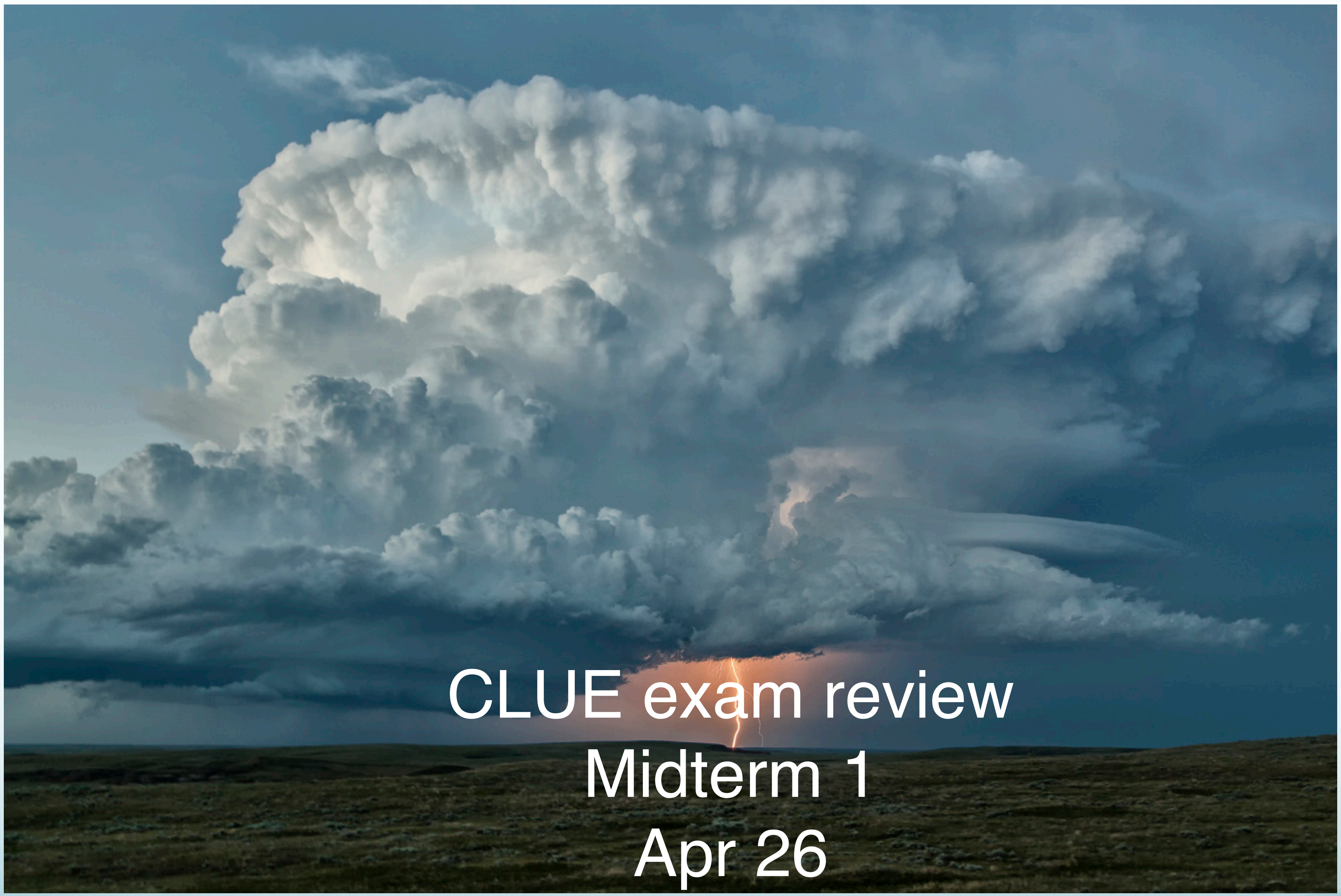
ATM S 103

Hurricanes and Thunderstorms



CLUE exam review

Midterm 1

Apr 26

Midterm 1: Wednesday May 1

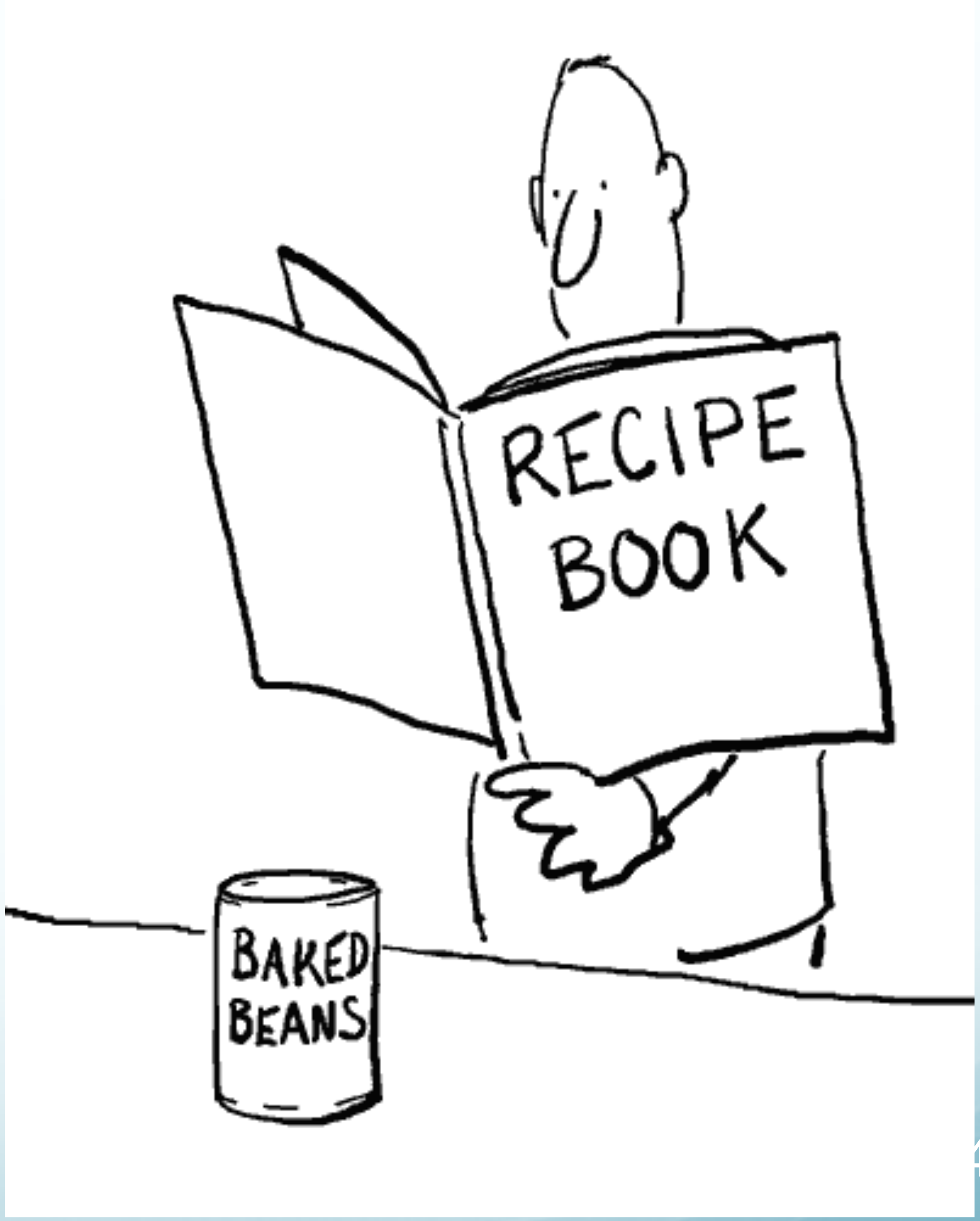
- Bring a Scantron form
- Closed book, notes, electronics
- 30 multiple choice questions (similar to homework)
- Covers
  - Homeworks 1-3
  - Lectures through today
  - Reading weeks 1-4

Outline

- Review lectures slides & selected homework questions [~50min]
- Q&A [~40min]

