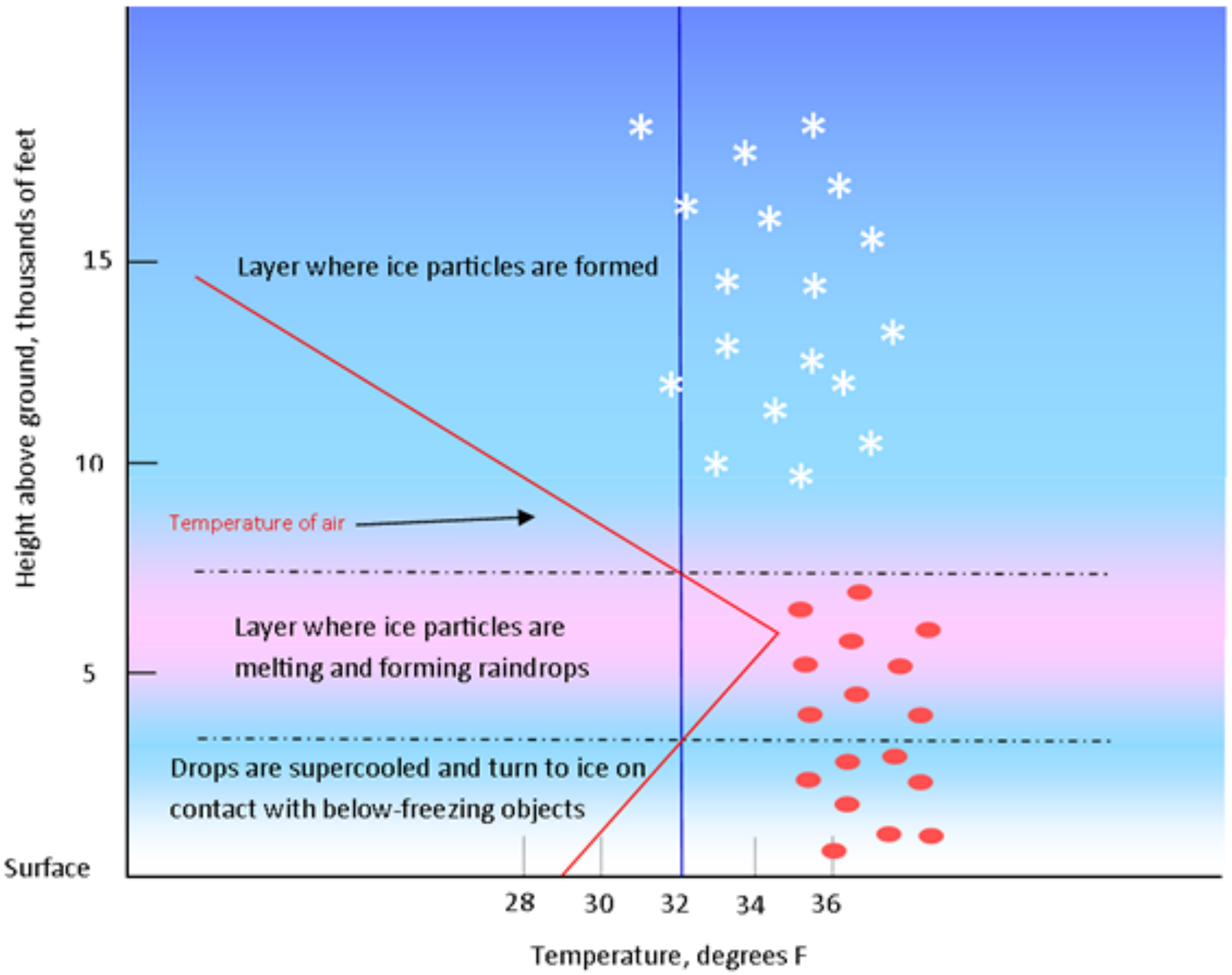
Freezing Rain

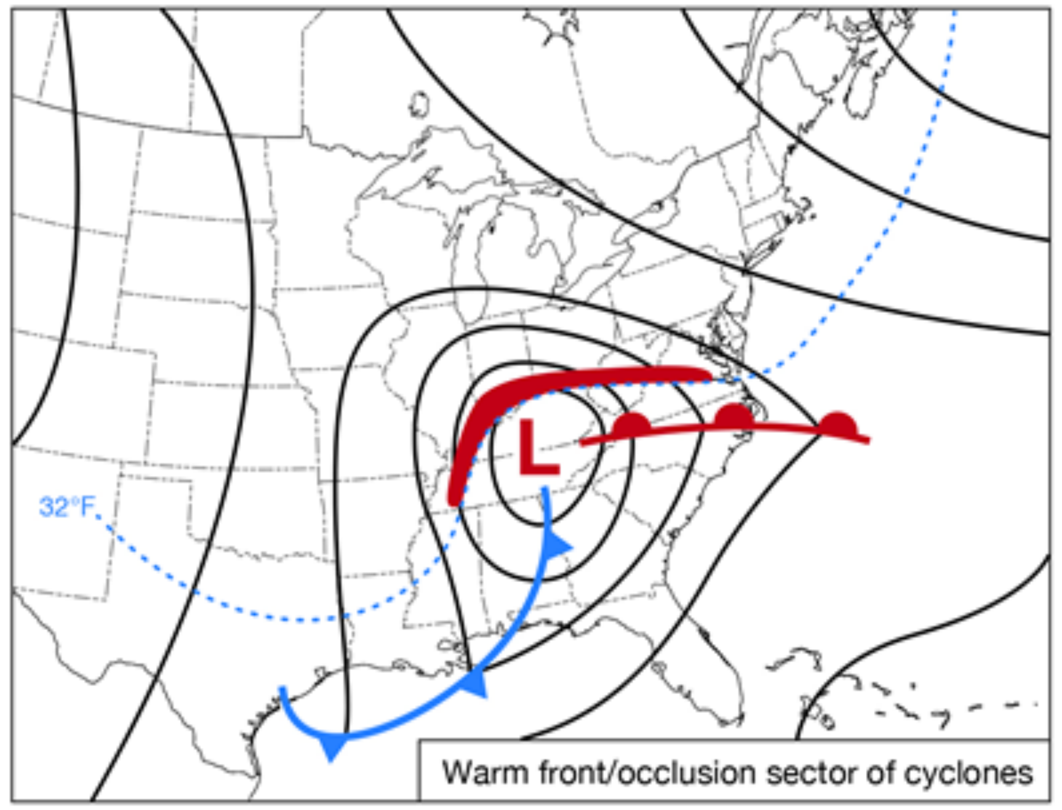


Freezing rain occurs when rain forms in a relatively warm (above freezing) layer of air and falls through a shallow layer of air that is below freezing. The rain is "supercooled" (still liquid) as it falls through the cold layer near the surface of the earth. When the supercooled, but still liquid, raindrops strike the ground or an object below freezing, they freeze on contact. The resulting coating of ice is commonly known as glaze.

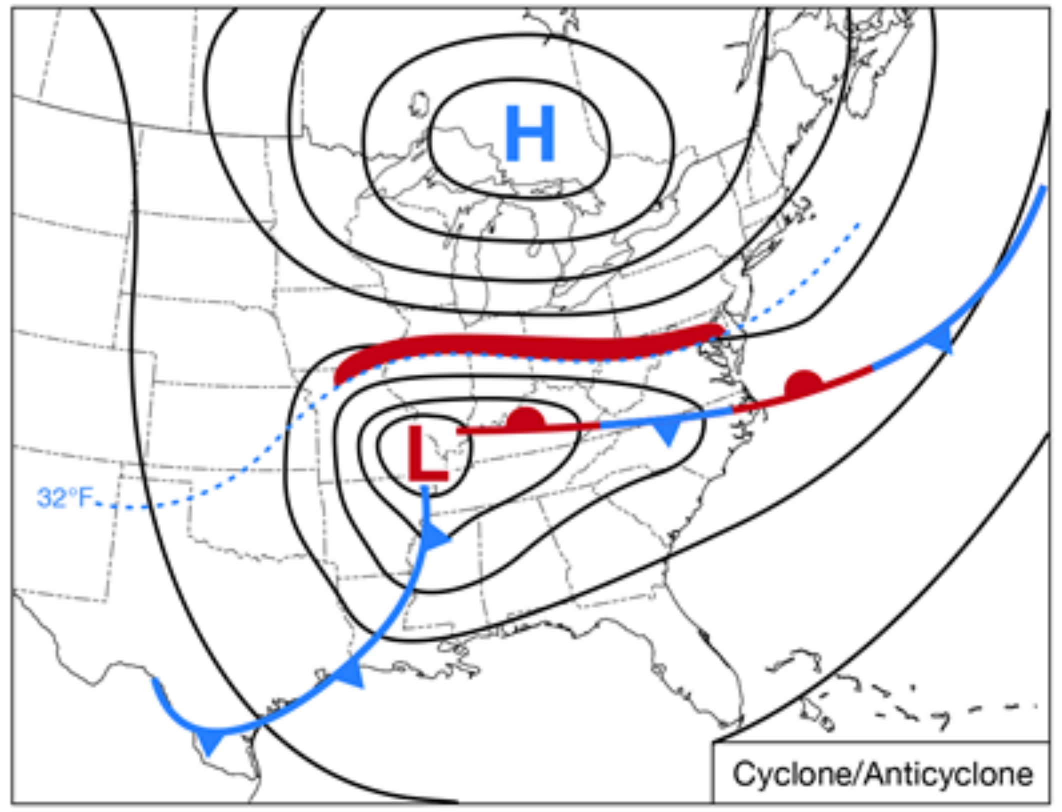
2009 Ice Storm Damage.
Photo courtesy NWS Paducah website

