I. Introduction
   A. We have a tendency to think specifically of tornadoes when thinking of extreme weather associated with thunderstorms. With good reason....tornadoes are probably the most “spectacular” of all weather phenomena and we will focus our discussion of “convective weather” on these features and the extreme thunderstorms from which they originate (supercell thunderstorms). However, it is important to discuss the more general topic of thunderstorms since they are important to other types of extreme weather. For example, in addition to tornadoes, they can produce damaging wind and hail. Because of the very vigorous ascent or updrafts that are the important component of thunderstorms they are usually associated with very heavy rain and sometimes flooding. “Convective” precipitation (thunderstorms) are the predominant mode of precipitation in the tropics (ITCZ) where flooding is the most important weather issue. In addition, flooding in the United States is frequently associated with clusters of thunderstorms called mesoscale convective systems (MCSs).

B. What is a thunderstorm? (Fig. 4.1)
   1. These structures are of a smaller scale than the ECs that we have been discussing although when they occur in middle latitudes they are frequently part of a larger EC
      a. Thunderstorms are on the order of tens of kilometers whereas ECs are usually thousands of kilometers
   2. They are designated as “convective” systems
      a. Convection is a mode of heat transfer from low levels to upper levels by the rising motion of warmer air parcels (and the sinking motion of cooler air parcels)
      b. This process occurs, and these storms develop, due to an “unstable environment” (much warmer at the surface than at upper levels)
         1. In this way, parcels remain much warmer than the environment and will rise very quickly, creating a vigorous updraft
      c. The vigorous updrafts and associated latent heat release (which enhances the updraft) generate heavy rain and the rain-cooled air generates vigorous downdrafts which are usually responsible for the strong winds associated with most thunderstorms
      d. The updrafts and downdrafts become so vigorous that friction generates electrical charges on water and ice particles and charge separation occurs within the cloud
         1. The ultimate result is lightning and thunder (this is an oversimplification but satisfactory for our purposes)
      e. The following three environmental conditions, each can vary in degree, are necessary for thunderstorms to form
II. Atmospheric Conditions Necessary for Thunderstorm Formation

A. Lifting mechanism (Fig. 4.2)

1. Lifting is needed to cause the ascent necessary for cloud formation. Once the clouds form, the unstable environment helps it to accelerate upward by keeping the parcel warmer than the environment (quite a bit warmer in many cases).

2. Any combination of the following lifting mechanisms may be present for thunderstorms to form. The more lifting mechanisms and the stronger they are, the stronger and more numerous the thunderstorms.
   a. Divergence aloft
      1. Jet stream and surface low pressure center
      2. Thunderstorms usually form in “warm sector” of surface low pressure systems (ECs)
         a. South of warm front and to the east of cold front
   b. Front or boundary between air of different density (usually a cold front or dry line but can be a gust front or outflow boundary from the downdraft of another thunderstorm) (Fig. 4.3)
   c. Surface solar heating (Fig. 4.4 and 4.5)
      1. This is frequently the only lifting mechanism in tropical locations where temperature contrasts are small (above two lifting mechanisms) and moisture and instability are strong enough that this is the only lift needed to trigger thunderstorms
   d. Tropical waves (Fig. 4.6)
      1. These are “gravity waves” that cause alternating rising and sinking motion in the east-west plane with clusters of thunderstorms forming in the regions of rising air
      2. These are the clusters of thunderstorms from which tropical cyclones (hurricanes) form (more on this later)

B. Atmospheric stability/instability (Fig. 4.7)

1. An air parcel will rise or continue to rise (if “lifted” by one of the mechanisms listed above) if it is warmer than its surroundings (environment)

2. Even in the presence of other lifting mechanisms, if the parcel is warmer than its environment this difference in temperature will tend to accelerate the parcel upward more rapidly than it would otherwise
   a. The greater the difference in temperature between the warmer parcel and the cooler environment, the more vigorous the
**upward motion** of the air parcel (and the worse the weather.....) because **warm air is less dense (or lighter) than cold air**

1. Analogy: An oil drop (less dense than water) in a glass of water will rise very quickly to the top of the glass

3. Lapse rates (Figs. 4.8, 4.9 and 4.10)

   a. **The rate at which temperature decreases with increasing altitude**
   
   b. In order to know how the temperature of the air parcel compares to its environment as it rises we need to know how quickly the parcel will cool relative to how quickly the environment cools as we go up (remember the structure of the troposphere (environment) ...... temperature generally decreases from surface to tropopause)

   c. Remember how a **rising air parcel** will cool as it increases its altitude (rises) and warm as it decreases its altitude (sinks).