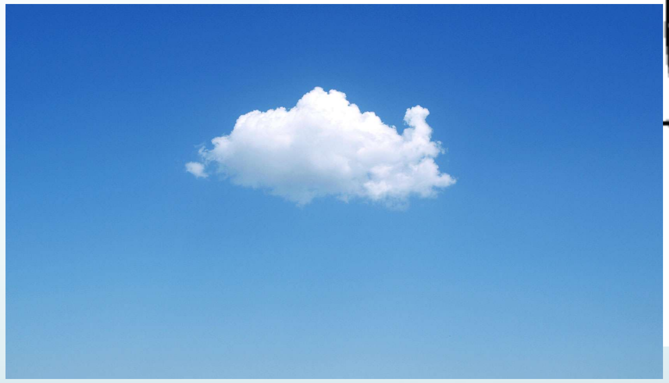
Four Main Recipes

- How to make clouds?
- How to make thunderstorm?
- How to make lightning?
- How to make a raindrop?



Ingredients for making a cloud

- **Water vapor**
  - High humidity means high dew point
- Cooling
  - Cooling air down to the dew point means the relative humidity is 100%
- Cloud condensation nuclei
  - It helps if the water has something to stick to
  - Makes the cloud more visible too



Water in the Atmosphere

Three states of water

Water vapor is invisible!

Vapor (gas): all bonds between molecules are broken

Liquid: some broken bonds between molecules

Ice (solid): almost no bonds broken between molecules

Change in temperature and energy between different states

Vapor

No bonds

Condensation →

← Evaporation

Liquid

Some bonds

Latent Heat

- The heat input required to break molecular bonds
- If bonds reform, the same amount of heat is released.

Change in temperature and energy between different states

Vapor

No bonds

Latent heat is released
Condensation →

← Evaporation
(Latent heat is absorbed)

Liquid

Some bonds

Latent Heat

- The heat input required to break molecular bonds
- If bonds reform, the same amount of heat is released.

Change in temperature and energy between different states

Vapor

No bonds

Latent heat is released
Condensation

→

←

Evaporation
(Latent heat is absorbed)

Liquid

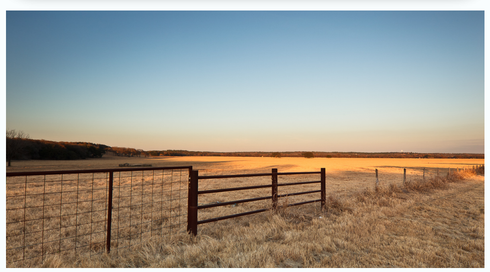
Some bonds

e.g.1. Evaporation: Sweat cools your body

e.g.2. Condensational heating

Cloud formation: phase change of water

Water vapor → Condensation → **Liquid**



- Condensation occurs when the air parcel is "**saturated**"
- What do we mean by an air parcel is **saturated**?

Saturation

- An air parcel is saturated when its vapor pressure exceeds its saturation vapor pressure.
- Or, its relative humidity becomes greater than 100%.
  - the ratio of actual vapor pressure to saturation vapor pressure (times 100%)
  - the ratio of water vapor content to water vapor capacity (expressed in percent)

$$\text{Relative humidity} = \frac{\text{(actual) Vapor pressure}}{\text{Saturation vapor pressure}} \times 100$$

- Or, its temperature reaches dew point

Measures of Humidity

Comparing two equal-sized volumes of air, we use

- *Relative humidity (in %)* to determine which is closer to saturation
- *Dew point (in ^{o}C or ^{o}F)* to determine which holds more water vapor molecules

Relative Humidity

$$\textbf{Ralative Humidity} = \frac{\textbf{Actual vapor pressure}}{\textbf{saturation vapor pressure}} \times 100\%$$

- It tells you how close the air is to saturation
- It depends on both humidity and temperature