http://mrcc.isws.illinois.edu/living_wx/icestorms/

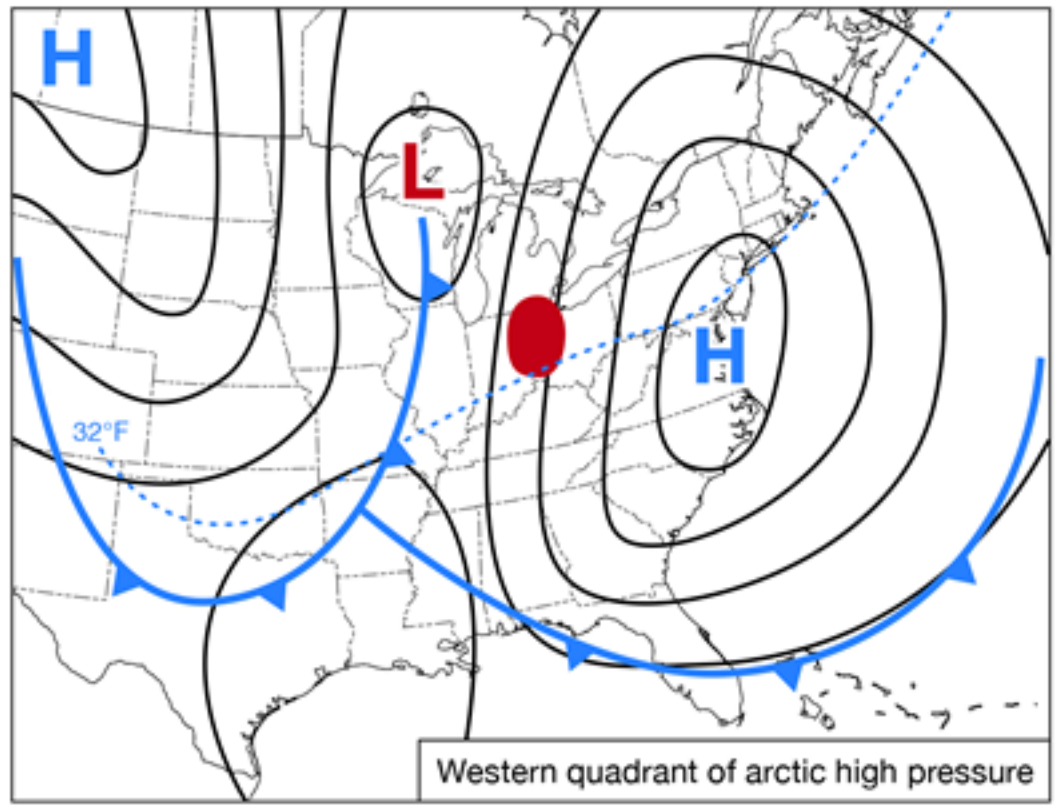
Freezing Rain



This is the typical winter storm “model” in the Midwest. The majority of the precipitation tends to occur north and west of the low pressure center (red band on the map).



This weather pattern differs from the first one in that the surface high pressure system is centered due north or northeast of the low pressure center.

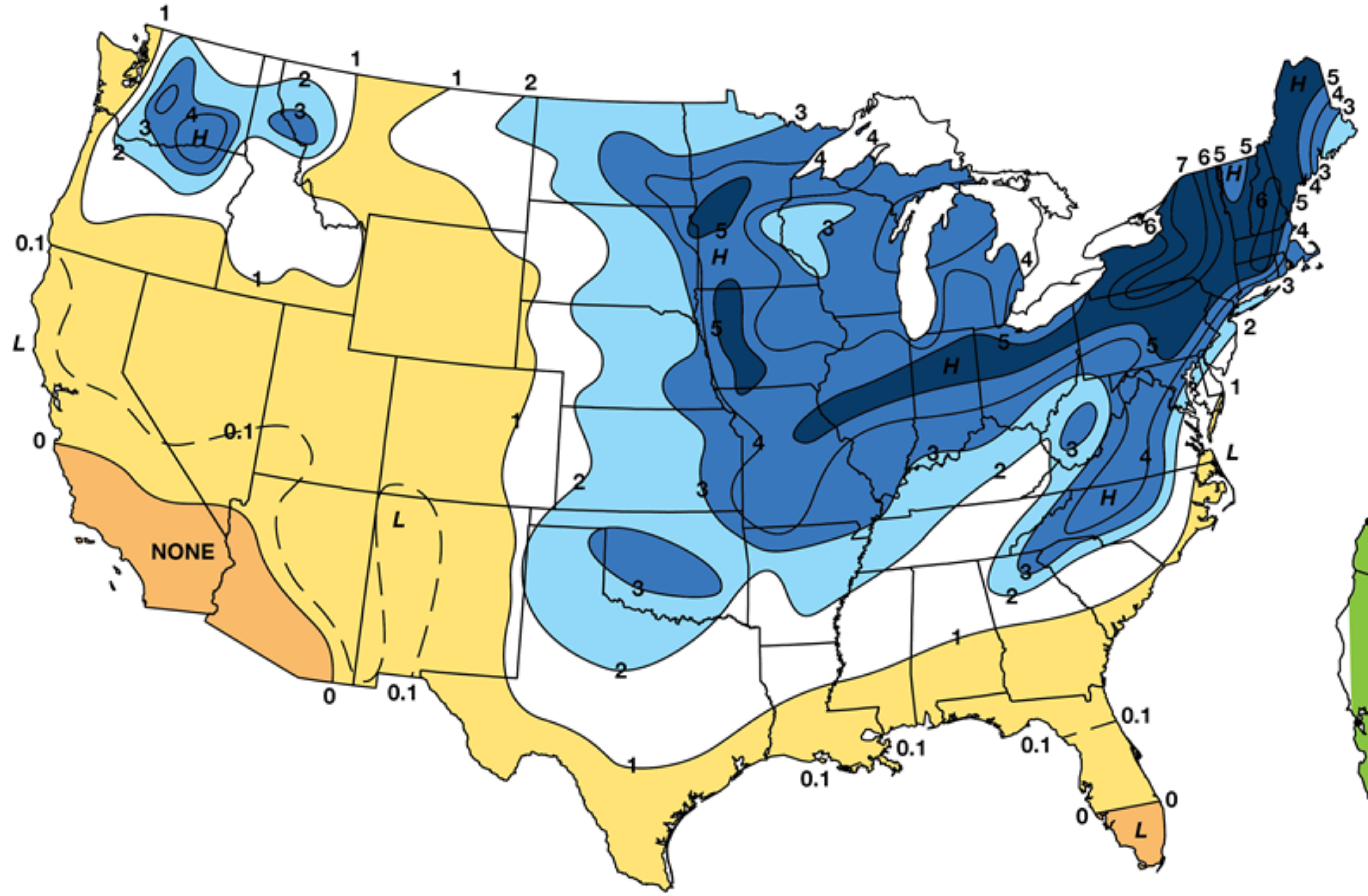


This weather pattern for freezing rain is the least common in the Midwest, occurring less than a third of the time compared to the previous two patterns.

