Natural Hazards and Disaster

Class 10: Tornadoes, Ice Storms, Meteotsunamis

- Tornadoes
  - Basics: What, Where, When
  - Strength
  - Origin
  - Warnings and Preparedness
  - Characteristics
  - Cases
  - In the Media
- Ice Storms
- Meteotsunamis

Tornadoes: Basics: What, Where, When

Tornado:
- a violently rotating column of air,
- in contact with the ground,
- either pendant from a cumuliform cloud or underneath a cumuliform cloud,
- and often (but not always) visible as a funnel cloud.

Size and Wind speed:
- Its vortex usually rotates cyclonically (on rare occasions anticyclonically rotating tornadoes have been observed).
- Wind speeds as low as 30 m/s (108 km/h) to as high as 135 m/s (486 km/h),
- Generally < 2 km in diameter.
- Some tornadoes may also contain secondary vortices (suction vortices, subvortices, multiple, & satellite vortices).

Tornado intensity:
- On a local scale, the tornado is the most intense of all atmospheric circulations.
- Is often estimated on the basis of wind damage using the Enhanced Fujita Scale.
- This estimate can be refined using other measurements, especially in the absence of damage indicators.

Locations and Timing:
- Tornadoes have been observed on all continents except Antarctica.
- Are most common in the United States, where the average number of reported tornadoes is roughly 1000 per year.
- Majority of tornados on the central plains and in the southeastern states (see Tornado Alley).
- They can occur throughout the year at any time of day.
- In the central plains of the United States they are most frequent in spring during the late afternoon."

Modified from *Glossary of Meteorology (2000). Section: T (2 ed.). American Meteorological Society.*
http://glossary.ametsoc.org/wiki/Tornado

Tornadoes: Basics: What, Where, When

Tornadoes are violently rotating columns of wind that cause intense, although local, destruction.

Tornadoes:

- Relatively narrow, violently rotating air columns, extend between a thunderstorm's cloud base and the ground surface.
- The outer walls of the rotating air column are rather sharply defined.
- Even though tornadoes inflict extreme destruction on everything within their path, the areas immediately adjacent to a tornado's touchdown may be completely unaffected.
- Outbreaks appear to be most prevalent in North America. Roughly 1,000 tornadoes occur annually, most often in the southern and southeastern states in the spring and early summer months.
- Occur frequently in Australia as well as in parts of South America, southern Russia, and Bangladesh, and also occasionally in Britain.
- They may occur in other countries too, but are not as well tracked and reported as they are in the U.S.A.

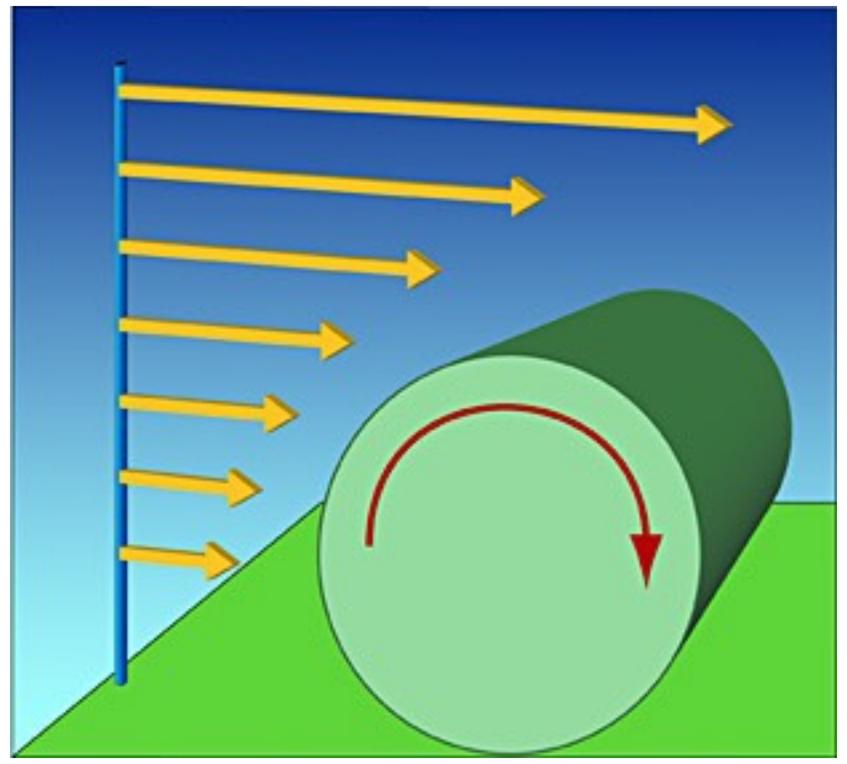
A tornado touchdown near Tuscaloosa, Alabama, U.S.A. on April 27, 2011, one of a swarm of more than 200 tornadoes that day in the southeastern U.S.A. that caused a total death toll of almost 400.

Tornado destruction in Pratt City area of Birmingham, Alabama, U.S.A. on April 27, 2011.

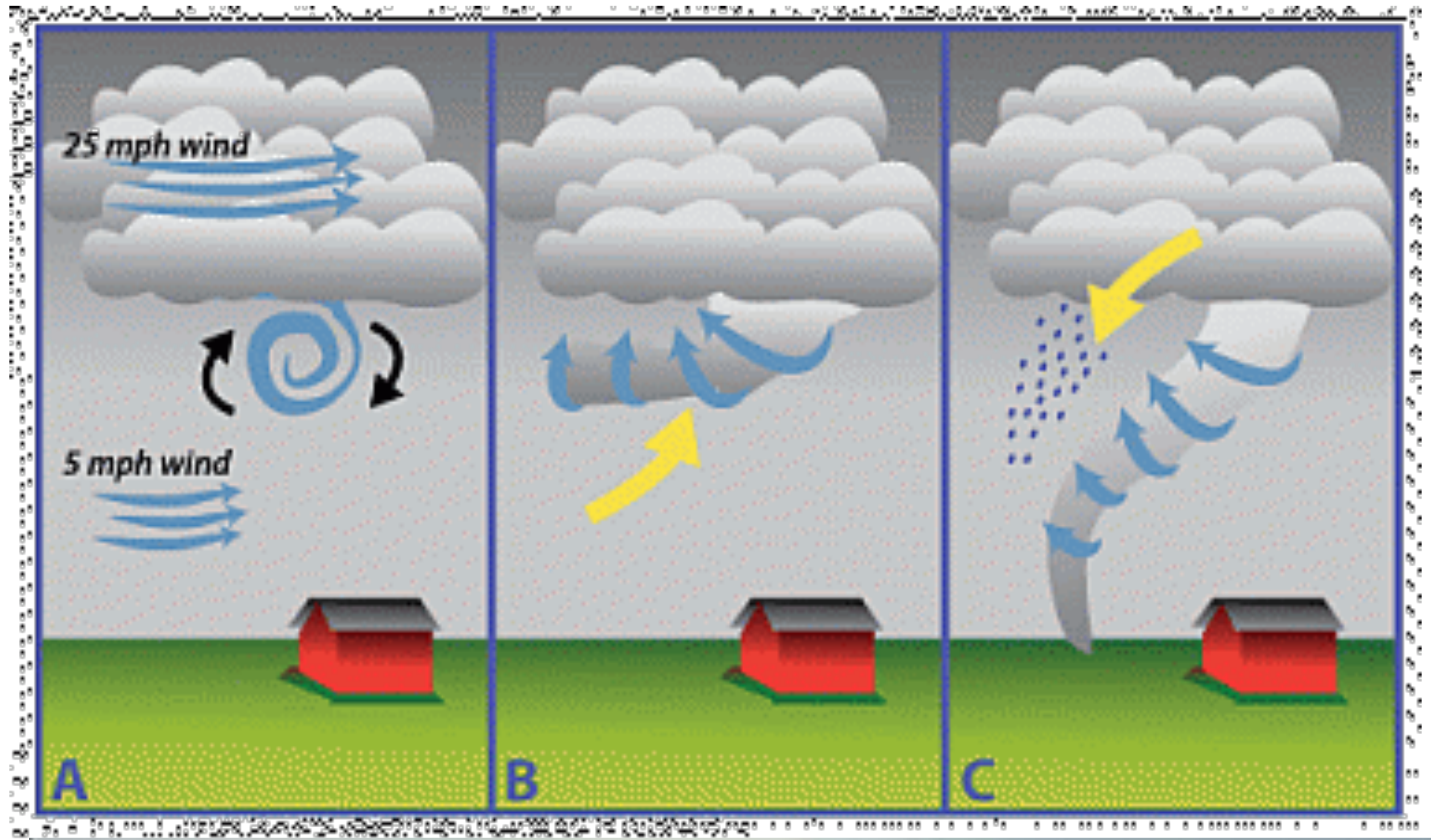
Tornadoes: Basics: What, Where, When

Funnels vs. Tornadoes

- A vortex of rapidly spinning air can form a funnel cloud that may, or may not, become a tornado.
- The wind at ground level often blows in a different direction and/or at a different speed than higher level air.
- This is especially true under thunderstorm conditions when the differential conditions create strong wind shear, which can form a spinning tube of air known as a vortex beneath the cloud base.
- Funnel clouds, which do not reach the ground, occur when condensed water vapor is entrained in the vortex and are not in themselves dangerous except to small aircraft that may fly into them (unlikely, as pilots are trained to avoid thunderstorms).
- However, strong downdrafts, such as occur in supercells, may push one end of the vortex downwards so that makes contact with the ground as a tornado.



Wind direction (left) and speed (right) vary with height above ground.



Left: Differential wind speeds create wind shear. Center: Wind shear and updrafts form a tilted, spinning tube of air, called a vortex, often seen as a funnel cloud. Right: Strong downdrafts with rain and/or hail connect the vortex to the ground as a tornado.

Funnel cloud seen over Oak Brook, near Chicago, Illinois, on June 24, 2014.

Tornadoes: Basics: What, Where, When

This tornado has no funnel cloud; however, the rotating dust cloud indicates that strong winds are occurring at the surface, and thus it is a true tornado.

Tornadoes: Basics: What, Where, When

A **multiple-vortex tornado** has two or more columns of spinning air that rotate about their own axis and at the same time around a common center. A multi-vortex structure is more likely to occur in intense tornadoes.

A **satellite tornado** is a smaller tornado which forms very close to a large, strong tornado contained within the same mesocyclone. The satellite tornado may appear to orbit around the larger tornado and this system may look like a large multi-vortex tornado. However, a satellite tornado is a distinct circulation and is much smaller than the main funnel.

A multiple-vortex tornado outside Dallas, Texas on April 2, 1957.

Tornadoes: Basics: What, Where, When

A **waterspout** is defined as a tornado over water. Fair weather waterspouts are less severe than tornadic waterspouts but far more common.

- Form at the bases of cumulus congestus clouds over tropical and subtropical waters.
- Have weak winds, smooth walls, and typically travel very slowly.
- Are mainly found in the Florida Keys and the northern Adriatic Sea.
- Tornadic waterspouts are stronger tornadoes over water. Can form over water or are stronger tornadoes which cross over water.
- Form from severe thunderstorms and can be far more intense, faster, and longer-lived than fair weather waterspouts, and they are more dangerous.

A **landspout**, or dust-tube tornado, is a tornado not associated with a mesocyclone.

- Waterspouts and landspouts share many defining characteristics, including relative weakness, short lifespan, and a small, smooth condensation funnel which often does not reach the surface.
- If they make contact with the ground, they create a distinctively laminar cloud of dust. Although they are usually weaker than classic tornadoes, they can produce strong and damaging winds.

A waterspout near the Florida Keys in 1969.

Tornadoes: Basics: What, Where, When

A **gustnado** is a small, vertical swirl associated with a gust front or downburst.

- They are not connected with a cloud base.
- They form when fast moving cold, dry outflow air from a thunderstorm is blown through a mass of stationary, warm, moist air near the outflow boundary, resulting in a "rolling" effect.
- If low level wind shear is strong enough, the rotation can be turned vertically or diagonally and make contact with the ground.

A **dust devil** or whirlwind looks like tornado in that it is a vertical column of swirling air.

- They form under clear skies when a strong convective updraft is formed near the ground on a hot day.
- They are comparable to the weakest tornadoes but they can result in major damage.
- If there is enough low level wind shear, a column of hot, rising air can develop a small cyclonic motion that can be seen near the ground because of the dust.

A large dust devil on June 10. Credit: NASA

https://www.nasa.gov/vision/universe/solarsystem/2005_dust_devil.html

Tornadoes: Basics: What, Where, When

Small-scale circulations can occur near any intense surface heat source.

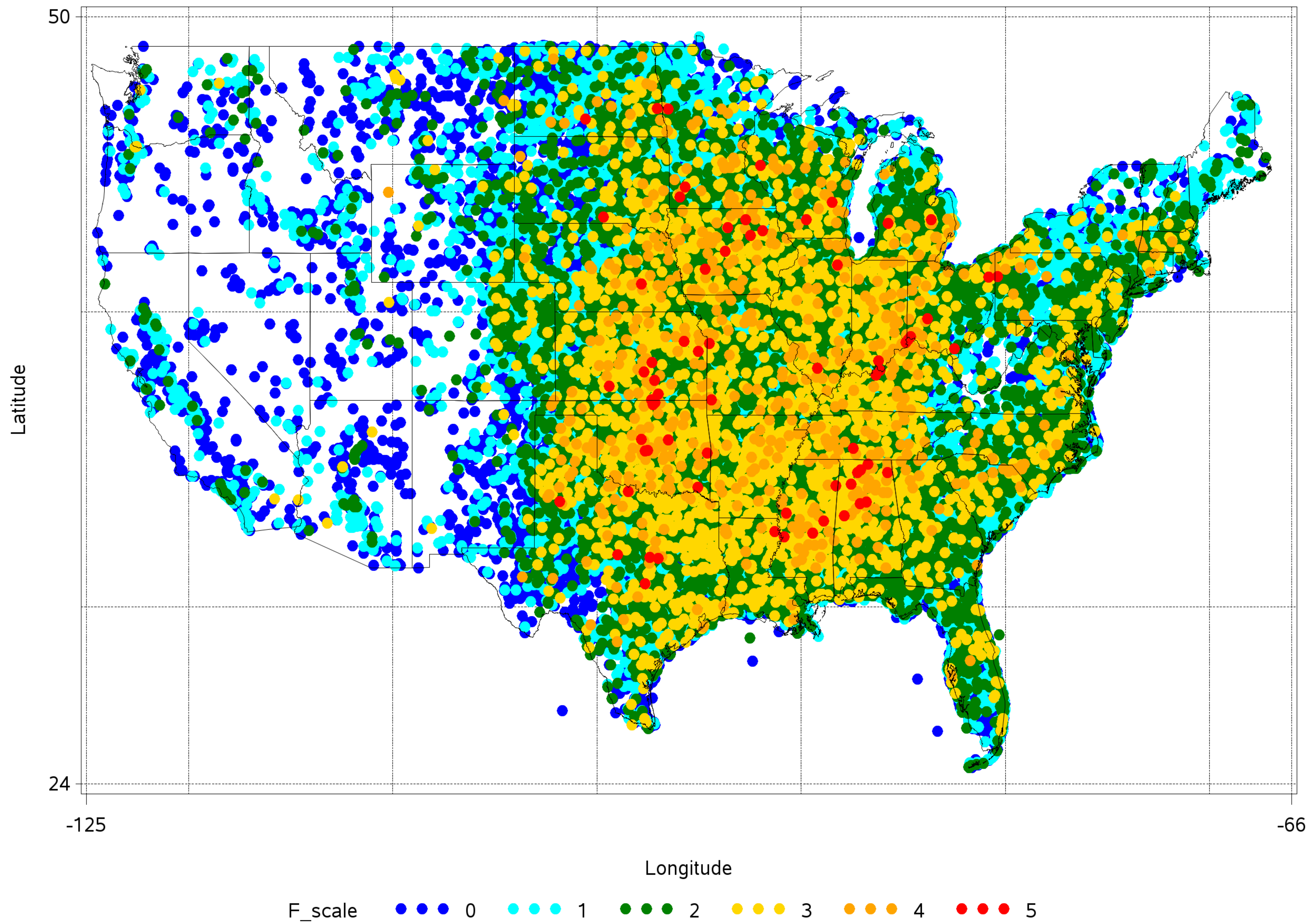
Fire whirls occur near intense wildfires.

- They are not considered tornadoes unless in the rare case where they connect to a pyrocumulus or other cumuliform cloud above.
- Fire whirls usually are not weaker than tornadoes associated with thunderstorms but they can produce significant damage.

A **steam devil** is a rotating updraft between 50 m and 200 m wide that involves steam or smoke.

- They do not have high wind speeds and only complete a few rotations per minute.
- Steam devils are very rare and most often form from smoke issuing from a power plant's smokestack.
- Hot springs and deserts may also be suitable locations for a tighter, faster-rotating steam devil to form.
- Steam devils can occur over water, when cold arctic air passes over relatively warm water.

Tornadoes: Basics: What, Where, When



All tornadoes in the US, 1950–2013, plotted by midpoint, highest F-scale on top, Alaska and Hawaii negligible, source NOAA Storm Prediction Center.

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Tornadoes: Strength

Tornadoes are rated according to the damage they cause, using an Enhanced Fujita Scale (EF-Scale).

- The strength of a tornado is estimated by the amount of property damage caused by its winds.
- The Fujita scale (F-scale) was introduced by Dr. T. Theodore Fujita in 1971.
- The Enhanced Fujita Scale (EF scale) was introduced in the U.S. , in 2007 and in Canada in 2013.
- For the EF, damage to various types of buildings has been calibrated by engineers and meteorologists.
- Like the original scale, the EF scale runs from EF0 (very little damage; wind speeds of under 30 m/s) to a maximum of EF5 (wind speeds over 116 m/s).
- Most damage is caused by EF3 and EF4 tornadoes.
- The most violent EF5 tornadoes destroy weather instruments, therefore no accurate measurements have yet been made of the strongest wind speeds within tornadoes.
- The highest near-surface tornado wind speeds measured to date were over 480 km/h in Oklahoma on May 3, 1999, using remote Doppler radar instruments.

Enhanced Fujita (EF) Tornado Intensity Scale

EF Scale	Class	Wind Speed			Description
		mph	$km\ h^{-1}$	$m\ s^{-1}$	
EF0	weak	65-85	105-137	29-38	Gale
EF1	weak	86-110	138-177	38-49	Moderate
EF2	strong	111-135	178-217	50-60	Significant
EF3	strong	136-165	218-266	61-74	Severe
EF4	violent	166-200	267-322	74-89	Devastating
EF5	violent	> 200	> 322	> 89	Incredible

Enhanced Fujita (EF) Scale estimates wind speeds from damage to buildings of various structural strengths, using a strongly-built wooden frame house as baseline. Original F-scale correlated building damage with wind strength, but did not allow for variations in the structural strength of buildings.

Tornadoes: Strength

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Damage caused by an EF4 tornado in Washington, Illinois, U.S.A. on November 17, 2013.

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Tornado rating classifications

EF0	EF1	EF2	EF3	EF4	EF5
Weak		Strong		Violent	
		Significant			
			Intense		

Tornadoes: Strength

Scale	Wind speed (Estimated)[5]			Relative frequency	Potential damage	Example of damage
	mph	km/h	m/s			
EF0	65–85	105–137	29–37	56.88%	Minor or no damage. Peels surface off some roofs; some damage to gutters or siding; branches broken off trees; shallow-rooted trees pushed over. Confirmed tornadoes with no reported damage (i.e., those that remain in open fields) are always rated EF0.	
EF1	86–110	138–177	38–49	31.07%	Moderate damage. Roofs severely stripped; mobile homes overturned or badly damaged; loss of exterior doors; windows and other glass broken.	
EF2	111–135	178–217	50–60	8.80%	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	136–165	218–266	61–73	2.51%	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 are badly damaged.	
EF4	166–200	267–322	74–90	0.66%	Extreme damage. Well-constructed and whole frame houses completely leveled; cars and other large objects thrown and small missiles generated.	
EF5	>200	>322	>90	0.08%	Total destruction of buildings. Strong-framed, well-built houses leveled off foundations are swept away; steel-reinforced concrete structures are critically damaged; tall buildings collapse or have severe structural deformations; some cars, trucks and train cars can be thrown approximately 1 mile (1.6 kilometres).	

https://en.wikipedia.org/wiki/Enhanced_Fujita_scale

Tornadoes: Strength

DI No.	Damage Indicator (DI)	Degrees of Damage (DOD)
1	Small Barns or Farm Outbuildings (SBO)	8
2	One- or Two-Family Residences (FR12)	10
3	Manufactured Home – Single Wide (MHSW)	9
4	Manufactured Home – Double Wide (MHDW)	12
5	Apartments, Condos, Townhouses [3 stories or less] (ACT)	6
6	Motel (M)	10
7	Masonry Apartment or Motel Building (MAM)	7
8	Small Retail Building [Fast Food Restaurants] (SRB)	8
9	Small Professional Building [Doctor's Office, Branch Banks] (SPB)	9
10	Strip Mall (SM)	9
11	Large Shopping Mall (LSM)	9
12	Large, Isolated Retail Building [K-Mart, Wal-Mart] (LIRB)	7
13	Automobile Showroom (ASR)	8
14	Automobile Service Building (ASB)	8
15	Elementary School [Single Story; Interior or Exterior Hallways] (ES)	10
16	Junior or Senior High School (JHSH)	11
17	Low-Rise Building [1–4 Stories] (LRB)	7
18	Mid-Rise Building [5–20 Stories] (MRB)	10
19	High-Rise Building [More than 20 Stories] (HRB)	10
20	Institutional Building [Hospital, Government or University Building] (IB)	11
21	Metal Building System (MBS)	8
22	Service Station Canopy (SSC)	6
23	Warehouse Building [Tilt-up Walls or Heavy-Timber Construction] (WHB)	7
24	Electrical Transmission Lines (ETL)	6
25	Free-Standing Towers (FST)	3
26	Free-Standing Light Poles, Luminary Poles, Flag Poles (FSP)	3
27	Trees: Hardwood (TH)	5
28	Trees: Softwood (TS)	5

- The EF scale currently has 28 damage indicators (DI), or types of structures and vegetation, each with a varying number of degrees of damage (DoD).
- Larger degrees of damage done to the damage indicators correspond to higher wind speeds.
- The links in the right column of the table describe the degrees of damage for the damage indicators listed in each row.

https://en.wikipedia.org/wiki/Enhanced_Fujita_scale

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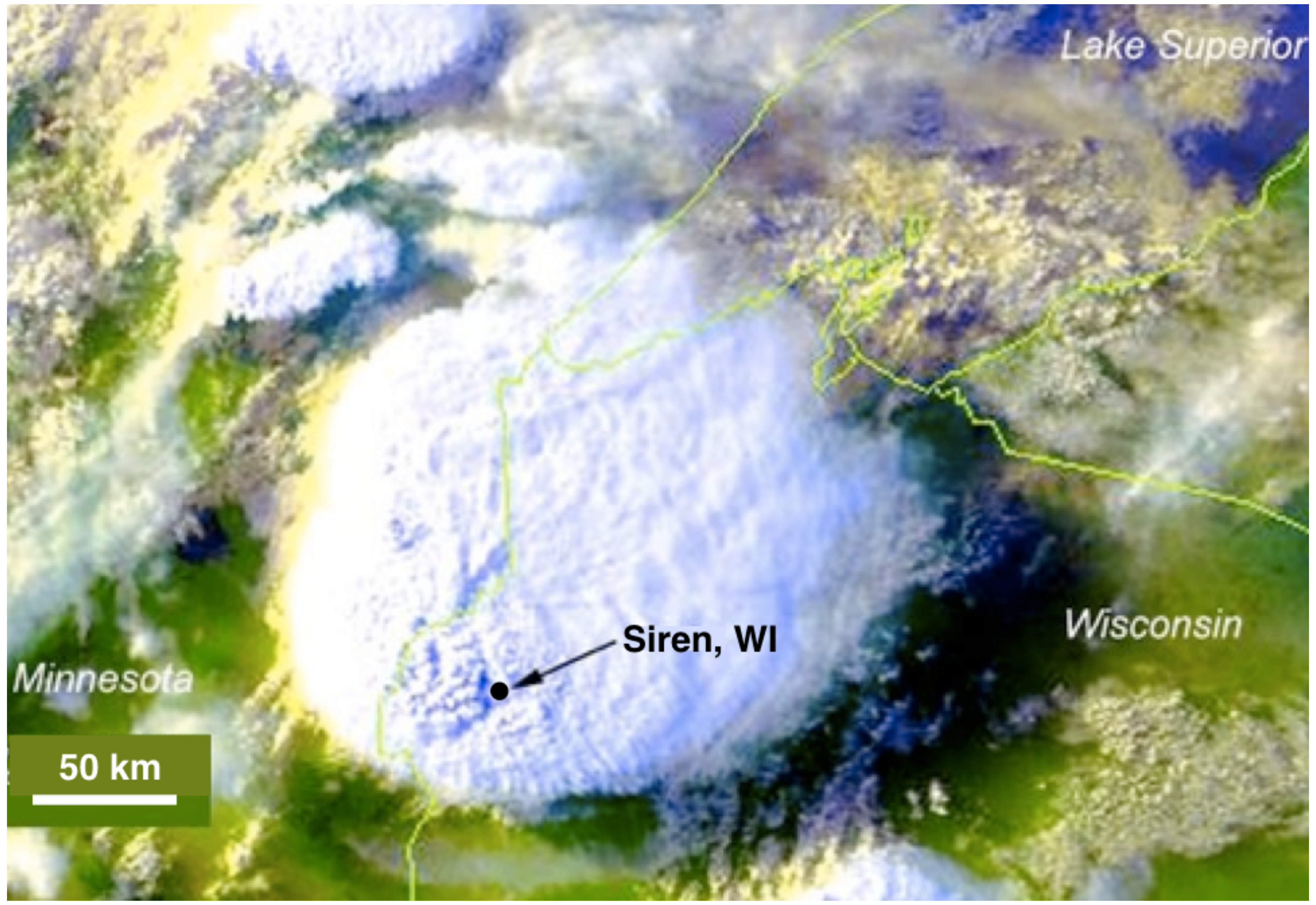
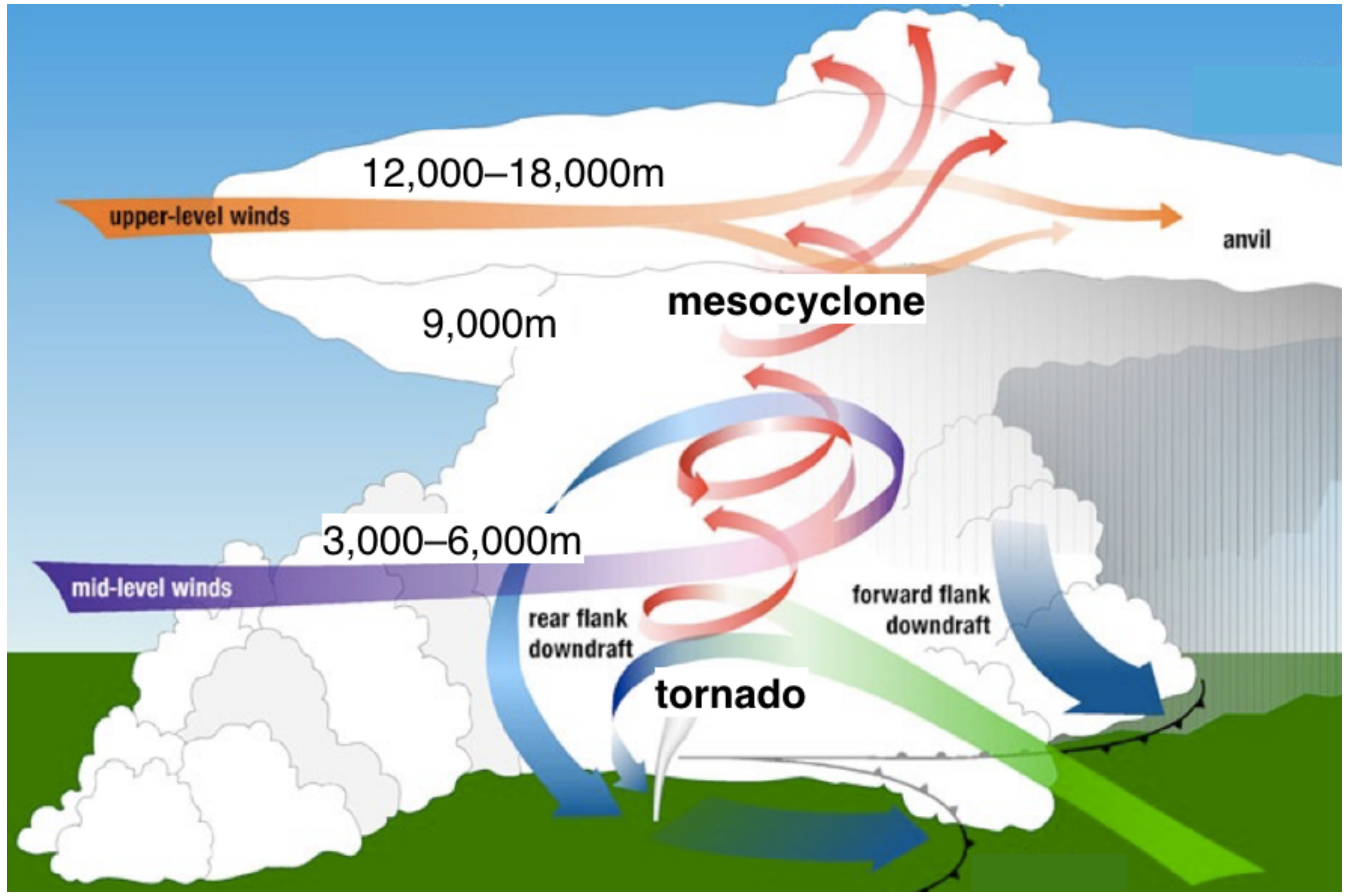
Tornadoes: Origin

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.

