Severe Storms

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Introduction

The word "storm" implies a disturbance of some sort in the weather, but many different types of weather can result in an event called a "storm." Thus, it is possible to have windstorms, dust storms (which also are windstorms), hailstorms, thunderstorms, winter storms, tropical storms, and so on. Generally speaking, events called "storms" are associated with cyclones; undisturbed weather is usually found with anticyclones.

Similarly, the meaning of severity needs to be considered. The *intensity* of the event in question is going to be the basis for deciding on the severity of that particular storm. However, if storm intensity is to be our basis for categorizing a storm as severe, then we have to decide what *measure* we are going to use for intensity. This also implies an arbitrary threshold for deciding the issue of severity. That is, weather events of a given type are going to the called severe when some measure of that event's intensity meets or exceeds a threshold which is usually more or less arbitrary. A hailstorm might be severe when the hailstone diameters reach 2 cm or larger, a winter snowstorm might be called severe when the snowfall rate equals or exceeds 5 cm per hour. On the other hand, some storms of *any* intensity might be considered severe. A tornado is a "storm" embedded within a thunderstorm; any tornado of any intensity is considered a severe storm.

The difficulty with *arbitrary* definitions is that they imply a change in character whenever the threshold criterion is met. That is, if a hailstorm produces hailstones 1.9

cm in diameter, a threshold of 2 cm means that such a storm is not severe. However, from most anyone's viewpoint, is it reasonable to try to distinguish between a storm producing 1.9 cm diameter hailstones from one producing 2 cm hailstones? In the majority of cases within the science of meteorology, there is no obvious way to distinguish events with this sort of precision. A small *quantitative* change in some intensity measurement is not necessarily associated with a *qualitative* change in the character of a storm. It is near the threshold (wherever that threshold is chosen) that it becomes challenging to analyze and predict storm "severity." This will be elaborated on in dealing with the specific events described below. However, the challenge of *defining* severity should be kept in mind in the following discussion, as we consider various types of severe storms.

Severe midlatitude storms

The Tropics are defined formally as lying equatorward of 23.5° latitude in the northern and southern hemispheres: the "Tropics" of Cancer and Capricorn, respectively. Poleward of these latitudes and equatorward of 60° latitude lie the so-called midlatitudes. There are important distinctions between the weather of midlatitudes and that of the Tropics. Notably, in midlatitudes, the Coriolis force is an important part of the meteorology, whereas in the Tropics, its impact on the large-scale weather is mostly trivial.

Synoptic Scale Storms

Cyclones in midlatitudes that are 1000s of km in horizontal extent are known as *synoptic scale* systems. These are the familiar rotating weather systems (Fig. 1) shown routinely in newspapers and on television. Such storms serve an important function in the global circulation, helping to carry warm air poleward from the tropics and cold air from the polar regions equatorward. This process keeps the imbalance of solar heating from creating too extreme a temperature contrast between the poles and the equator. In association with these synoptic-scale cyclones, intense temperature contrasts can develop (Fig. 2), called *fronts*, which are the leading edges of the cold air flowing equatorward and warm air flowing poleward. These midlatitude cyclones are part of the normal progression of weather systems, typically bringing clouds and precipitation with them.

In some situations, where the hemispheric weather patterns have become slow-moving, these cyclones can bring prolonged periods of heat or cold to some regions. When extreme temperatures (hot or cold) are reached, these can be hazardous to humans for a variety of reasons, but would not generally be considered “storms” in spite of that.

Synoptic-scale cyclones become particularly intense, and the pressures at their cores can become quite low, in comparison to the average. Often, in the process of intensification, the pressures can fall quite rapidly as the result of the dynamic processes operating to cause the intensification. Cyclones with fast-falling pressures are sometimes called “bombs” and, whereas they can be considered storms in their own right, the cyclones may be responsible for several different types of stormy weather.