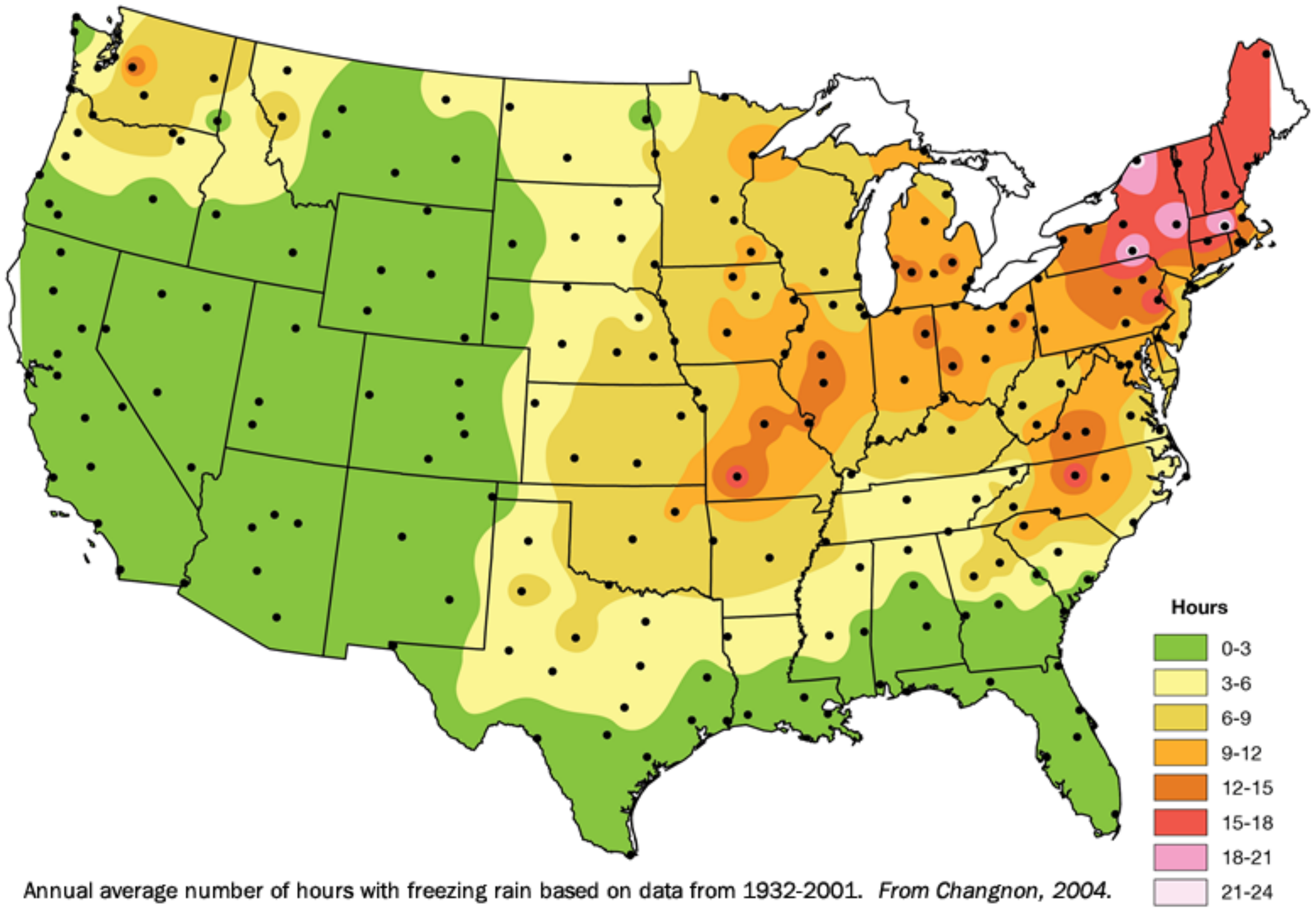
http://mrcc.isws.illinois.edu/living_wx/icestorms/

Freezing Rain

While freezing rain can occur anytime between November and April, most freezing rain events occur during December and January.



The average annual number of days with freezing rain, based on 1948-2000 data. *From Changnon and Karl, 2003.*



Annual average number of hours with freezing rain based on data from 1932-2001. *From Changnon, 2004.*

http://mrcc.isws.illinois.edu/living_wx/icestorms/

Freezing Rain

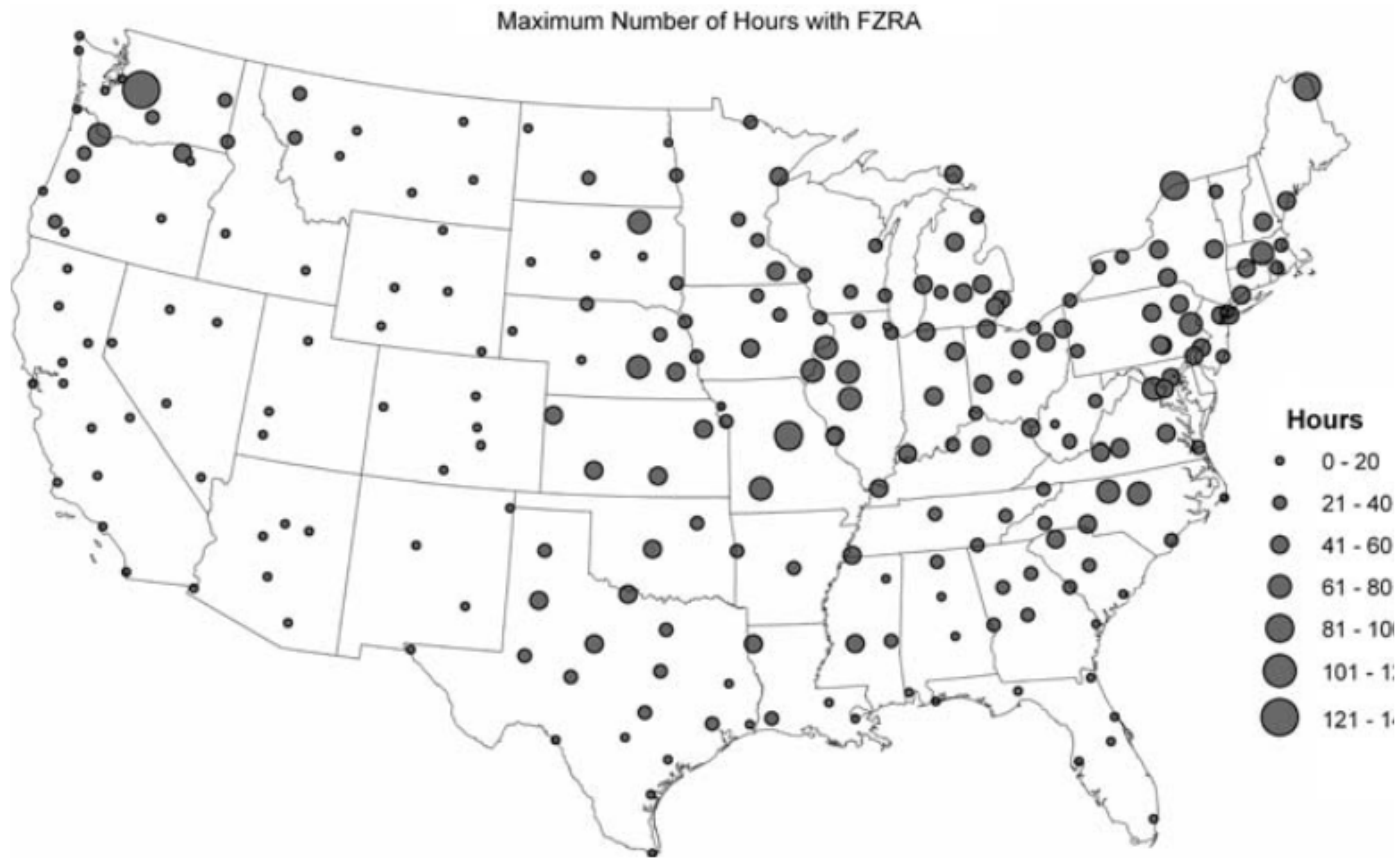


Fig. 2 Maximum number of hours with freezing rain in a single year, 1928–2001

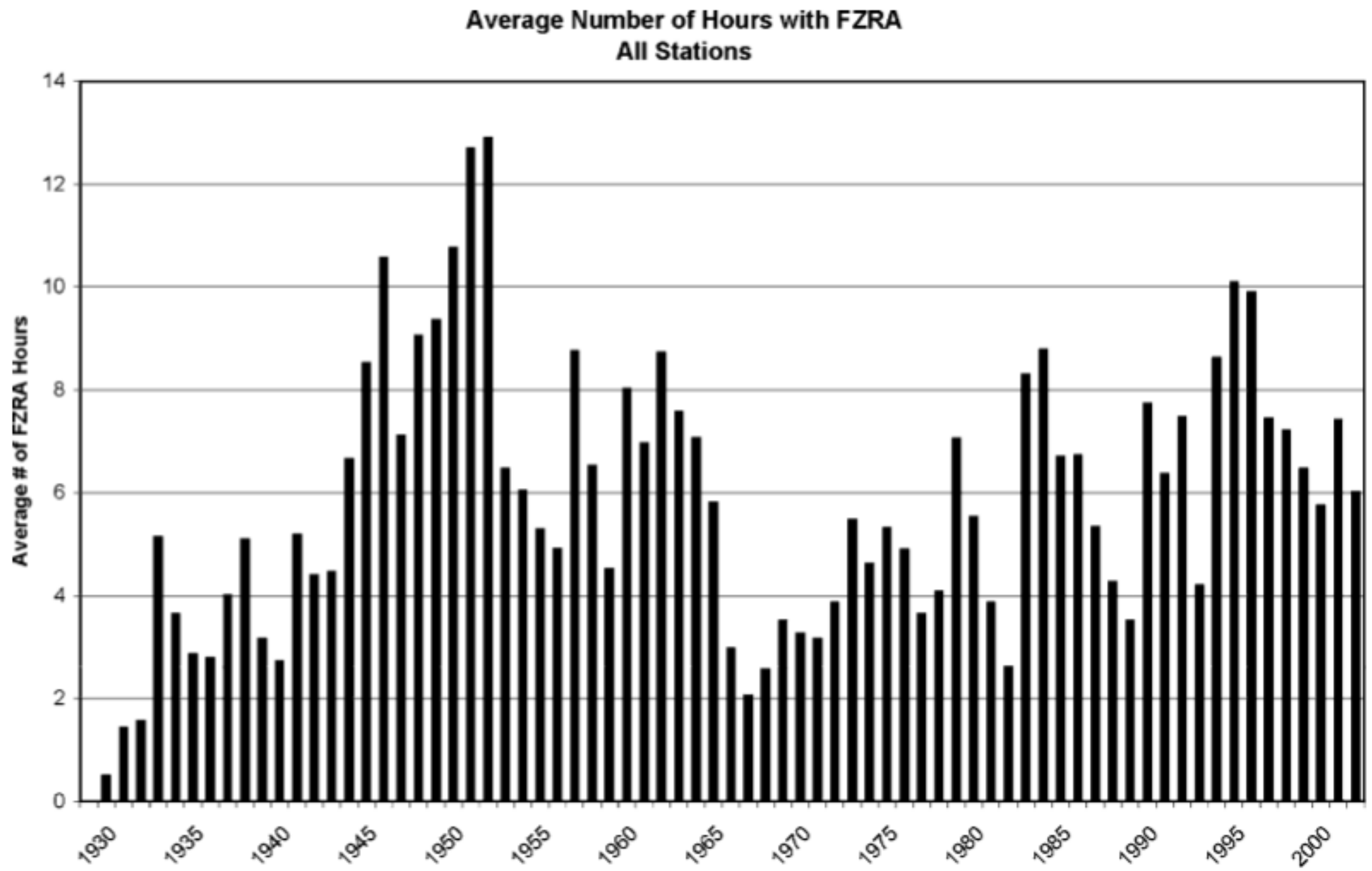


Fig. 3 Temporal distribution of the annual number of hours of freezing rain, 1928–2001