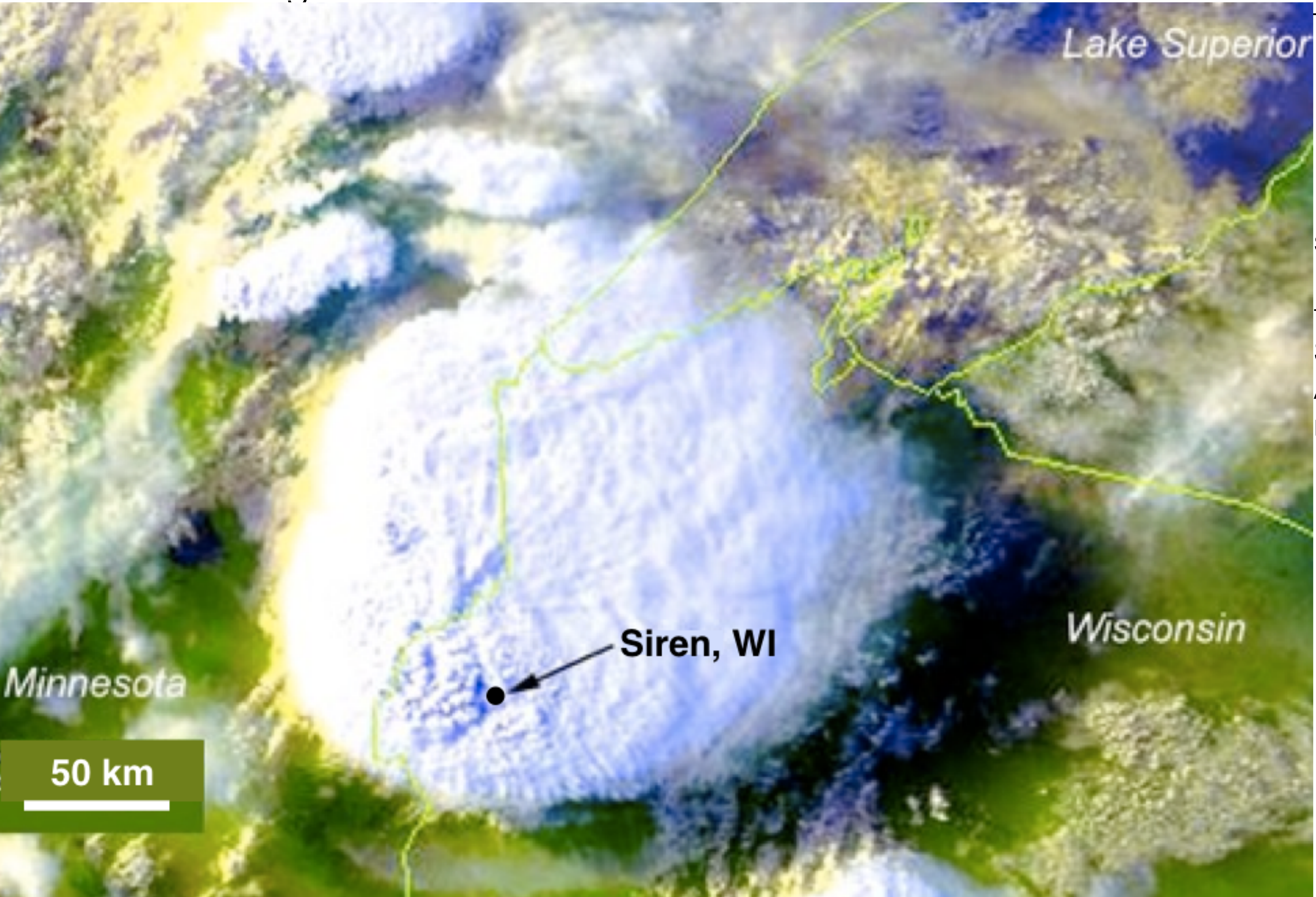


NOAA satellite imagery of a supercell storm on June 19, 2001 that spawned a fatal tornado touchdown in Siren, Wisconsin. In North America, supercells usually rotate counterclockwise.



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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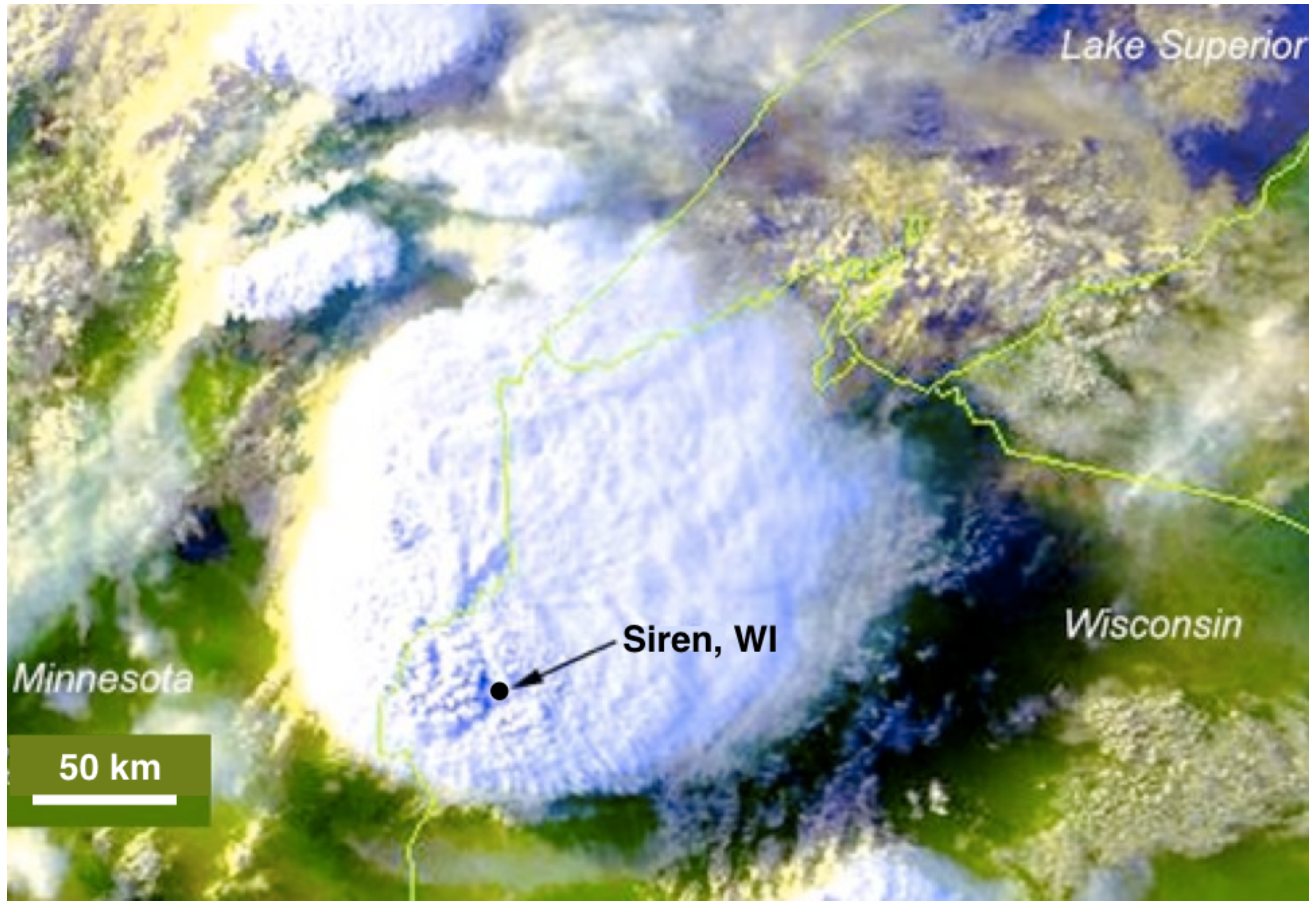

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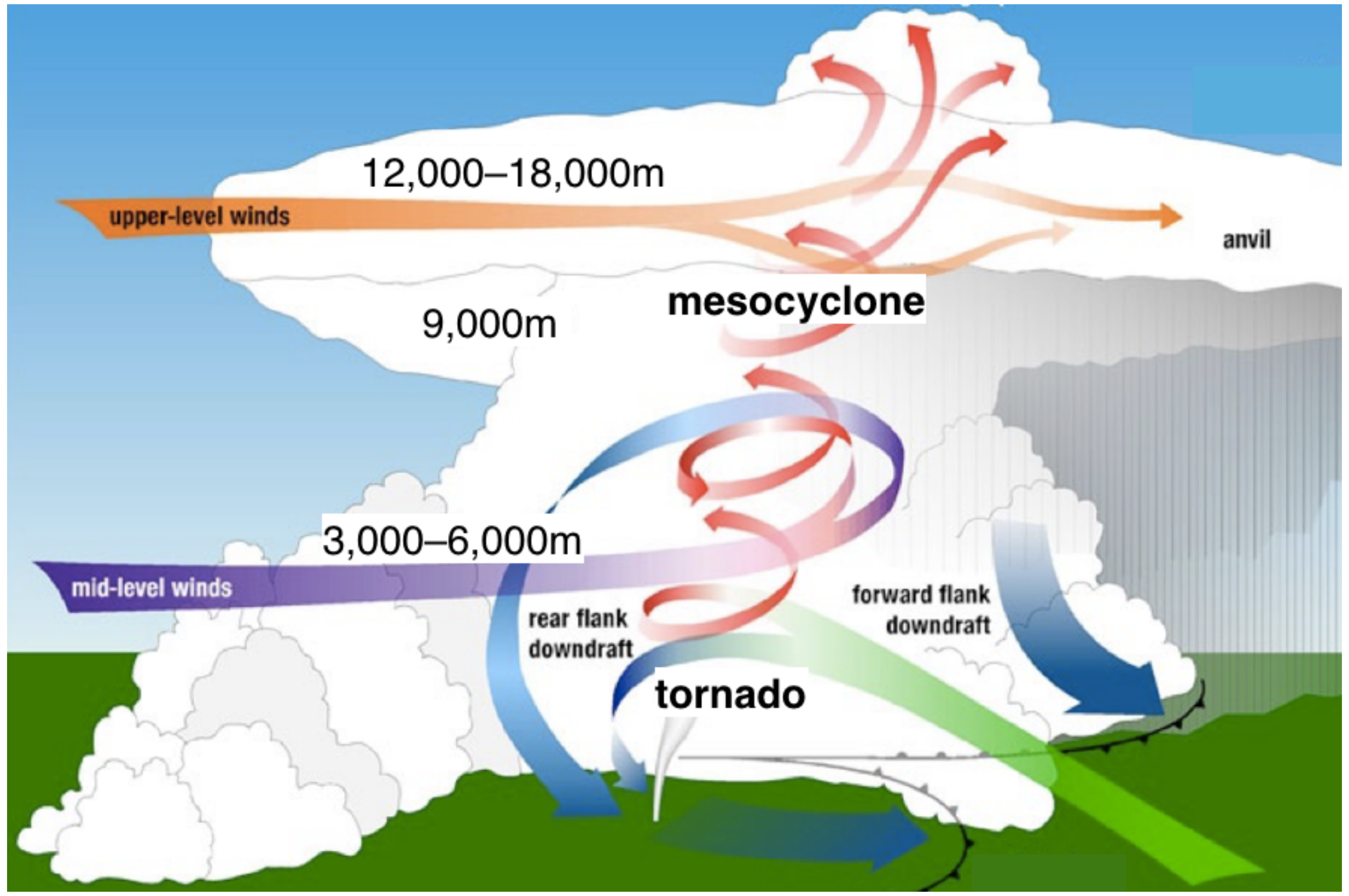

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Tornadoes: Origin

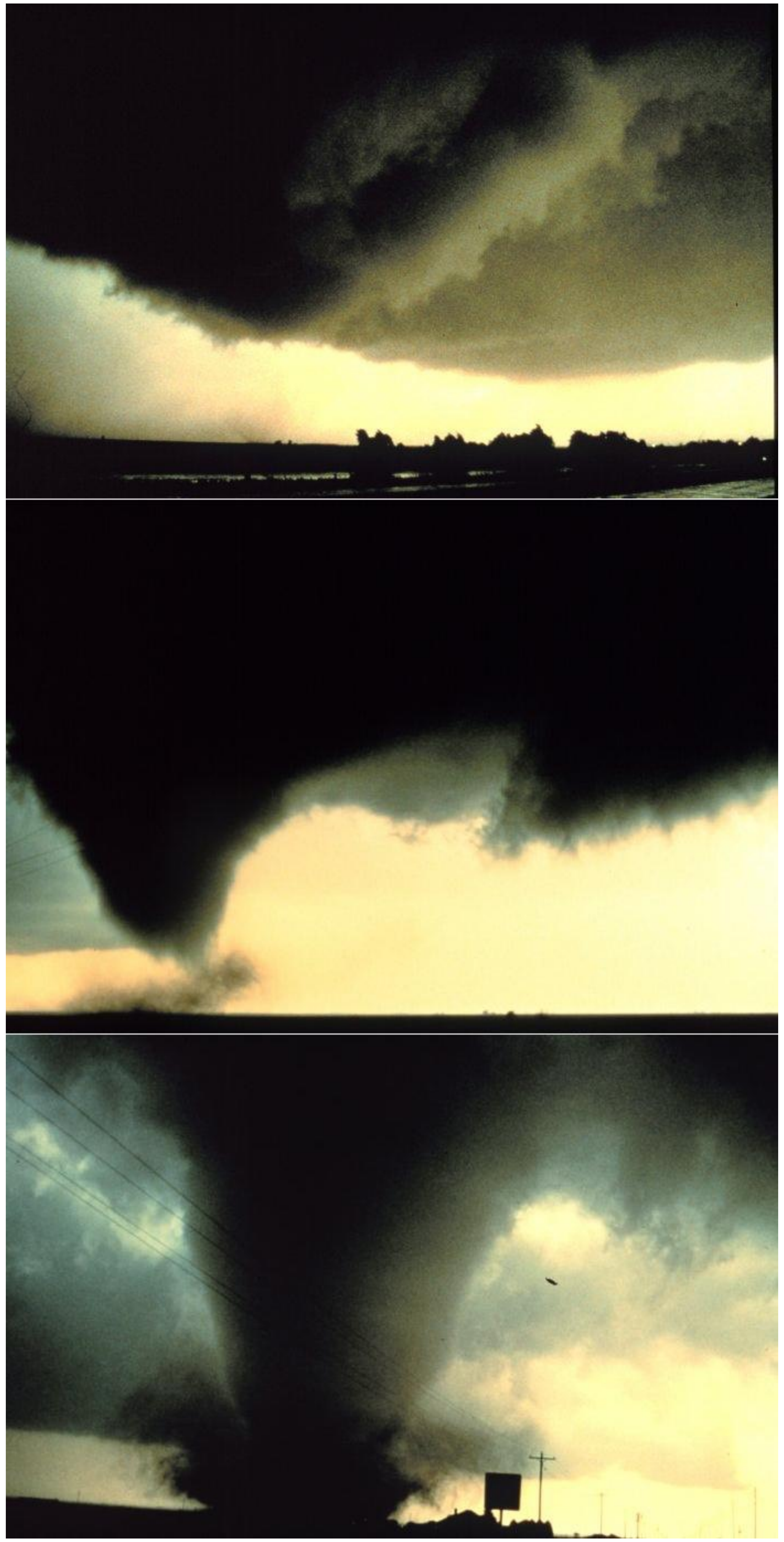
Most tornadoes from supercells follow a recognizable life cycle.

The Beginning:

- The life cycle 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.



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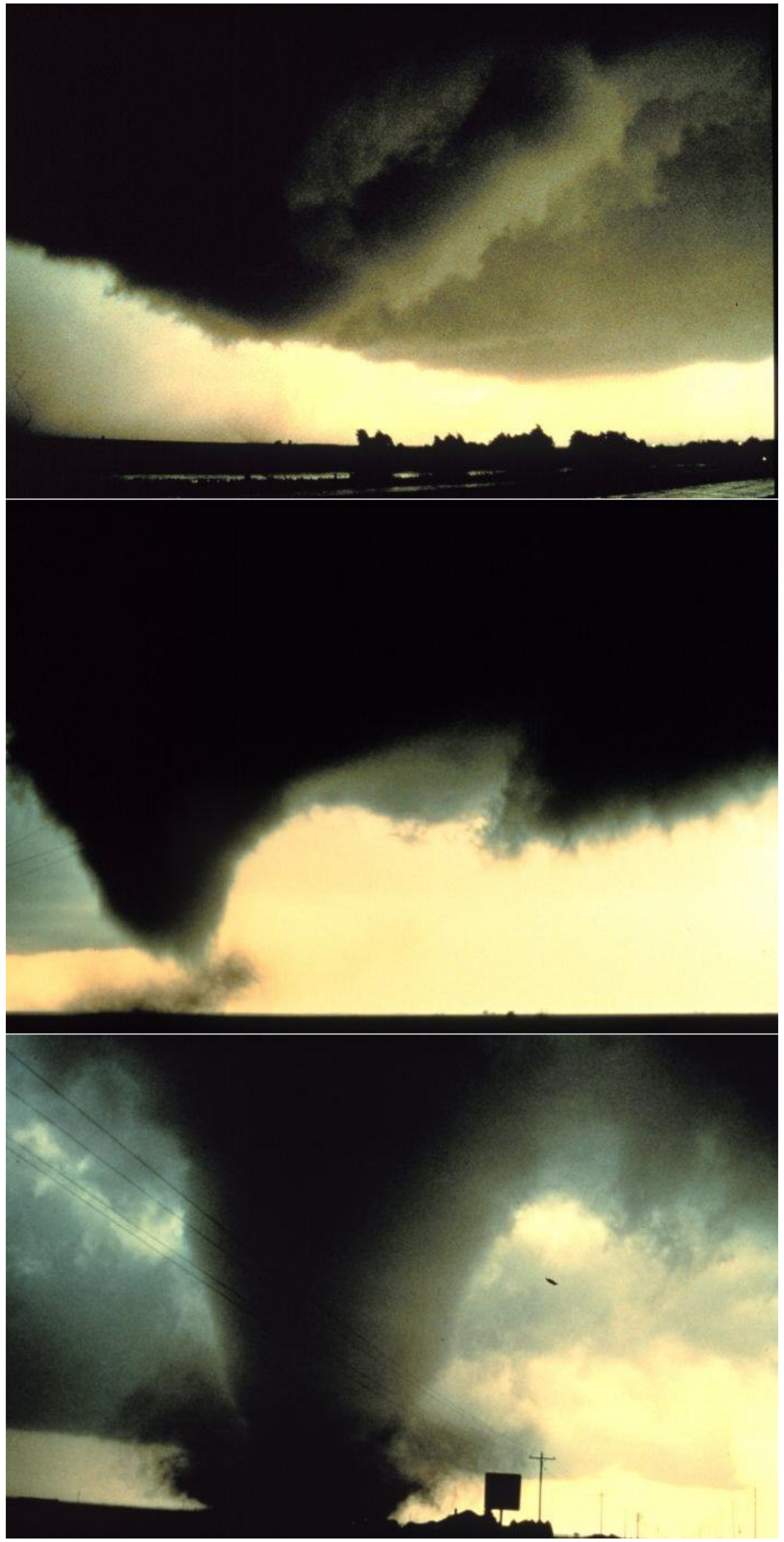


A sequence of images showing the birth of a tornado.

- 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.

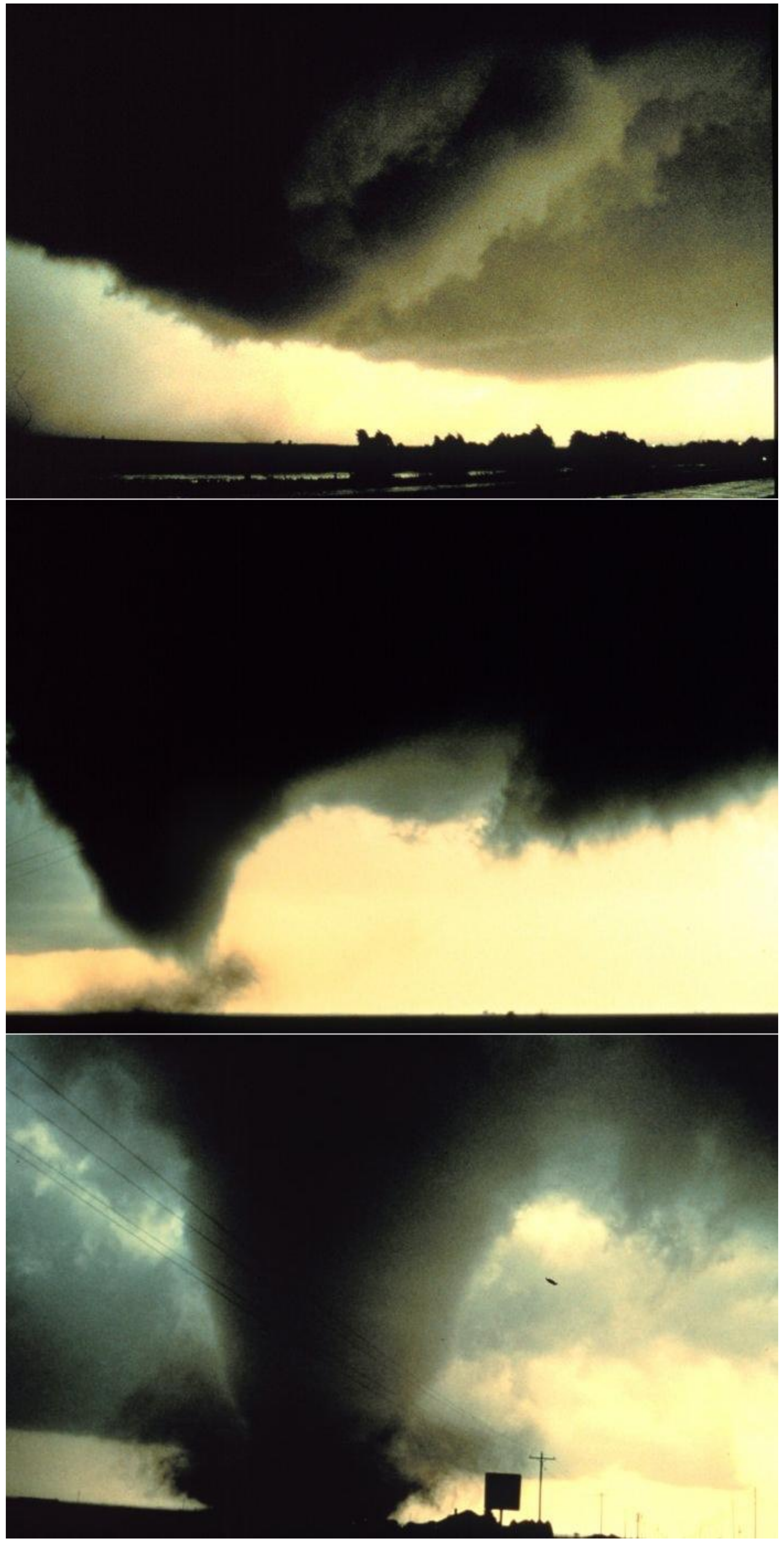
This tornado, near Dimmitt, Texas was one of the best-observed violent tornadoes in history. http://www.photolib.noaa.gov/nssl/tornado3.html

Tornadoes: Origin

Most tornadoes from supercells follow a recognizable life cycle.

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.



Tornadoes: Origin

Most tornadoes from supercells follow a recognizable life cycle.

Dissipation:

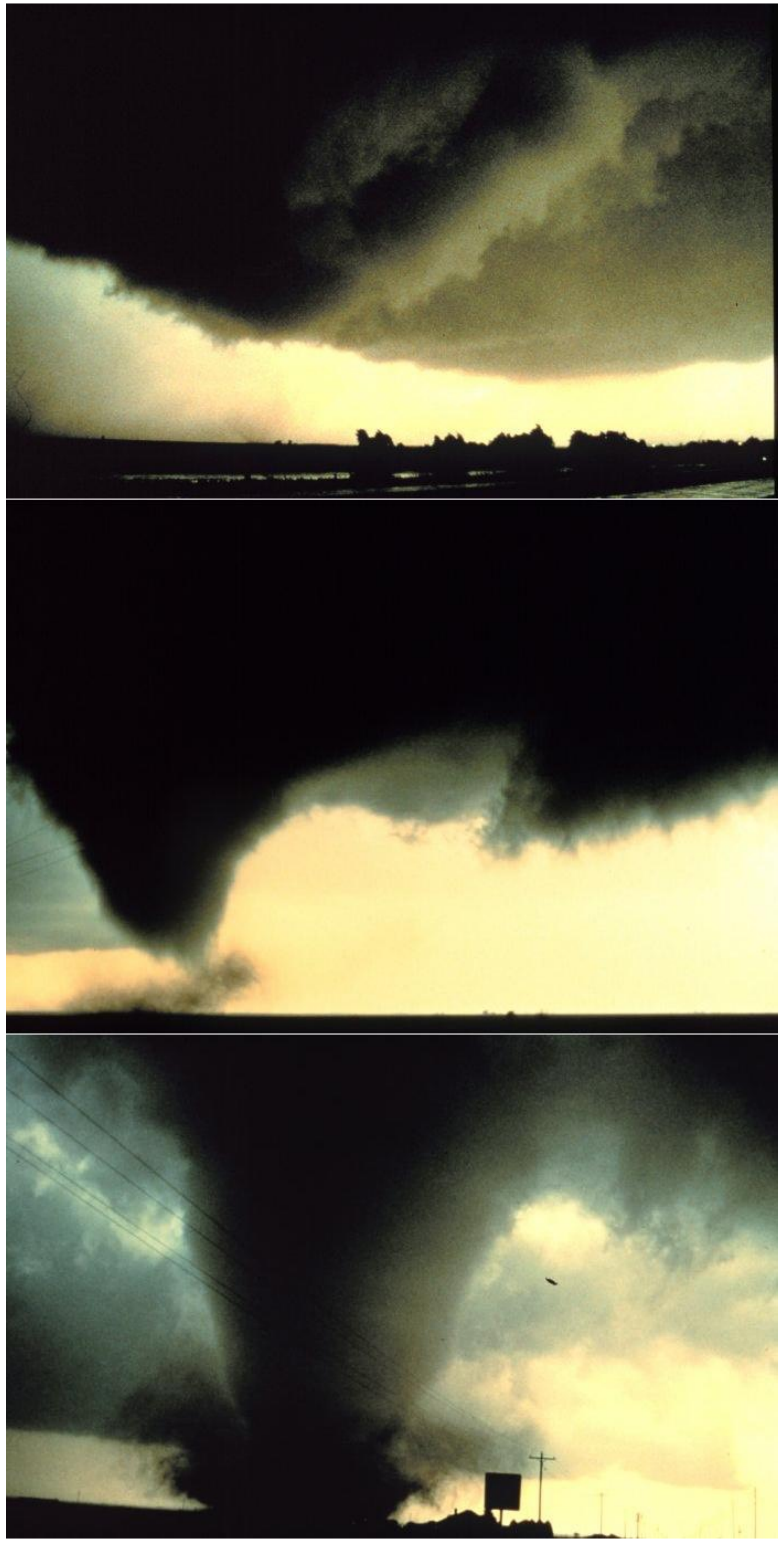
- As the RFD completely wraps around and chokes off the tornado's air supply, the vortex begins to weaken, and become thin and rope-like.
- This is the "dissipating stage", often lasting no more than a few minutes, after which the tornado ends.
- During this stage the shape of the tornado becomes highly 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.



Tornadoes: Origin

Most tornadoes from supercells follow a recognizable life cycle.

- 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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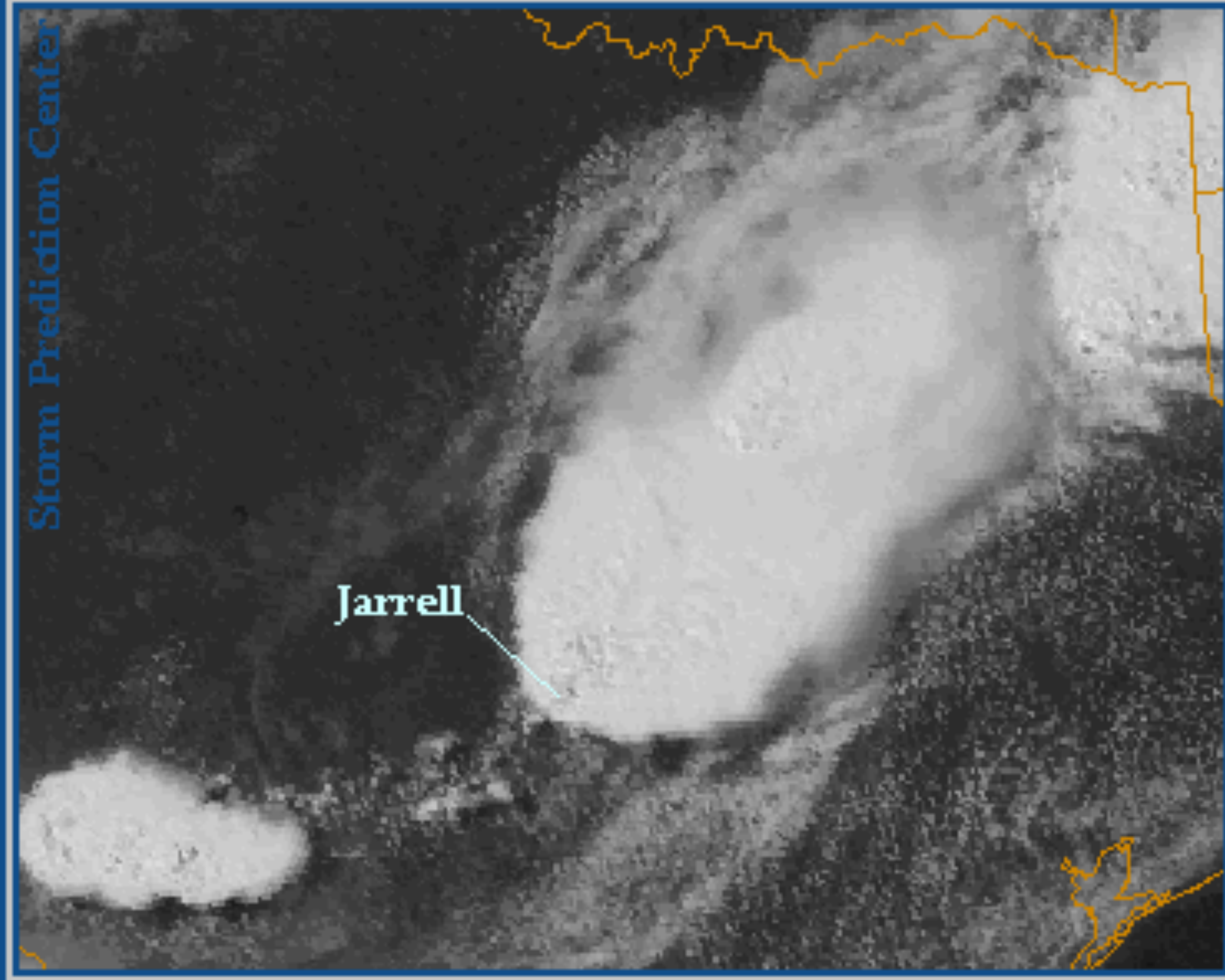
Tornadoes: Warnings and Preparedness

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.