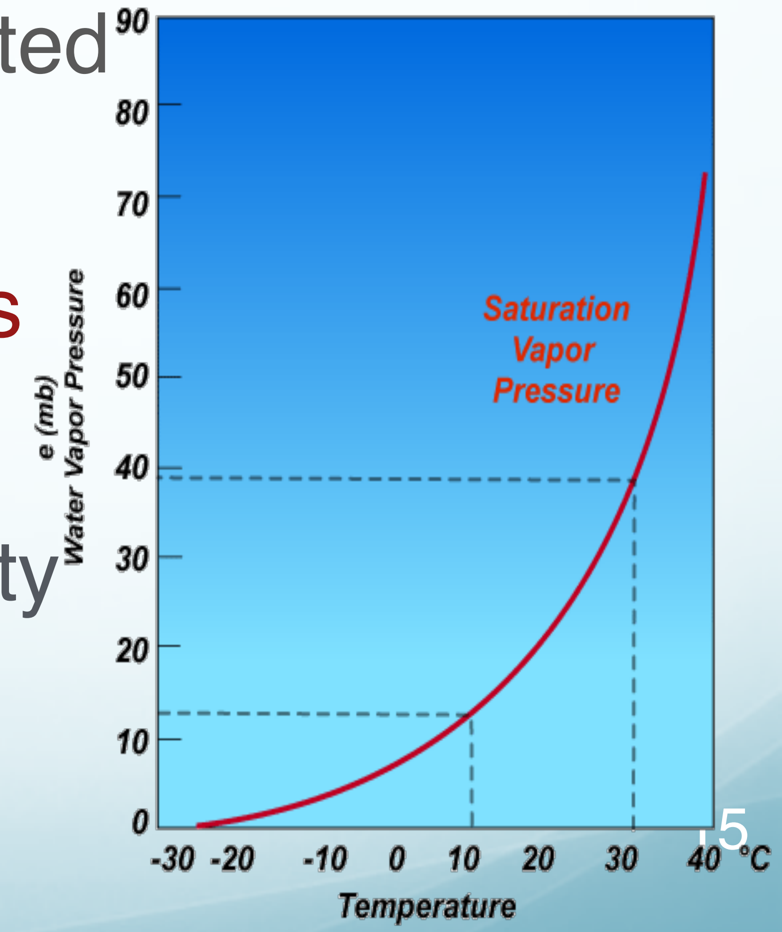
RH decreases if air is heated without adding or removing water vapor.

- Why do we care about relative humidity?

clouds are formed by processes that bring RH in previously unsaturated air to 100%

$$\textbf{Ralative Humidity} = \frac{\textbf{Actual vapor pressure}}{\textbf{saturation vapor pressure}} \times 100\%$$

- Vapor pressure: The net force per unit area exerted by molecules of water vapor in a parcel of air.
- Saturation vapor pressure: the pressure exerted by water vapor when the air is saturated.
  - It depends only on temperature(increases rapidly with temperature)
  - It doesn't tell you about the actual humidity



Dew point

- Is the temperature to which air must be cooled, without changing the pressure or the number of water vapor molecules, to cause saturation.
- It tells us how much water vapor molecules the air holds
- Depends only on the amount of actual water vapor: a higher dew point means a higher number of water vapor molecules
- Can be used to compare the mass of water vapor in two equal-volume parcels having the same pressure.

Measure of humidity

- 1. Relative humidity (ratio)
- 2. Dew point (temperature)

But it's not a function of temperature!

- Saturation vapor pressure… is not a measure of current humidity!

Attempts: 137 out of 141

+0.45

Discrimination Index ?

For a parcel of air at a given pressure, which of the following is the best indicator of the total number of water vapor molecules in the parcel?

