1. **Raindrops, Graupel and Hail**
   1) Formation of raindrops [continues]
      a) Condensation (simple, but quite slow)
      b) Collision and coalescence (fast, more details in Mid-term1 study Guide)
      c) Ice crystal process (i.e. Bergeron-Findeisen Process)
         - Another way of growing rain drops quickly
         - Ice in the clouds
           T > -10°C, almost no ice crystals
           -40°C < T <-10°C, mixed ice and liquid droplets
           T <-40°C, all ice
         - Ice crystal process becomes active when both ice and liquid water (super-cooled liquid) are present
           Supercooled water: liquid water that exist below 0 °C. The liquid needs to get to –40°C to ensure freezing will happen rapidly without the help of an ice nucleus.
           Ice Nuclei (IN): particles (e.g. clay particles, plant material) help form ice crystals from water droplets by providing seed to start crystal growth. Ice Nuclei is rare compared to CCN and most are not active at temperatures warmer than –10 °C.
         - Net transfer of water-vapor molecules from liquid droplets to the ice. Saturation vapor pressure over the super-cooled liquid water exceeds the saturation vapor pressure over the ice at the same temperature. Ice grows rapidly because the air is supersaturated with respect to ice.
         - Example: Aircraft Icing
         - Snow Melts to form rain: when ice crystals or snow get large(heavy) enough, they fall down and form rain. Outside the tropics, almost all precipitation starts as ice crystals or snow.
           Collisions help falling ice crystals grow large→ Graupel and hail
   2) Graupel:
      a) formed by riming (falling ice crystals grow by collecting liquid droplets)
      b) white, lightweight and crunch because air is trapped within the ice
   3) Hail [grow beyond graupel]
      a) Layered Growth: White layers: new ice froze instantly when it contacted the stone (air trapped, light) Clear ice: water freezes slowly when it contacted the stone (dense ice)
      b) Terminal Fall speeds of hail depends on the its size
      c) Hailstone can grow by circulating within the thunderstorm clouds until it is too large for clouds to hold and falls to ground
      d) Hail Records
2. **Thunderstorms [continues]**
   1) Types of thunderstorms
      a) Single cell ("air mass") – generates lightning, rain, downburst [Mid-term1]
      b) Multi-cell - seldom makes tornadoes
      c) Supercell - long-lived, often severe, associated with most strong tornadoes

2) What determines the type of thunderstorms?
   a) CAPE
   b) Low level wind shear (the change of wind speed and direction with height in the lowest 5 km of the atmosphere)
      - Single cell: weak low-level wind shear
      - Multi-cell: moderate low-level wind shear
      - Supercell: strong low- level wind shear

   Low level wind shear helps multi-cell and supercell last longer (extending the lifetime beyond that of a single cell storm)
3) Multi-cell thunderstorms
   a) A "group" or "family" of single cells at various stages of their life cycles.
   b) Multi-cell thunderstorms live longer because low-level wind shear keeps the cold pool from surging out to cutoff the updraft
   c) Low level wind shear is able to keep the gust front near to the storm updraft by moving the thunderstorm clouds with the cold pool. This triggers new convection close enough to the old cells that they can interact each other and form a Multi-cell thunderstorm.
      No wind shear → cold pool cuts off updraft
      With wind shear → clouds may move at the same speed as the gust front
4) Supercell thunderstorms
   a) Severe hail, violent tornadoes, high lightning flash rates
   b) Long-lived (because wind shear separates the cold pool and the updrafts)
   c) Distinguishing property: strong rotation in the updraft
   d) What is special about supercell environments?
      - Decent but not unusually large CAPE
      - Strong vertical wind shear (both low-level and the deep-layer)