Houston and Shannon, 2007

Natural Hazards and Disaster

Class 22: Ice Storms, Meteotsunamis

- Freezing Rain
- Meteotsunamies

Natural Hazards and Disaster

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Meteotsunami

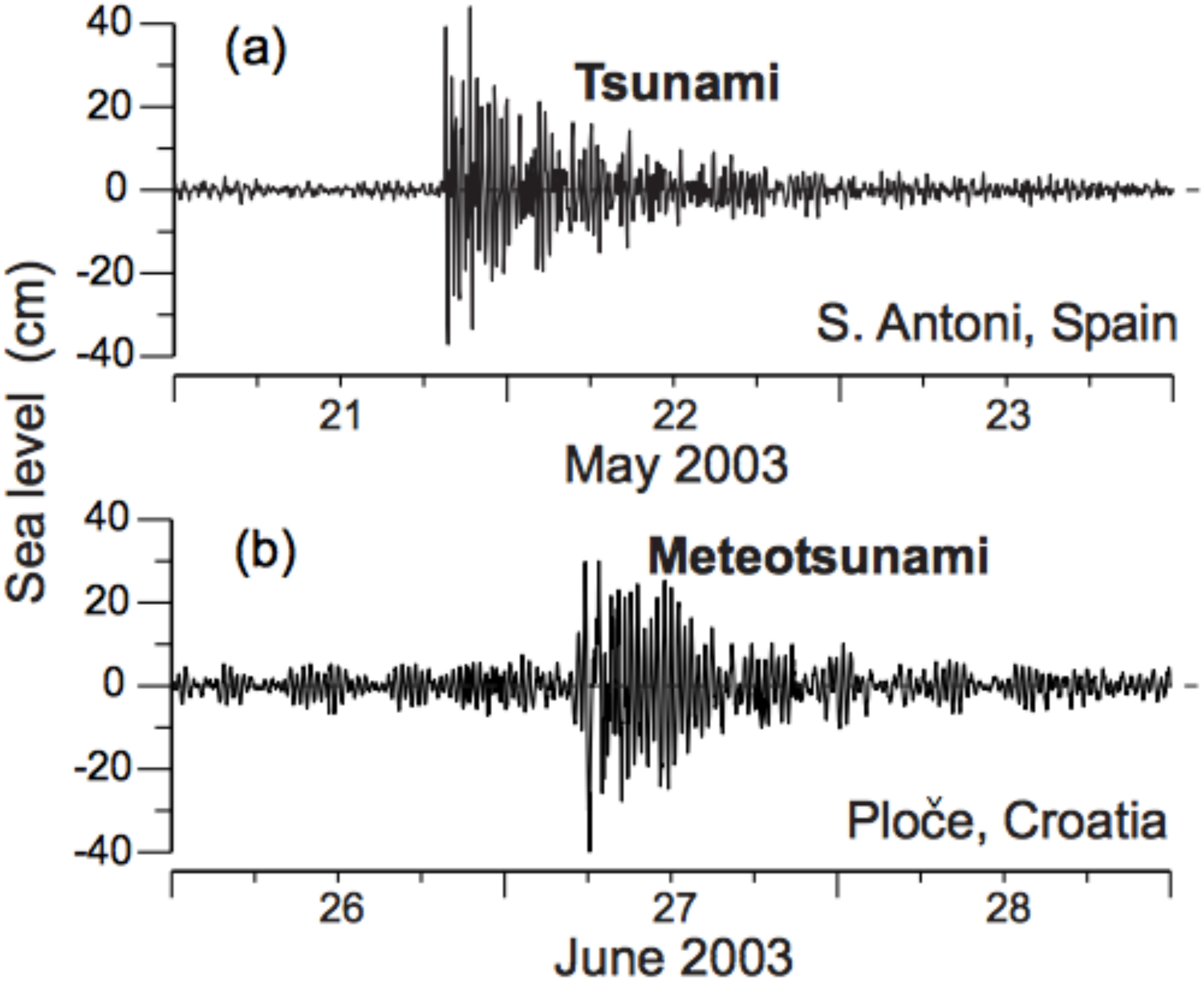


Fig. 1. (a) Tsunami oscillations recorded at Sant Antoni (Ibiza Is- land, Spain) after the Algerian earthquake of 21 May 2003; and (b) the meteotsunami recorded at Ploc̆e Harbour (Croatia) on 27 June 2003. Both records have been high-pass filtered to eliminate oscillations with periods longer than 2 h.

Monserrat et al., 2006

Meteotsunami

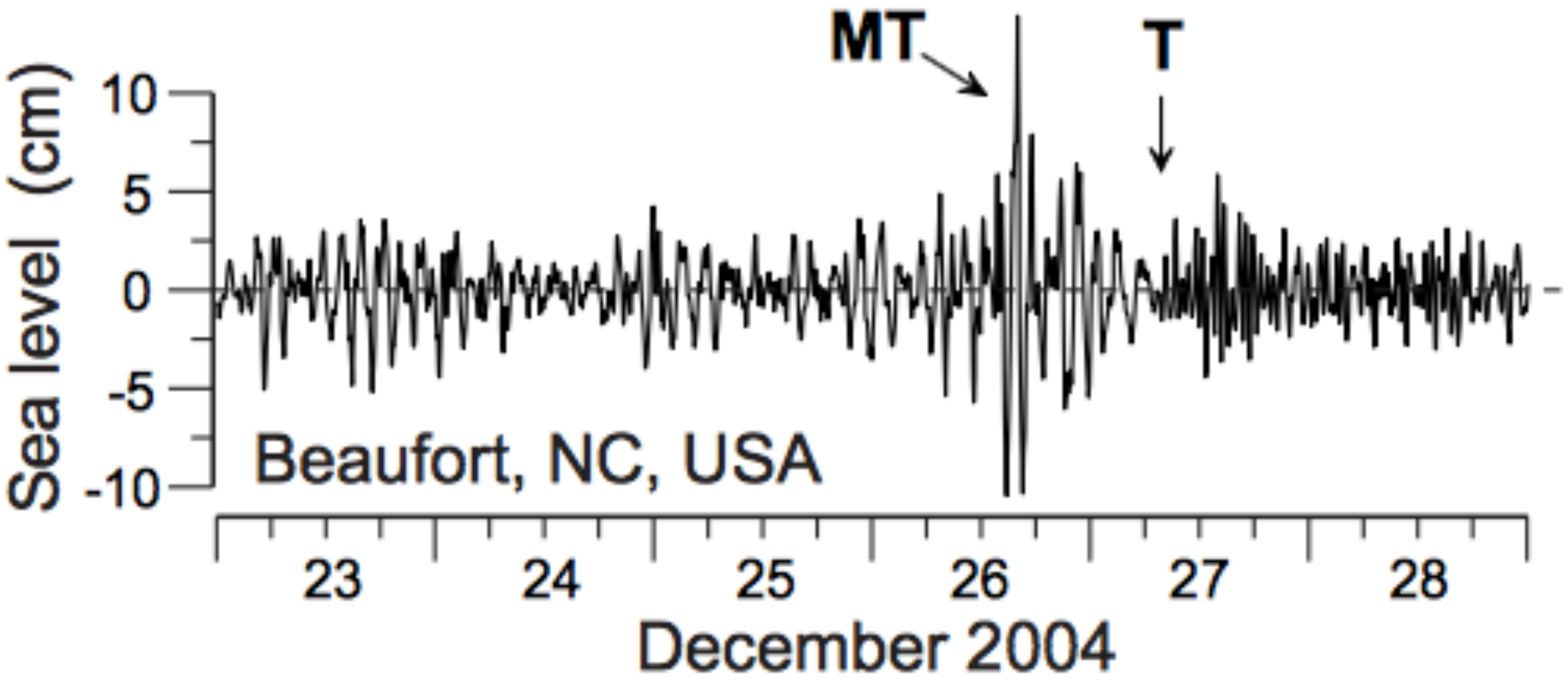


Fig. 2. Sea level oscillations at Beaufort (North Carolina, USA) for the period 23–28 December 2004. "MT" indicates intensive seiche oscillations generated by a strong storm travelling northward along the east coast of North America; "T" marks the arrival time of tsunami waves associated with the 2004 Sumatra earthquake (Rabinovich et al., 2006).