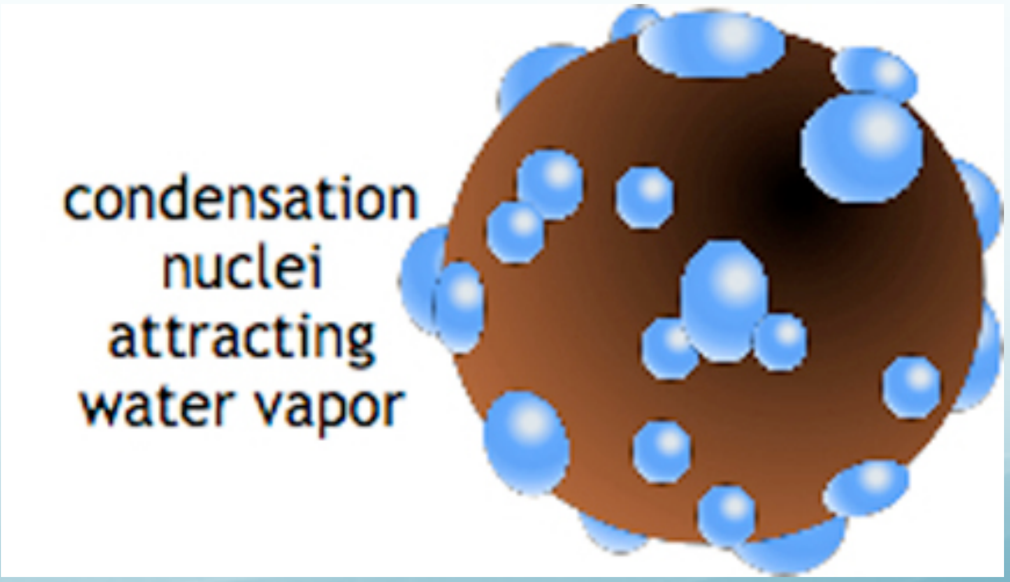
temperature	6 respondents	4 %
dew point ✓	80 respondents	**57 %**
relative humidity	37 respondents	26 %
saturation vapor pressure	14 respondents	10 %
No Answer	4 respondents	3 %

Ingredients for making a cloud

- Water vapor
  - High humidity means high dew point
- Cooling
  - Cooling air down to the dew point means the relative humidity is 100%
- **Cloud condensation nuclei**
  - It helps if the water has something to stick to
  - Makes the cloud more visible too

Cloud Condensation Nuclei

- Water vapor condenses into liquid more easily if the droplet is larger than a few molecules.
- Water vapor condenses on tiny particles of sand, dust, smoke, sea salt, …
  - These are cloud condensation nuclei (CCN)

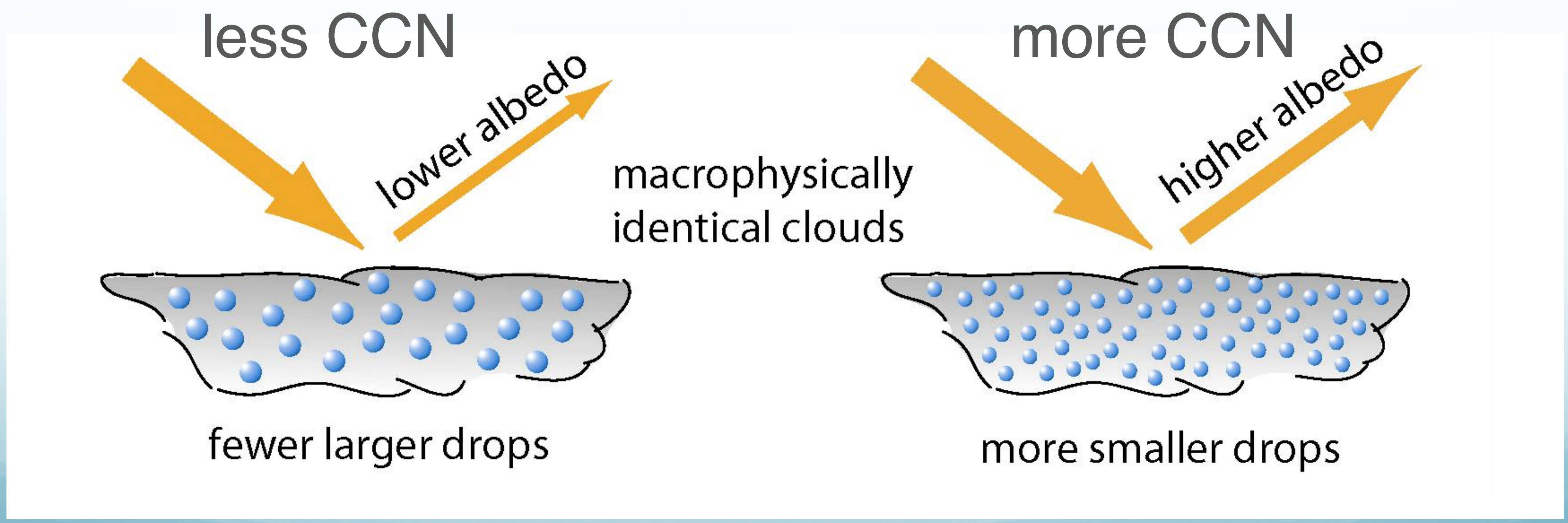


Why CCN is important?