   **These air parcels will have a lapse rate, which will always be the same**, depending on whether the air in the parcel is not saturated/no clouds (**dry adiabatic lapse rate**) or saturated/cloudy (**moist adiabatic lapse rate**)

2. **Dry adiabatic lapse rate** (cloudbless/unsaturated air parcel) is **~10°C/km** (Figs. 4.8 and 4.9)
   
   a. All air parcels in the atmosphere, that are not saturated with respect to water vapor (cloudless), will cool (warm) 10°C (~18°F) for every one kilometer (~3280 feet) that they rise (sink)
   
   1. This is a constant, and holds true for **all** unsaturated (cloudbless) air parcels, no matter what environment they are in

3. **Moist adiabatic lapse rate** (cloudy/saturated parcel) (Figs. 4.8 and 4.9)
   
   a. Once the parcel rises and cools enough that it becomes saturated and forms clouds it will begin to cool more slowly as it continues to rise....why?
   
   1. As the water vapor condenses into cloud droplets, it releases **latent heat** into the air parcel, therefore the parcel will begin to cool less quickly as it rises than it would if it was cloudless
   
   2. **~6°C/km** (higher at high altitudes with less water vapor available for condensation)

4. **Environmental lapse rate** (Fig.4.10)
   
   a. **The lapse rate outside the air parcel (balloon)**
   
   b. This is measured twice a day by weather balloons (rawinsonde) which records the temperature of the environment as a function of height
c. As opposed to the adiabatic (parcel) lapse rate, this lapse rate is not constant but is **highly variable** from day to day at a particular location, from location to location and even from one layer of the troposphere to the next at a particular location.

4. **Unstable environments**......where thunderstorms tend to form (Figs. 4.11, 4.12 and 4.13)

   a. *If the environmental lapse rate in a layer of the atmosphere is greater/steeper (cools quicker with height) than the adiabatic lapse rate (cools slower with height)* the parcel will tend to remain warmer than its environment and continue to rise......the **bigger the difference, the quicker the upward motion of the parcel**

   b. **An unstable environment generally means that it is very warm at the surface and cold aloft (steep environmental lapse rate)**

   c. If the environmental lapse rate is greater than the dry adiabatic lapse rate (~10°C/km), the environment is **absolutely unstable** (this is a *rare* condition)

   d. If the environmental lapse rate is less than the moist adiabatic lapse rate (~6°C/km), the environment is **absolutely stable**

   e. The most common environment for thunderstorms is where the environmental lapse rate is generally greater than the **moist (cloudy) adiabatic lapse rate (~6°C/km) and less than the dry adiabatic lapse rate (~10°C/km)**......the environment is **conditionally unstable** (Figs. 4.11, 4.12 and 4.13)

   f. It is unusual for the environmental lapse rate to be greater than the dry (cloudless) adiabatic lapse rate so usually there is some other lifting process (e.g. a front or convergence associated with a surface low pressure system) which lifts the parcel from the ground to the point at which it becomes saturated and clouds begin to form (called the **lifting condensation level**) (Fig. 4.13)

      1. Once the air parcel reaches a point (called the **level of free convection**)(*Fig. 4.13*) where it is warmer than the environment and the environmental lapse rate is greater than the moist adiabatic lapse rate (conditionally unstable environment), the parcel will accelerate upward, forming clouds, sometimes all the way to the tropopause, resulting in a thunderstorm (more on this later)

      2. One can see how the tropopause acts like a lid by looking at Figs. 4.13 and 4.14

         a. As our accelerating, cloud forming, parcel hits the tropopause and moves into the stratosphere (where the environment **warms** with altitude) the air parcel will suddenly become colder than the
surrounding stratosphere and sink back down to the troposphere

C. Low-level moisture
   a. Abundant low-level moisture allows for more condensation and thus more latent heat release which enhances the vertical circulation by:
      1. Warming the parcels to create a larger difference between the temperature of the parcels and the environment (instability effect)
      2. Creating relatively lower pressure at the surface and relatively higher pressure at the tropopause (remember the expanding warm air and resultant separation of the pressure lines in class diagram)
   b. Abundant low-level moisture also allows for cloud formation at a lower level (lifting condensation level [LCL]) which enables the parcels to assume the less steep moist adiabatic lapse rate (cool less quickly as they rise once they become saturated and condensation releases latent heat into the parcel) at a lower level

D. These conditions......instability, moisture and lifting mechanism ......can be present in a variety of atmospheric scenarios and locations from the tropics to middle latitudes and garden variety thunderstorms are pervasive around the globe.......however, if we impose an additional atmospheric condition, thunderstorms become more destructive and may generate a tornado (more on this later)