      Low-level wind shear
         → helps separate the rain and the updrafts

      deep-layer wind shear
         → also helps to move the precipitation away from the updraft
         → interacts with the updrafts to produce important pressure variations throughout the storm and add upward directed pressure forces to the updraft. The upward pressure forces enhance updraft in addition to buoyance of warm air.
   e) Some characteristics: Overshooting top; Anvil; Wall cloud, etc.
   f) Key tool in identifying and studying supercell observation: Doppler radar
      Radar features [should be able to recognize them on a radar picture]:
      - <u>Hook echo</u>: a hook-shaped signature as part of some supercell thunderstorms in the radar reflectivity images. A hook is often associated with a mesocyclone and indicates favorable conditions for tornado formation. The low reflectivity region inside the hook lies within the updraft.
      - <u>Bounded Weak Echo Region</u> (BWER): some regions within the strong updraft turn to have low reflectivity, i.e., because air is rising too fast,

therefore precipitation is also held aloft, and cloud droplets do not have time to grow

- Velocity couplet: adjacent pixels have sharply different velocities, typically with one inbound and one outbound. It can indicate rotation in a storm.
- Debris ball: usually associated with a tornado, may be present at the end of the Hook.

All supercells have mesocyclones, but only a few mesocyclones make tornadoes

3. **Tornado**

1) Definition:
   a) A violently rotating column of air
   b) In contact with the ground
   c) Connecting up to the cumulus cloud
   d) Often (but not always) visible as a funnel cloud
2) Tornado intensity: Enhanced Fujita (EF) scale
   a) Based on the damage to estimate winds (because there no practical way to measure the wind speed in most tornados)
   b) EF 0 (weak) --- EF5 (strong)
3) What makes tornado
   a) In brief: initial rotation ⇒ air gets sucked into updraft ⇒ rotation speeds up
   b) When a fluid is stretched vertically in an updraft, initial rotation intensifies.
   c) This is due to conservation of angular momentum
   d) Other examples: Dust Devil (swirling motion on hot days)
4) Two types of tornado
   a) Non-mesocylonic tornadoes
      - Source of initial rotation: horizontal wind shear
        … also true for waterspouts, landspouts (develops along a shear line)
      - Horizontal wind shear is present when the wind speed varies with horizontal position in the direction perpendicular to the wind itself. Horizontal wind shear → Shear instability
   b) Mesocyclonic tornadoes (requires a supercell)
      - Source of initial rotation: vertical wind shear (stronger)
      - Initial rotation is about a horizonal vortex line, which then tilted into a vertical vortex line by updraft, giving rotation about a vertical axis
      - Vortex line: Lines directed along the axis about which fluid would turn a paddle wheel.
      - Strom splitting: falling precipitation the initial updraft splits the storm into an anti-symmetric pair of developing supercells.
      - Direction: cyclonic (counterclockwise, in NH) rotation dominates
        Because typical vertical wind shear conditions create an upward pressure force that favors the cyclonically rotating storm (right mover).
5) Tornado Damage and Safety
   a) Severe damage: suction vortices

b) Tornado Watch vs Tornado Warning
"Watch": conditions are expected but not occurring or imminent
"Warning": conditions are occurring or imminent
c) The biggest danger is flying debris. How to avoid them?
Stay away from window; cover yourself with protection; go to the basement
d) Encountering a tornado while you are driving: drive away at right angles to its path; seek shelter; if trapped in the car, take cover there with seat belt on
e) Do not shelter under an overpass (e.g. bridge)

6) Tornado climatology
   a) Global distribution --- hot spots in US, South America, Southern China
   b) US
      - Distribution per state: Texas, Oklahoma, Kansas, Nebraska, Colorado…
      - Time of day: e.g. late-afternoon in Kansas due to max. low-level heating
      - Nocturnal Tornadoes Distribution
      - Seasonal Distribution: spring, autumn
7) Tornado Adaptation: upgraded building codes; storm cellar, safe room, etc.

4. **Hurricane**

1) Clarification on definition

Hurricane and Typhoon all refer to tropical cyclone, the only difference between a hurricane and a typhoon is the location where the storm occurs.
[Hurricane: Atlantic Ocean and northeastern Pacific Ocean; Typhoon: northwestern Pacific Ocean; in the south Pacific or Indian Ocean, comparable storms are referred to simply as "tropical cyclones" or "severe cyclonic storms"]

2) Mid-latitude cyclone VS tropical cyclone

	Mid-latitude cyclone	tropical cyclone
Shape	No circular symmetry	circular symmetry
Eye	No eye	with eye
Fronts	Does have fronts	
Winds	Has strong winds aloft near the jet stream	maximum wind speed near the surface around the eyewall
Powered by	horizontal temperature differences	latent heat released in thunderstorms