Rapidly falling pressures create strong winds over a wide region. These windstorms resulting from synoptic-scale cyclones can produce considerable damage and associated casualties; recent examples occurred in France during December of 1999, along the east coast of the United States in February 2000 and March 1993 (the so-called “Superstorm” of 1993). Another well-publicized example hit the United Kingdom in

October 1987. The damaging winds can extend over many hundreds of km and last in any one place for a full day or more. The result of such widespread damaging wind can be overwhelming to emergency services and power outages alone can last for days in some places simply because of the sheer size of the affected area. At sea, strong winds from intense synoptic-scale cyclones produce large waves that represent hazards to ships of all sorts. While still at sea, the winds from intense cyclones can cause serious damage, including beach erosion, when they affect coastal areas.

In addition, intense synoptic-scale cyclones can produce a full spectrum of hazardous precipitation. The time of such storms runs from Fall through Spring, and so the cyclones are capable of paralyzing snowstorms, ice storms, heavy rain storms, and even severe thunderstorms. Accumulations of ice and snow during winter storms of this type are potentially hazardous to ships and aircraft.

Depending on the circumstances, two or more of these different severe weather types could be happening at the same time, in different places. A given location might experience all of them in the course of a single day during the passage of a synoptic-scale cyclone. In other situations, only one form of severe weather occurs within such a cyclone.

Synoptic-scale cyclones are important in creating the conditions for the development of smaller-scale storms. It is a general principle in meteorology that as the size of a weather system decreases, the maximum intensity of the weather it can create increases. Although synoptic scale systems certainly can produce widespread damage, it is usually not of the most extreme intensity. However, the conditions within such storms can result in smaller concentrations of severe weather that become even more potentially hazardous.

Mesoscale Storms

Whereas synoptic-scale weather happens on scales of several thousand kilometers, *mesoscale* weather is in the range of hundreds of kilometers. Synoptic-scale weather processes go on essentially all the time (although the really intense events are generally rare), whereas mesoscale storms are intermittent. That is, they arise only occasionally in any given location and then only when the conditions for their formation are produced by the processes operating on the synoptic scale. There are two general classes of mesoscale storm systems: those that arise from interactions between the atmosphere and the underlying surface, and those that occur even in regions of uniform conditions at the surface.

Those systems that depend on the underlying surface cover a wide range of phenomena. There are many atmospheric circulations, like land-sea breezes that are more or less routine processes, driven by the underlying topographic conditions; in the case of the land-sea breeze, it is the temperature contrast between the land and the sea that drives the flow. During the day, the land is warmer and air tends to rise over land, to be replaced by cooler air flowing in from the sea. At night, the opposite happens. Of course, most of these circulations would not be considered "storms" in the sense that we have been using. However, such processes as land-sea breezes can be influential in the *development* of stormy weather, often in the form of thunderstorms that are initiated along them.

Occasionally, the circumstances produced by the synoptic-scale flow as it interacts with the surface result in stormy conditions. A common example is when the airflow interacts with complex terrain, producing localized windstorms. There are examples of these mesoscale windstorms around the world, often given colorful names. Mesoscale windstorms such as the Chinook (in Alaska), the Foehn (in the European Alps), the Traumontana (in the western Mediterranean), the Bora (in the Adriatic), and so forth have been recognized as important weather events for centuries. Windstorms in complex terrain arise in different circumstances; they are not all driven by the same mechanism. Some are simply cases where cool, stable air is being funneled through gaps in the terrain (e.g., the Traumontana); others develop when strong winds aloft are brought down to the surface by processes induced by airflow over the Mountains (as in Boulder, Colorado). The situation creating the windstorms is created by the synoptic-scale flow, but the strongest winds are confined to a mesoscale area.

Another class of mesoscale storms can arise when cold air flows over relatively warm waters. Storms of this sort, called "polar lows," apparently arise through processes not unlike those of tropical cyclones, drawing energy from the ocean to develop their intense circulations. They occur when outbreaks of very cold polar air flows over relatively warm waters. Given their mesoscale size, they often are characterized by intense pressure gradients, leading to the occurrence of strong windstorms. Their size means the weather they bring may only last for part of a day, but during the passage of the storm, winds can meet, and even exceed, the hurricane threshold: 33.5 m s^{-1}. The windstorms associated with polar lows can be quite hazardous, especially when they occur in association with low temperatures (resulting in severe windchill conditions). In addition, polar lows can produce blinding snowstorms with snowfall rates of perhaps 200 mm hr^{-1}, leading to extremely dangerous blizzard conditions. On some occasions, they can be associated with strong and possibly severe thunderstorms, as well.