III. Airmass thunderstorms (Ordinary thunderstorms) (Figs. 4.15 and 4.16)
   A. Have this name because usually not associated with boundaries or the vertical wind shear that is associated with severe thunderstorms
   B. A better name for them is ordinary thunderstorms
   C. The vertical motions (ascent/updraft) which generates these storms is not created by the divergence associated with the jet stream
      1. The upward motion is created by the relatively subtle lifting of uneven daytime solar heating of the surface and accelerated by the unstable environment
         a. These are the thunderstorms that form on hot, humid sunny summer days
         b. These are also the type of thunderstorms that form in the tropics
            1. These are enhanced by lifting from surface convergence at the ITCZ as well as “tropical waves” that eventually result in groups of thunderstorms
   D. To reiterate, these storms do not form near the polar front and thus the wind does not increase rapidly with height (they are not located near the jet stream – remember, the strong meridional temperature gradient near the polar front creates the strong pressure gradient at the tropopause the generates the jet stream)
      1. For this reason, they have an upright vertical configuration (Figs. 4.15 and 4.16)
2. For the same reason, they have relatively short lifetimes
   a. As the heavy precipitation falls, it falls through the updraft, slowing the updraft
      1. Eventually a downdraft develops due to the drag from the rainfall and because of evaporation from the raindrops
         a. Evaporation removes heat from the atmosphere (requires energy) which creates cool air parcels which are denser/heavier than their environment and sink (downdraft)
      b. Eventually the downdraft overwhelms the updraft and the storm dies
   c. However, do not fret, as the downdraft hits the ground it spreads out and creates surrounding mini-cold fronts (gust fronts/outflow boundaries) which lift the surrounding heated surface air and create new thunderstorms
      1. This process can multiply (like little bunnies) and create groups of thunderstorms with very heavy rainfall (flooding?) called mesoscale convective systems

IV. Mesoscale Convective Systems (MCSs)......mesoscale just defines the scale of these systems (tens to hundreds of kilometers....synoptic scale means thousands of kilometers)

   A. Any system of grouped thunderstorms including MCCs (below) to frontal squall lines to organized tropical convection (ITCZ)
      1. These are critical to human life on earth as they provide the majority of the rainfall necessary in agricultural regions during growing season
      2. Can be associated with floods but tornadoes are relatively rare and weak

   B. Mesoscale Convective Complexes (MCCs) (Figs. 4.17 and 4.18)
      1. This is what the book refers to as MCSs....confusing, I know, but jargon and semantics in any field frequently are. Most people consider MCCs as just one category of MCSs
      2. The technical details in the book are not important for our purposes
         a. As a summary.....
            1. Form over regions with large environmental instability
               a. Begin to form during the day
            2. Can form more thunderstorms (group) and don’t die out like isolated ordinary thunderstorms because the updraft becomes tilted so that the downdraft is not superimposed on it (Fig. 4.17)
            3. The evaporation cooled downdraft spreads out when it hits the ground and lifts the warm air out in front of it forming what is called a “gust front” (acts like a cold front) (Fig. 4.18)
3. This type of grouped thunderstorms tends to develop over continental \textit{land} masses over what would be considered \textit{“subtropical latitudes”} during the summer season (Fig. 4.19) 
   a. Central Plains and Midwest U.S. during summer 
   b. Central Africa (Sahel Region) 
   c. South America 
   d. Monsoon regions of China, India and Australia 
4. Note that these are, in general, critical agricultural regions 
5. Can be associated with strong \textit{“straight-line winds”} (no rotation)....caused by the downdraft bringing stronger winds aloft down to the surface.....but only occasionally \textit{very weak} tornadoes 
6. Environment different than ordinary thunderstorms 
   a. Usually there is a temperature contrast and what is called a \textit{“low-level jet stream”} 
C. Frontal squall lines (Figs. 4.20 and 4.21) 
   1. \textbf{Line of thunderstorms in advance of a cold front} which is associated with a EC [extratropical cyclone....surface low pressure system....in case you forgot :) ], and thus, the strong polar-front jet stream 
   2. The dense, cold air behind the cold front \textbf{lifts} the warm, \textit{moist} air out in advance of the cold front which is usually in an \textit{unstable} environment 
      a. Remember the three conditions for thunderstorm formation...\textit{moisture, instability and lift} 
3. \textbf{Not} usually associated with hail and tornadoes 
   a. Can have \textit{strong “straight-line” winds} due to the downdraft bringing strong winds aloft down to the surface 
4. A \textit{“pre-frontal”} squall line can from out in advance of the main squall line as the gust front (from the downdraft) moves quickly to the east and lifts unstable air in advance of the cold front 