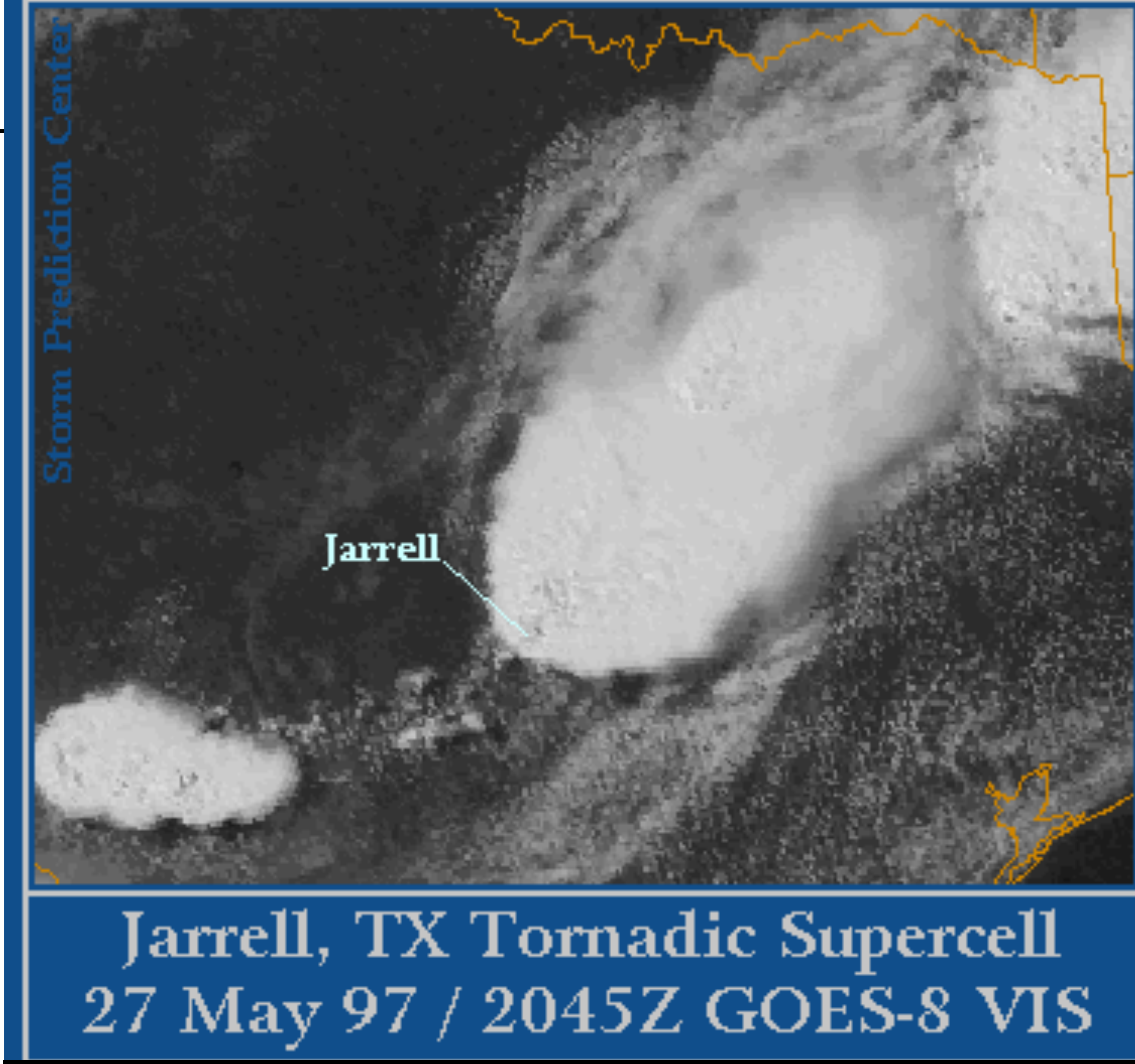
Jarrell, TX Tornadic Supercell
27 May 97 / 2045Z GOES-8 VIS

Tornadoes: Warnings and Preparedness

Precursors to Tornado Formation

- 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.

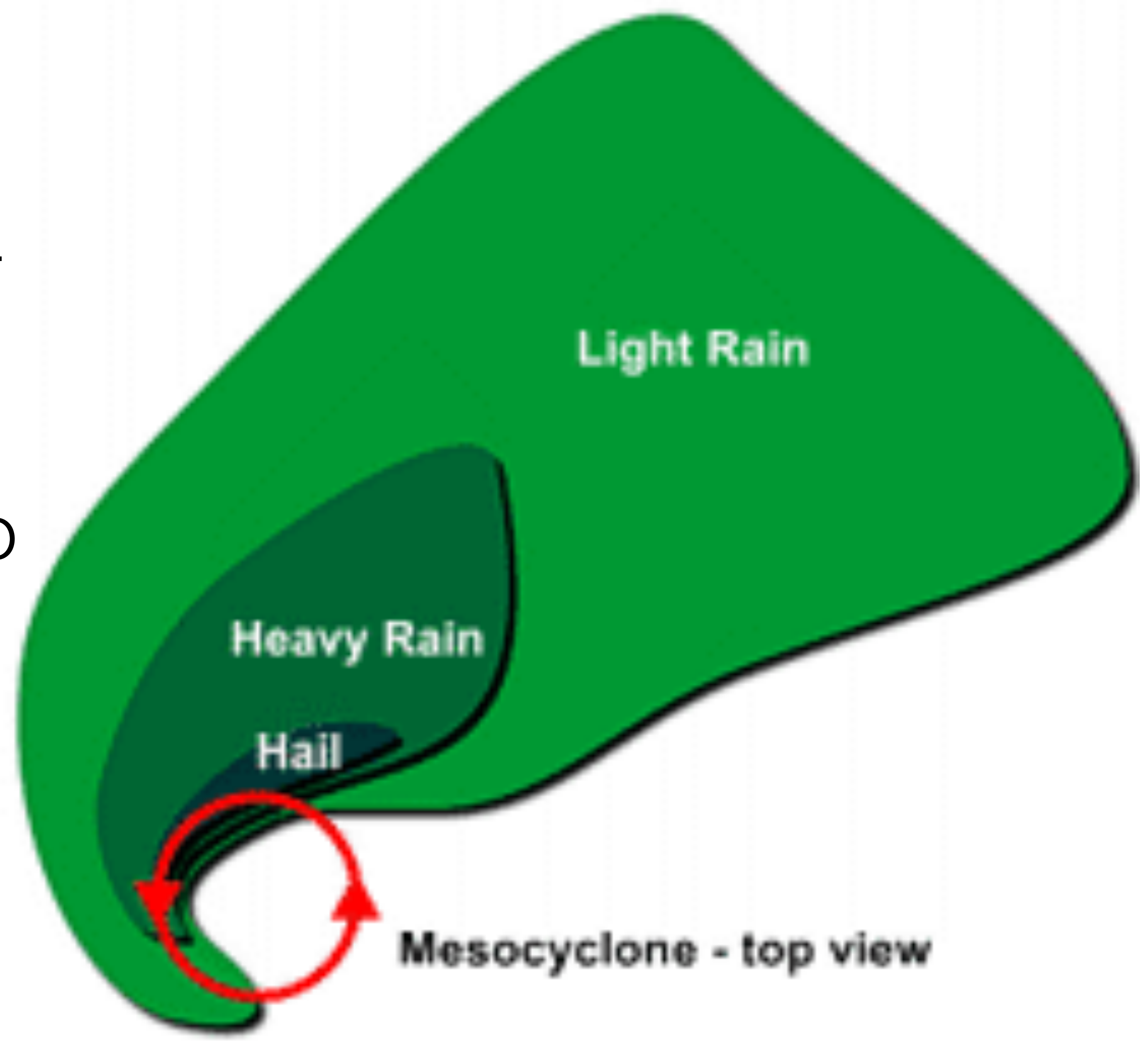


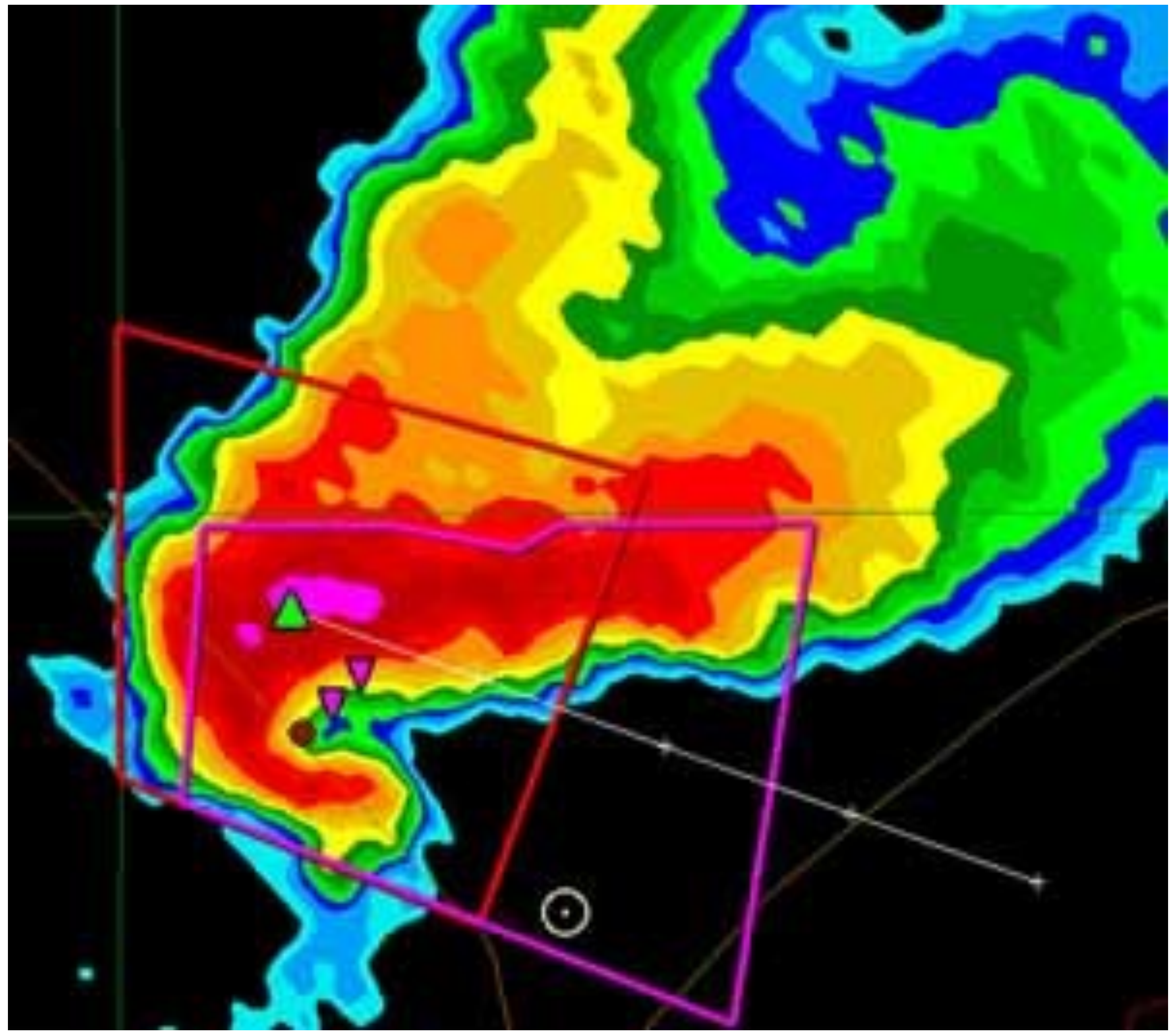
EF5 tornado touches down near Jarrell, TX, on May 27, 1997, causing 27 human fatalities and the death of more than 300 cattle.

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.



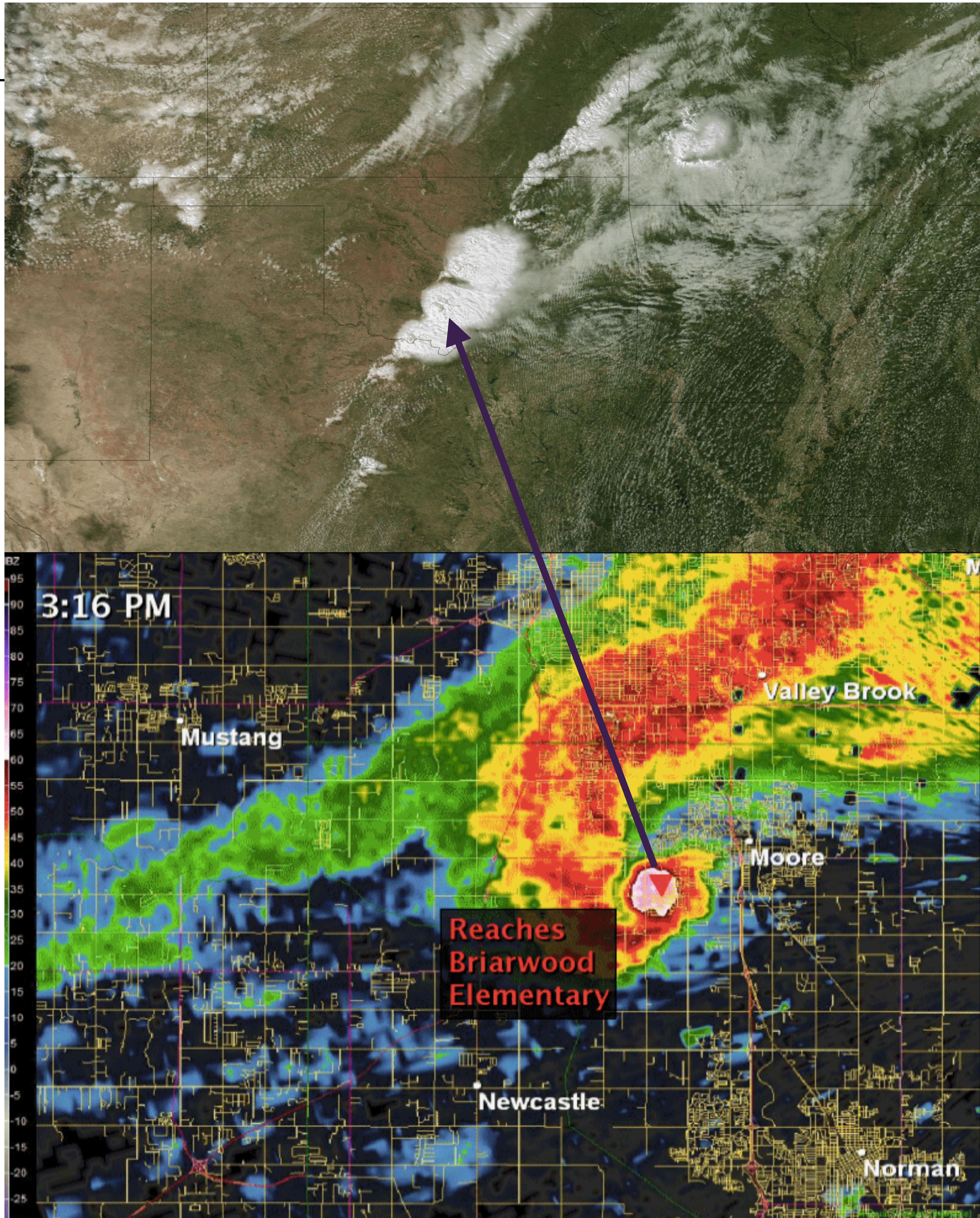


Left: Schematic view from above of hookshaped cloud (green) indicating a supercell (mesocyclone) with the potential for tornado formation.
Right: Radar image of an actual mesocyclone hook. Red and pink colors indicate areas of highest rain intensity.

Tornadoes: Warnings and Preparedness

Tornado Warning Signs

- 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: 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 PM that day.

Measuring Tornadoes

Tornado chasing is not recommended!!

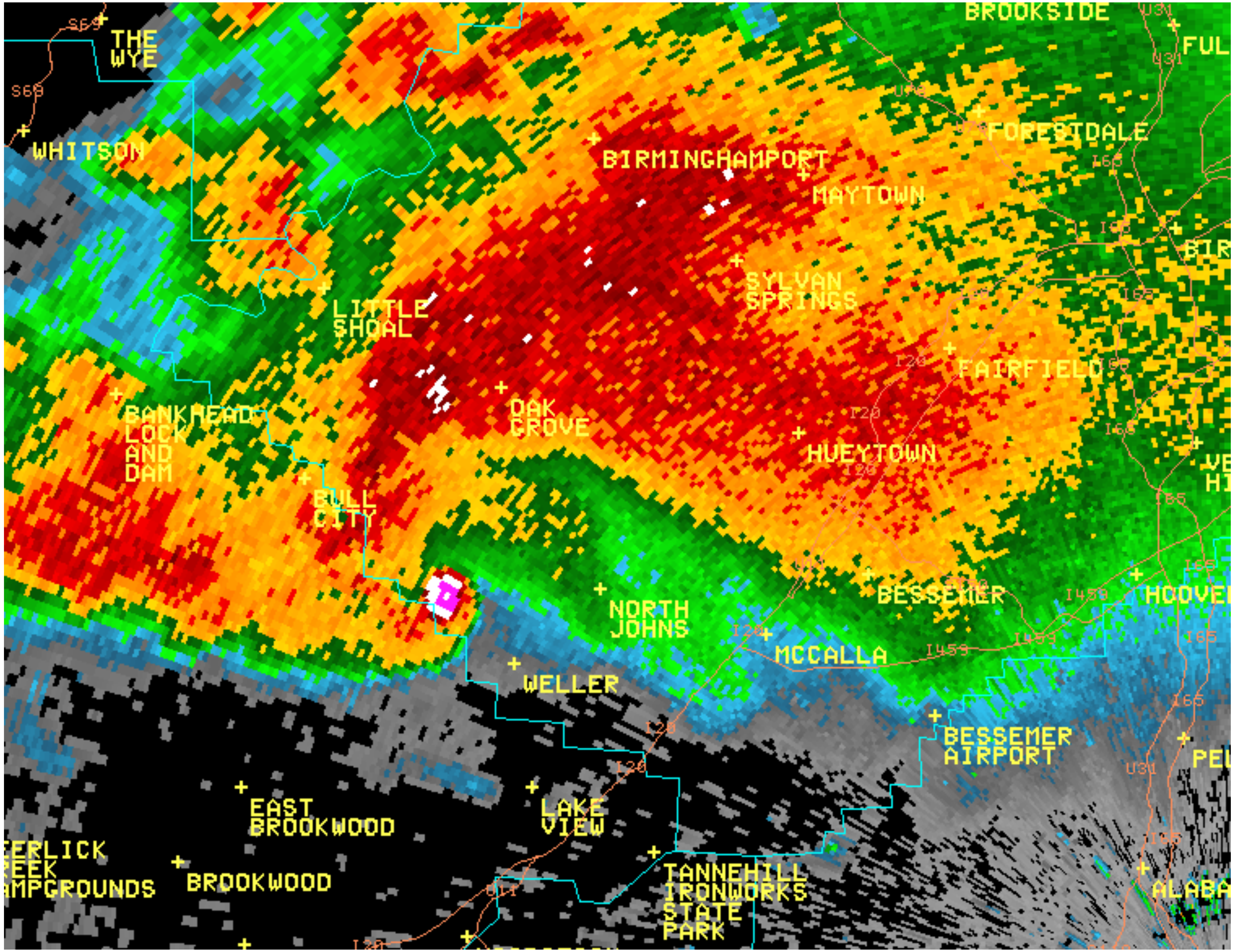
- Despite all the imagery and after-the-fact reports that are available about tornadoes, there is still much that remains unexplained regarding their formation and their internal structure.
- Scientists at NOAA's National Severe Storms Laboratory (NSSL) in Norman, OK, work to develop more accurate forecasts 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.

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

Tornadoes: Warnings and Preparedness

Measuring Tornadoes

- 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.



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.

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.

Tornadoes: Warnings and Preparedness

Tornado Mitigation

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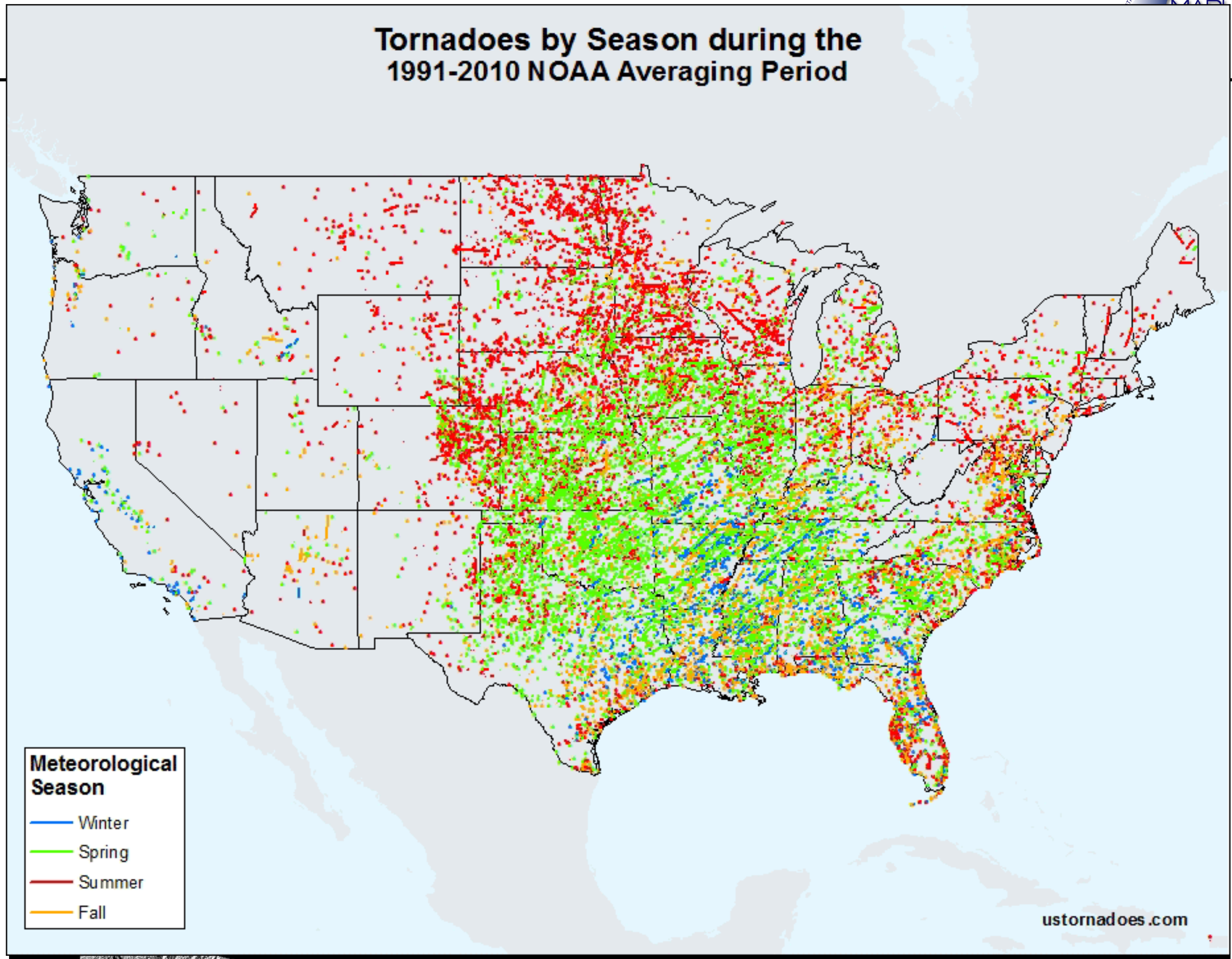
Typical tornado shelter signs.

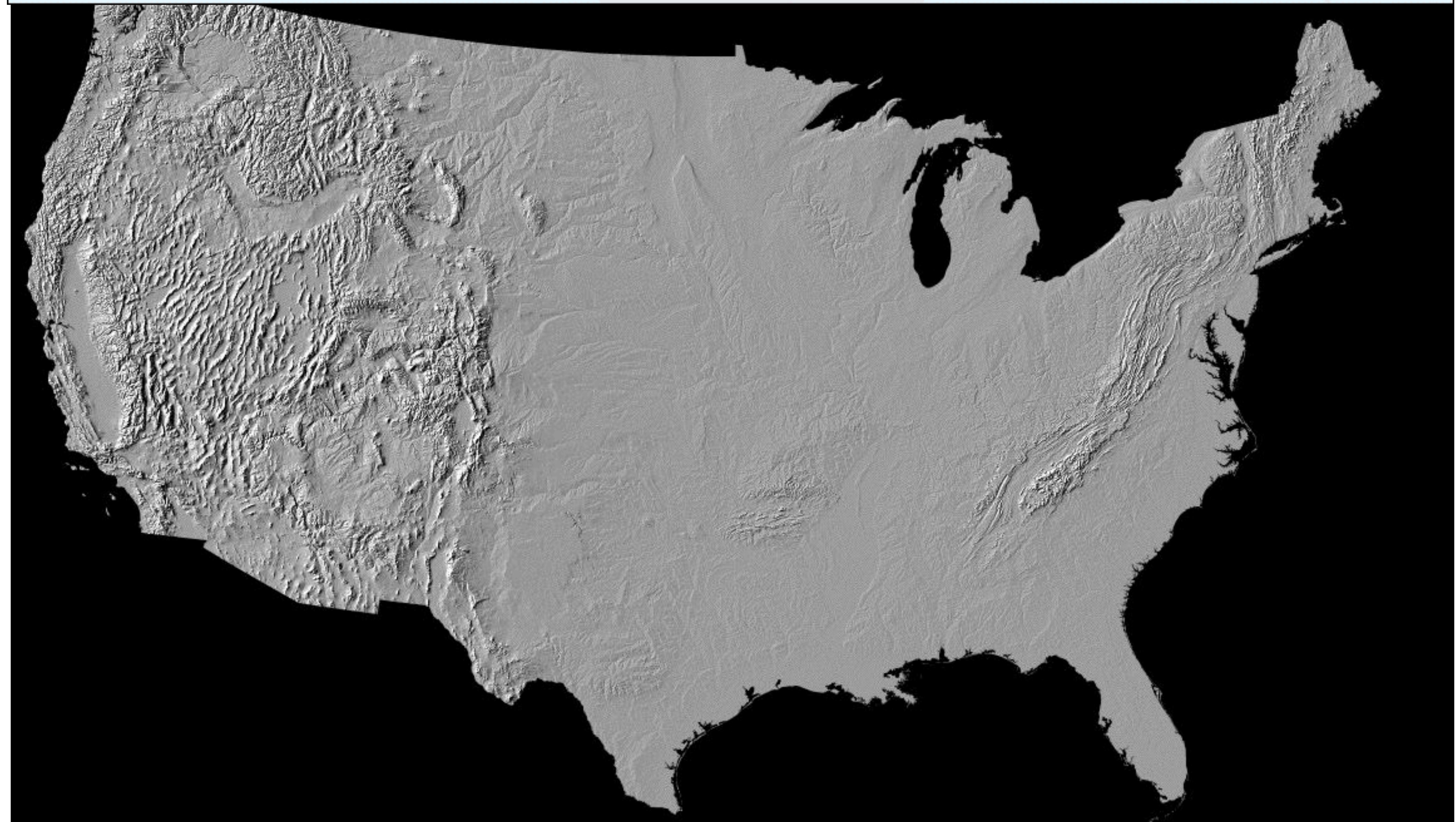
Left: Schematic home tornado shelter.
Right: Surface view of a home tornado shelter in Dallas, TX.

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.