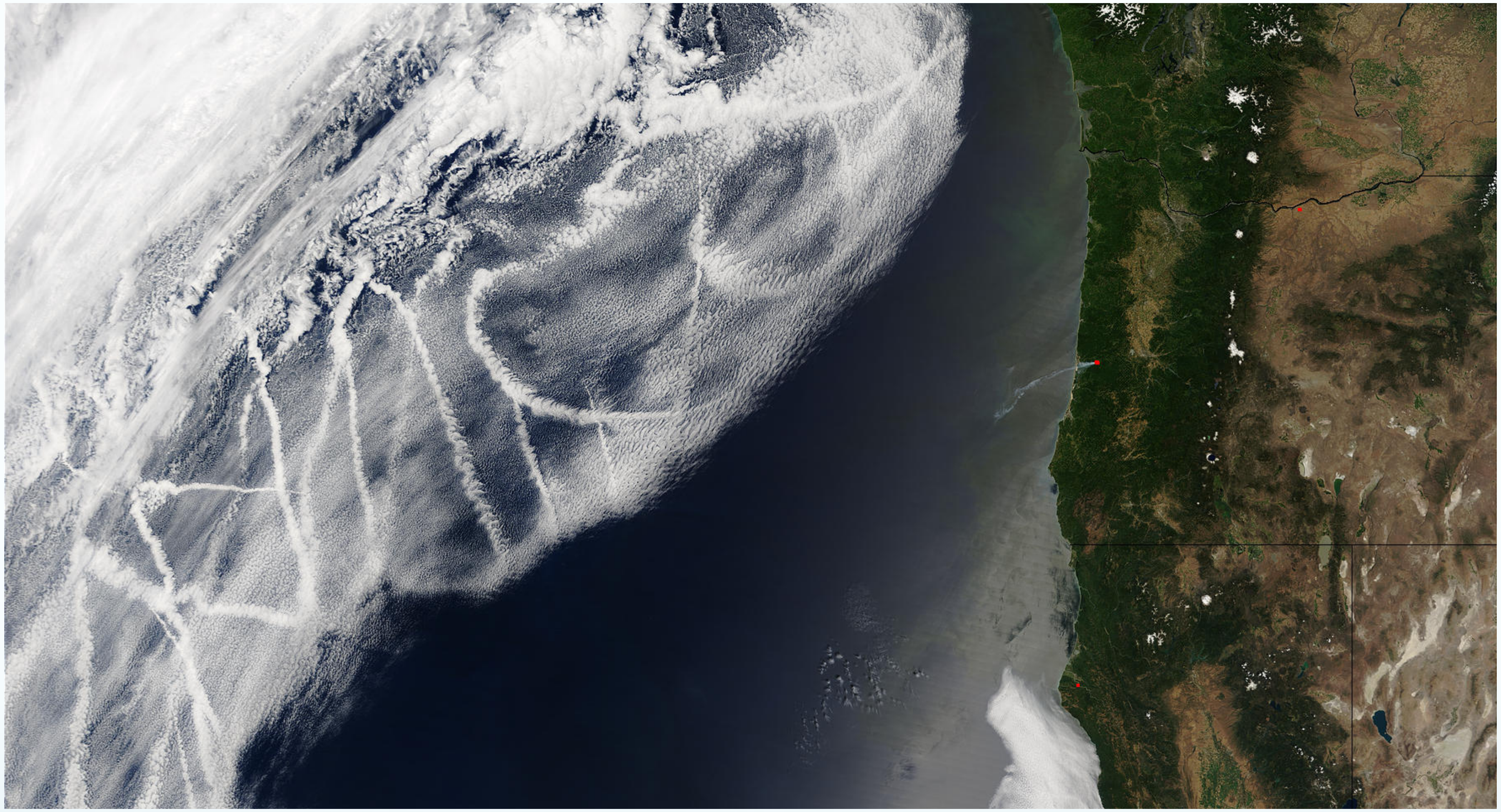
- There are always enough CCN present to ensure that water vapor condenses into liquid droplets as soon as the air saturates.
- But the same is not true for … Ice nuclei (IN)!