Even when the underlying surface is more or less uniform, mesoscale storms can develop *within* synoptic-scale cyclones (Fig. 3). These usually are tied to a disturbance in the middle or upper troposphere that encounters conditions favorable for its development. Such systems can produce unforeseen snow and ice storms in the winter, and severe thunderstorms during the warm season. There may not be a strong cyclone near the surface in such events.

Severe thunderstorms

Severe thunderstorms typically produce weather events that cover a wide range of size scales, from a few hundred kilometers down to just a few kilometers, or even smaller. This is because thunderstorms can occur as isolated events or in groups. In the United States, a thunderstorm-related event is considered severe when the wind gusts equal or exceed 25 m s^{-1}, or the hailstone diameters exceed 2 cm, or if a tornado is produced.

A thunderstorm is composed of one or more cells, where a *cell* is the basic building block of a thunderstorm. Cells, in turn, are viewed as being made up of one group of air parcels being driven upward by positive buoyancy and another being driven downward by negative buoyancy and the presence of precipitation in the air. Positive buoyancy arises in updrafts by the release of latent heat during the condensation of water vapor. This heat release acts like the burner of a hot air balloon, reducing the density of the air in which condensation is occurring and thereby causing the air to rise. As the process continues, precipitation can be formed in the updraft. This precipitation can produce downdrafts simply by its accumulating weight dragging downward on the surrounding air. Moreover, when precipitation falls into relatively dry air surrounding a developing storm, the evaporation of that precipitation chills the air; evaporation absorbs latent heat from the air in the same way that condensation releases that heat.

When downdrafts caused by thunderstorms reach the surface, they are forced to spread out, like pancake batter poured onto a griddle. This creates an outflow at the surface (often called a *downburst*), with the outflow winds sometimes reaching the criterion for calling the thunderstorm severe. On some occasions, these outflow winds can exceed 40 m s^{-1}.

Under the right circumstances, notably when the updraft is particularly strong, the possibility of hail formation arises. Hailstones develop in the part of the storm where supercooled water and ice crystals are both present; liquid water is said to be supercooled when its temperature is below the melting point (0ºC) and the water is not yet frozen. Hailstones can become quite large, exceeding 5 cm diameters at times, and be capable of penetrating roofs, shattering windows, and even creating human casualties. Even small hail can cause crop damage, of course.

Occasionally, tornadoes form in association with severe thunderstorms. Tornadoes are intense low-pressure vortices that can produce the strongest winds of any storm: at their highest intensity, tornadic windspeeds can approach 140 m s^{-1}. Most tornadoes, however, are not that intense. Tornadoes over bodies of water are called *waterspouts*. Tornadoes are created in thunderstorms when pre-tornadic, relatively weak circulations are intensified through conservation of angular momentum.

Isolated events

The most intense form of thunderstorm is the so-called *supercell* thunderstorm, which typically is isolated from surrounding storms. Supercells are rotating thunderstorms that develop their rotation by tapping the vertical wind shear in the storm environment. The vast majority of supercells produce some sort of severe weather: hail, damaging straight-line winds, and/or tornadoes; only about 20% of them are tornadic. The most violent severe weather of all types is almost always associated with supercells (Fig. 4), including the majority of strong and violent (F2-F5 on the Fujita Scale) tornadoes and giant hailstones (exceeding 5 cm in diameter).

Whereas the typical thunderstorm cell has a lifetime of about 20-30 minutes, supercells can persist for many hours. This means that all forms of severe weather from supercells can be prolonged, sometimes leaving long, wide swaths of damage. The organized nature of a supercell, associated with its overall rotation, means that supercells produce a disproportionate share of the damage associated with thunderstorms. Perhaps only about 10% of all thunderstorms are supercells, but they are responsible for the majority of thunderstorm damage in areas where they occur.

Because supercell updrafts are often intense, supercells can become prolific hail producers; a noteworthy example was a supercell that hit the Dallas-Fort Worth metroplex on the evening of 05 May 1995 with softball-sized hail and torrential rains. The damage from that one storm was estimated at $1 billion.