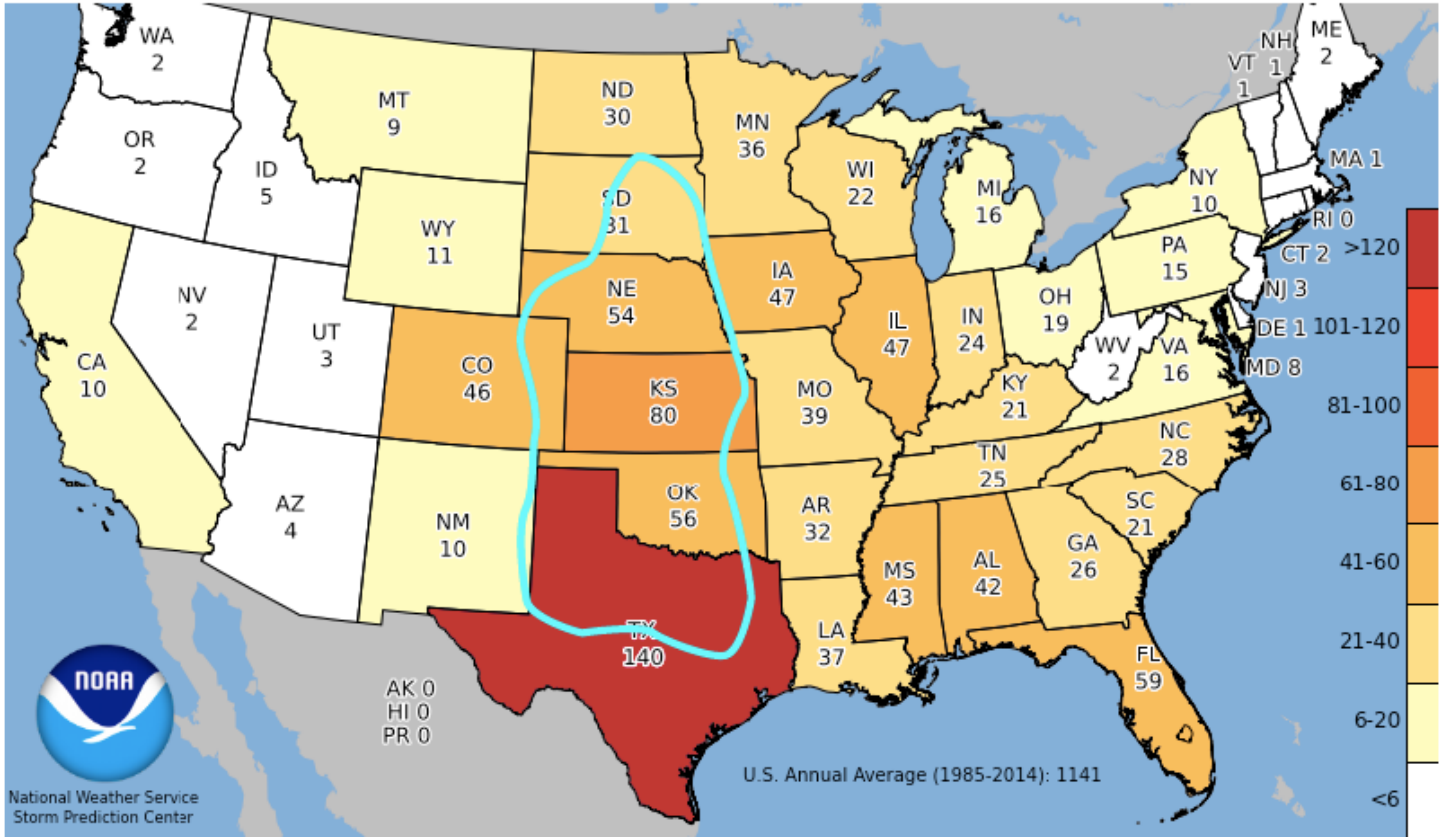




Top: Location of tornadoes in the U.S.A. for the period 1991-2010, color-coded by season. Compare tornado concentrations with shaded relief map (bottom).

Tornado Season In The U.S.A.

- 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.



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.

Natural Hazards and Disaster

Class 10: Tornadoes, Ice Storms, Meteotsunamis

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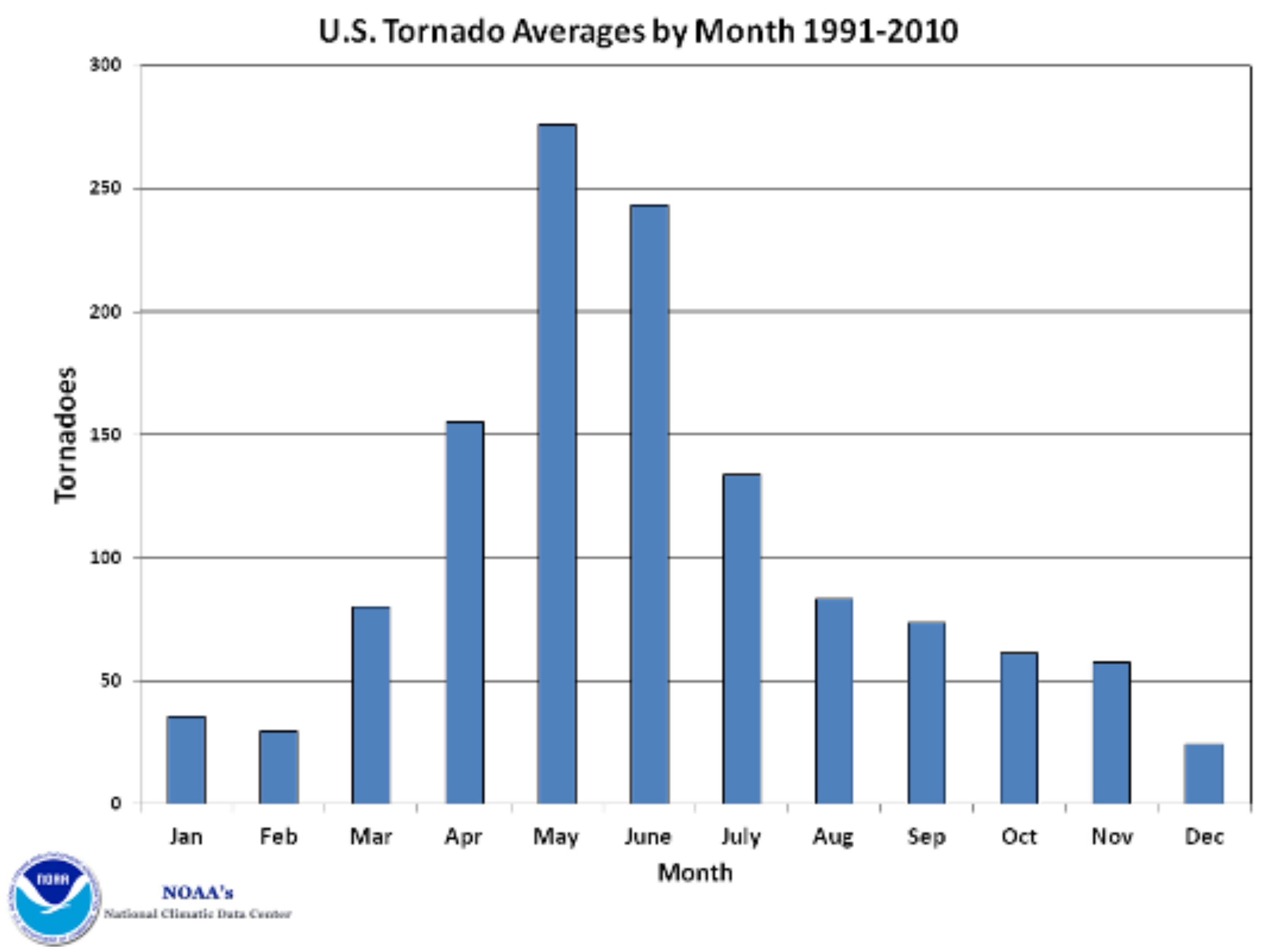
Tornadoes: Characteristics

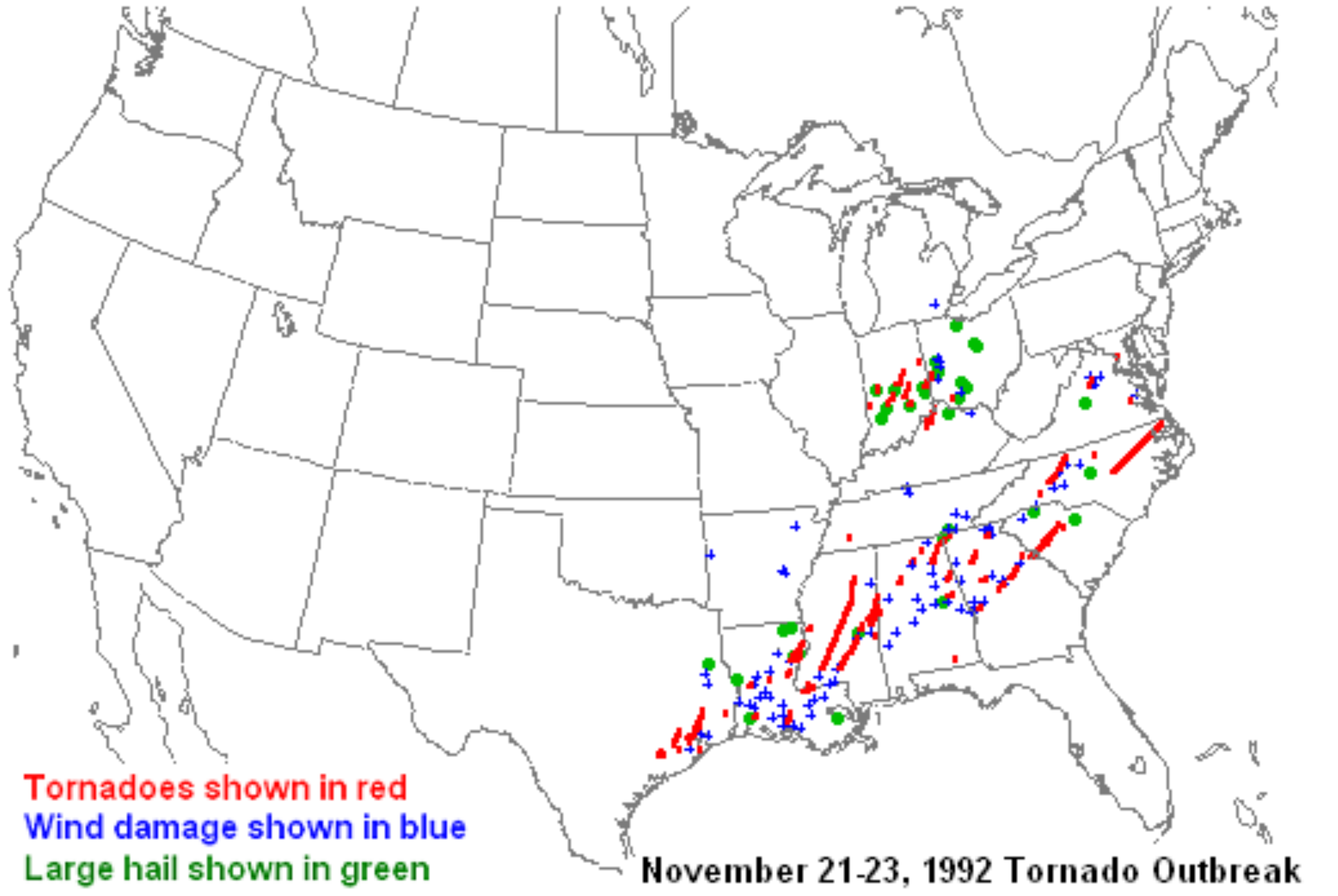
U.S. Tornadoes In Fall

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.

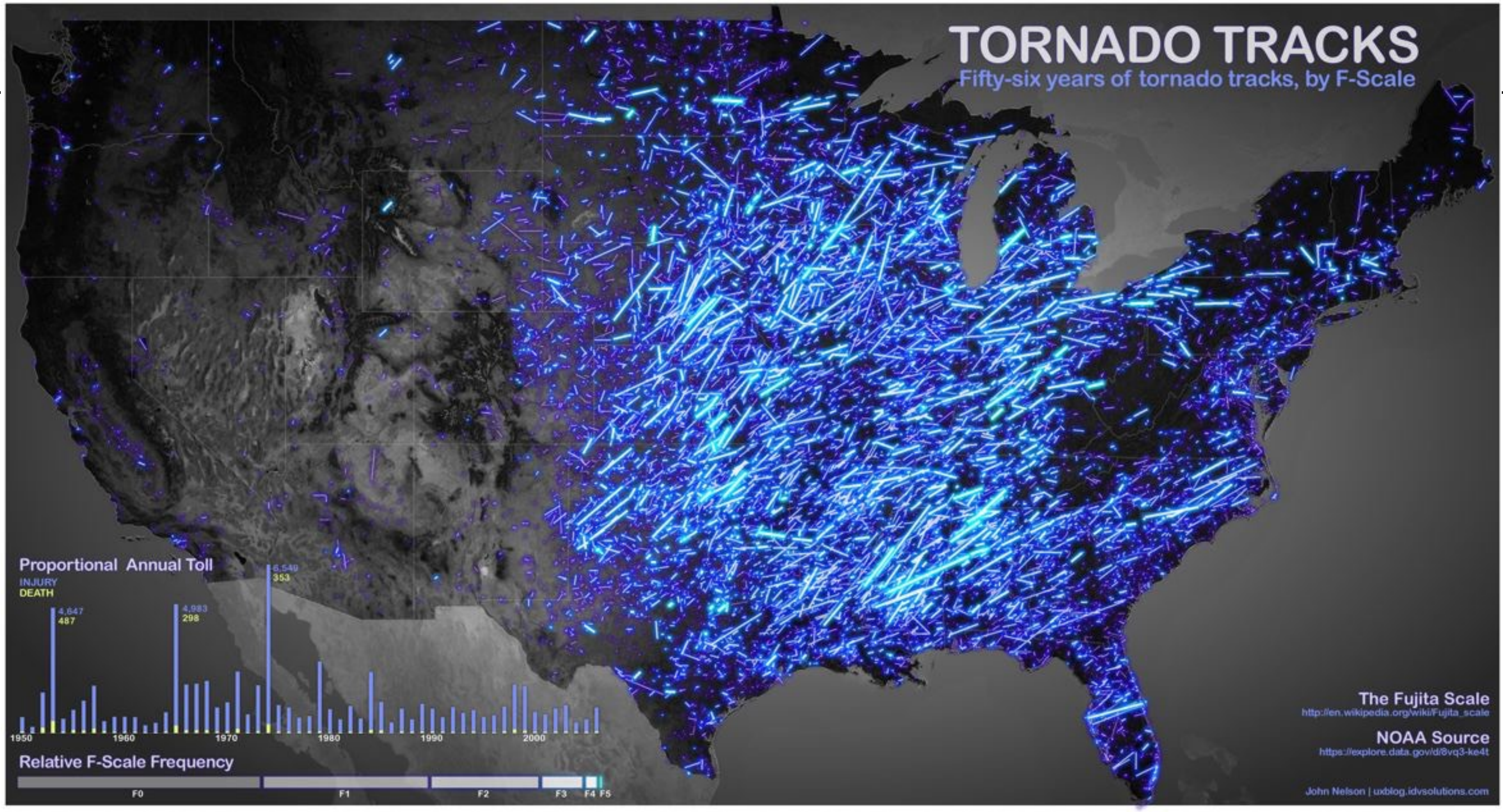
Left: Damage caused by an EF4 tornado (seen at right) in Rowlett, TX on December 26, 2015

Tornadoes: Characteristics

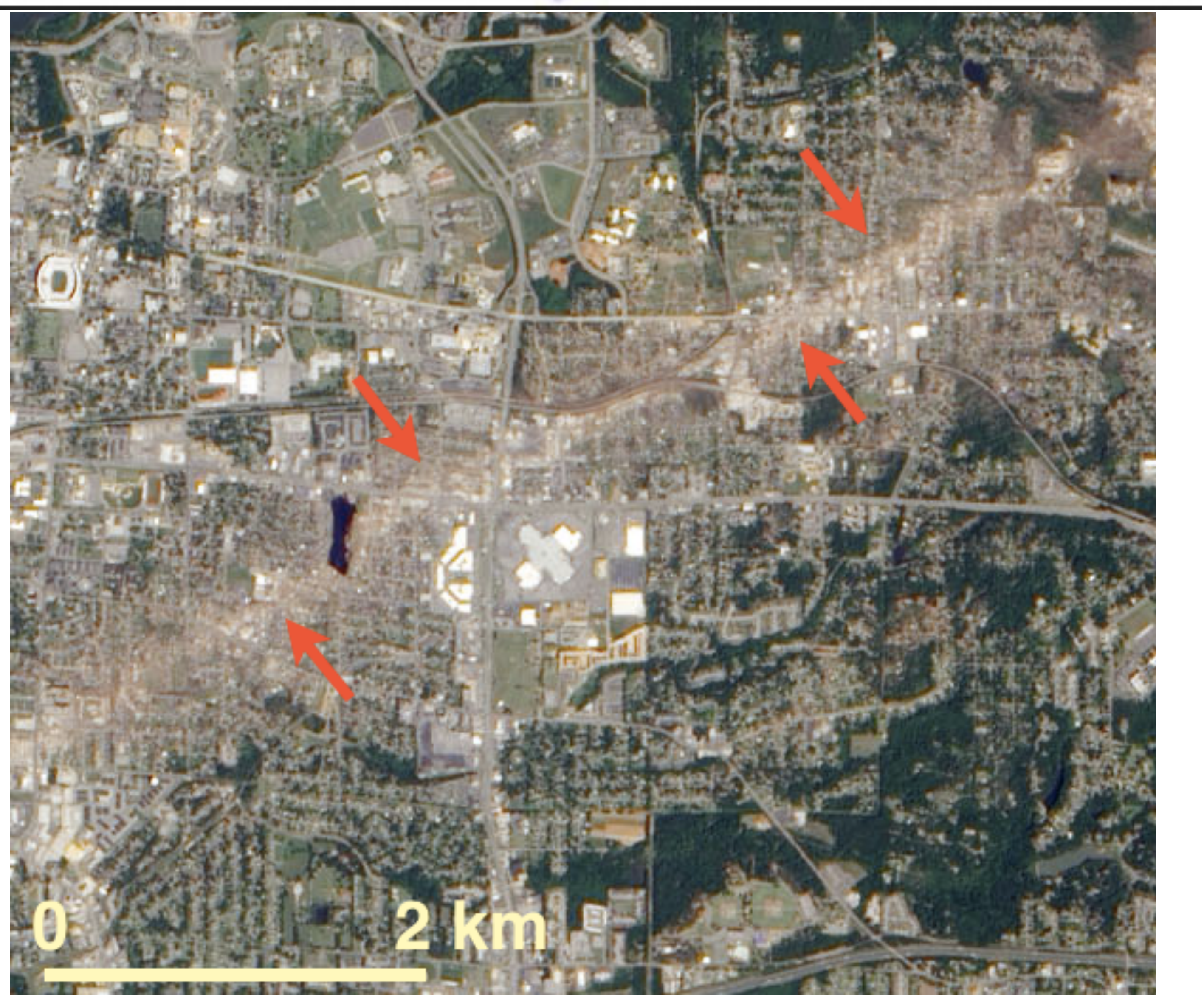
Tornado Tracks

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.

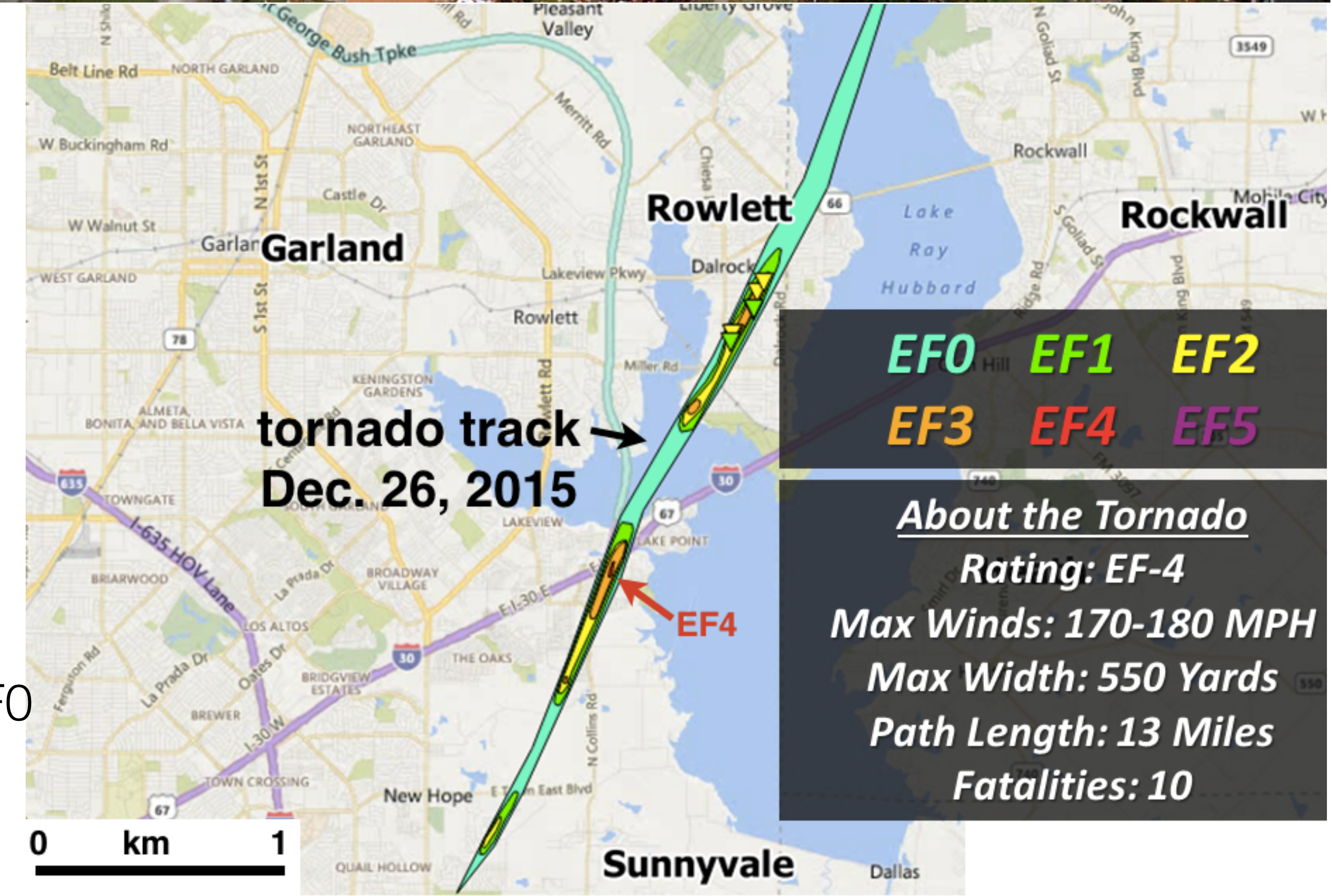
Tornadoes: Characteristics

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.

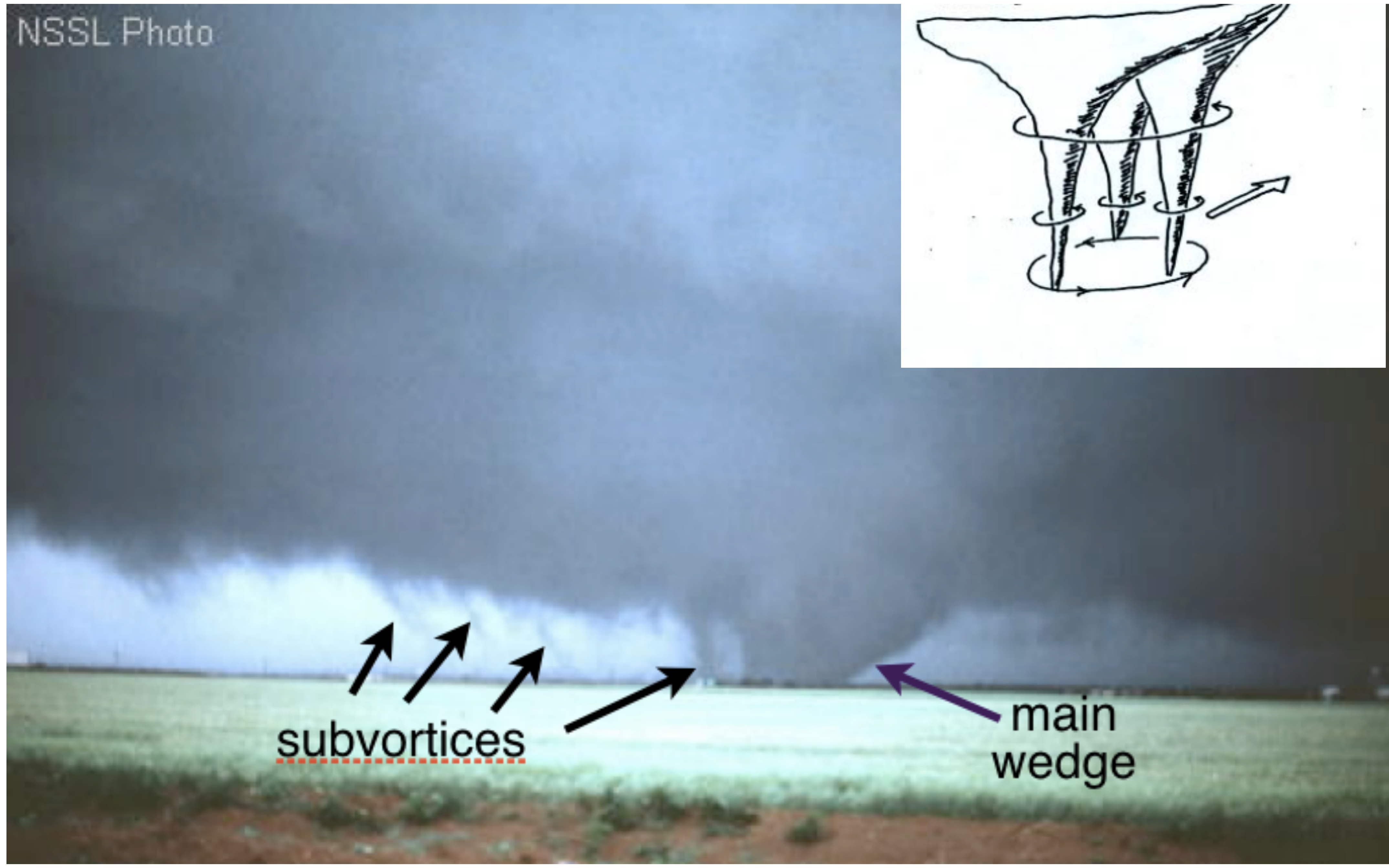
Tornadoes: Characteristics

Multiple Vortex Tornadoes

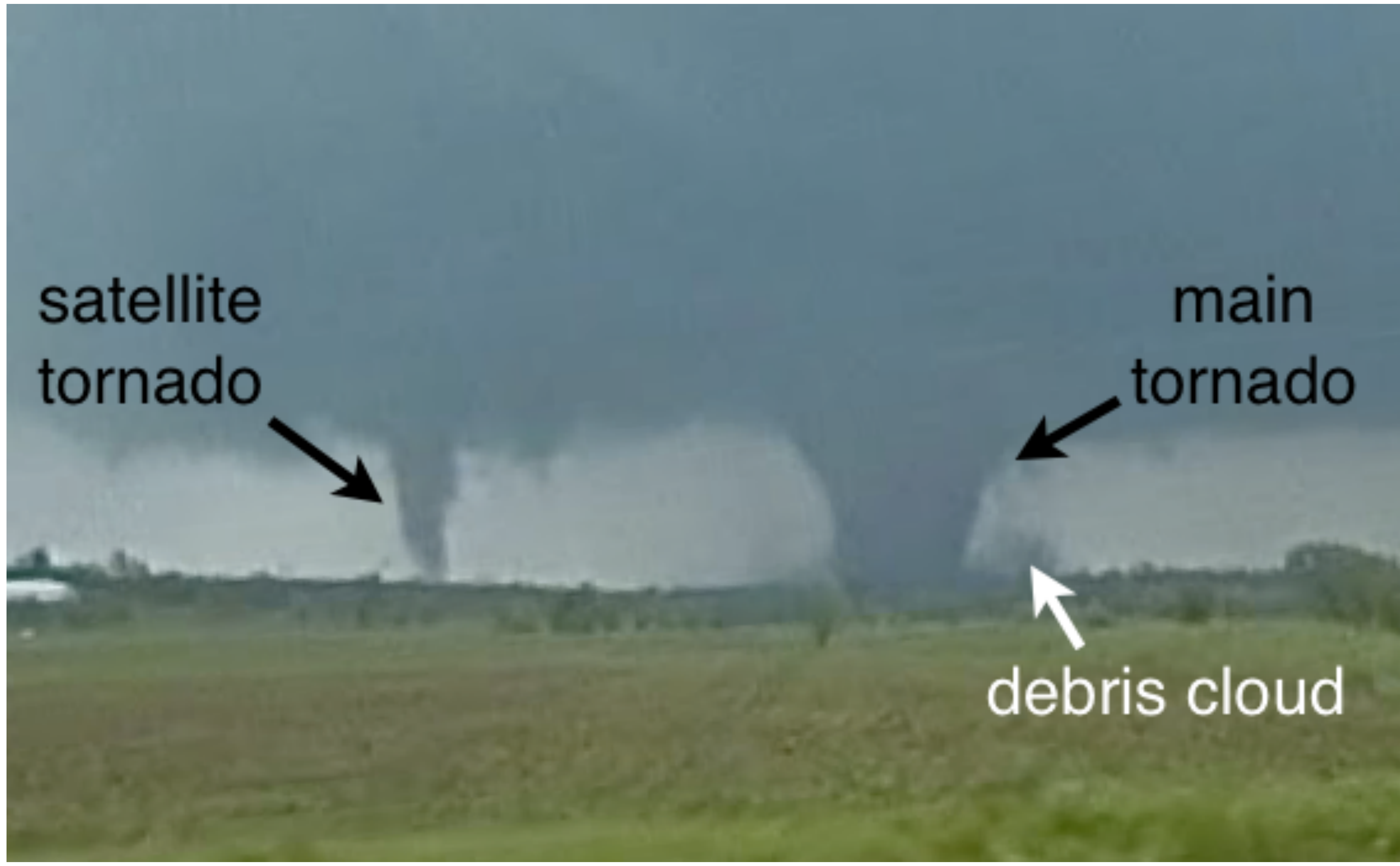
Many large tornadoes contain short-lived multiple subvortices that add to the overall damage caused.