Monserrat et al., 2006

Meteotsunami

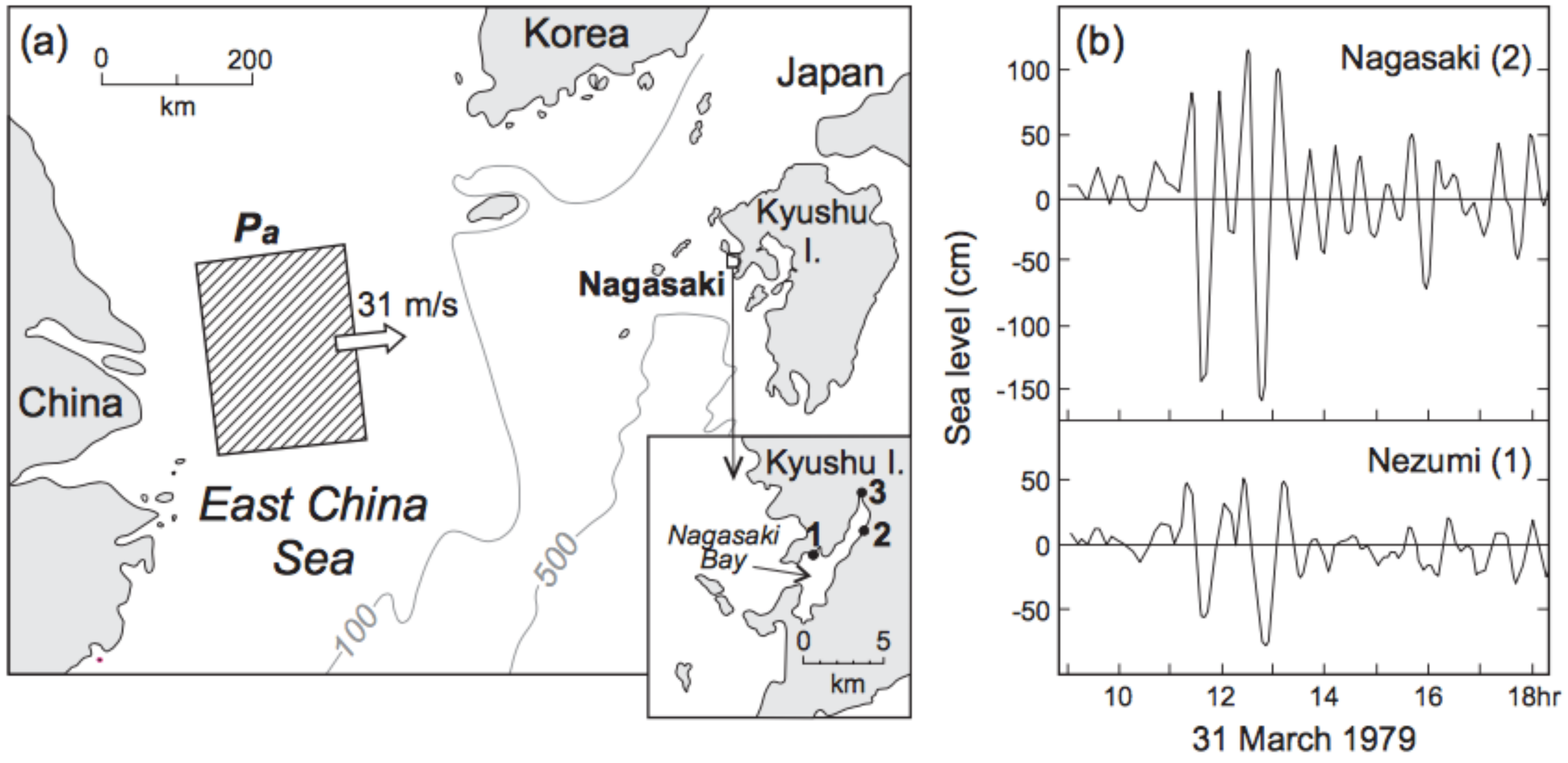


Fig. 5. (a) A map showing the location of Nagasaki Bay and the site of the initial atmospheric pressure disturbance (shaded rectangular); numbers “1” and “2” in the inset indicate positions of tide gauges Nezumi and Nagasaki, respectively; site “3” is at the head of the bay where the maximum wave of 478 cm was observed on 31 March 1979. (b) Tide gauge records of the catastrophic meteotsunami (“abiki waves”) of 31 March 1978 at Nezumi (1) and Nagasaki (2); positions of the tide gauges are shown in the inset in panel (a).

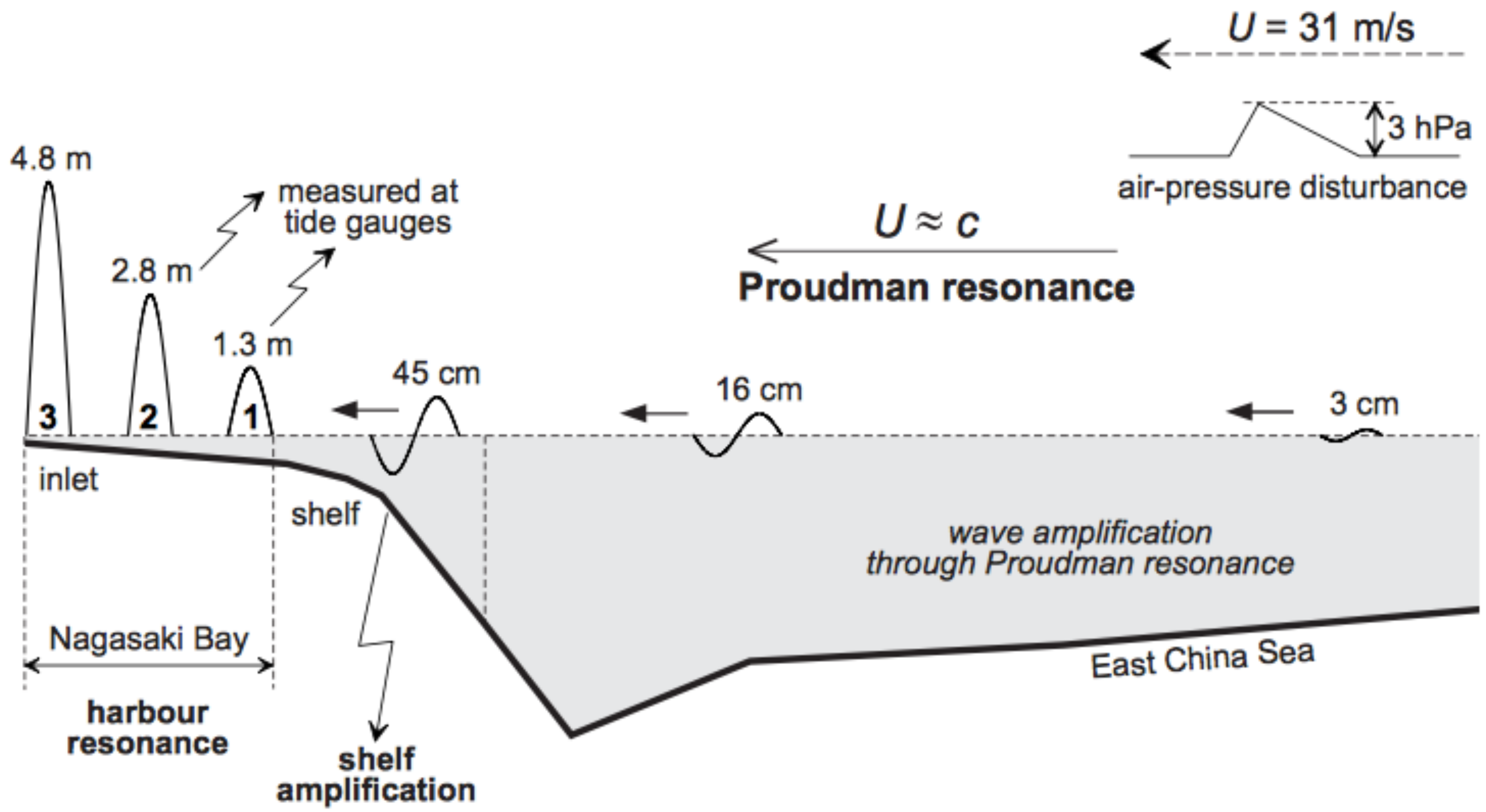


Fig. 4. A sketch illustrating the physical mechanism responsible for formation of the catastrophic meteotsunami at Nagasaki Bay (Japan) on 31 March 1979. The initial pressure jump over the western part of the East China Sea was about 3 hPa. The long waves generated by this event first amplified from 3 cm to 16 cm as a result of the Proudman resonant effect, then to 45 cm due to the shelf amplification and finally to 478 cm at the head of the bay due to the harbour resonance. Numbers “1”, “2”, and “3” correspond to locations shown in the inset in Fig. 5a.