Apart from supercells, isolated thunderstorms usually are non-severe and typically do not last very long. On rare occasions, isolated thunderstorms can produce a brief "pulse" of severe weather, usually hail or winds that are only marginally severe.

Aggregations of thunderstorms

Thunderstorms do not typically occur as isolated events. Instead, they tend to form in groups, in either lines or clusters of individual cells. The most common grouping is in lines, sometimes referred to as *squall lines*. When thunderstorm cells form in aggregations, then the collection of storms can live for a much longer time than the individual cells (which usually retain their 20-30 minute lifecycles). This means that the hail and wind events produced by such groupings of thunderstorms are intermittent, rather than prolonged (as with supercells), as cells form and decay. Severe weather still can go on in such cases for many hours in this intermittent fashion. The interactions between individual cells in lines and clusters of thunderstorm cells are often complicated and hard to predict, but those interactions are responsible for severe weather.

A particularly dangerous form of thunderstorm aggregation arises when new cells are constantly forming in one place, and tracking over the same region repeatedly, a situation called “training” because the cells are like cars in a train. This means that a particular area experiences rainfall from a succession of thunderstorm cells, which can result in extremely heavy rainfall. This is the process associated with the majority of flash flood events, worldwide. In the United States, heavy rainfall is not considered to be a criterion for what is officially considered to be "severe" in spite of the importance of such rainfall in flooding events. On the other hand, many other nations around the world consider heavy rainfall to be an important form of severe storm.

Severe tropical storms

The most obvious severe weather associated with the tropics are *tropical cyclones*. These storms are known by different names in different parts of the world: hurricanes (in North America), typhoons (in the tropical Pacific), and cyclones (in the Indian Ocean and Australia), among others. However, they all are the same phenomenon. Such storms arise when sea surface temperatures become warm, the vertical wind shear is weak, and tropical weather disturbances move through the easterly Trade winds of the Tropics. They produce winds in excess of 33.5 m s^{-1} and the peak sustained winds (i.e., not gusts) can approach 90 m s^{-1} in extreme cases. The size of the region of damaging winds can vary considerably from one event to another, but winds exceeding "hurricane force" (33.5 m s^{-1}) can found within a circle on the order of 100 km or so in diameter. Such a large region of strong winds means that damaging windspeeds can go on for many hours.

Although they are well known for strong winds, tropical cyclones can pack a lethal combination of hazards: storm surge, heavy rainfalls, and even embedded tornadoes, as well as the more well-known strong winds. Storm surge is created by a combination of strong winds and low pressure, resulting in an elevated sea level near the center of the storm. When this surge, which can be several meters high, makes landfall, low-lying coastal regions can be inundated. The rainfall component is nothing to take lightly, either. Hurricane Mitch (Figure 5) devastated parts of Nicaragua and Honduras in 1998, mostly from flash floods and landslides. There were more than 9 thousand fatalities, making it the worst weather disaster in this century in the Western Hemisphere.

Tropical cyclones are usually several hundred kilometers in diameter and can last for tens of days. Their paths often take them out of the Tropics into midlatitudes, where they can maintain their structure for a time before eventually dissipating or transforming into midlatitude cyclones. Tropical storms usually dissipate shortly after making landfall, because their energy source (warm seawater) is cut off. Nevertheless, dissipated tropical cyclonic storms can remain dangerous well after they lose their strong winds by creating an environment favorable for heavy rain-producing thunderstorms.

Relatively little is known about other types of severe storms in the Tropics. Severe thunderstorms, especially supercells, are uncommon in the Tropics because of a general lack of vertical wind shear. Of course, heavy rain-producing tropical thunderstorms are relatively common in some parts of the Tropics.

Societal impacts and their mitigation

Severe storms in all their variety cause the loss of hundreds of lives and several billion dollars in property during the course of a year in the United States. It is worth noting that the United States can recover from such property damage because of its large, generally healthy economy. Severe storm economic losses in the United States typically are much less than one percent of the gross domestic product (currently several trillion dollars), so by spreading out the impact of severe storms, the areas affected can recover and rebuild. On the other hand, when severe storms (like Hurricane Mitch) devastate less-developed nations with small economies, the damage to their infrastructure can be so large that it might take decades to recover.