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.

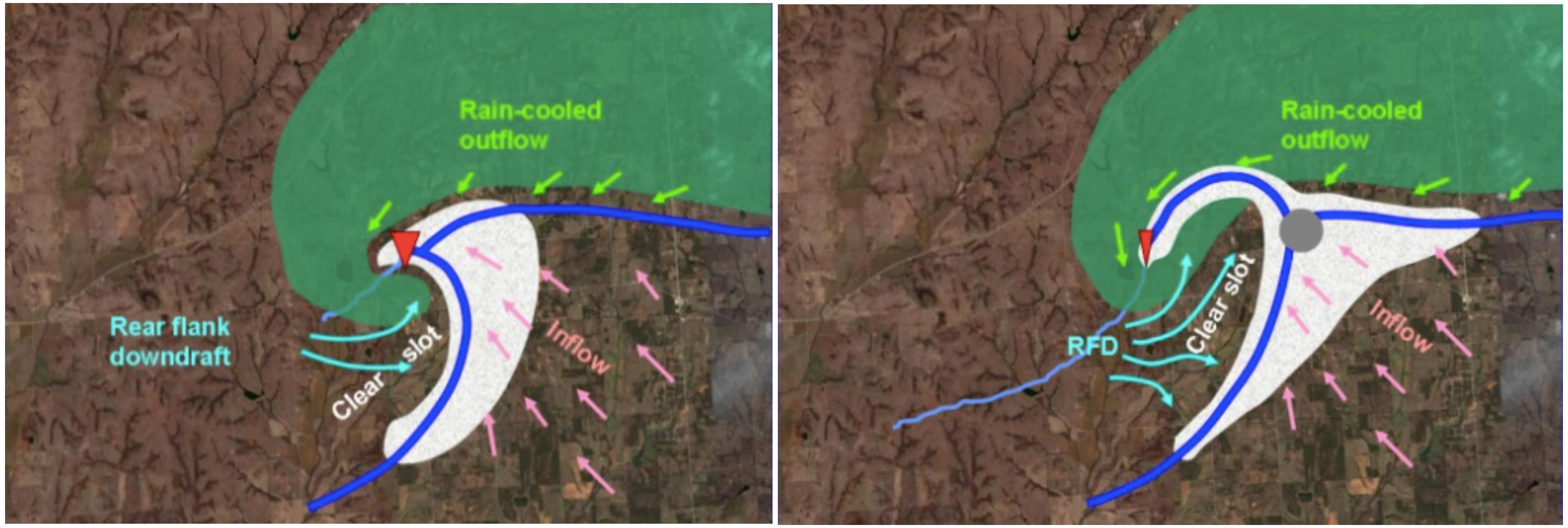
Destroyed Wrangler denim factory in Hackleburg, AL, from an EF5 tornado on April 27, 2011.

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.

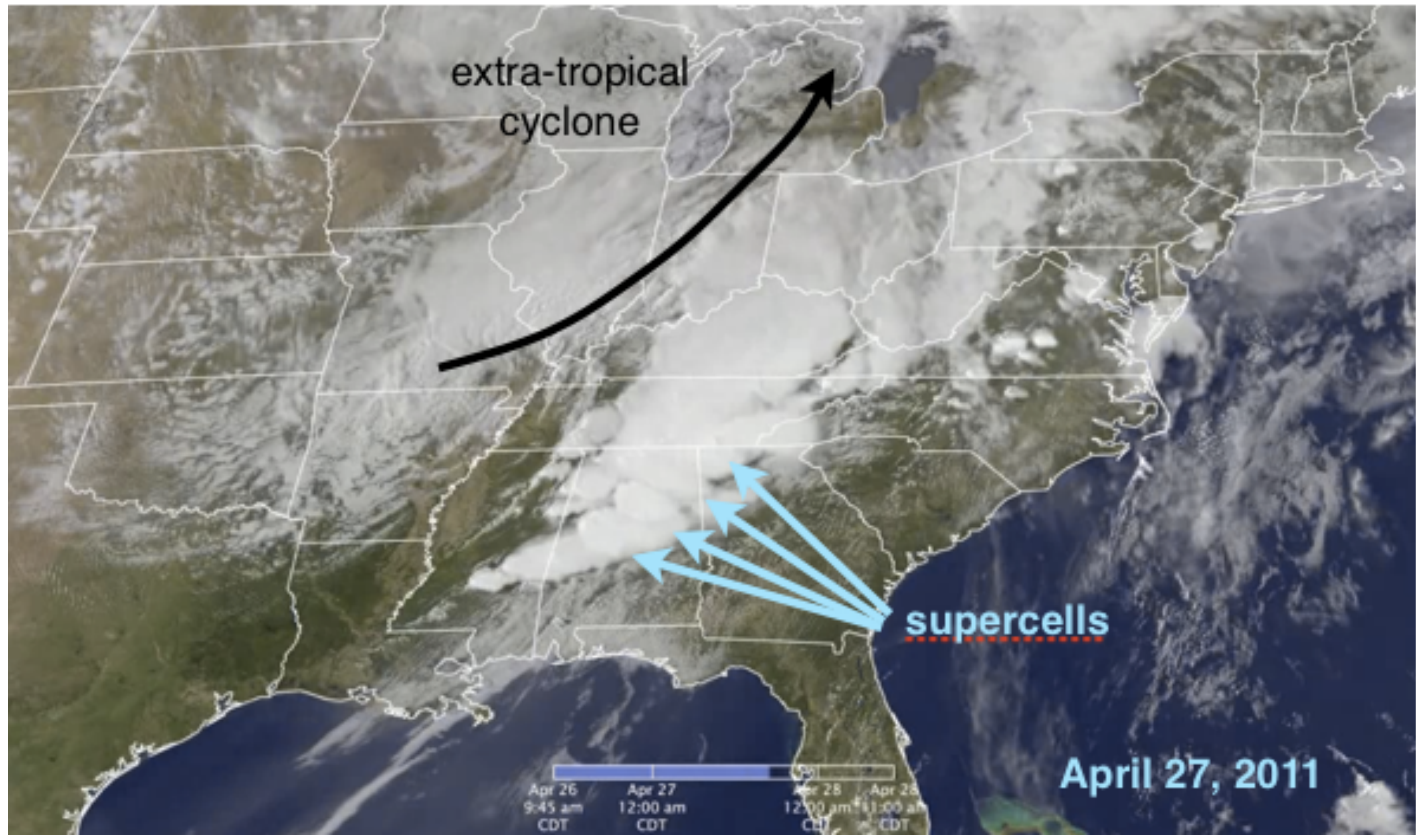
Total destruction of homes caused by an EF4 tornado in Washington, IL, on November 17, 2013.

Tornadoes: Cases

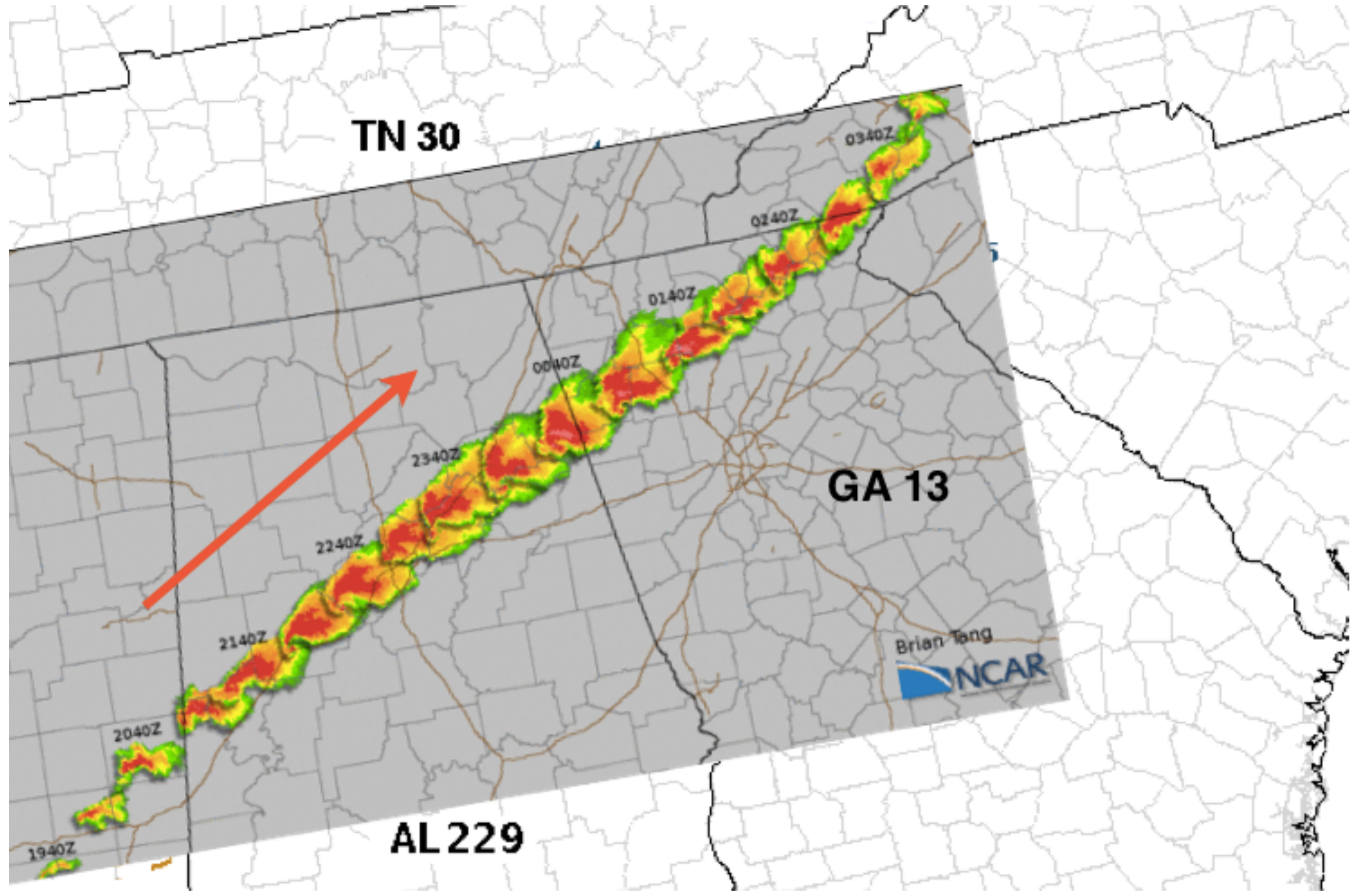
April 2011 Super Outbreak

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.

Tornado data for April 2011 Super Outbreak

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+

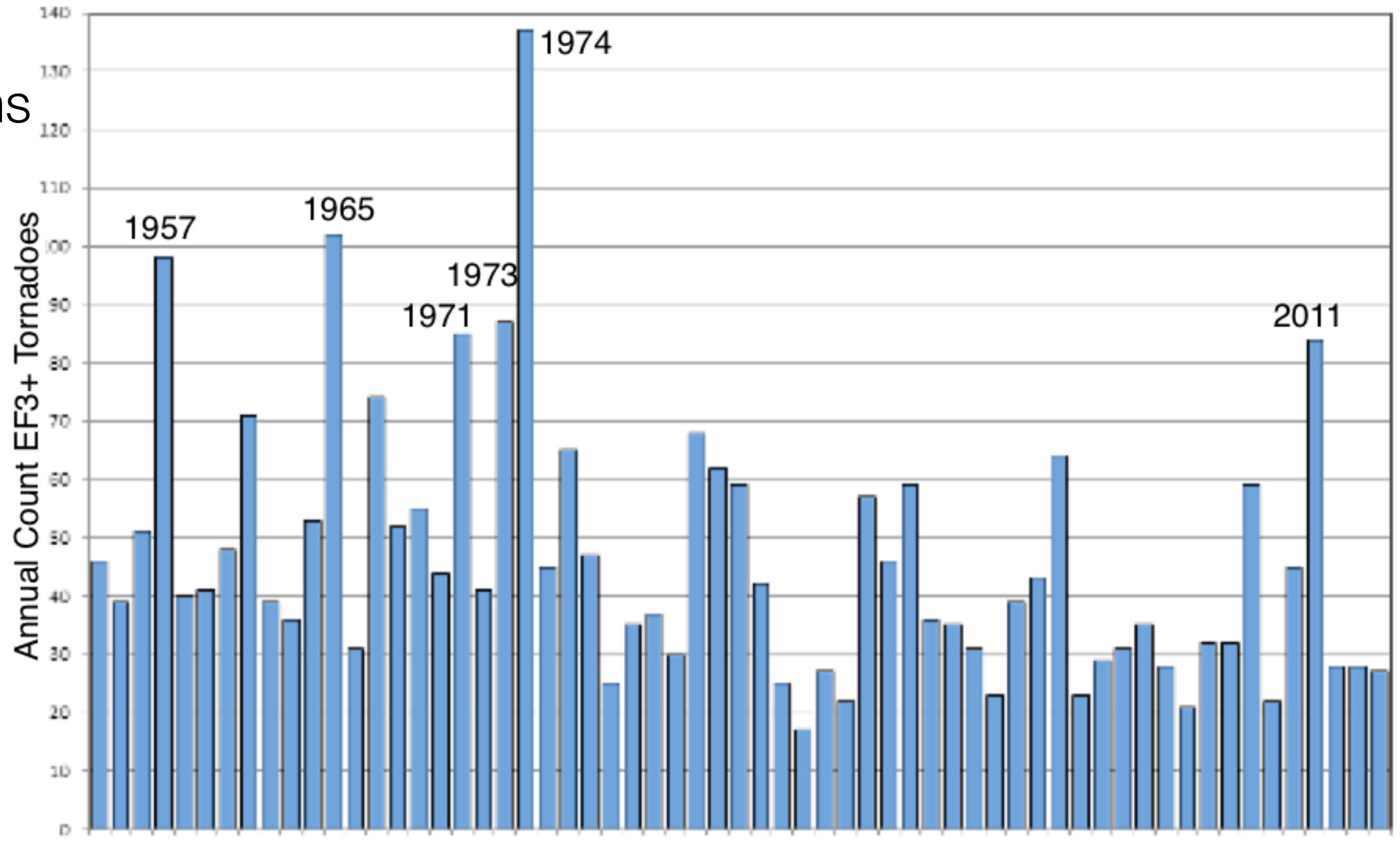
Tornadoes: Cases

The 1974 Super Outbreak

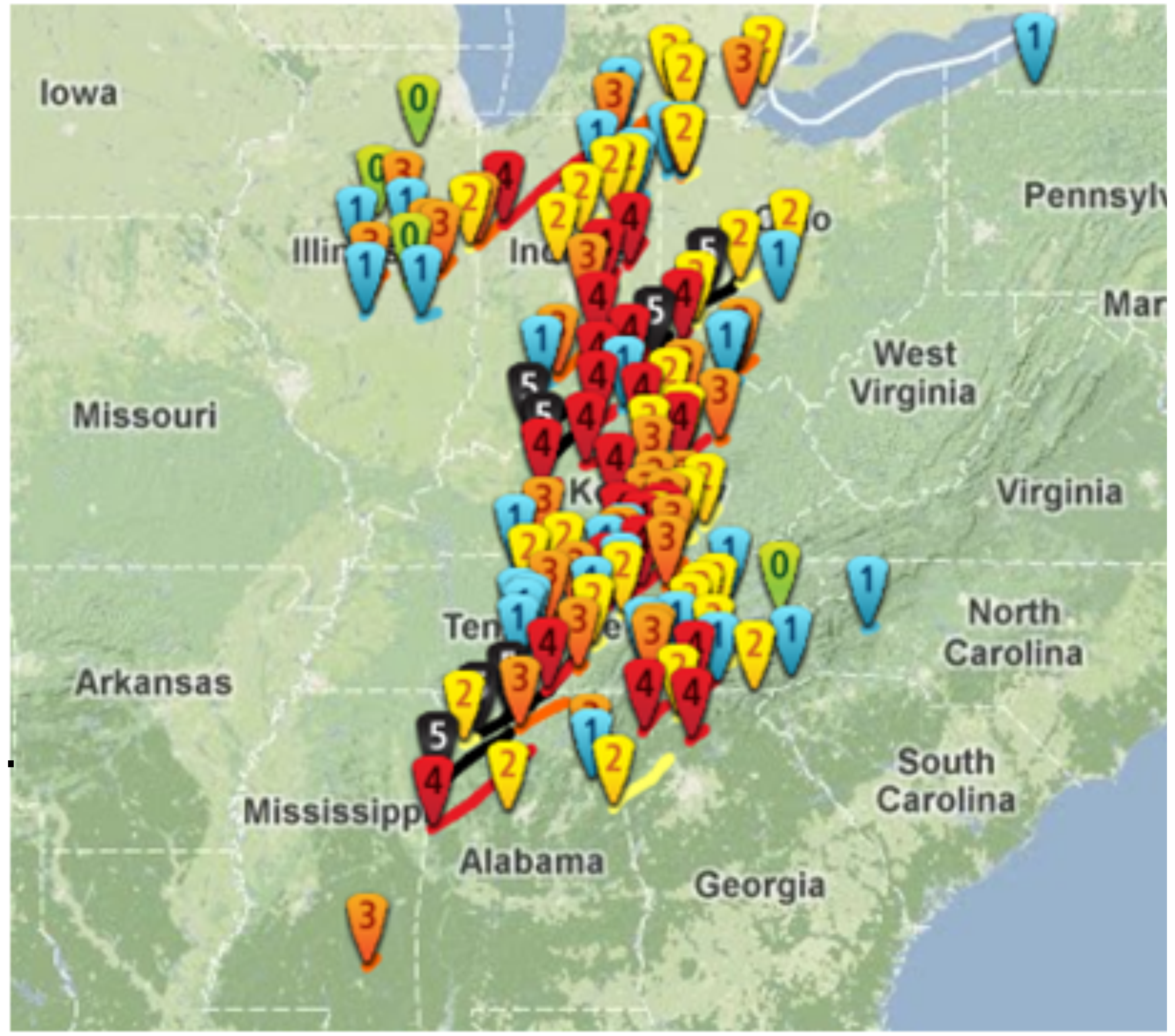
A Super Outbreak is one in which there is an exceptional number of tornadoes in one day.

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

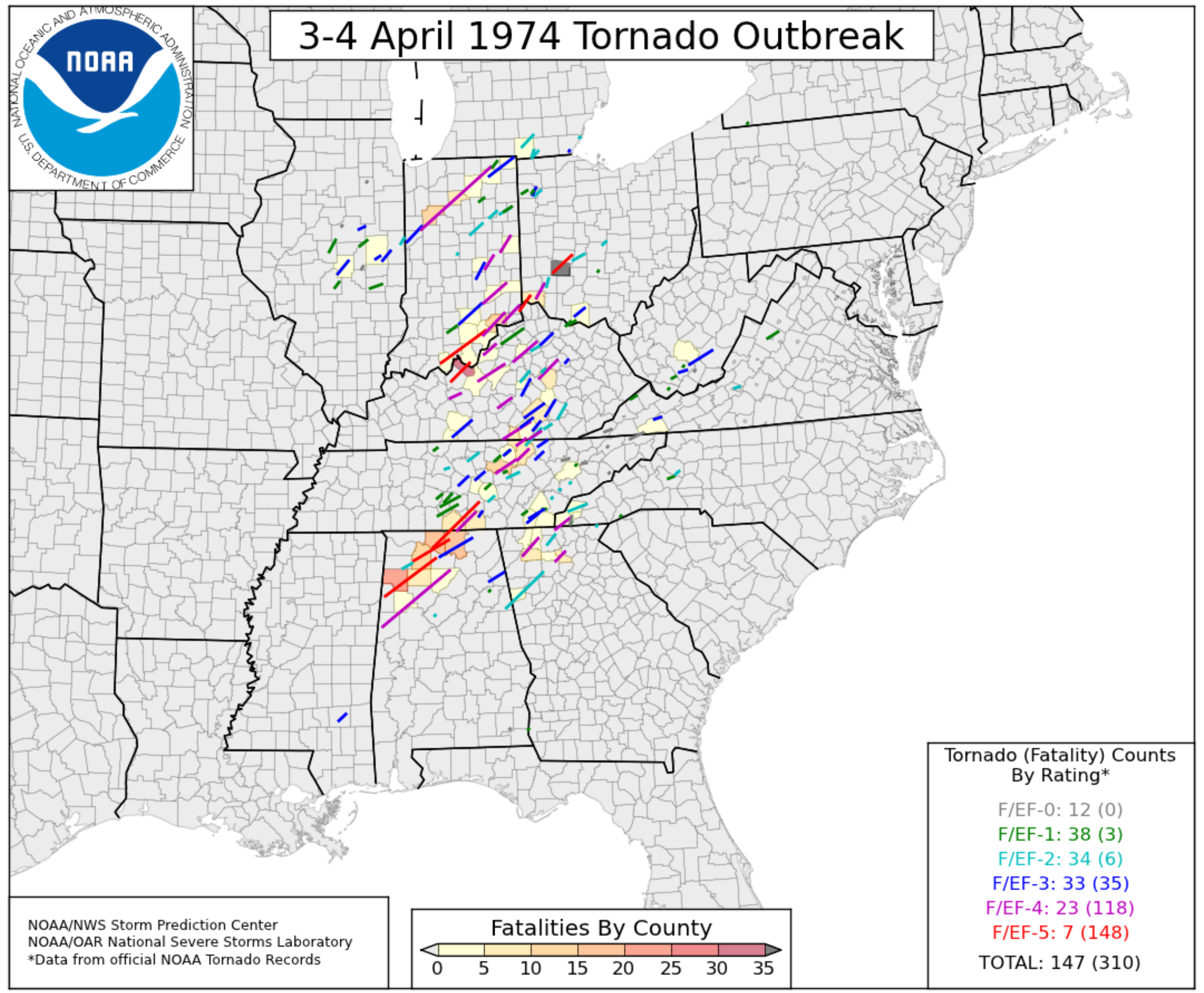
Annual count of EF3 and higher tornado touchdowns in the U.S.A. from 1954 to 2014.



April 3rd



April 4th



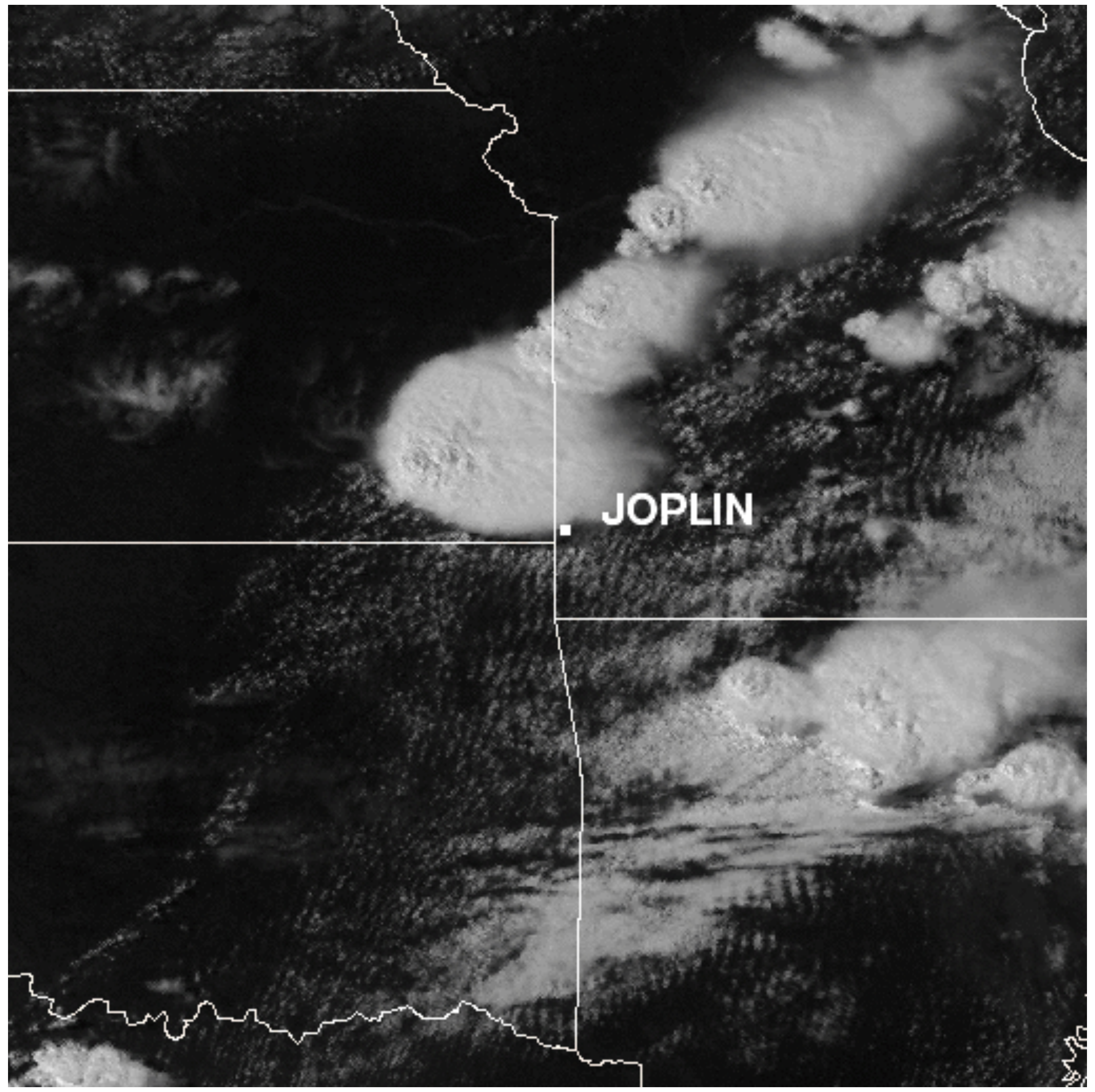
Tornado touchdowns in the eastern U.S.A. on April 3, 1974. Left: Number/color indicates EF rating. Right: Tornado tracks for April 3 and 4, 1974: blue = EF3; magenta = EF4; red = EF5.