3) Hurricane intensity: Saffir-Simpson scale
   a) Scale from 1 to 5 rating based on measured/estimated wind speed
   b) Wind values are averaged over 1 minute, at a height 10 m above the surface.
4) Basic structure
   a) Circular symmetry
   b) Eye: clear area in the center (but not always clear)
   c) Eyewall: clouds immediately surrounding the eye (highest winds & rain)

d) Spiral rain bands: outer raining areas
e) Inflow at the surface but outflow aloft
f) Air sinks in the center of the eye, but updrafts in the eye wall
g) The eye of a hurricane aloft is warmer than its surroundings
h) Minimum surface air pressure at eye. Maximum surface wind speed at eyewall.

5) Rotation in hurricane
   a) Caused by Coriolis force
   b) Coriolis force turns wind to the right in NH, and to the left in SH
   c) Hurricanes are **all** counterclockwise in NH, **all** clockwise in SH
6) Hurricane climatology
   a) Hurricanes occur over the warmest water
      e.g. most intense in the West Pacific; almost none in SE Pacific
   b) No hurricanes at the equator (very weak Coriolis force)
7) Hurricane damage
   a) High winds
   b) Storm surge
   c) Flooding, heavy rainfall
8) Why do hurricanes exist?
   a) To keep the tropics from getting too warm as a result of the solar heating
   b) Hurricanes cool the tropics by cooling tropical ocean surface via evaporation
   c) Hurricanes warm the extratropics via releasing latent heat there
   d) Heat is ultimately lost to space via thermal radiation

<u>Miscellaneous</u>

1. Doppler radar

1) How does it work?
   Radar sends out pulses and receives the return signals.
   - <u>Reflectivity</u> measures the strength of the return signals.
     Stronger signal is from bigger targets.
   - <u>The Doppler velocity</u> measures the speed of the target along the line back to the radar (i.e. toward or away from the radar)
2) What does it detect?
   Raindrops, hail, snow, birds, building…etc. (but it cannot "see" vapor!)
3) If Doppler radar sees hook echo (reflectivity) and Doppler Velocity Couplet, is it seeing tornadoes?
   No. The tornado is too small and too fast to be seen by the radar.
   The radar is picking up the larger rotating updraft, the mesocyclone.
4) Some regions within the strong updraft turn to have low reflectivity, why?
   Because air is rising too fast, such that precipitation is also held aloft, and cloud droplets do not have time to grow $\Rightarrow$ Bounded Weak Echo Region (BWER)

2. Different types of tornadoes

Types	**Non-mesocyclonic tornadoes**	**Mesocyclonic tornadoes**

Requirement	Any thunderstorm (or even deep cumulus) may generate	supercells (mesocyclone)
Strength	weaker	Strong and violent
Initial rotation	Horizontal wind shear	Vertical wind shear
	Waterspouts, landspouts	

3. Tornado VS hurricane

Type	**Tornado**	**Hurricane**
Where they form	Mostly over land	Over tropical warm ocean water
Spatial scale	No more than ¼ mile wide	Up to several hundred miles
Time scale	No more than an hour	Can last up to 3 weeks
Source of Rotation	Wind shear (horizontal or vertical)	Coriolis force
Rotation direction	Cyclonic rotation dominates Sometimes anticyclonic	Counterclockwise in NH Clockwise in SH
Intensity	Enhanced Fujida scale (use damage to estimate winds)	Saffir-Simpson scale (use winds to estimate damage)

4. How does Coriolis force affect wind direction in hurricane?

1) Winds always tend to move toward low pressure and hurricanes are always low-pressure centered
2) Coriolis force turns winds to the right in NH and to the left in SH
3) This is why hurricanes are counterclockwise in NH, clockwise in SH
4) Coriolis force exists because we are looking at motions in a rotating frame of reference (the Earth)
5) Coriolis force has a major impact on motions that take place over times comparable or longer than the period of the Earth's rotation (many hours).
6) Coriolis force does not affect tornadoes (and also drains), because their time scales are too fast compared to the rotation of the Earth