Forecasting severe storms has shown a slow increase in accuracy during the past several decades, as new technologies are leading to improved understanding and predictability. The accuracy of forecasts generally increases as the scale of the storm increases; it is possible to be more accurate with a synoptic-scale forecast than with a forecast on the scale of a single thunderstorm in most cases. There is more complete understanding of the synoptic-scale meteorology than on scales smaller than synoptic. Furthermore, forecast accuracy generally decreases with the age of the forecast, at a rate that also depends on the scale. The accuracy of a synoptic-scale forecast stays high longer than a short-range forecast of a thunderstorm-scale event, in general.

Property damage mitigation depends mostly on making the right preparations for the storms that are possible in a given location, well in advance of the storms. Once the storms are underway, there tends to be relatively little that can be done to prevent property damage. For example, a home built on a barrier island that can be swept by landfalling tropical cyclones is unlikely to remain undamaged for more than a few decades, at most. Thus, some damage can be prevented by not building in vulnerable areas. As another example, there are several ways in which homes can be built to resist tornado damage, unless the homeowner is unlucky enough to be hit by the most intense winds in a violent tornado. Even within the whole violent tornado damage area, only a few places will actually experience the most violent winds; most of the rest of the structures will encounter winds that can be resisted through appropriate construction practices.

Casualty mitigation can be a complex topic, as well. In some instances, as with tropical cyclones, evacuation is possible and may be the best way to protect lives when it is feasible. For tornadoes, having access to a suitable shelter is preferred; in situations where proper shelter is not available, the alternatives during tornadoes are not very good. For flooding situations, evacuation to higher ground is the appropriate way to prevent casualties, when time permits. Clearly, our ability to detect and predict severe storms is also important for casualty mitigation. In the United States, there has been a gradual reduction in weather-related fatalities with time, in part because there are fewer "surprise" storms today, and in part because education about severe storm hazards has led to improved public preparations. Nevertheless, we continue to be vulnerable as a nation to disasters caused by severe storms, and complacency can be a fatal error.

See also: **Air-Sea Interaction (Storm Surges), Anticyclones, Aviation Weather Hazards, Baroclinic Instability, Bow Echos and Derechos, Convective Storms, Coriolis Force, Cyclogenesis, Cyclones (Extratropical Cyclones), Diurnal Cycle, Downslope Winds, Dynamic Meteorology (Waves and Instability), Flooding, Fronts, Hurricanes, Jet Streams, Lake Effect Storms, Land/Sea Breeze, Lee Waves and Mountain Waves, Mesoscale Meteorology (Mesoscale Convective Systems), Mountain and Valley Winds, Nowcasting, Orographic Effects (Lee Cyclogenesis), Polar Lows, Predictability and Chaos, Rossby Waves, Synoptic Meteorology, Tornados, Water Spouts, Weather Prediction (Severe Weather Forecasting)**