Tornadoes: Cases

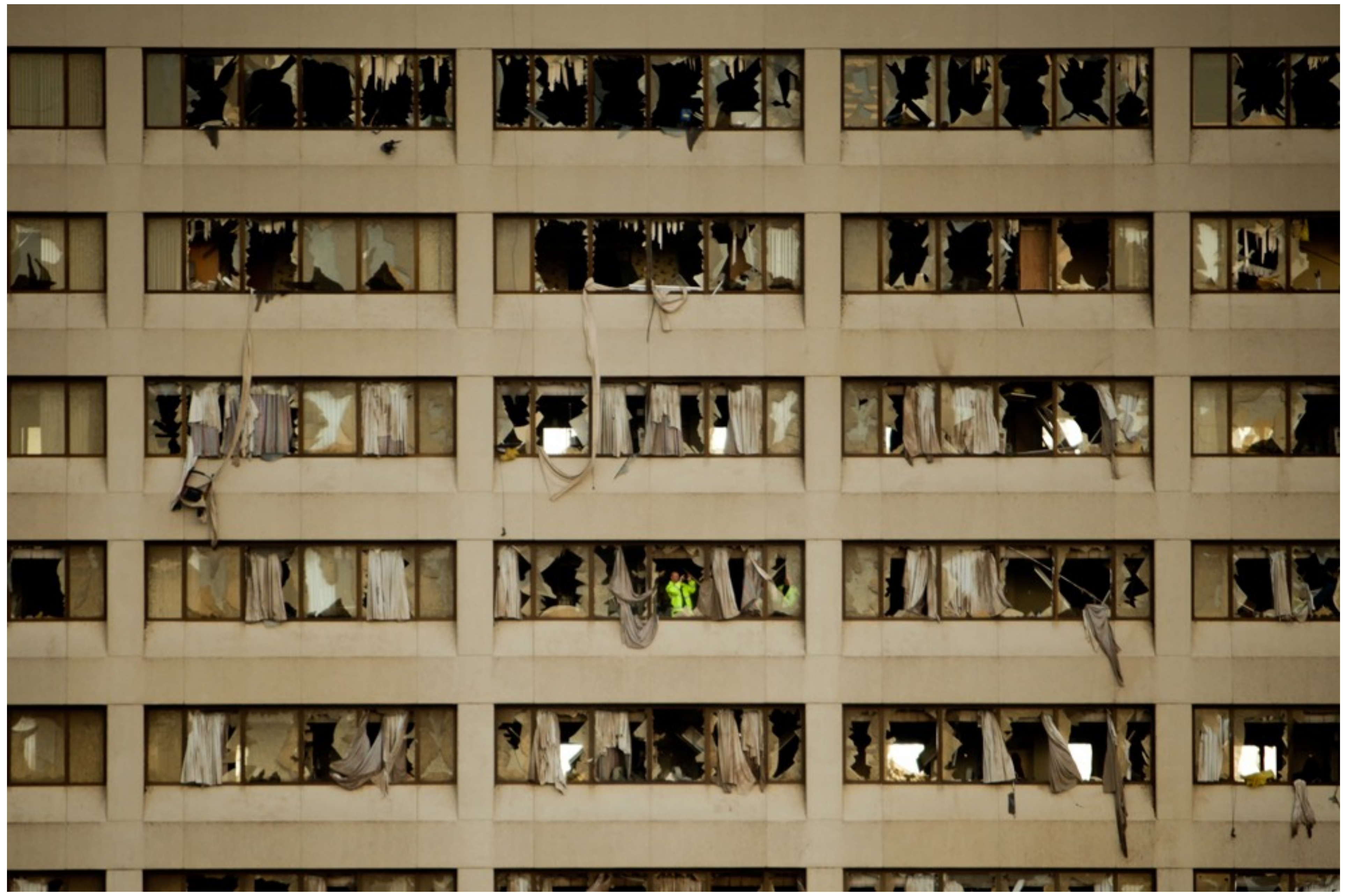
Joplin, MO, May 22, 2011

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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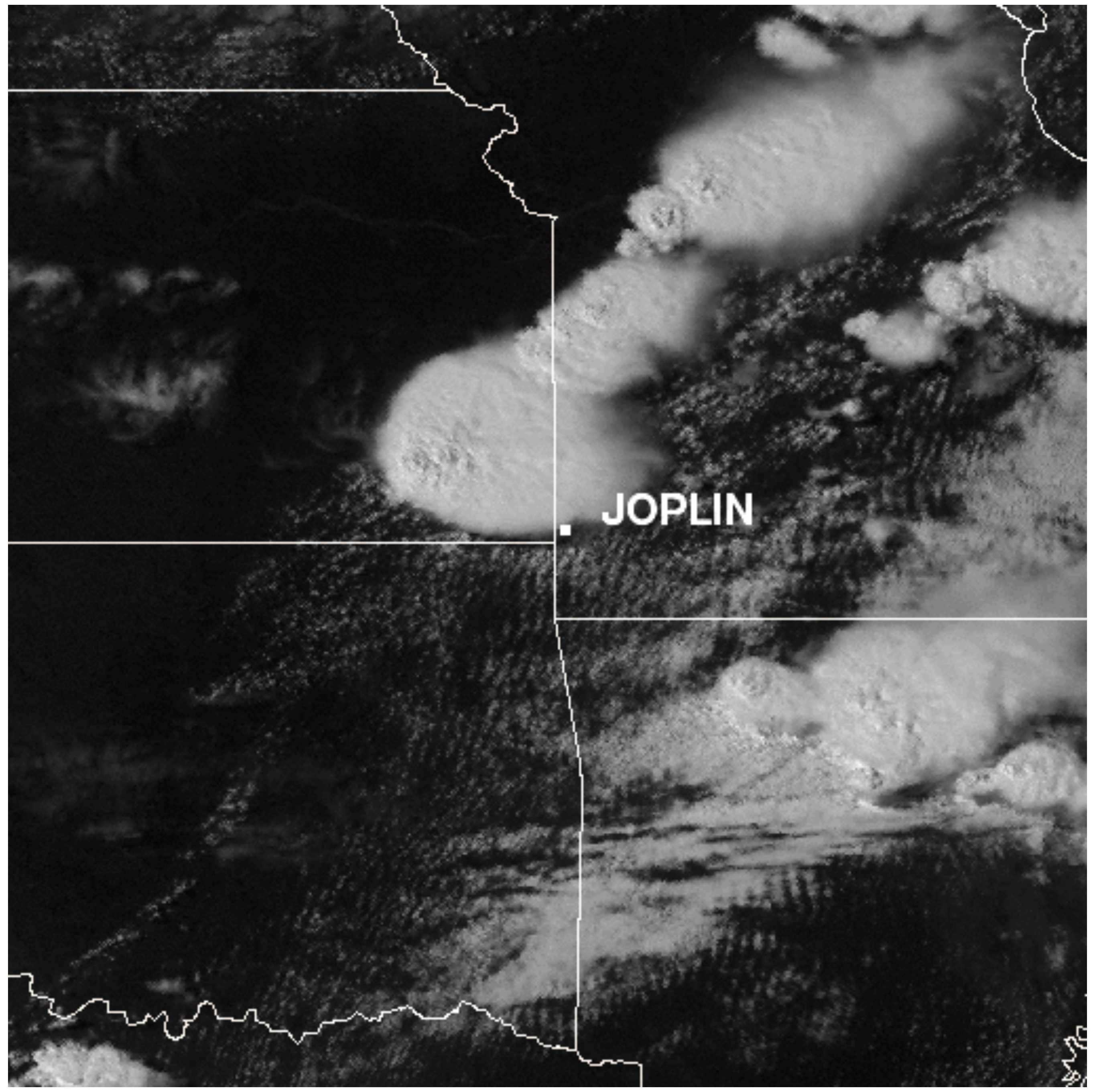

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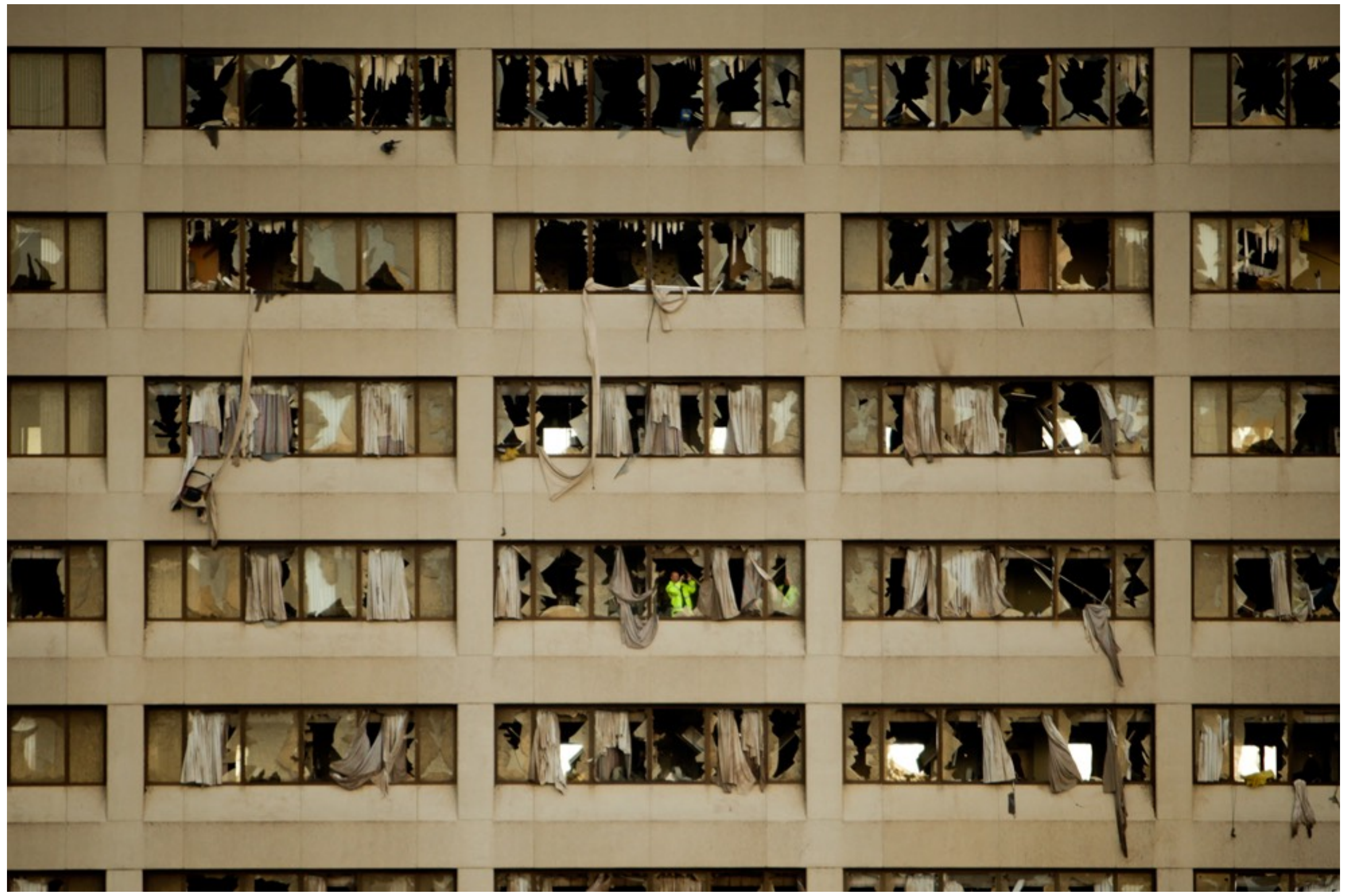


Rescuers (in green) search for survivors and injured patients of St. John’s Regional Medical Center, Joplin, MO, after an EF5 tornado on May 22, 2011.

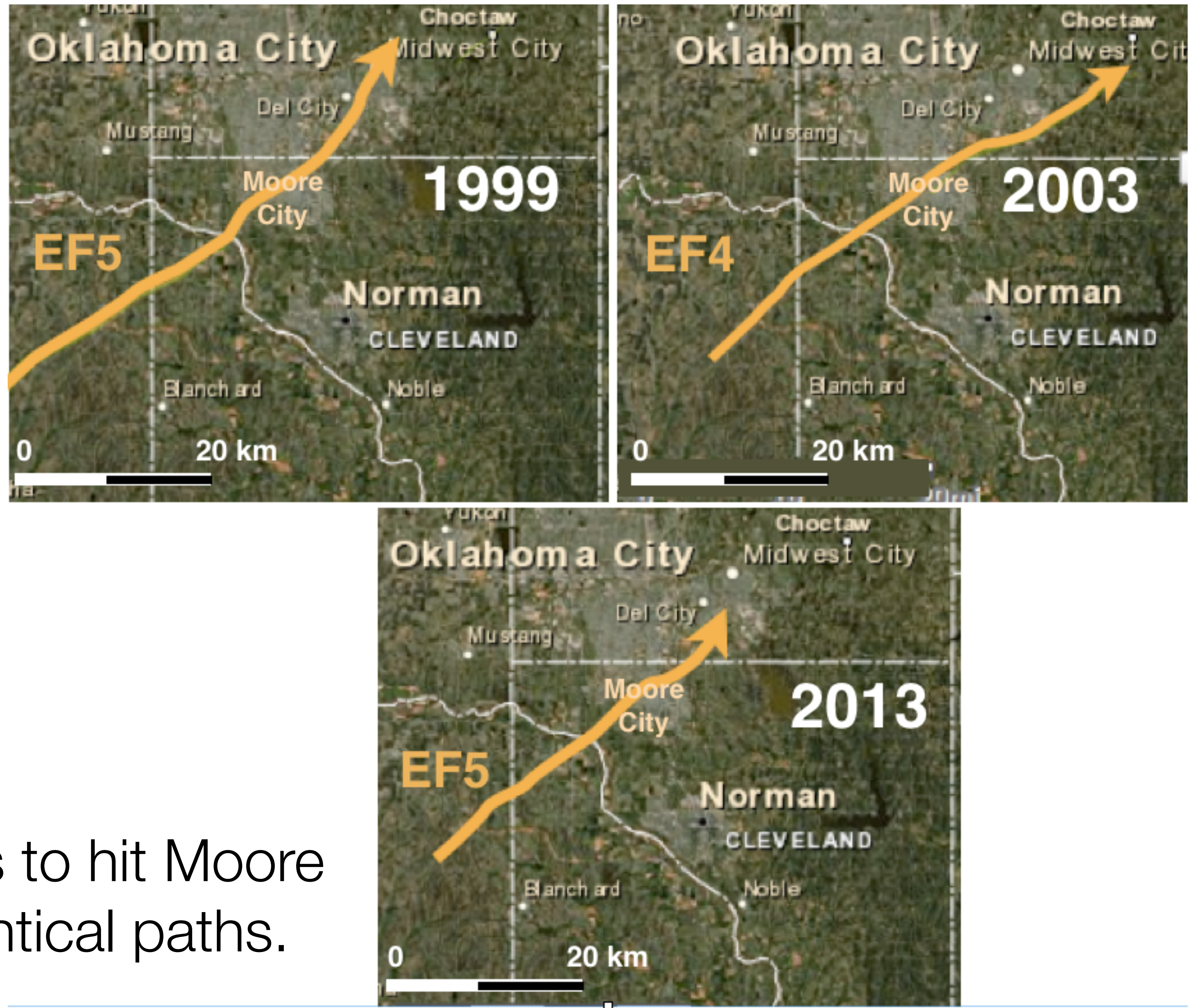
Tornadoes: Cases

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.



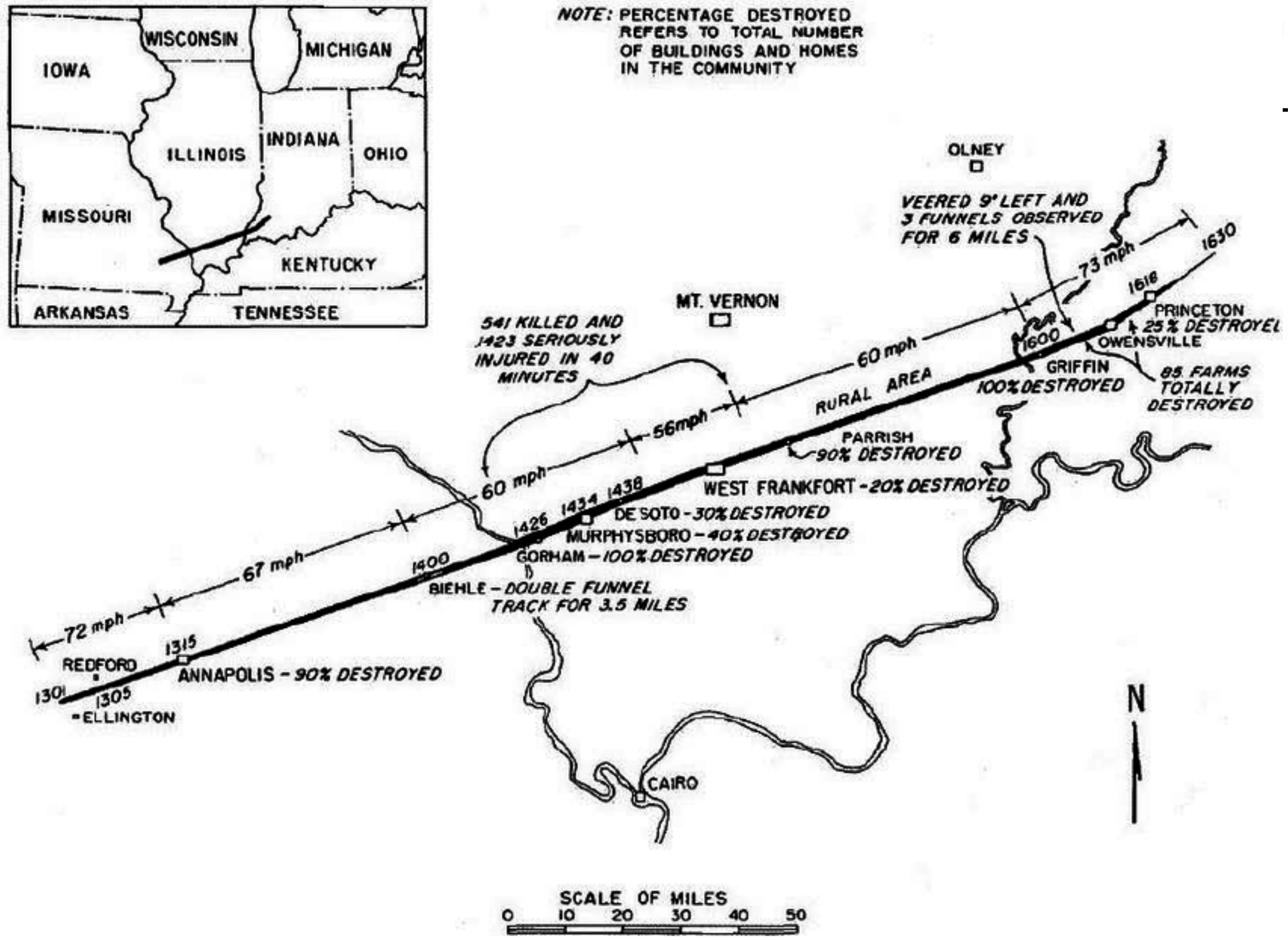
Three of the most severe tornadoes to hit Moore City, OK, travelled along almost identical paths.

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.

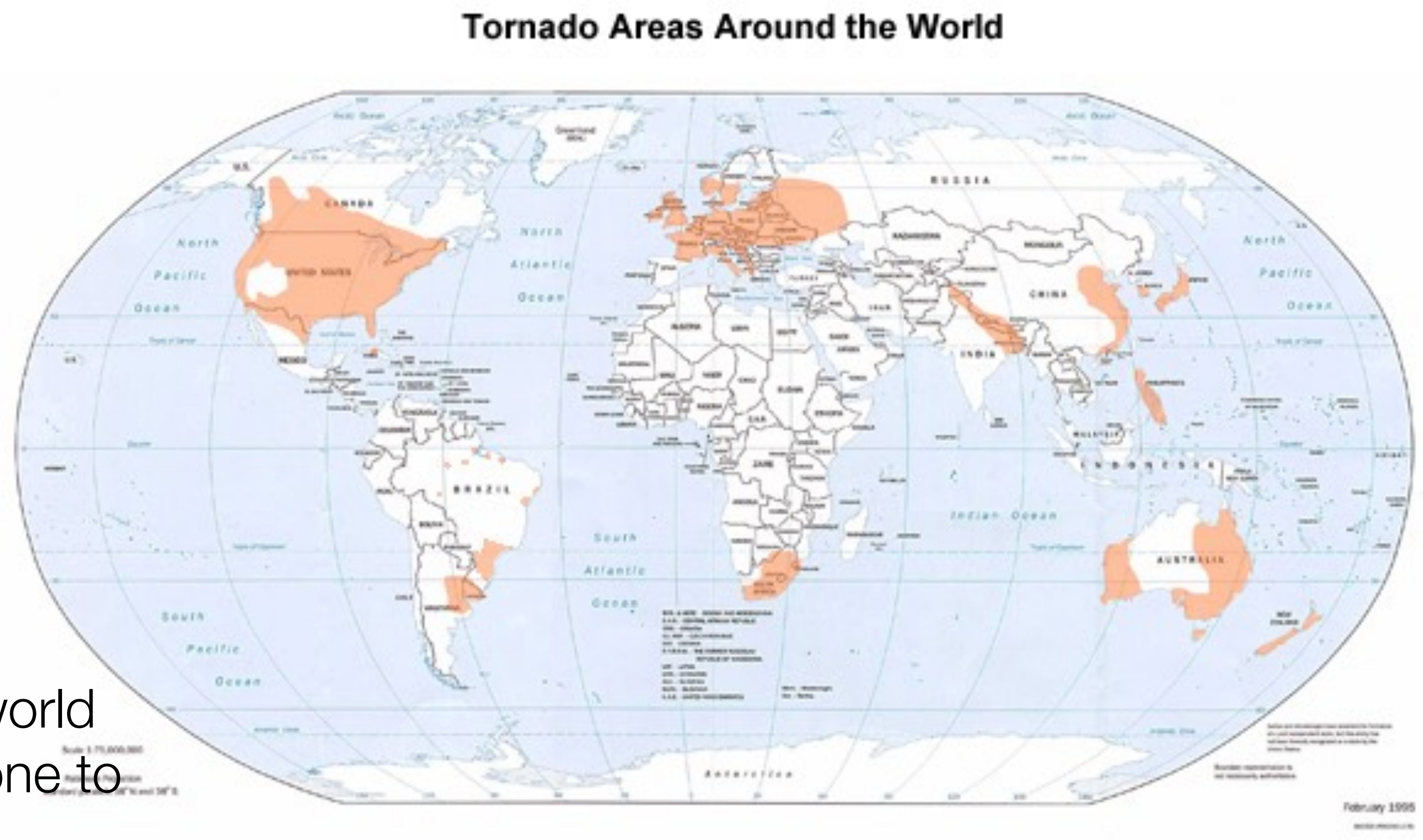
Devastation caused in Murphysboro, Illinois, by the Tri-States tornado of March 18, 1925. Southern Illinois was the worst-affected area.

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.

Natural Hazards and Disaster

Class 10: Tornadoes, Ice Storms, Meteotsunamis

- Tornadoes
  - Basics: What, Where, When
  - Strength
  - Origin
  - Warnings and Preparedness
  - Characteristics
  - Cases
  - In the Media
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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*.

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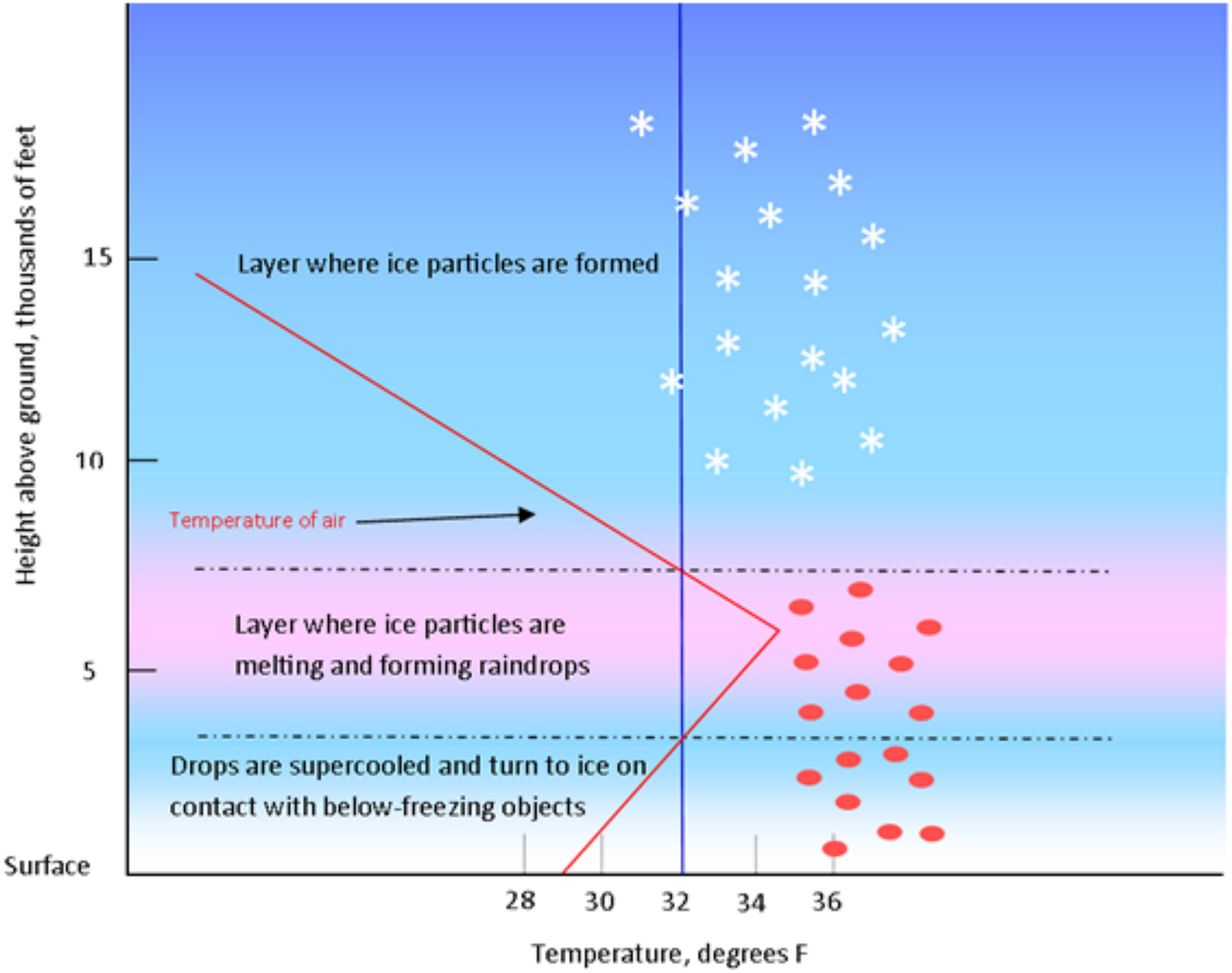
Freezing Rain

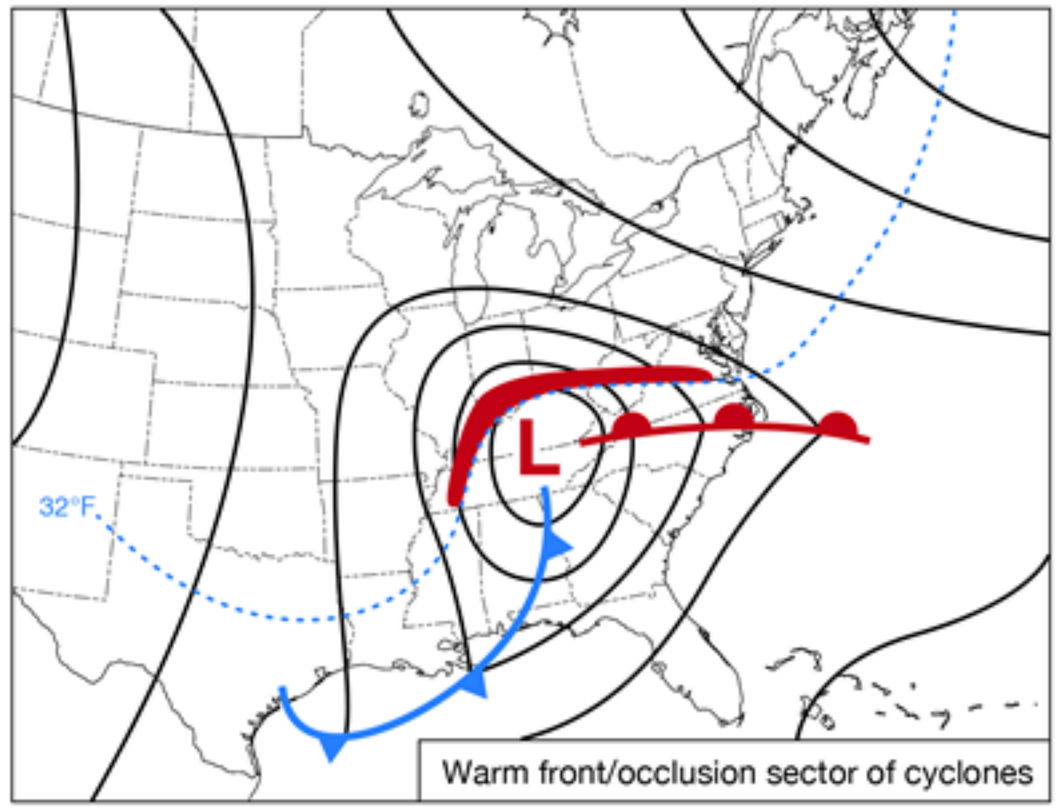


Freezing rain occurs when rain forms in a relatively warm (above freezing) layer of air and falls through a shallow layer of air that is below freezing. The rain is "supercooled" (still liquid) as it falls through the cold layer near the surface of the earth. When the supercooled, but still liquid, raindrops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

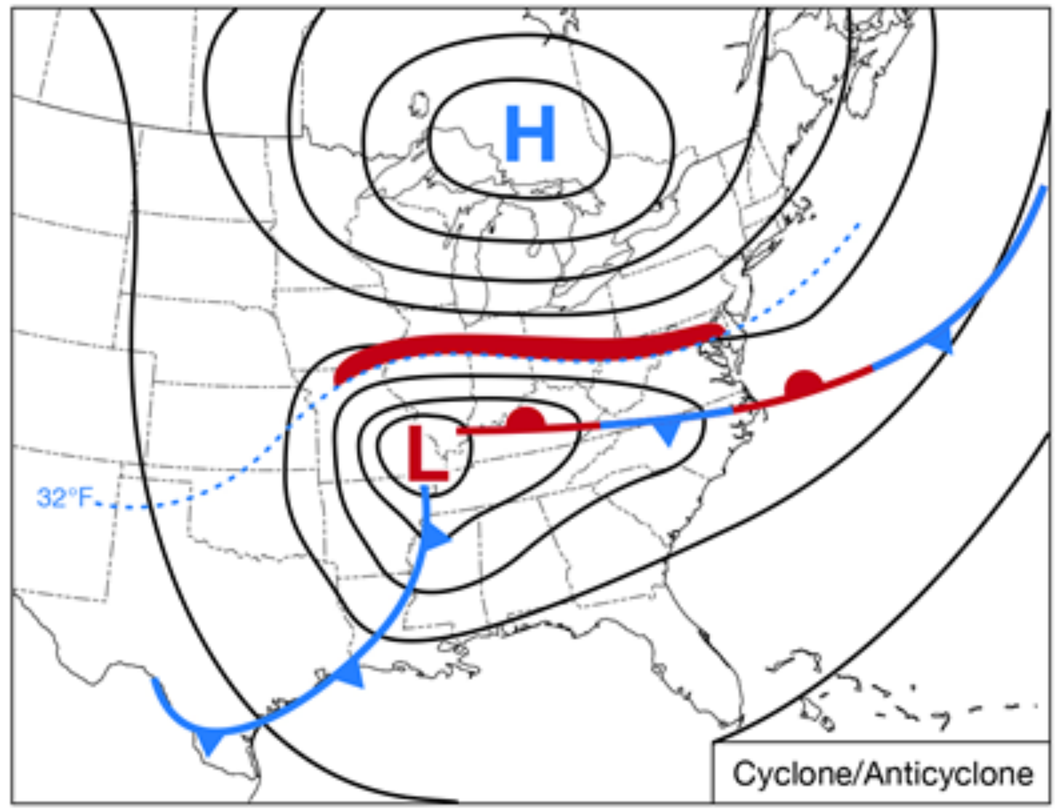
2009 Ice Storm Damage.
Photo courtesy NWS Paducah website

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

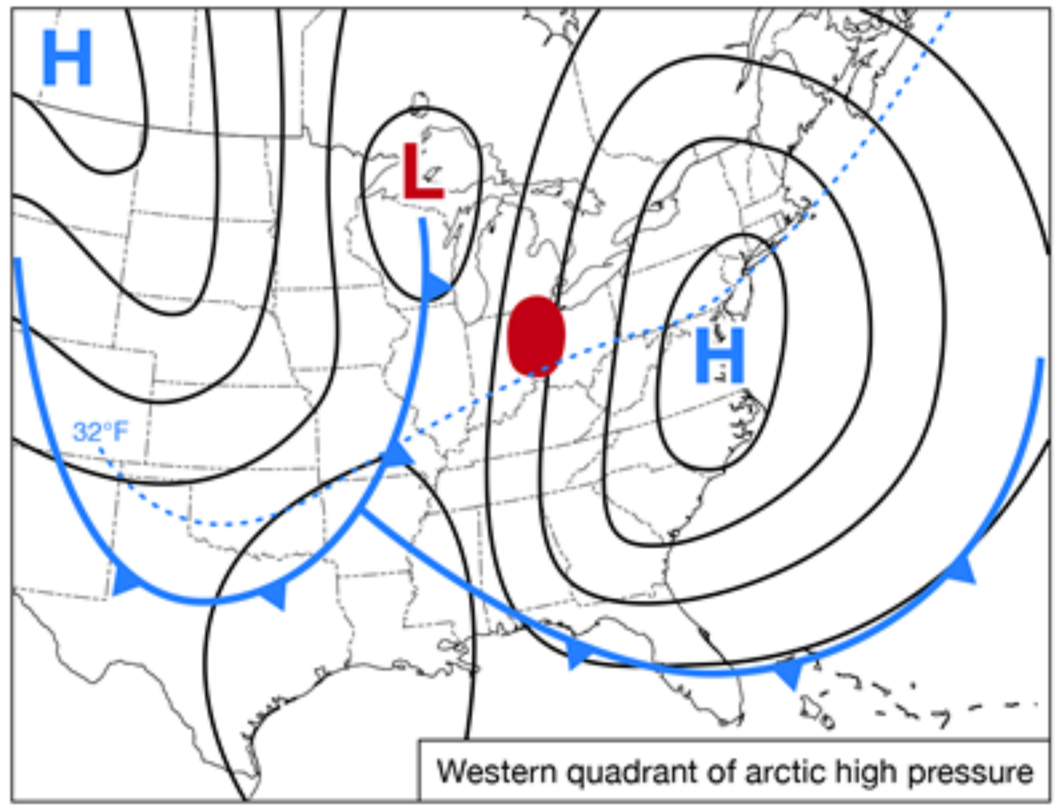
Freezing Rain



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.