V. Severe Thunderstorms 
   A. Aside from the heavy rain/flooding aspect of thunderstorms (either flash flooding from a single storm or flooding from groups of thunderstorms or thunderstorm complexes) a single thunderstorm cell can be extremely destructive if conditions are right. These are usually designated \textit{“severe thunderstorms”}. 
   B. Atmospheric conditions in the Great Plains and Midwest regions of the United States are conducive to these thunderstorms which are designated \textit{“severe”} by the National Weather Service if they generate \textit{any} of the following three: 
      1. \textit{Hail with 3/4 inch diameter or more} 
      2. \textit{Winds in excess of 50 knots (58 mph)} 
      3. \textit{A tornado} 
   C. Require four elements for formation 
      1. \textit{Moisture} 
      2. \textit{Instability} 
      3. \textit{Lifting mechanism}
b. Upper-level divergence
c. Front or boundary between air of different density
c. Surface solar heating

(Usually all three of these lifting mechanisms are present)

Note: These three elements are necessary for formation of any type of thunderstorm......the fourth condition generates the rotation that is necessary for rotating thunderstorms (supercell thunderstorms) and tornadoes

4. Vertical wind shear
   a. Rapid change in wind speed and direction with altitude......(more on this later)

VI. Supercell Thunderstorms
   A. These are (by far) the most intense thunderstorms and are responsible for most of the damaging hail and straight line winds and virtually all damaging tornadoes
   B. They are single entities as opposed to thunderstorm “complexes” and their distinguishing characteristic is that they rotate
   C. We have discussed the characteristics necessary for any thunderstorm to form....moisture, instability and lift. These are present, and are very strong, in supercell environments. However, an additional component must be present in order to generate a rotating supercell thunderstorm....strong vertical wind shear (wind increasing rapidly in speed and direction with altitude) (Fig. 4.22). As you might imagine, this occurs in the vicinity of ECs and the polar front jet stream

   D. They form in the warmest, moistest, and most unstable area of an EC, the “warm sector” which lies between the cold front (or dry line) and the warm front (Figs. 4.23 and 4.24). They also occur close to the surface low pressure center where.....
      1. Lifting is the strongest
         a. Fronts and the vertical circulation associated with the surface low pressure
      2. There is the greatest instability and moisture
         a. Very warm and moist at the surface and cold aloft as the cold side of the polar front is present at upper-levels
      3. There is the greatest vertical wind shear
         a. Underneath the polar front jet stream (Fig. 4.24)

   E. There are certain characteristics, which are relatively unique to the Great Plains and Midwest of the U.S. (although similar, though not as extreme, conditions occur in certain areas of South America and China) which all come together in just the right way (usually from March to June) to create these most extreme storms (Figs. 4.25 and 4.26)
      1. Vertical wind shear
         a. Strong westerly polar-front jet stream(Fig. 4.27) formed by the clash of very cold arctic continental air with very warm air from the Gulf of Mexico and Gulf Stream and relatively weak southeast winds at the surface (Fig. 4.28) (winds are always
weakest at the surface) circulating around the surface low 
pressure and semi-permanent subtropical “Bermuda” high 
pressure center
1. This creates strong deep layer vertical wind shear 
2. This causes the storm to tilt so that the updraft and 
downdraft remain separate
b. Strong low-level jet stream forms above the surface in the Plains 
and Midwest due to a pressure gradient which arises due to 
differential daytime heating from the mountains to the lowlands 
(west to east temperature gradient) which can create a strong 
southwest wind above the surface (Fig. 4.29)
1. This creates a very strong low-level vertical wind shear 
that is critical for tornado formation (more on this 
later)
2. High levels of instability (Fig. 4.30) formed by the same clash of air 
masses
a. Very warm environmental air being drawn into the EC at low-
levels with cold environmental air at high-levels above the 
EC (remember, always think of the environment that the self-
contained rising air parcels are in)
3. Abundant moisture
a. The combination of the circulation around the surface low 
pressure center and the “Bermuda” (semi-permanent 
subtropical) high pressure center pumps moisture into these 
storms from the Gulf of Mexico on southeasterly winds (Fig. 
6.20) (and also moisture at low levels off the gulf provided by 
the “low-level jet stream” mentioned above)
b. This moisture provides the fuel for these intense storms...the 
same fuel that, as we will learn, powers hurricanes....latent heat 
c. This latent heat release combined with the existing 
environmental instability results in updrafts in supercell 
thunderstorms that are estimated at 45 – 100 mph. This 
compares to updraft speeds in a blizzard of only a few miles an 
hour.
4. Lifting mechanism
a. Divergence aloft associated with the jet stream and development 
of surface low pressure system (EC)
1. The jet stream is very strong (Fig. 4.27) across the Great 
Plains and Midwest in the spring due to strong 
temperature contrast between cold Canada and warm 
Gulf of Mexico
b. The cold front associated with the EC (Fig. 4.31)
1. These are also very strong across this region in spring 
due to the strong temperature contrast 
c. A dry line formed by dry, hot air from Mexico or descending 
from the Rocky Mountains (remember, descending air warms
and dries)
1. This dry air is much denser (heavier) than the moist air from the Gulf of Mexico so this line acts like a “cold front” even though there is little temperature change across the dry line (Figs. 4.31 and 4.32)

c. A gust front or outflow boundary from another thunderstorm (Fig. 4.31)
d. Solar heating
1. Usually this “lifting” mode is combined with one or more of the other four