Further Reading

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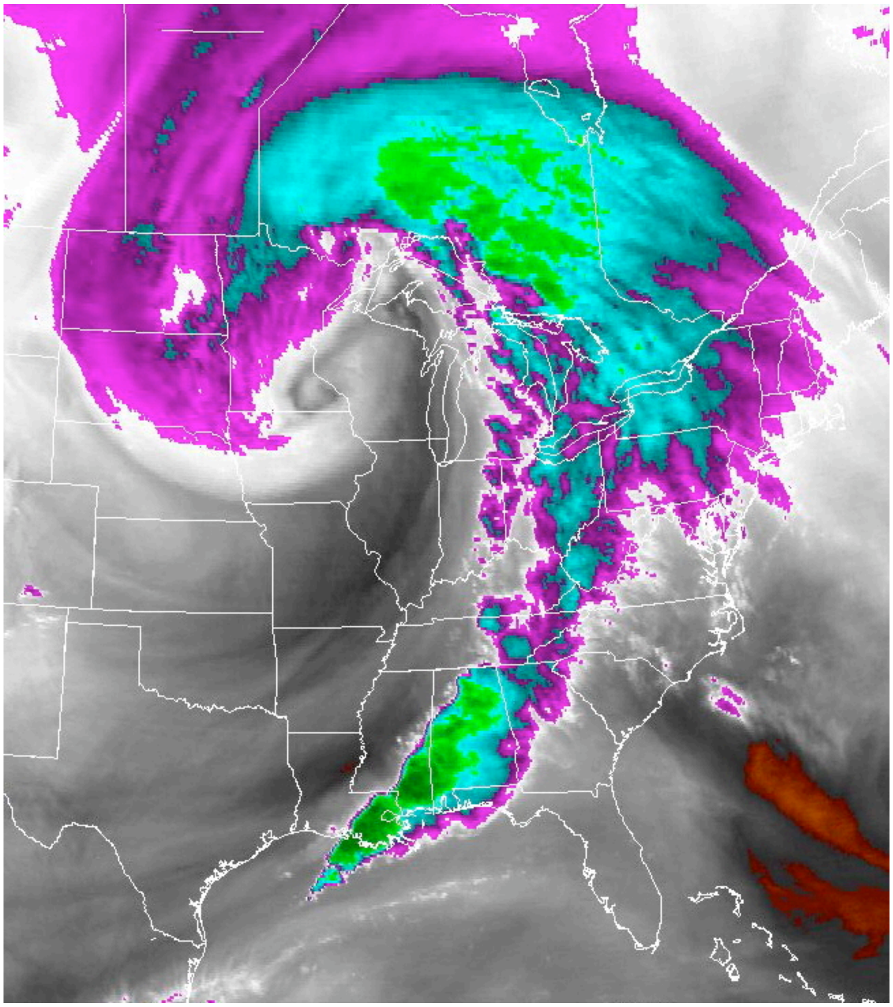

Figure 1. False color-enhanced satellite image of a synoptic-scale cyclone on the afternoon of 10 November 1998, showing the center of the cyclone near the spiral of clouds in southeastern Minnesota. This cyclone was producing severe thunderstorms in and near the Gulf of Mexico, as well as snow and high winds on the northern plains, in North and South Dakota

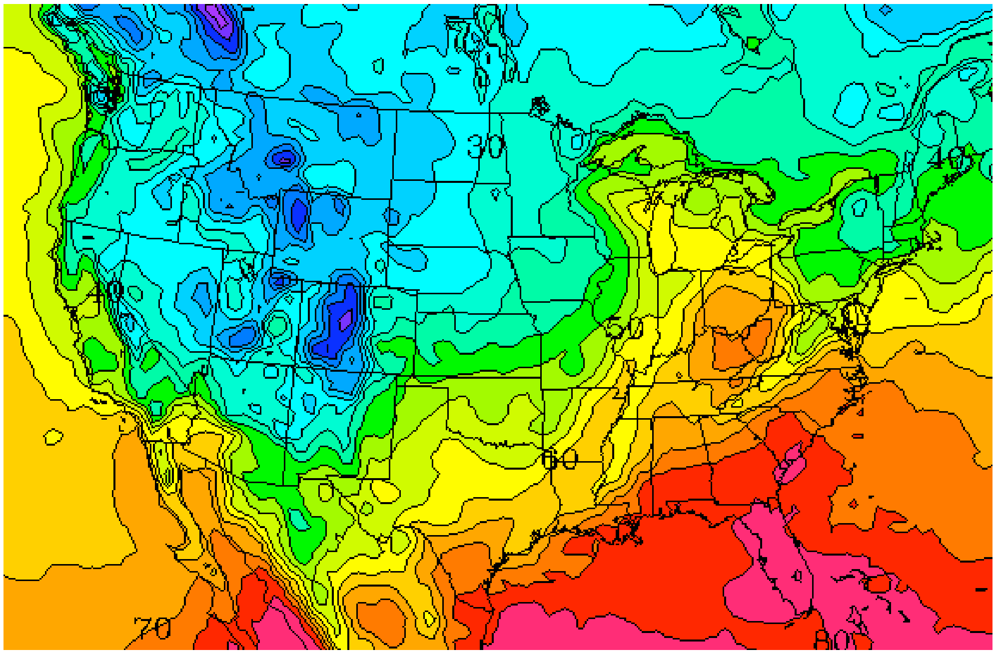

Figure 2. Map of surface temperatures at about the same time as Fig. 1, showing the strong contrast in temperatures long the cold front, with subfreezing temperatures in North and South Dakota at the same time that quite warm temperatures are present over the Gulf of Mexico. Many subsynoptic-scale features also can be seen in mountainous regions; for example, in the Appalachian and Rocky Mountains.