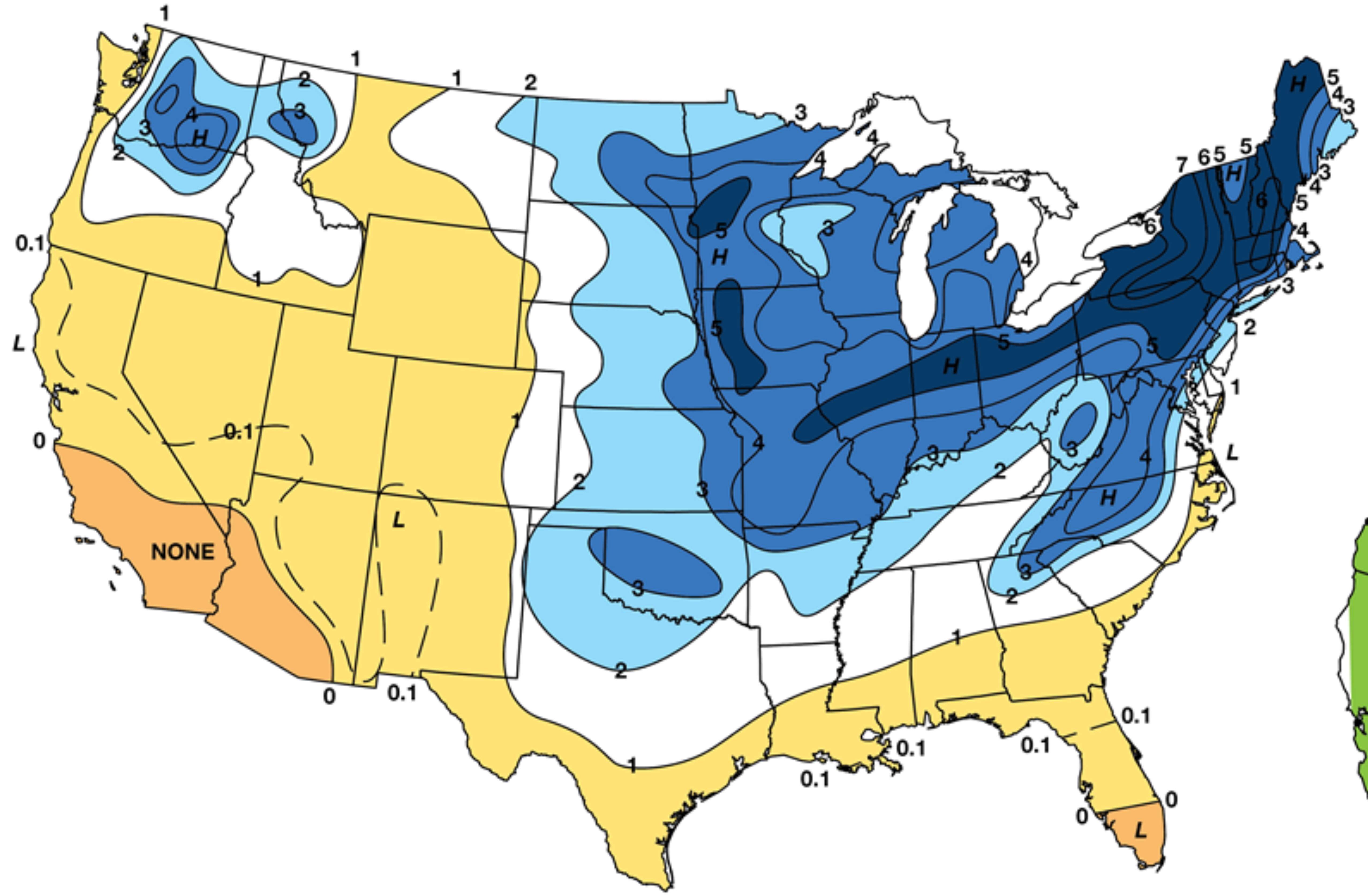


This weather pattern for freezing rain is the least common in the Midwest, occurring less than a third of the time compared to the previous two patterns.

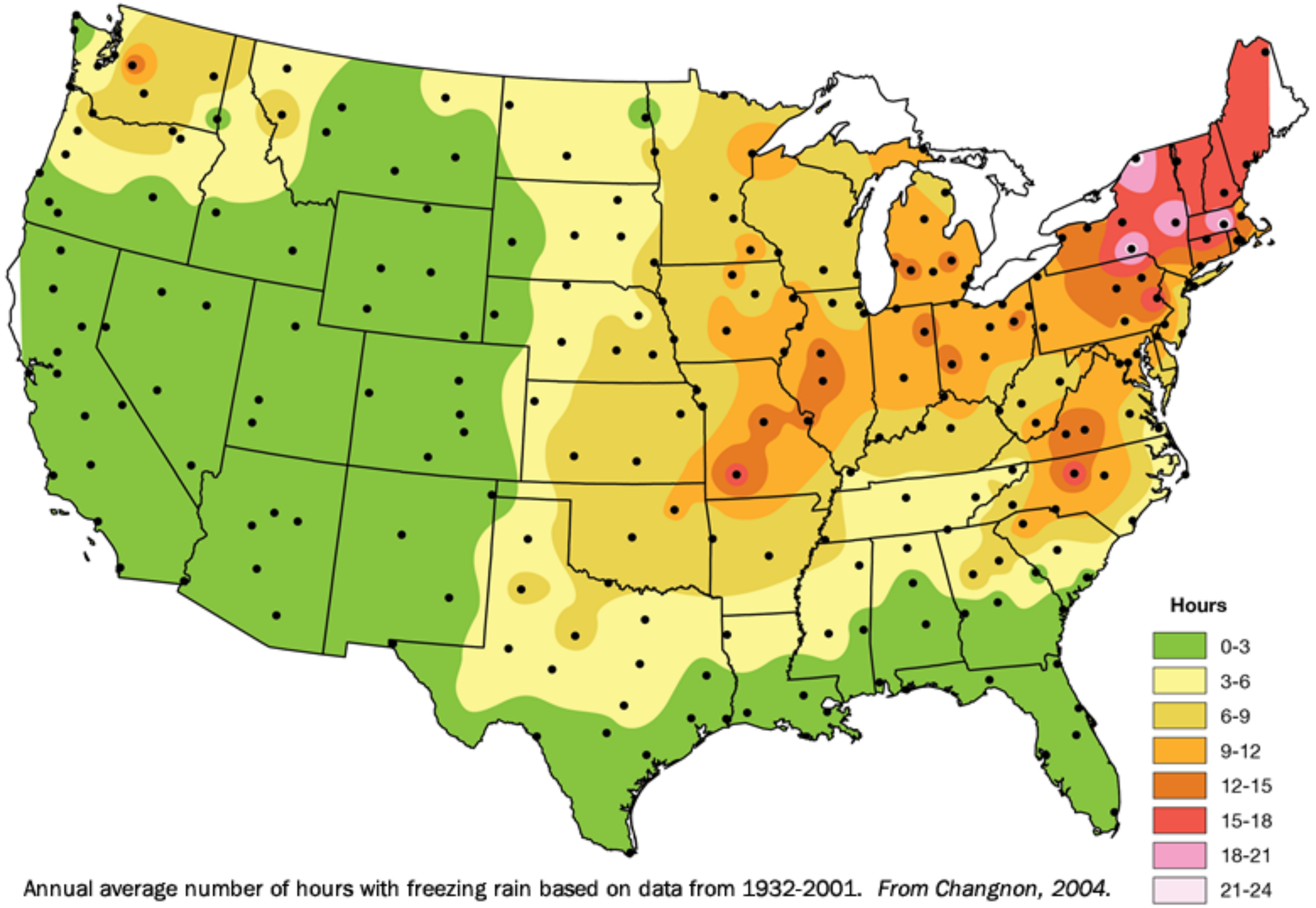
http://mrcc.isws.illinois.edu/living_wx/icestorms/

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

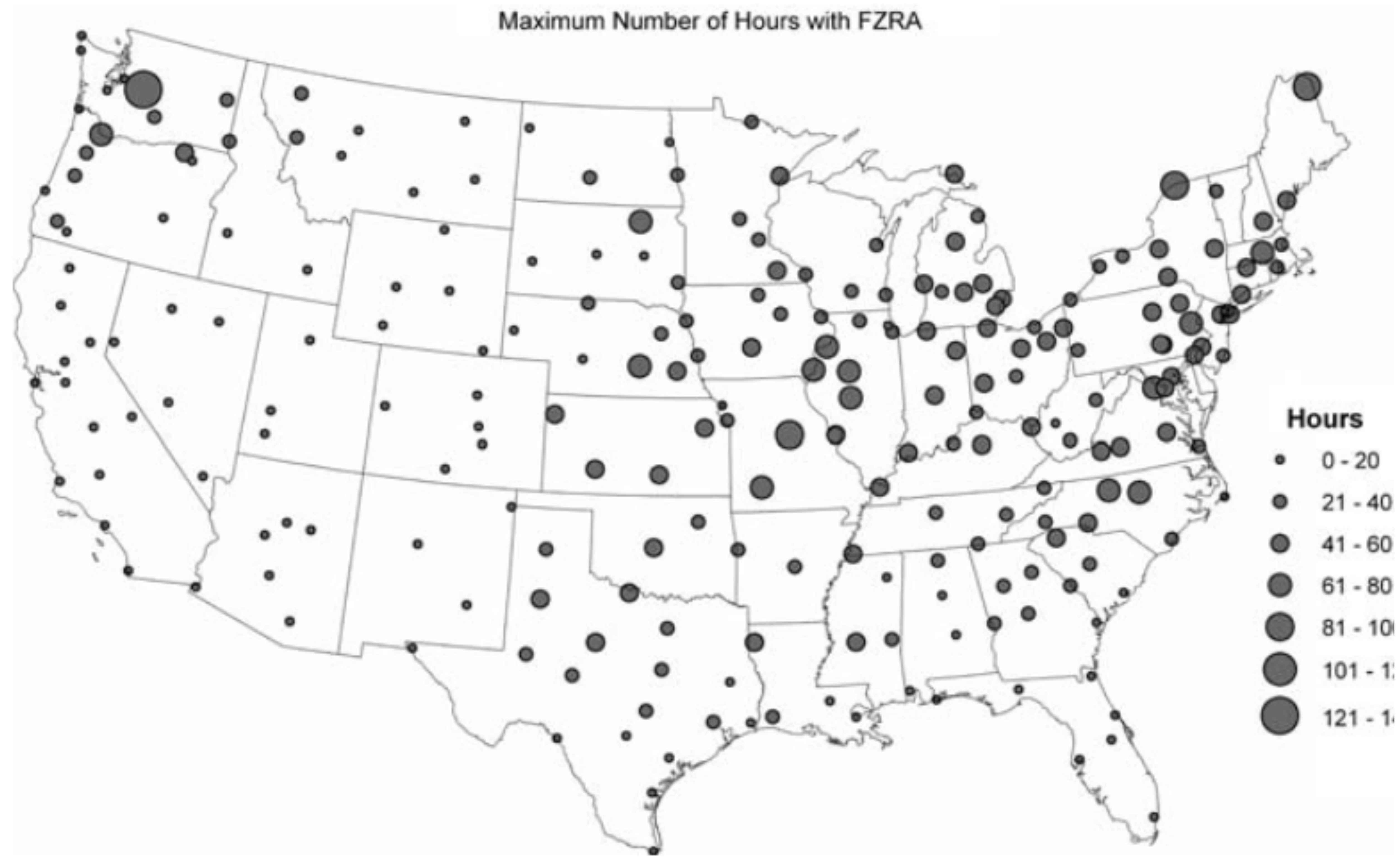


Fig. 2 Maximum number of hours with freezing rain in a single year, 1928–2001

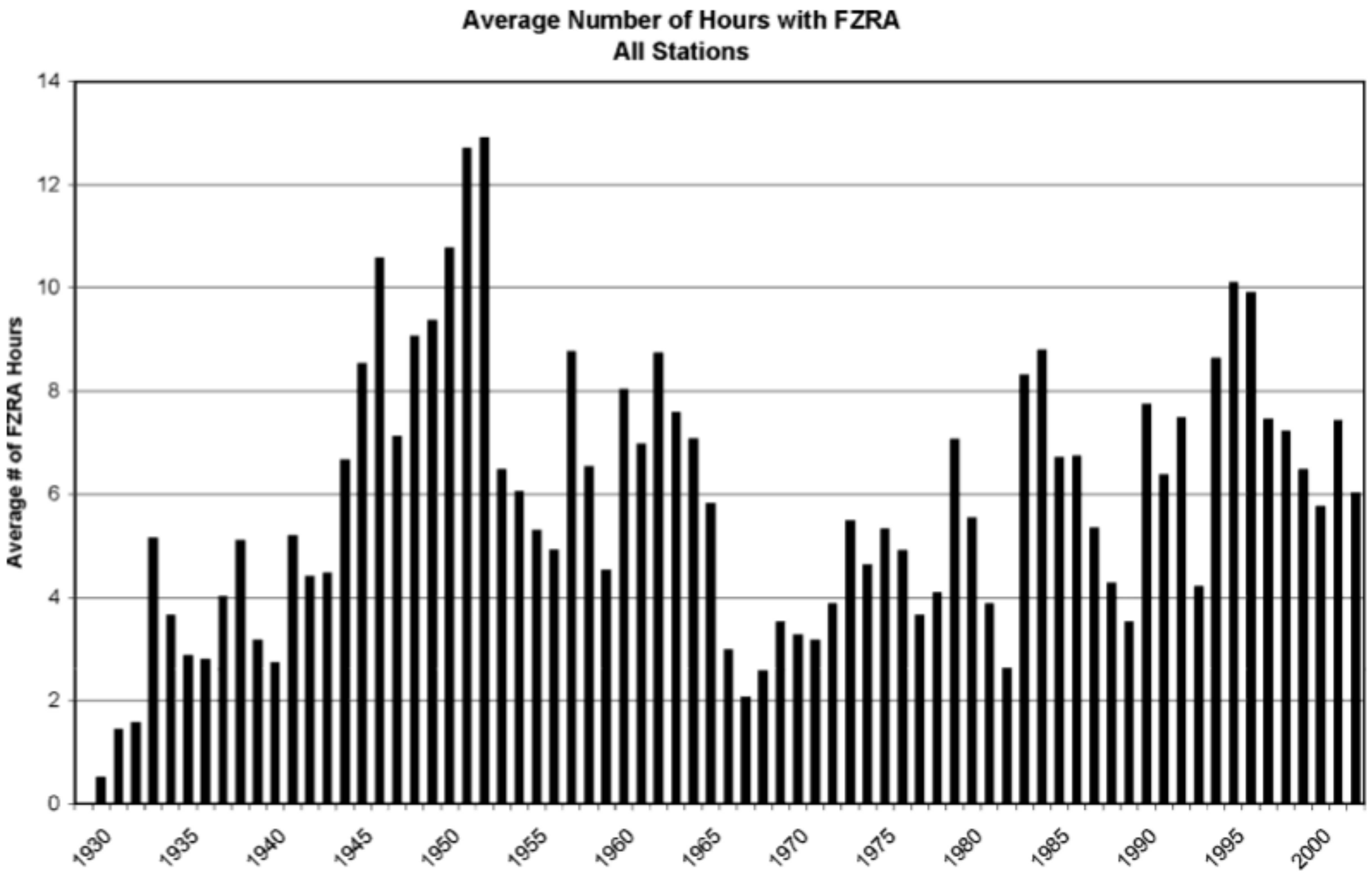


Fig. 3 Temporal distribution of the annual number of hours of freezing rain, 1928–2001

Houston and Shannon, 2007

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Meteotsunami

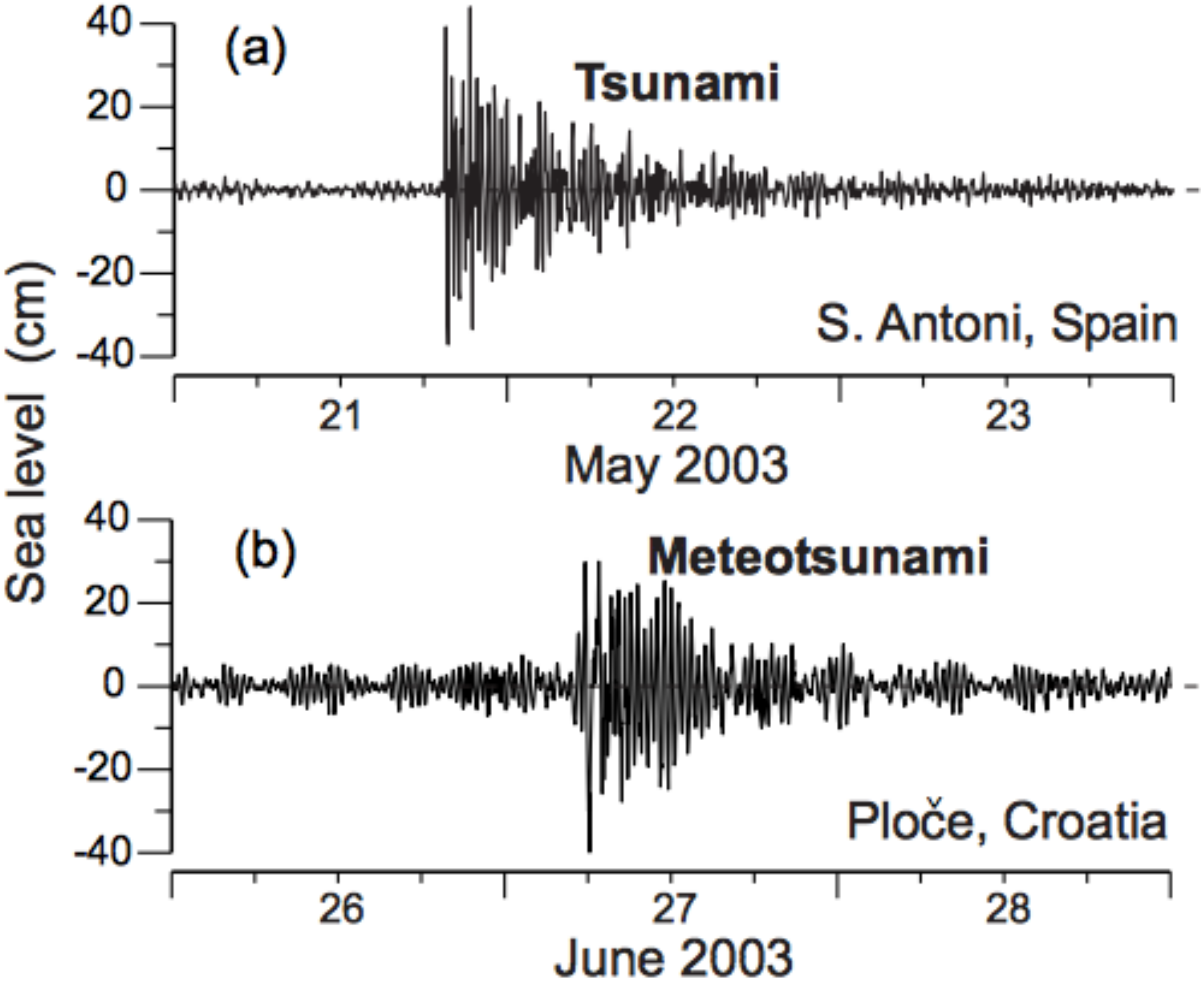


Fig. 1. (a) Tsunami oscillations recorded at Sant Antoni (Ibiza Is- land, Spain) after the Algerian earthquake of 21 May 2003; and (b) the meteotsunami recorded at Ploč̌e Harbour (Croatia) on 27 June 2003. Both records have been high-pass filtered to eliminate oscillations with periods longer than 2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

Monserrat et al., 2006

Meteotsunami

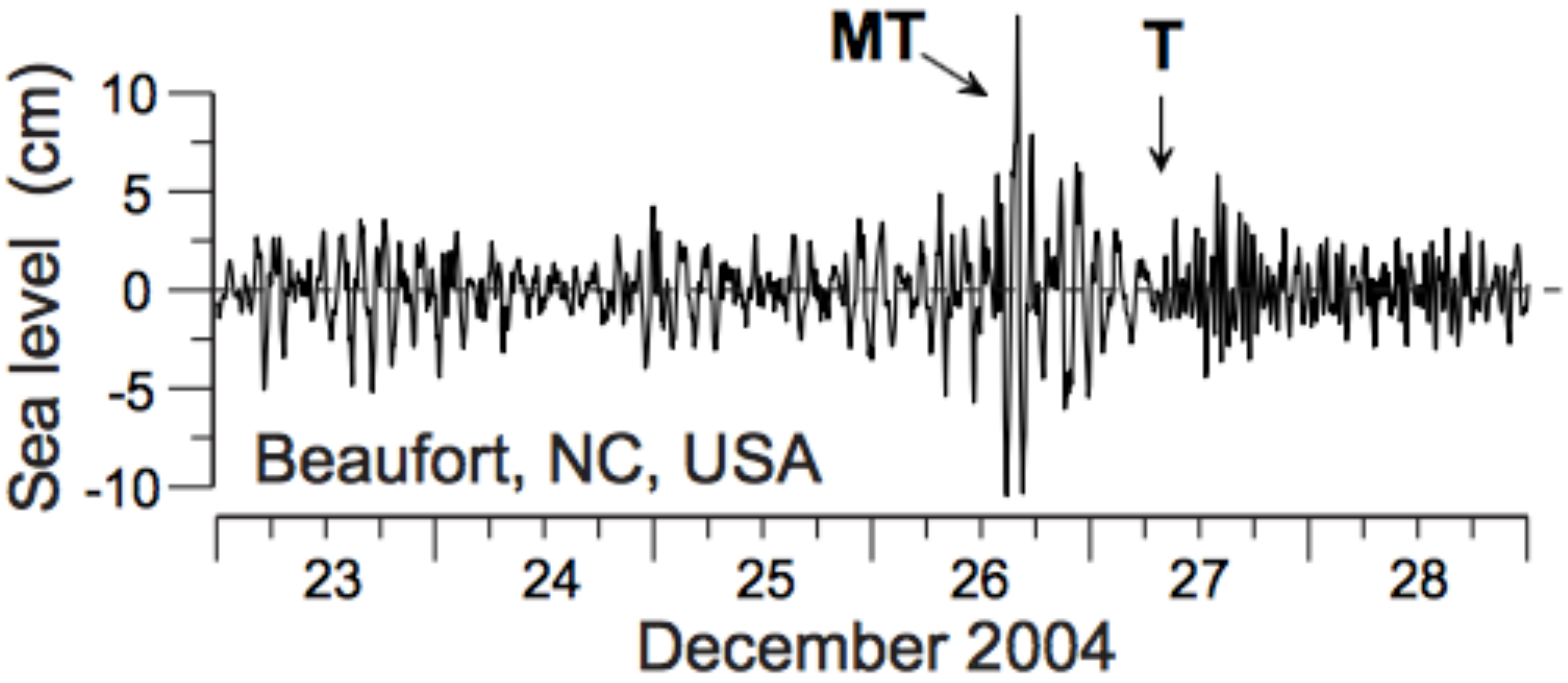


Fig. 2. Sea level oscillations at Beaufort (North Carolina, USA) for the period 23–28 December 2004. "MT" indicates intensive seiche oscillations generated by a strong storm travelling northward along the east coast of North America; "T" marks the arrival time of tsunami waves associated with the 2004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

Monserrat et al., 2006

Meteotsunami

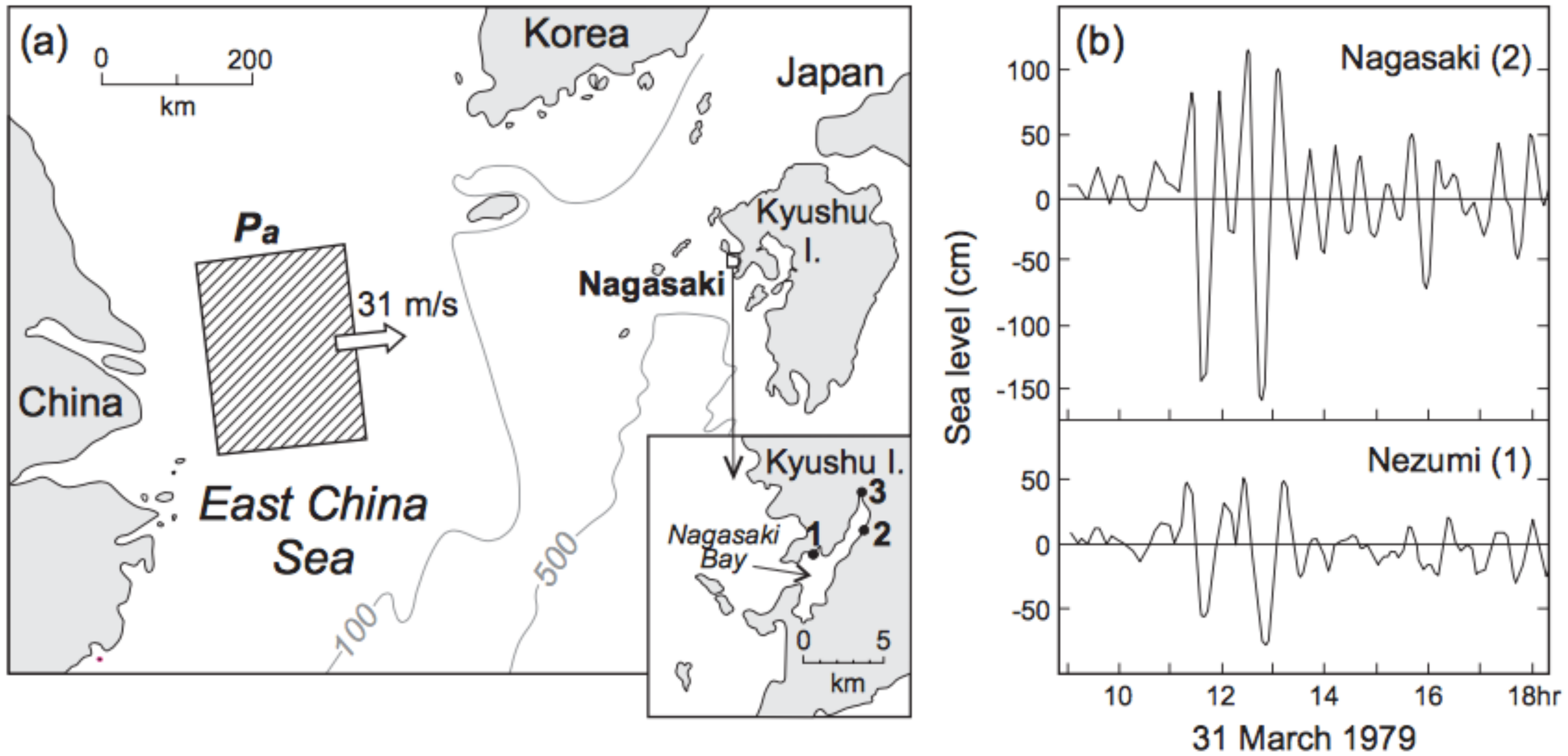


Fig. 5. (a) A map showing the location of Nagasaki Bay and the site of the initial atmospheric pressure disturbance (shaded rectangular); numbers “1” and “2” in the inset indicate positions of tide gauges Nezumi and Nagasaki, respectively; site “3” is at the head of the bay where the maximum wave of 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).