5. Capping inversion (Fig. 4.33)
a. Frequently, but not always, present
b. Very dry and warm air moves off the elevated Mexican plateau and Rocky Mountains creating a warm layer (and thus an inversion since the temperature will rise with altitude) at about 10,000 feet (700 mb) (Figs. 4.33 and 4.34)
1. Forms at this level because this is the altitude of the plateaus of origin
c. This inversion serves like a lid on a boiling pot.....
1. The sun heats the surface all day and all this energy builds up below the cap....
2. When the temperature finally gets warm enough (warmer than the cap) below the cap late in the day all of the warmed parcels explode upward generating a very vigorous updraft

F. It is the combination of all of these factors (lift, instability, moisture, vertical wind shear and [frequently] a capping inversion) that results in the very vigorous updraft combined with the supercell’s rotation that sets the stage for tornado formation....(Figs. 4.22 and 4.24)

G. Supercell structure (Figs. 4.35 – 4.38)
1. The rotating updraft or mesocyclone
   a. Southwest side of the storm
   b. Rain free under the updraft and weak radar echoes (inner part of hook in Figs. 4.36 and 4.37) because precipitation is carried downwind (to the northeast by the strong southwest, usually, winds aloft)

2. Wall cloud
   a. Rotating cloud below the mesocyclone
   b. If a tornado develops it will emerge from the wall cloud

3. Supercell precipitation (Figs. 4.35 – 4.37)
   a. Heavy rain and hail
   b. Hail falls just to the northeast of the updraft

4. Supercells travel in a northeasterly direction (carried by the southwesterly flow) so that the northeast side is called the forward flank and the southwest side the rear flank

5. Downdrafts (Figs. 4.35 and 4.38)
a. Caused by evaporative cooling from falling precipitation
b. Forward flank and rear flank
c. Gust front from rear flank gust front can generate new supercells in the rear flanking line (Fig. 4.35)

VII. Tornadoes
A. Introduction
1. “Tornadoes are violently rotating columns of air that extend from a thunderstorm cloud to the ground”
2. “Exceptionally strong tornadoes can destroy steel-reinforced structures, throw automobiles over 100 feet and sweep trains off their tracks”
3. Range in diameter from 150 ft. to ½ mile
4. Windspeeds range from 65 to 300mph
5. Most are short-lived but can remain on ground for as much as one hour
6. 75% of all tornadoes, and the vast majority of significant tornadoes (EF2 or greater....only 25% of all tornadoes) occur in the U.S.
7. Approximately 1,000 tornadoes per year in the U.S. kill, on average, 56 people and injure 975 with $855 million in property damage

B. Formation
1. The vast majority of all tornadoes, and virtually all destructive tornadoes (F2 or higher) are associated with supercell thunderstorms.....therefore, we will discuss the formation of tornadoes in supercells specifically
   a. Weak tornadoes can form along squall lines and within land-falling hurricanes
2. First important point: Not much is known about tornado formation....they are difficult to study because....
   a. They are rare
   b. Where they will occur is difficult to predict
      1. An environment conducive to supercell formation can usually be identified but....exactly where they will form is uncertain
      2. Also, only about 25% of supercells actually generate a tornado
   c. For obvious safety reasons, they are difficult to get close to
3. So....although there is observational data available, much of the theory of tornadogenesis is based upon computer models and theoretical physical studies
4. With that in mind.......a. One thing scientists have a pretty good handle on is what causes the updraft of the supercell thunderstorm itself to rotate (Figs. 4.35, 4.39 and 4.40)
   1. This rotating updraft is called a mesocyclone because it is associated with surface low pressure and the circulation is counterclockwise, just like a MLC except much smaller (meso scale)
2. The rotation develops because the vertical wind shear creates a rolling tube of air parallel to the ground which gets tilted vertically by the updraft (Figs. 4.39 and 4.40)

3. This mesocyclone is not the tornado....it is about 3 miles wide (tornadoes rarely are wider that 0.5 miles) and wind speeds are much slower than in a tornado

b. Tornadoes form within this mesocyclone....
   1. There are multiple theories but the lynchpin of all of them is **vortex stretching**
   a. It has been noted that tornadoes form when the downdrafts form an “occlusion” (like an occluded front) and surround the updraft, isolating it from its warm, low level air source (Fig. 4.41)
   b. The updraft decreases at low-levels but continues at robust speeds at mid and high levels
   c. This causes the mesocyclone to stretch vertically, becoming much narrower
   d. By the law of **conservation of angular momentum** (Fig. 4.42 and 4.43) the central part of the mesocyclone begins to spin much faster