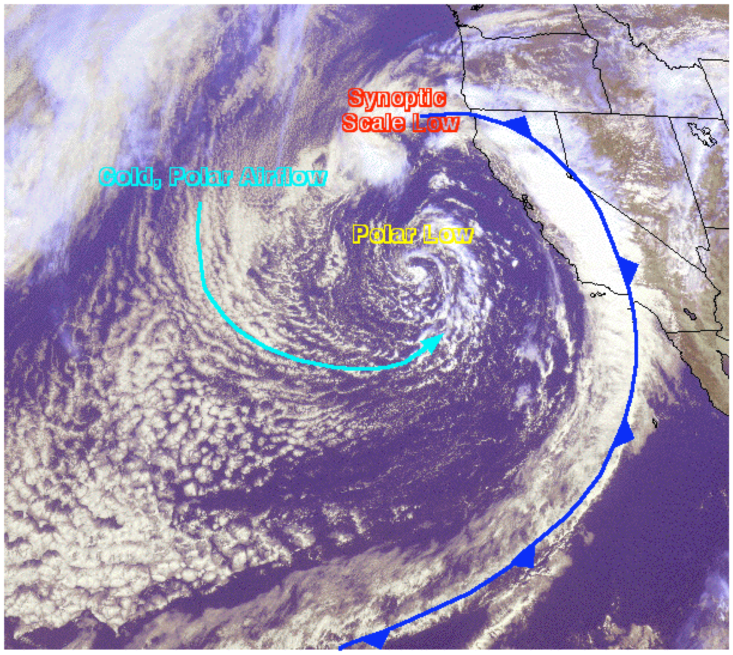

Figure 3. An example of a polar low in the cold airstream behind a wintertime synoptic scale cold front associated with a synoptic-scale cyclone (a low pressure center).

Figure 4. Supercell-associated tornado on 22 May 1981, near Alfalfa, Oklahoma. Image © 2000 C. Doswell (used by permission).

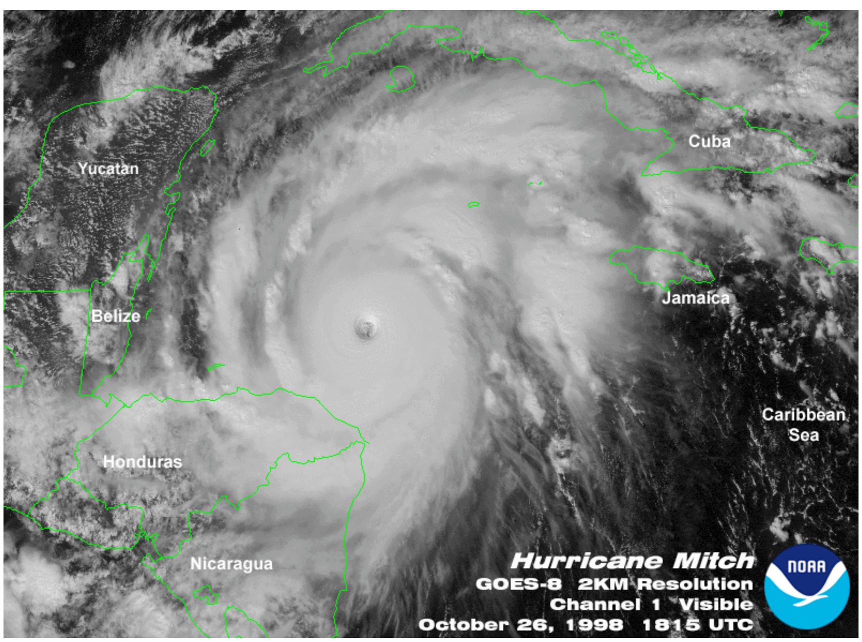

Figure 5. View from the GOES-8 geostationary satellite of Hurricane Mitch near Honduras and Nicaragua.

Figure 6. Damage caused by the violent tornado that hit the city of Moore, Oklahoma on 3 May 1999.