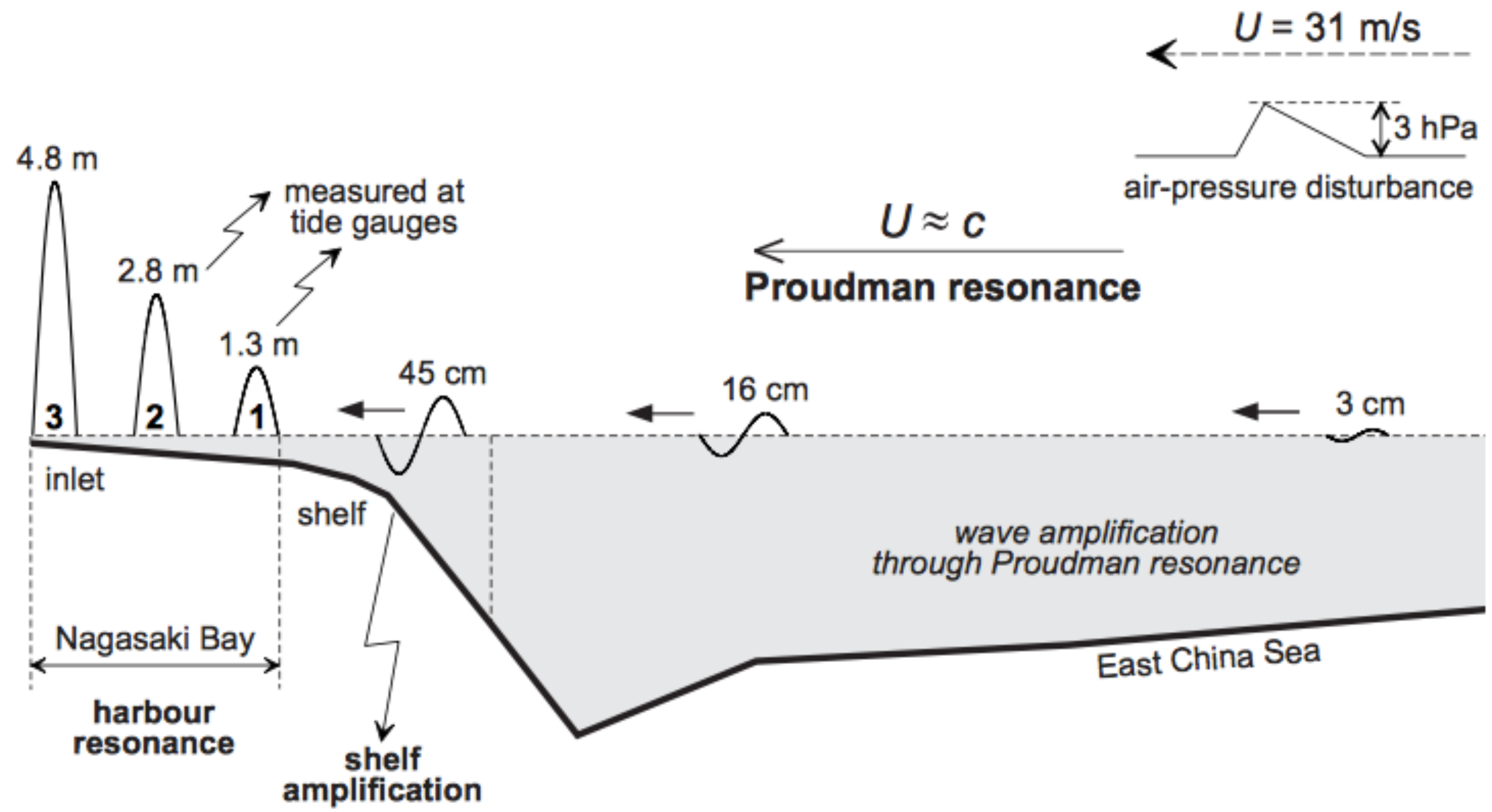


Fig. 4. A sketch illustrating the physical mechanism responsible for formation of the catastrophic meteotsunami at Nagasaki Bay (Japan) on 31 March 1979. The initial pressure jump over the western part of the East China Sea was about 3 hPa. The long waves generated by this event first amplified from 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

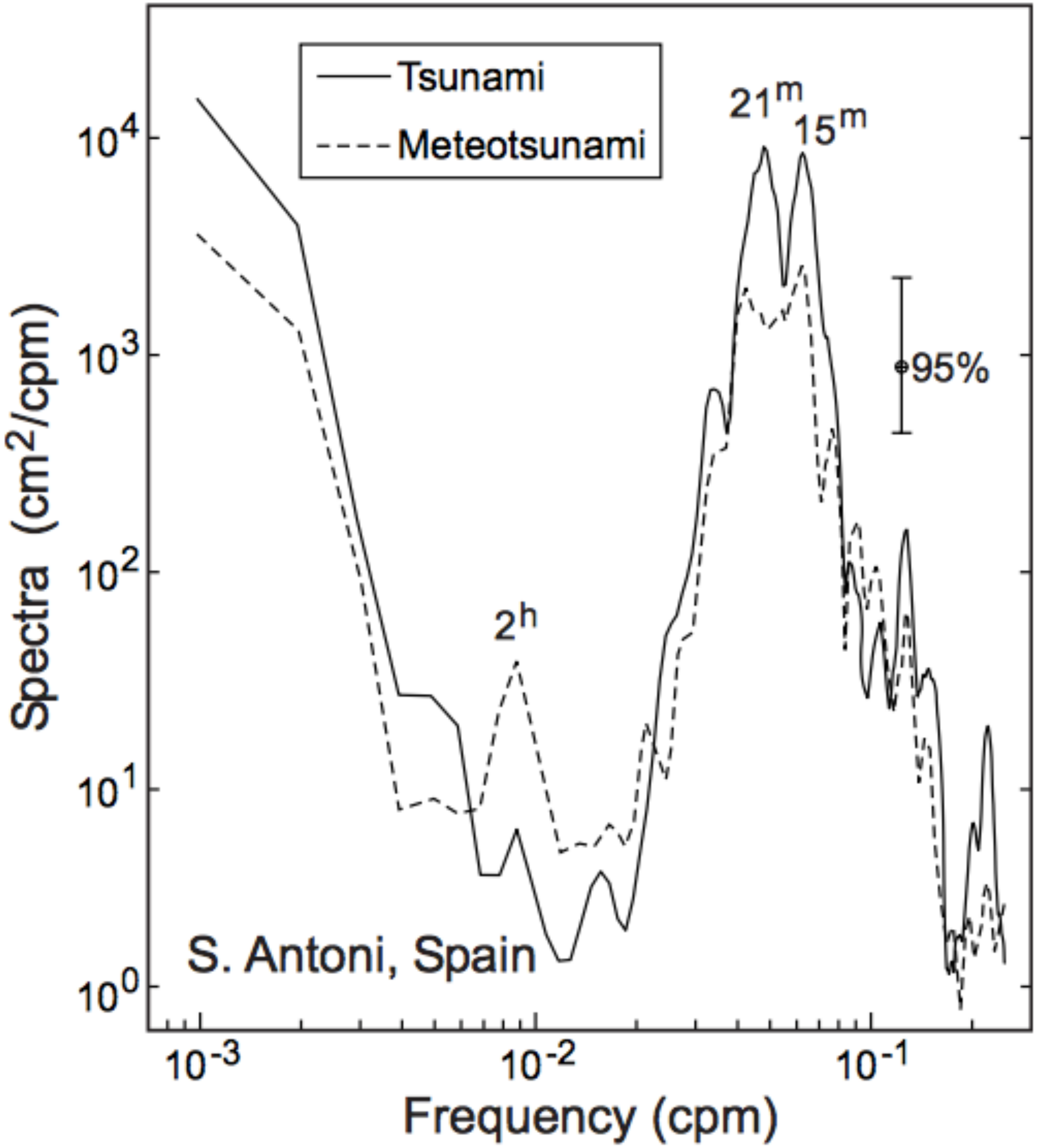


Fig. 6. Sea level spectra for the tsunami of 21 May 2003 and the moderate meteotsunami event of 1 May 2003 recorded at Sant Antoni (Ibiza Island, Spain). Each event has a duration of 4 days with a sampling interval of 2 min (2880 points). Spectra have been estimated with a Kaiser-Bessel window (cf. Emery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

Monserrat et al., 2006

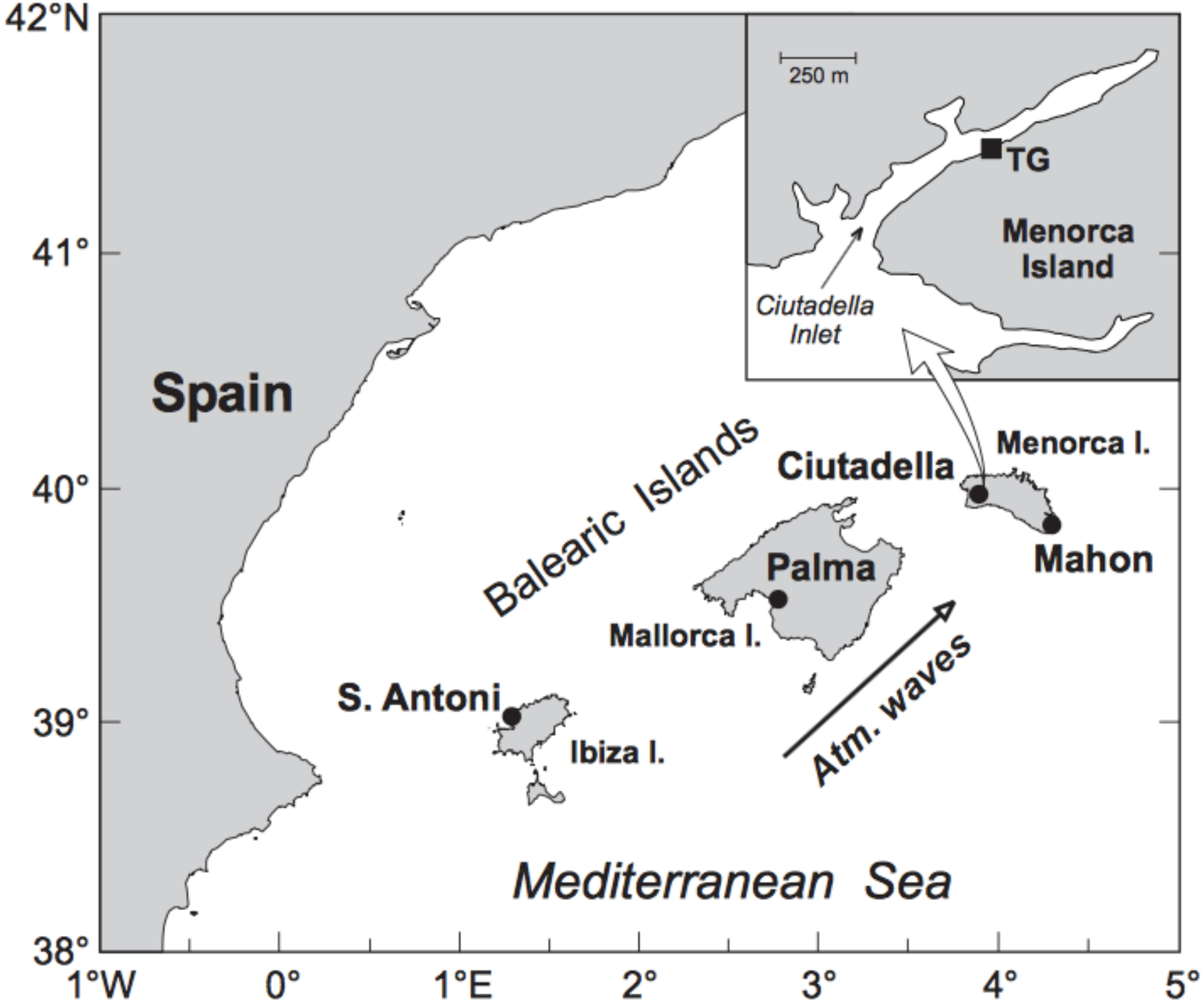


Fig. 7. A map of the Balearic Islands and positions of microbaro- graphs at Palma de Mallorca and Mahon and tide gauges at Sant Antoni and Ciutadella (marked “TG” in the inset). The arrow shows the predominant direction of propagation of the atmospheric waves during “rissaga” events.

Monserrat et al., 2006

Meteotsunami

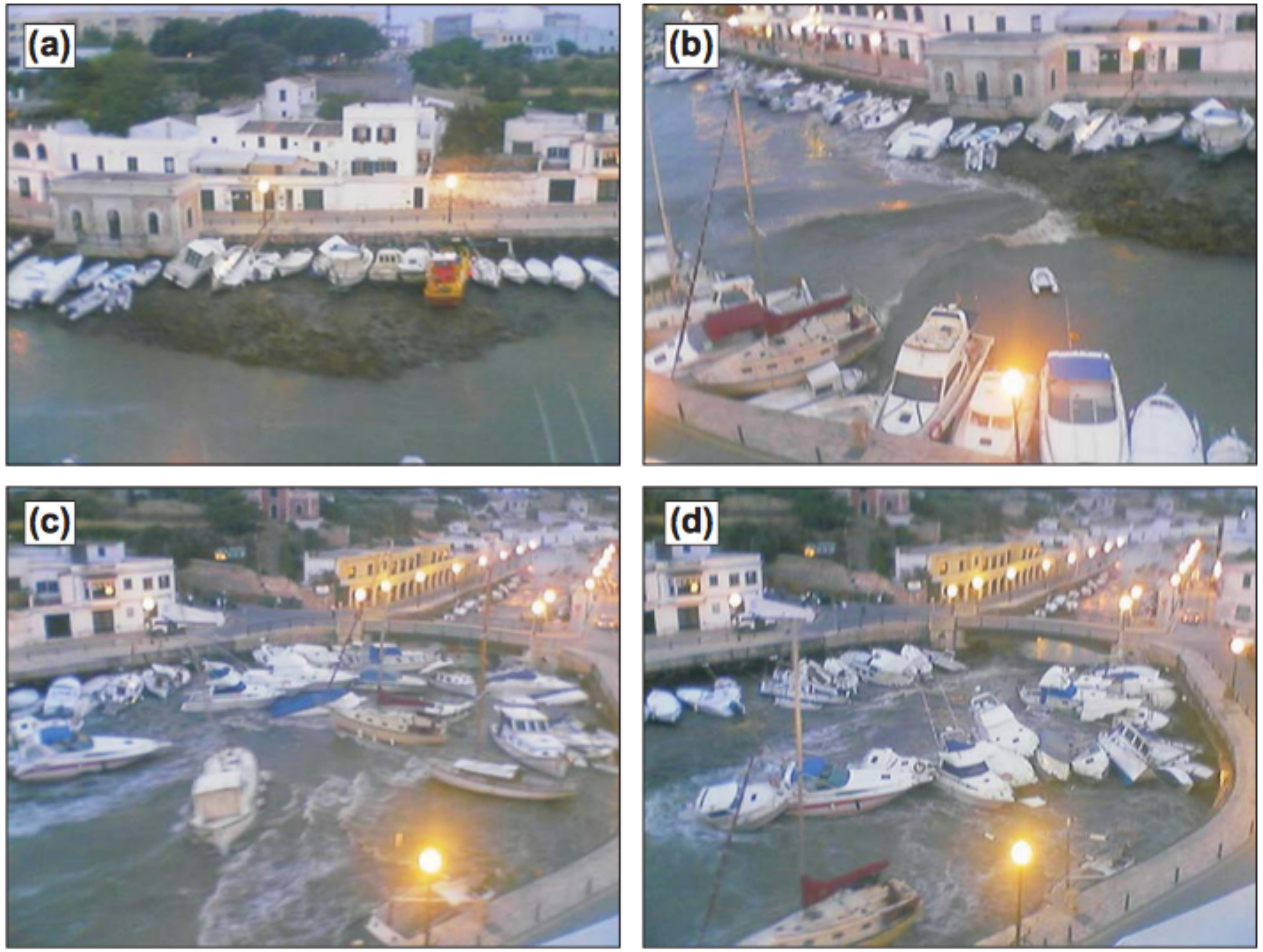


Fig. 9. Photographs taken during the strong rissaga event of 15 June 2006 at Ciutadella Harbour. (a) After the sudden first negative wave (~–4 m), most of the boats broke free from their moor- ings and were left high and dry on the harbour bottom. (b) A few minutes later, the water re-entered the harbour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

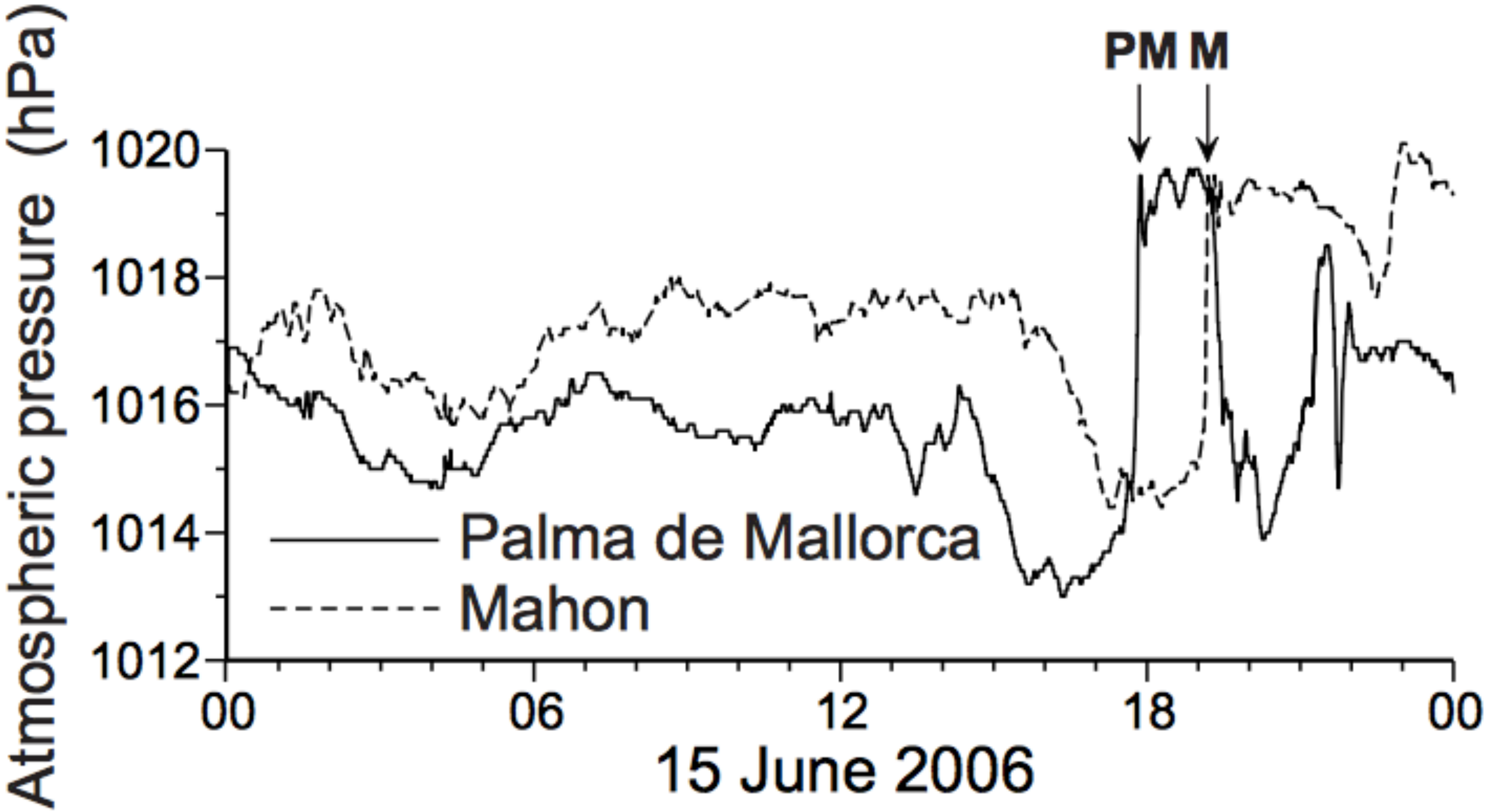


Fig. 10. Atmospheric pressure records from Palma de Mallorca (Mallorca Island) and Mahon (Menorca Island) on 15 June 2006. The arrows "PM" and "M" indicate the strong jump in atmo- spheric pressure that occurred at Palma de Mallorca at approximately 17:50 UTC and at Mahon at 19:07 UTC, respectively.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

$Q \sim L/W$

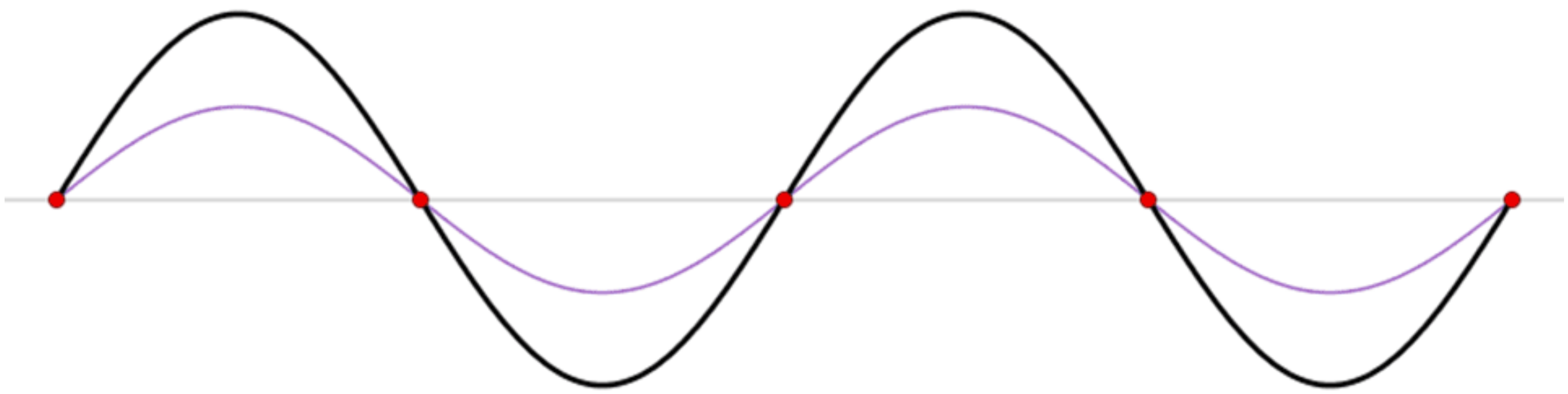
L: length of harbor
W: Width of harbor

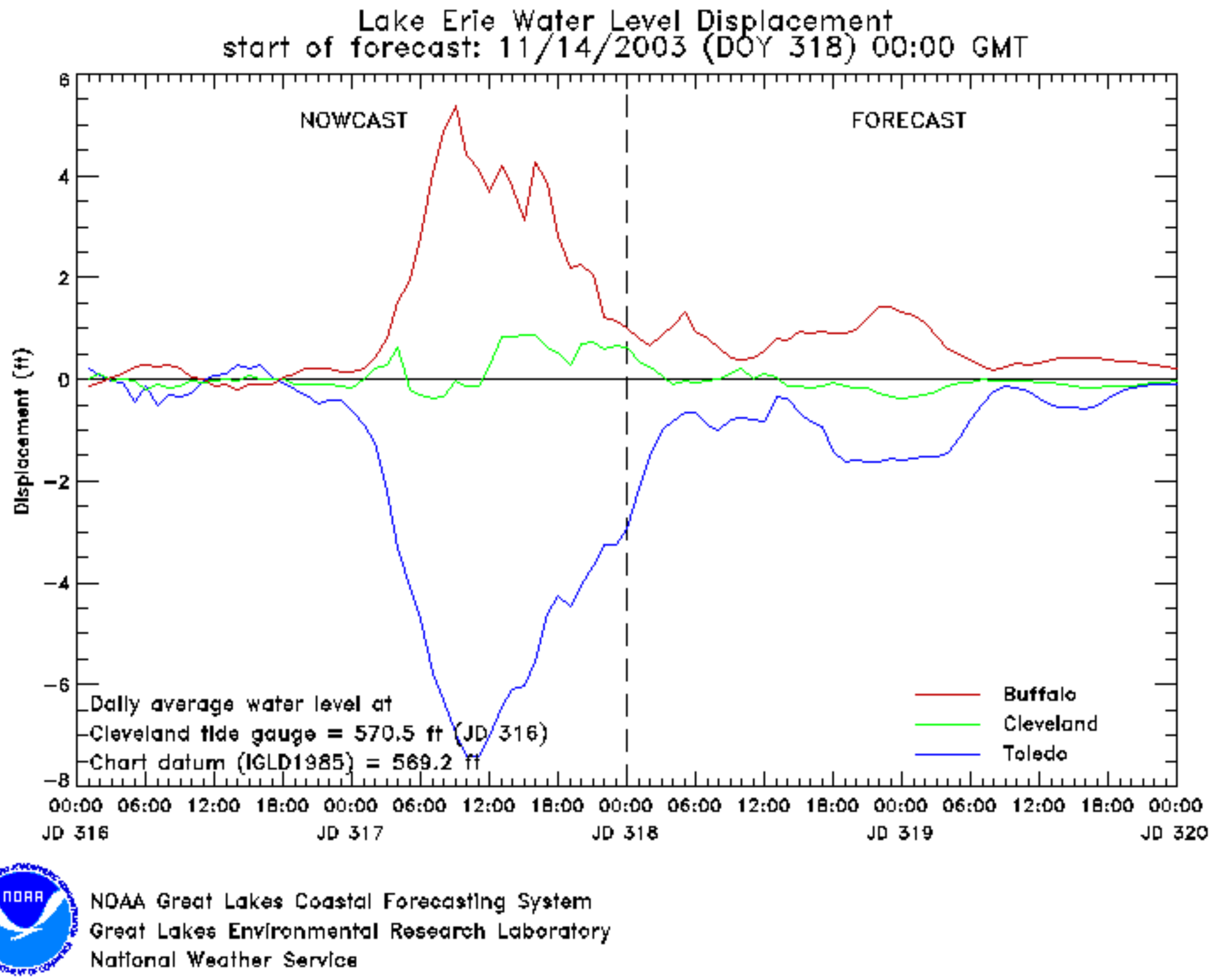
$Q >> 1$ leads to amplification

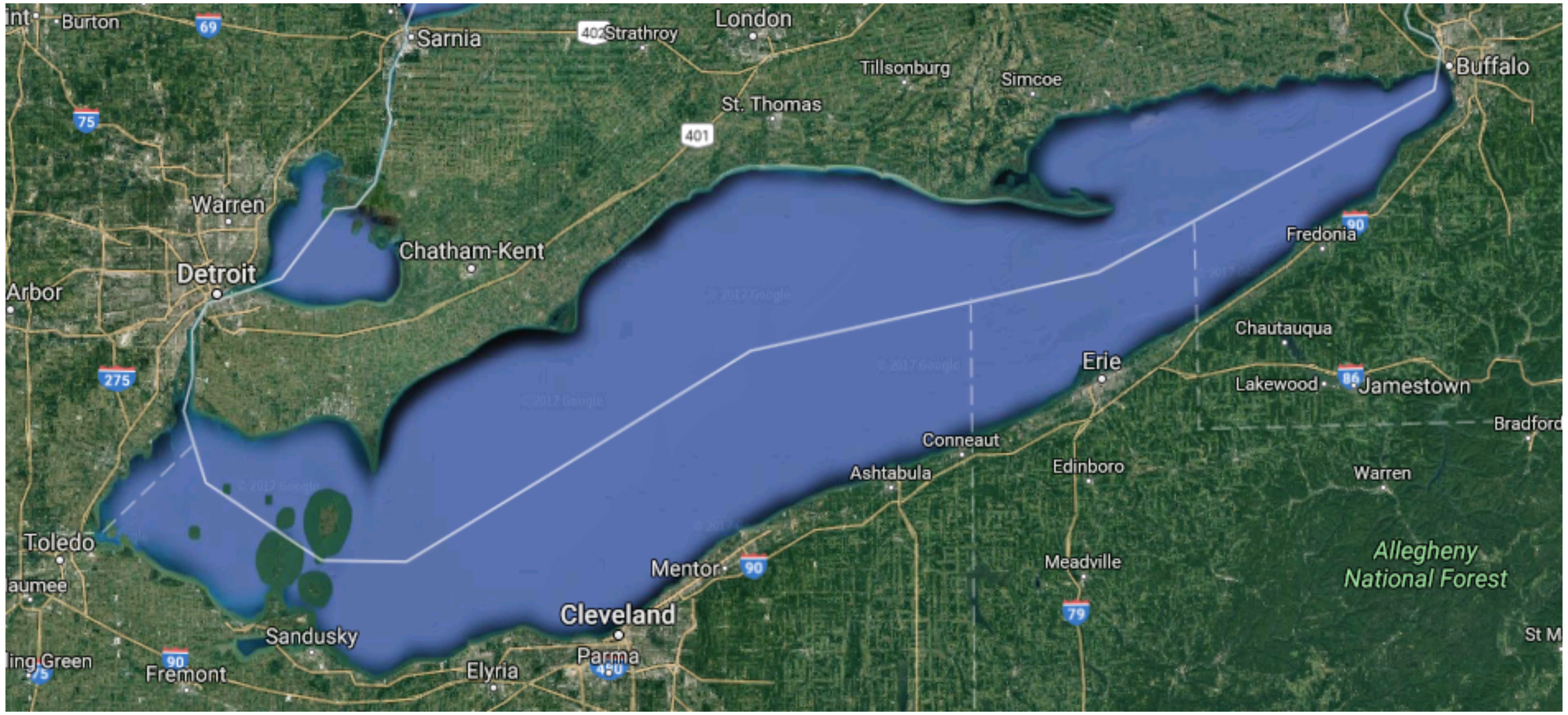
Thomas and Ryan, 2010

Meteotsunami

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







Meteotsunami

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