Monserrat et al., 2006

Meteotsunami

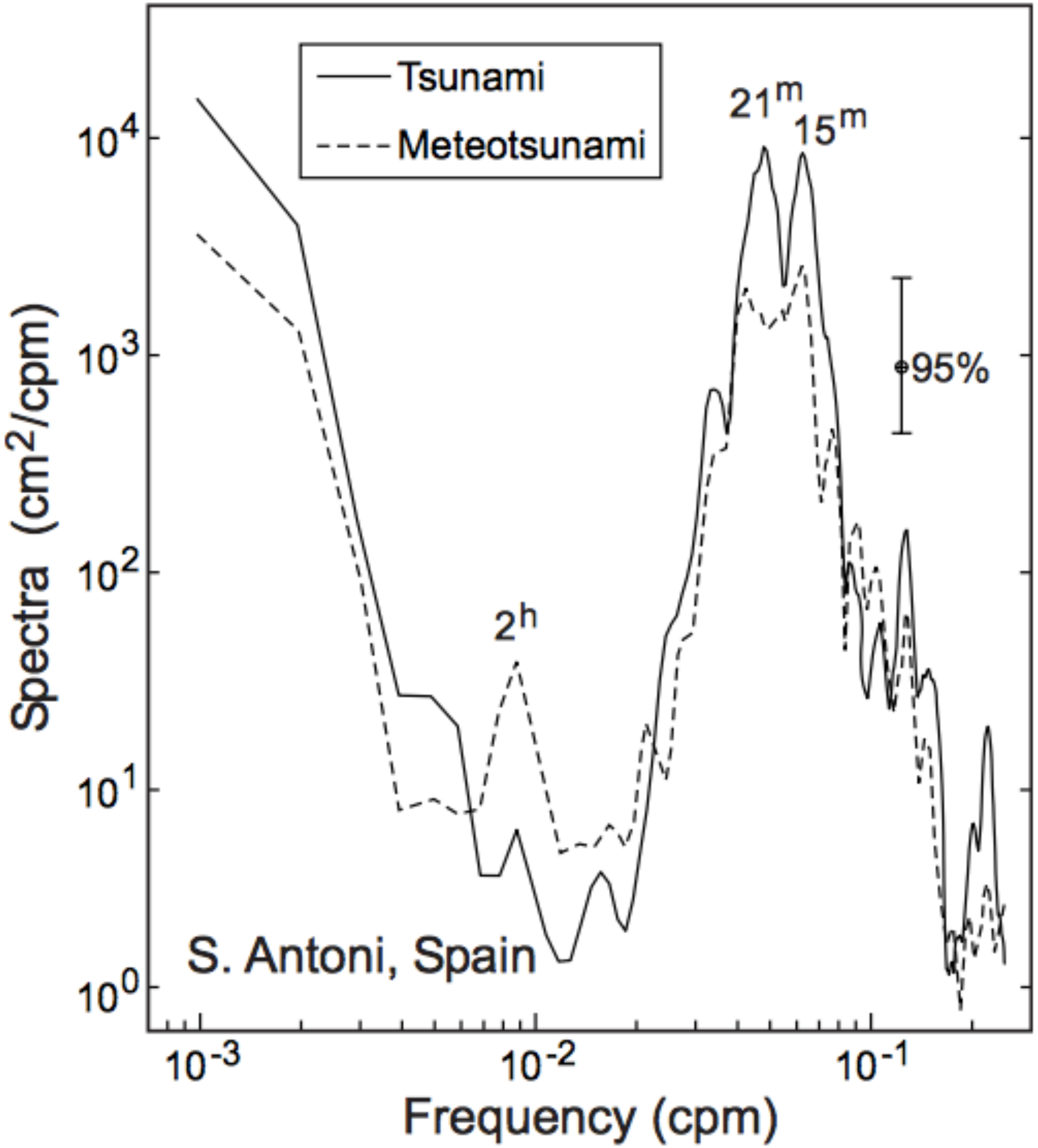


Fig. 6. Sea level spectra for the tsunami of 21 May 2003 and the moderate meteotsunami event of 1 May 2003 recorded at Sant Antoni (Ibiza Island, Spain). Each event has a duration of 4 days with a sampling interval of 2 min (2880 points). Spectra have been estimated with a Kaiser-Bessel window (cf. Emery and Thomson, 2001) of 128 points with half-window overlaps resulting in 42 degrees of freedom.

Monserrat et al., 2006

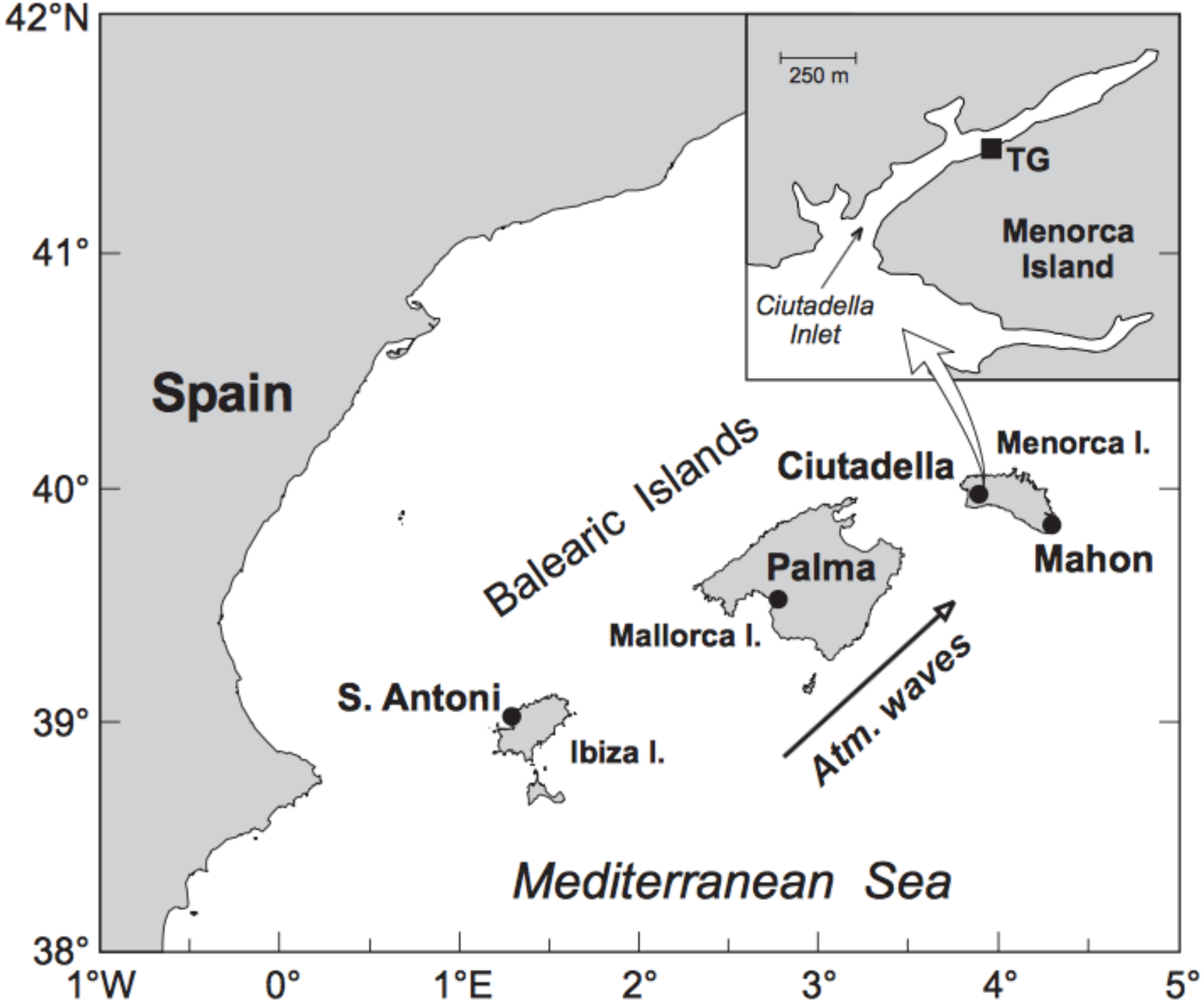


Fig. 7. A map of the Balearic Islands and positions of microbaro- graphs at Palma de Mallorca and Mahon and tide gauges at Sant Antoni and Ciutadella (marked “TG” in the inset). The arrow shows the predominant direction of propagation of the atmospheric waves during “rissaga” events.