2. There are three general theories of how this rapidly rotating column extends beyond the cloud base to the ground to form the tornado.....interesting, but not necessary to know the details....
   a. Dynamic pipe effect (Fig. 4.44)
   b. Tilting of the buoyancy gradient along the gust front (Fig. 4.45)
   c. **Vortex breakdown (Fig. 4.47)**
      1. There is observational evidence that this is how a thin tornado can develop into a very strong wide tornado with **suction vortices** which generate the strongest tornado winds (rotational speed plus translational speed) (Fig. 4.46)
      2. This process occurs because the surface low pressure becomes so low that hydrostatic balance breaks down and a downdraft develops at the center of the rotating updraft (Fig. 4.47)
      3. There is also evidence that a mesocyclone can sometimes generate a tornado in this way (the tornado in Fig. 4.47 is the mesocyclone in this case and the tornado is the suction vortex) [observed in formation of the “Garden city tornado” mentioned in the book]
c. Tornadoes are frequently only on the ground for several minutes but can be on the ground for up to an hour
   1. Tornado dies when cold gust front completely chokes off the updraft
   2. A single supercell can generate multiple tornadoes (tornado families) as new updrafts are generated to the southeast of the “occluded updraft” (Figs. 4.48 – 4.50)

B. Statistics
1. 75% of all tornadoes, and the vast majority of significant tornadoes (EF2 or greater....only 25% of all tornadoes) occur in the U.S. (Figs. 4.25 and 4.26)
2. Tornado classification scale (Figs. 4.51 and 4.52)
   a. Fujita (F) scale developed in 1971 to categorize tornadoes based upon severity
   b. Based upon the damage incurred by the winds
   c. Weakness of scale included an over-estimation of wind speeds
   d. “Enhanced” Fujita (EF) scale designed in 2007 as an attempt to more accurately categorize tornado severity
   f. A single tornado may produce different fujita scale damage in different sections and regions of its path
      1. Tornado categorized by the worst damage along its path
      2. Usually only small regions of an “EF5” tornado will incur that degree of damage (suction vortices)
   3. 2.3% of all tornadoes (EF4 and EF5) are responsible for roughly 70% of tornado deaths (Figs. 4.53 and 4.54)
4. Majority of tornadoes, particularly significant tornadoes occur in tornado alley, the southern Great Plains of the U.S. (Fig. 4.55 and 4.56)
   a. 56 F5/EF5 tornadoes since 1950, all in the Great Plains and Midwest (Fig. 4.57)
5. Majority of tornadoes occur between April and June (Fig. 4.58)
   a. When the tropical to polar temperature gradient (meridional) is still large (combination of strong jet streams and fronts) and surface heating is great enough to generate large amounts of environmental instability
   b. Peaks in different months in different regions of U.S. depending on mean location of jet stream (Fig. 4.59)
6. Tornadoes peak in late afternoon to evening (Fig. 4.60)
   a. Daytime heating builds up and breaks the capping inversion

C. Tornado detection and forecasting
1. Detection
   a. Storm spotters
      1. Folks on the ground that report evidence of a severe thunderstorm or tornado
   b. Radar hook echo (Figs. 4.36 and 4.37)
      1. Formed by precipitation in the “rear flank downdraft” wrapping around the precipitation free updraft
2. This radar signal is indicative of a **supercell thunderstorm...not a tornado. Remember, most supercells do not have tornadoes**

3. This is seen on **standard radar**...don’t need Doppler radar for this....before Doppler this was the only way to identify what thunderstorms had the potential to form tornadoes

c. **Doppler** radar (Figs. 4.61 and 4.62)

1. Detects rotation in a thunderstorm

2. **Mesocyclone** signature

   a. Circulation identified by evidence of wind moving away from the radar next to wind moving toward it (Fig. 4.61)

   b. This is evidence of the supercell’s updraft rotation (mesocyclone) not the rotation of the smaller tornado

   c. With doppler, forecasters can now warn people, on average, 12 minutes before a tornado forms

3. Tornado Vortex signature (TVS)

   a. Usually, tornado is smaller than the resolution of the radar beam and can’t be seen with doppler velocity image

   b. If large enough, can see a few pixels (smallest resolution.... “box” on the radar) of very high velocity away from the radar next to pixels with very high velocity toward the radar (Fig. 4.62)

2. Forecasting

   a. Storm Prediction Center (SPC... [http://www.spc.noaa.gov](http://www.spc.noaa.gov))

      1. Analyze conditions for the next 3 days to ascertain where supercell thunderstorms and tornadoes are most likely to form and what the probability is that they will form

      2. Utilize soundings (weather balloons) and computer model **forecast soundings** to assess the vertical structure of the atmosphere (Fig. 4.63)

         a. Can calculate indices based upon these soundings to guide where and how likely severe thunderstorms are

            1. Convective Available Potential Energy (CAPE)

               a. Measure of **instability** and thus the potential **strength of the updraft**

               b. On a sounding it is the difference between the environmental temperature line and the air parcel temperature line

               c. Measure of the kinetic energy that
buoyant air parcels will attain as they rise through the atmosphere

2. Storm-relative Helicity (SRH)
   a. Measure of vertical wind shear
   b. Potential for storm rotation

3. Energy Helicity Index (EHI)
   a. Combination of CAPE and SRH

VIII. Severe thunderstorm (see I. C. for definition) and tornado watches and warnings
   A. Watch.....conditions are right for formation
   B. Warning.....presently occurring, either observed by storm spotters or identified on doppler radar

IX. Tornado Impacts
   A. Death and destruction
   B. A picture is worth a thousand words.............
      1. Pictures and videos to be presented in class

X. Tornado Case Studies
   A. May 29, 1995 Great Barrington, MA F3 tornado
   B. May 4, 2007 Greensburg, KS F5 tornado
      1. These two cases presented by me in class

XI. Hail
   A. *Different than sleet*, these balls of ice are unique to thunderstorms
   D. Most hailstones are hard but can contain liquid and air bubbles and be relatively soft
   E. Hailstones > 1 inch relatively rare....largest recorded stone in Nebraska in 2003 (7 inches in diameter)
   F. Vast majority of damaging hail (3/4 inch or greater) occurs in supercell thunderstorms (Fig. 4.64)
   G. Formation (Fig. 4.65)
      1. Tiny cloud droplets are present within the supercell updraft region
      2. These droplets become *supercooled* between 0 and -15°C
      3. When reach the -15°C level form tiny ice crystals
      4. Majority of these ice particles are transported to the storm anvil
      5. Some ice particles at the periphery of the updraft (where it is weaker) fall and grow by collecting supercooled droplets and becoming *graupel (1 – 5 mm snowballs)*
      6. These graupel particles than fall back into the updraft
      7. These particles then spiral upward around the periphery of the updraft collecting supercooled droplets and growing
      8. Eventually are carried to the northeast edge of the updraft (by the southwesterly winds) where they become heavy enough to fall out of the slanted updraft to the ground
         a. Hail, therefore, tends to fall to the east/northeast of any tornado
location (Figs. 4.65 and 4.66)

I. Detection....radar reflectivity > 60 dBZ but this is non-specific

H. Impacts

1. Can cause tremendous amount of crop and structural damage as well as livestock deaths
   a. Note that the majority of large hail falls in the “bread belt” (Fig. 4.64)
   b. This impact is notable as well in Europe and South Asia (e.g. Bangladesh)

2. Human deaths relatively rare but significant injuries can occur

3. Property damage
   a. Cars, homes, businesses

XII. Global Warming and Supercell Thunderstorms/Tornadoes

A. Supercell thunderstorms and tornadoes form in a very complex and poorly understood manner. Many extreme conditions need to occur simultaneously. Climate models do not have the spatial or temporal (space or time) resolution to simulate these relatively small and complex features. For this reason, any prediction for change in number and intensity of these storms with global warming is speculative. The IPCC was particularly vague about these events in the 2007 report. We can, however, take a look at the change in number and intensity of tornadoes over the past several decades of global warming. In addition, as we did with ECs, we can look at the conditions necessary for supercells and tornadoes to form and assess whether global warming should make these conditions more or less likely.

B. Recent tornado history (Figs. 4.67 – 4.69)

1. There has been an increase in reported tornadoes in the U.S. since 1950 (Fig. 4.67)
   a. However, this increase has been almost exclusively due to an increase in F0 and F1 tornadoes and is most likely because of a marked increase in tornado awareness and storm spotters

2. There has been a decrease in violent (F3 – F5) tornadoes in the U.S. since 1950 (Fig. 4.68)

3. There has been a marked decrease in U.S. tornado deaths since the early 20th century (Fig. 4.69)
   a. This is most likely due to increased tornado awareness, improved tornado forecasting and warning systems, and better construction (higher percentage of houses with storm cellars)

C. Likely change in atmospheric conditions necessary for supercell/tornado formation in a warmer world

1. Lift, instability and vertical wind shear are all related to meridional temperature contrast in the atmosphere
   a. We have already concluded that this contrast has diminished and is likely to continue to decrease with increasing global warming

2. Low-level moisture is likely to increase as saturation vapor pressure
and dewpoints rise with increasing surface temperatures