Monserrat et al., 2006

Meteotsunami

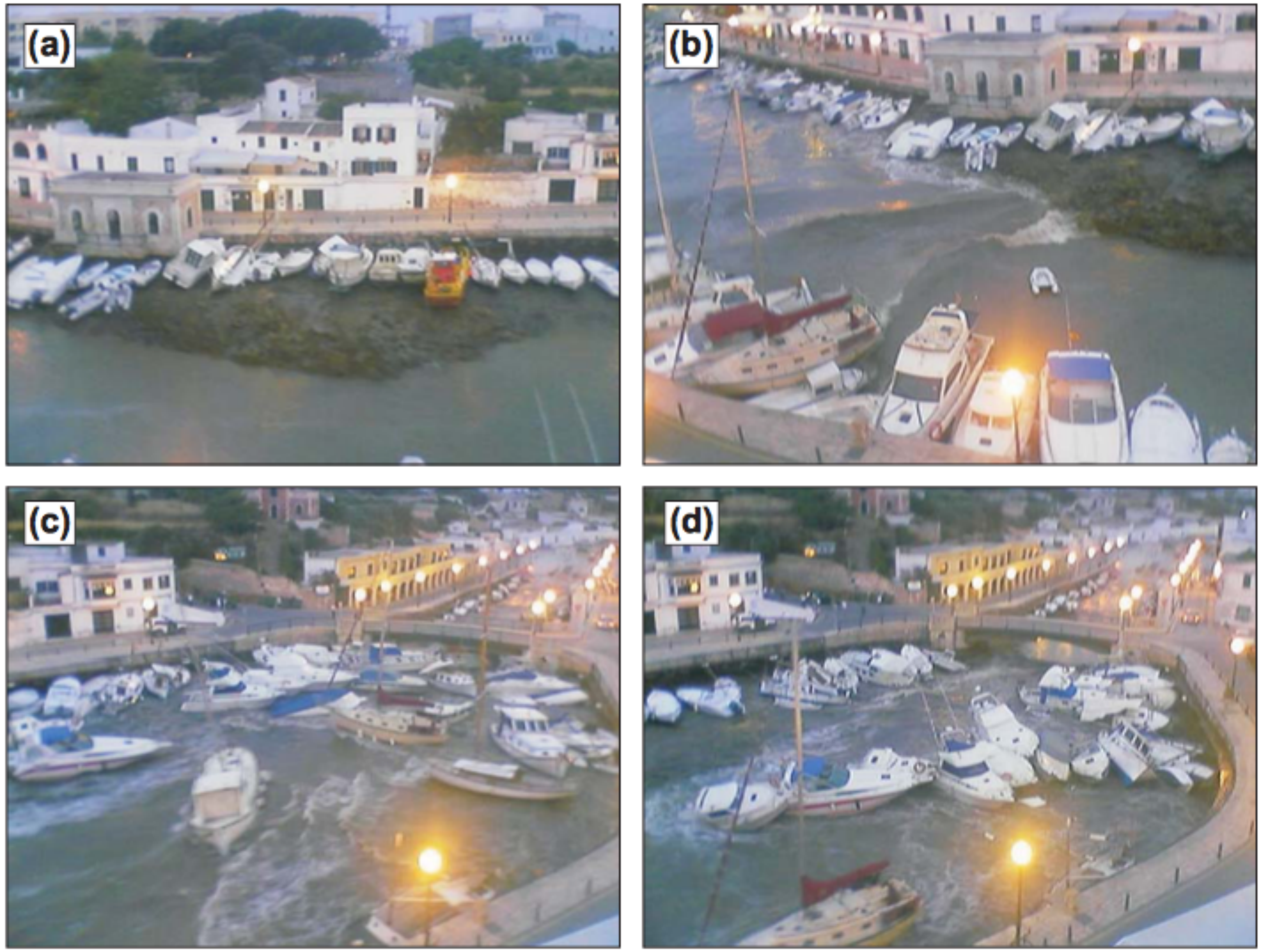


Fig. 9. Photographs taken during the strong rissaga event of 15 June 2006 at Ciutadella Harbour. (a) After the sudden first negative wave (~−4 m), most of the boats broke free from their moor- ings and were left high and dry on the harbour bottom. (b) A few minutes later, the water re-entered the harbour and the boats were freely dragged by the current. (c) and (d) More than 40 boats were severely damaged.

Fig. 11. Photographs of Vela Luka Bay (Croatia) taken during the meteotsunami event of 21 June 1978.

Houston and Shannon, 2007

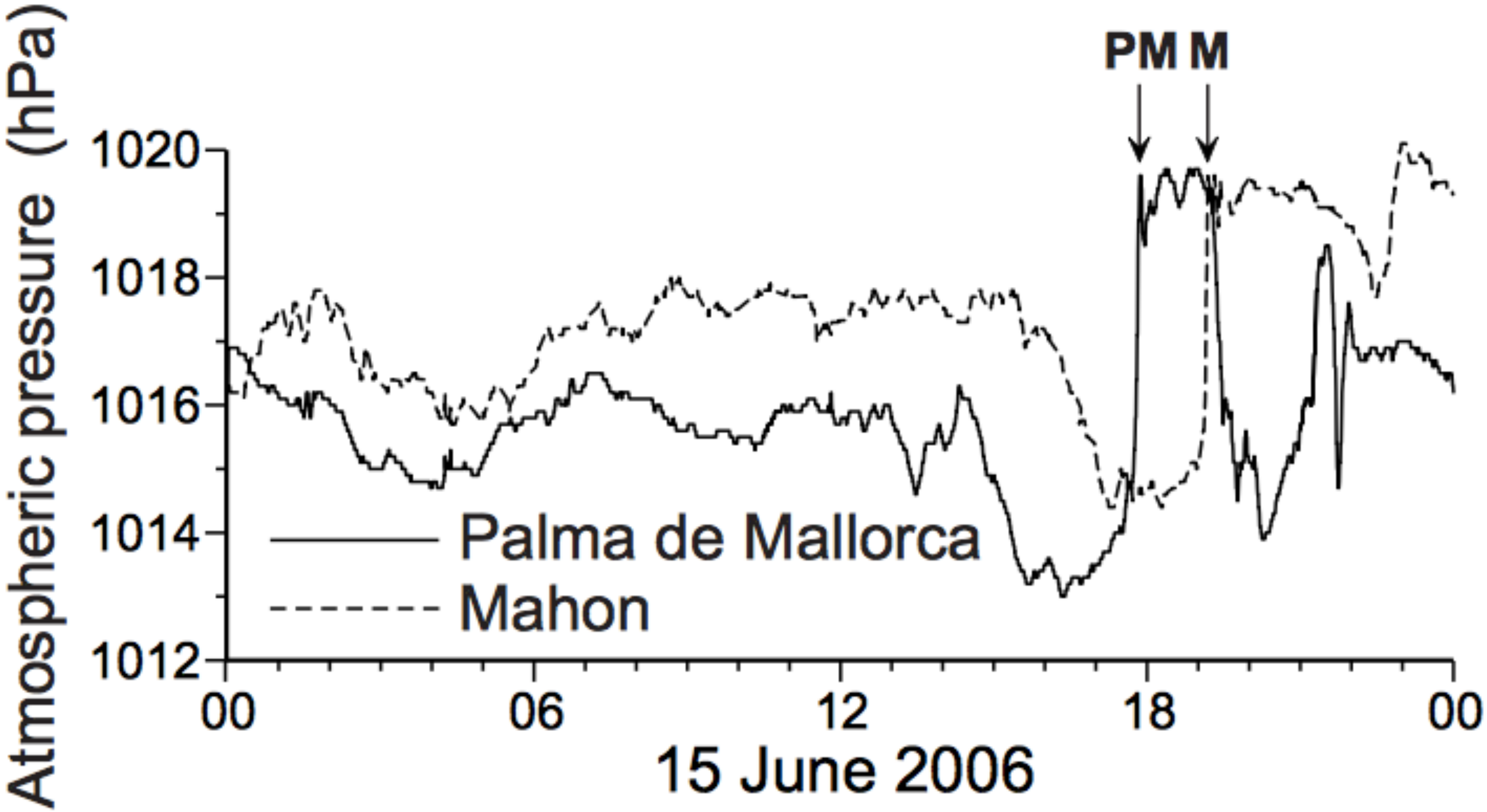


Fig. 10. Atmospheric pressure records from Palma de Mallorca (Mallorca Island) and Mahon (Menorca Island) on 15 June 2006. The arrows "PM" and "M" indicate the strong jump in atmo- spheric pressure that occurred at Palma de Mallorca at approximately 17:50 UTC and at Mahon at 19:07 UTC, respectively. Posi- tions of the stations are shown in Fig. 7.

Monserrat et al., 2006

Meteotsunami

In general, there are three main mechanisms required for the creation of a meteotsunami:

1. A meteorologic disturbance

2. Resonance: Speed of disturbance is very close to deep-water wave speed

$U = C = \sqrt{gd}$

U: speed of disturbance
C: deep-water wave speed
g: gravitational acceleration
d: depth of water

3. Amplifying qualities of a harbor, bay or inlet

Q ~ L/W

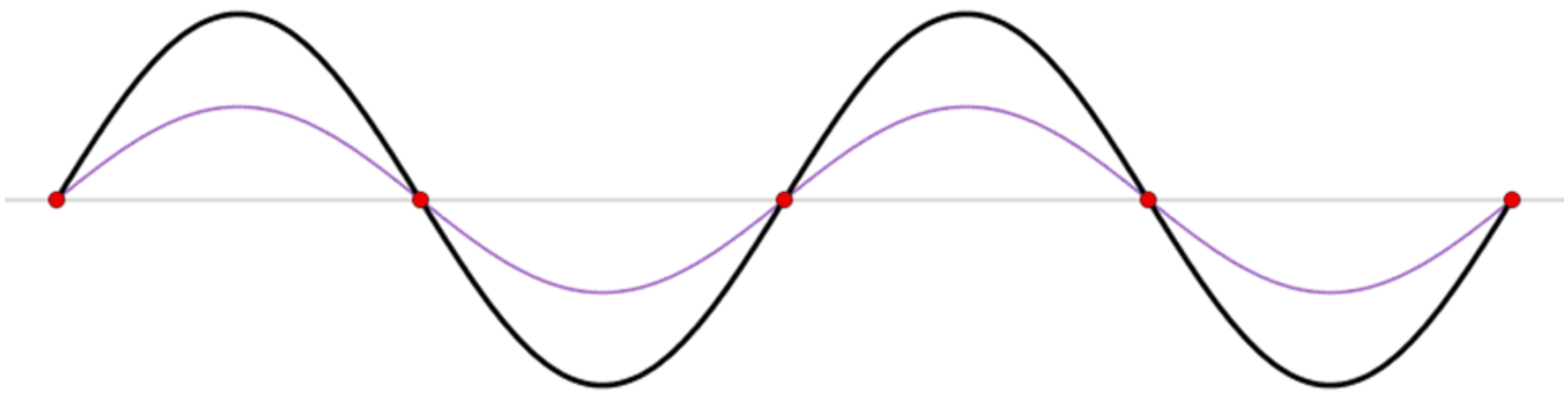
L: length of harbor
W: Width of harbor

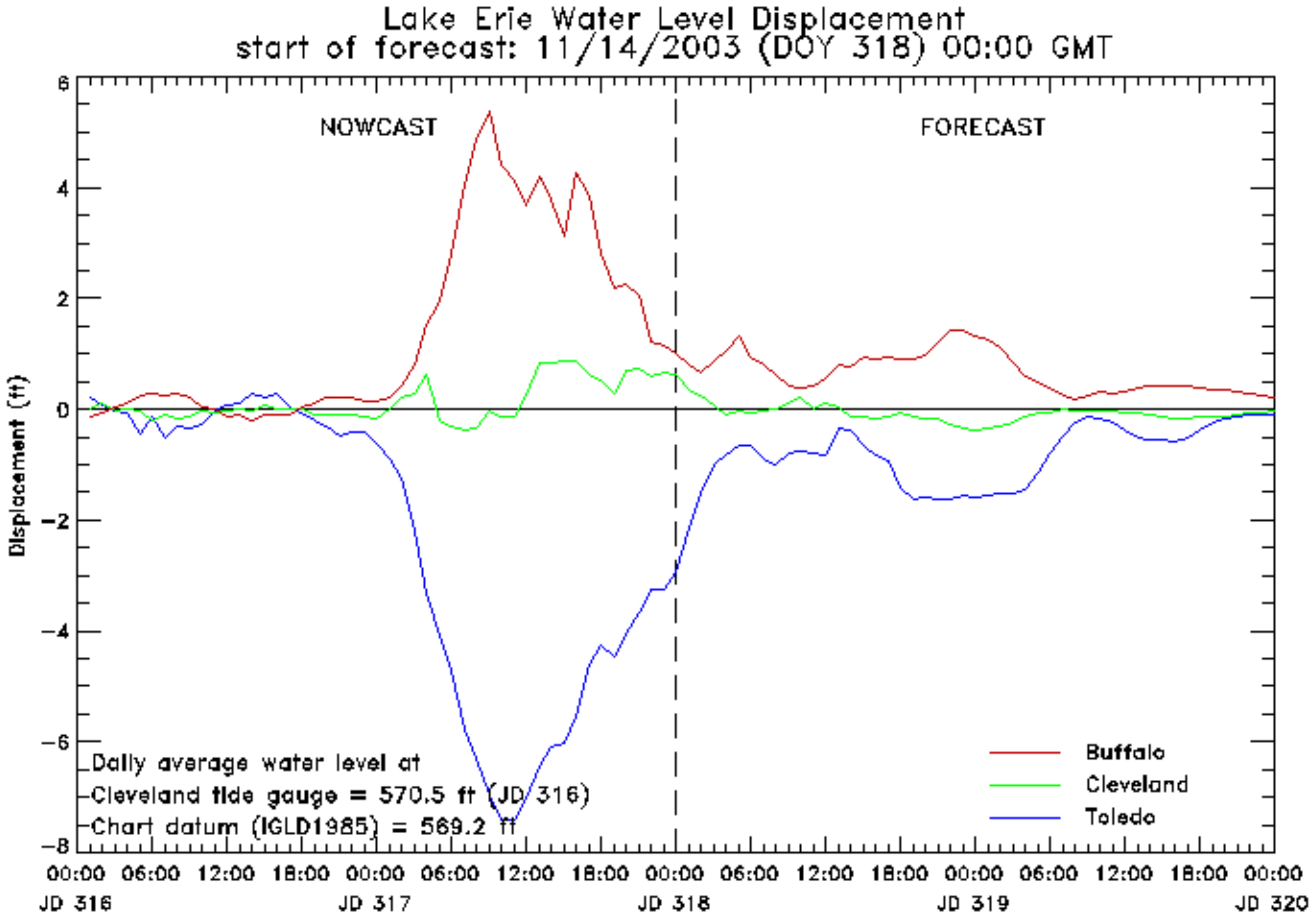
Q >> 1 leads to amplification

Thomas and Ryan, 2010

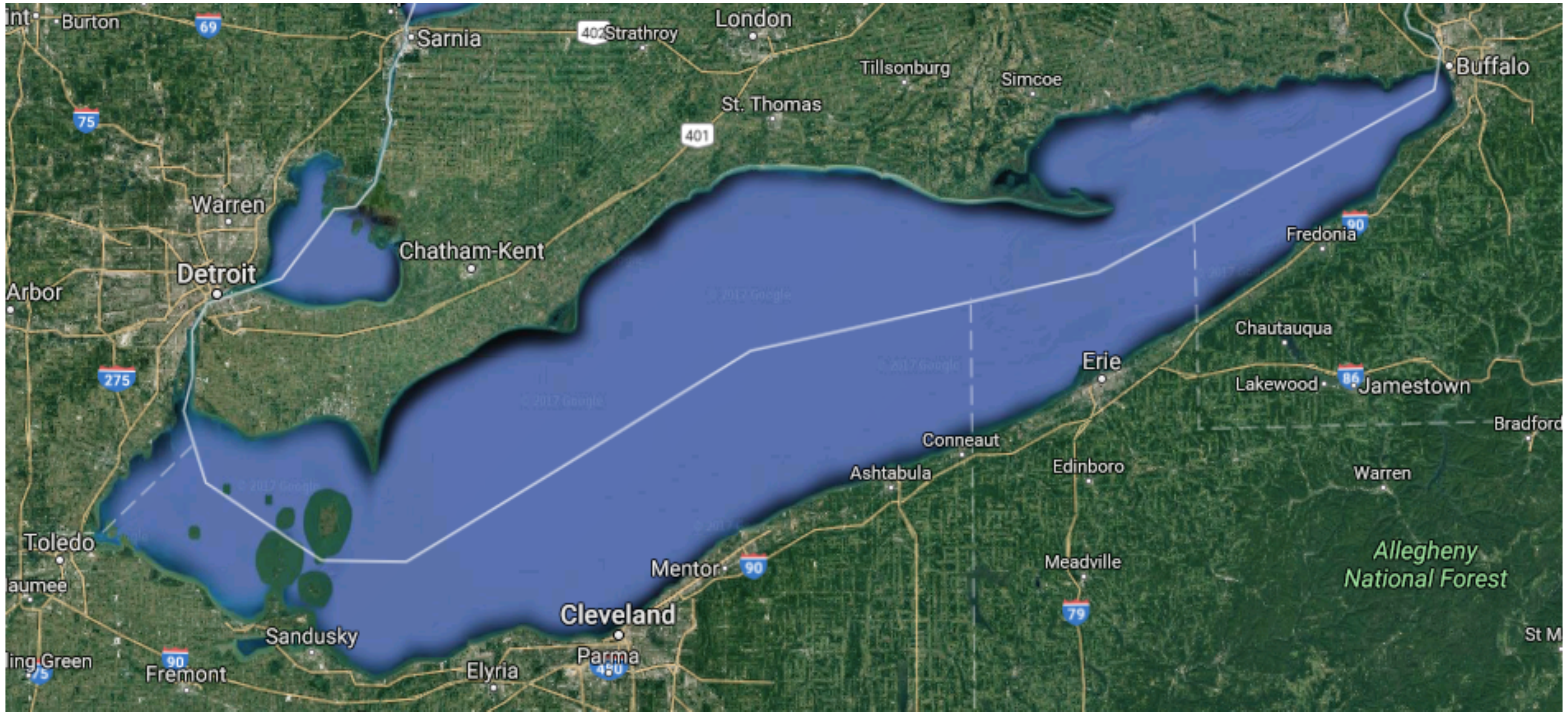
Meteotsunami

A seiche is a **standing wave** oscillating in a body of water.





NOAA Great Lakes Coastal Forecasting System
Great Lakes Environmental Research Laboratory
National Weather Service



Meteotsunami

A seiche is a **standing wave** oscillating in a body of water.