3. Bottom line: **Global warming generally favors a decrease in the conditions necessary for tornado formation**

D. Conclusions

1. There has been a *decrease* in violent tornadoes with global warming to this point
2. Global warming generally favors a *decrease* in the conditions necessary for tornado formation
3. These two findings *suggest* that there *may be a decrease*, but certainly not a marked increase, in supercells and tornadoes with *future global warming*. However........
4. *Given the scale and complexity of tornado formation, as well as our limited understanding of their behavior, any projection of change in number and intensity of these features in the warmer climates of the future is speculative at best*
### Fig. 4.11

Environmental Lapse Rate Is... | Environment Is... | Means What?
--- | --- | ---
Less than saturated adiabatic lapse rate | Absolutely stable | No parcels keep rising
Greater than dry adiabatic lapse rate | Absolutely unstable | All parcels keep rising
Less than dry adiabatic lapse rate and greater than saturated adiabatic lapse rate | Conditionally unstable | Only saturated parcels keep rising

### Fig. 4.12

### Fig. 4.13
Fig. 4.23

Fig. 4.24

Fig. 4.25

Fig. 4.26
Fig. 4.30

Fig. 4.31

Fig. 4.32
Fig. 4.41

Fig. 4.42

Conservation of Angular Momentum and Tornado Winds

\[ r = \text{radius}, \ \nu = \text{rotational velocity} \]

\[ r(\text{meso}) \times \nu(\text{meso}) = r(\text{wall}) \times \nu(\text{wall}) = r(\text{tornado}) \times \nu(\text{tornado}) \]

\[ 4000 \text{ m} \times 2.5 \text{ m/s} = 1000 \text{ m} \times 10 \text{ m/s} = 100 \text{ m} \times 100 \text{ m/s} \]

Fig. 4.43

Fig. 4.44
### Table 11.3 The Fujita Scale for Tornadoes

<table>
<thead>
<tr>
<th>Category</th>
<th>Damage</th>
<th>Wind Speed Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>F0 Light</td>
<td>Tree branches broken; heavy damage to crops; chimneys damaged.</td>
<td>64–118 km/hr</td>
</tr>
<tr>
<td>F1 Moderate</td>
<td>Trees uprooted, some snapped; mobile homes overturned; moving cars pushed off road.</td>
<td>119–181 km/hr</td>
</tr>
<tr>
<td>F2 Considerable</td>
<td>Large trees uprooted and snapped; mobile homes destroyed; roofs torn off houses; railroad boxcars pushed off track.</td>
<td>182–253 km/hr</td>
</tr>
<tr>
<td>F3 Severe</td>
<td>Most trees in a forest uprooted or snapped; walls torn off well-constructed frame houses; trains overturned; autos lifted off ground and moved.</td>
<td>254–332 km/hr</td>
</tr>
<tr>
<td>F4 Devastating</td>
<td>Trees debarked by flying debris; well-constructed frame houses leveled; autos thrown some distance.</td>
<td>333–419 km/hr</td>
</tr>
<tr>
<td>F5 Incredible</td>
<td>Trees completely debarked; strong frame houses lifted off foundations and demolished over some distance; steel-reinforced concrete structures badly damaged; autos become missiles and fly distances of 100 meters.</td>
<td>420–513 km/hr</td>
</tr>
</tbody>
</table>

Fig. 4.51

<table>
<thead>
<tr>
<th>Fujita Scale</th>
<th>3-second gust speed (mph)</th>
<th>Operational Enhanced Fujita Scale</th>
<th>3 Second Gust Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F0</td>
<td>45-78</td>
<td>EF0</td>
<td>65-85</td>
</tr>
<tr>
<td>F1</td>
<td>79-117</td>
<td>EF1</td>
<td>86-110</td>
</tr>
<tr>
<td>F2</td>
<td>118-161</td>
<td>EF2</td>
<td>111-135</td>
</tr>
<tr>
<td>F3</td>
<td>162-209</td>
<td>EF3</td>
<td>136-165</td>
</tr>
<tr>
<td>F4</td>
<td>210-261</td>
<td>EF4</td>
<td>166-200</td>
</tr>
<tr>
<td>F5</td>
<td>262-317</td>
<td>EF5</td>
<td>&gt; 200</td>
</tr>
</tbody>
</table>

Fig. 4.52
Fig. 4.53

Percent of Tornado Related Deaths 1950–1994 by Fujita Scale Class

- Weak F0-F1*: 67%
- Strong F2-F3: 29%
- Violent F4-F5: 4%

Fig. 4.54

Fig. 4.55
Fig. 4.60

Fig. 4.61

Fig. 4.62
Fig. 4.63

Fig. 4.64

Fig. 4.65

Fig. 4.66
Fig. 4.67

Fig. 4.68

Fig. 4.69