More CCN means visually thicker clouds

- Clouds are harder to see through when their liquid water is distributed among lots of smaller droplets instead of a few larger droplets.
- This happens when there are more cloud condensation nuclei (CCN).



More CCN means visually thicker clouds



- when there are more cloud condensation nuclei (CCN), Clouds are harder to see through (thicker)

Ingredients for making a cloud

- Water vapor
  - High humidity means high dew point
- **Cooling**
  - Cooling air down to the dew point means the relative humidity is 100%
- Cloud condensation nuclei
  - It helps if the water has something to stick to
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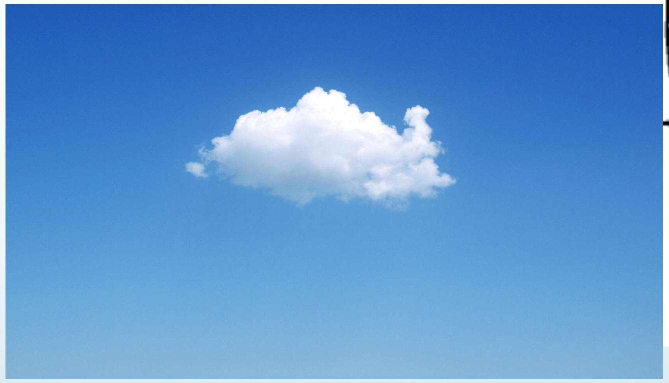


Adiabatic cooling & Buoyancy

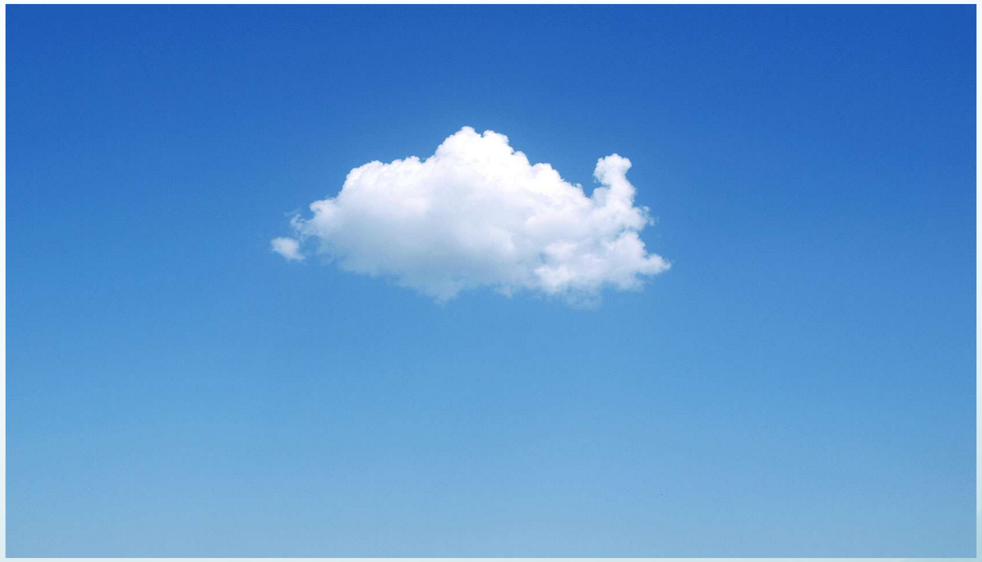
- How/when do clouds form?
- Why does rising air cool?
- When does an air parcel rise?

When do clouds form?

Most clouds form when air is cooled without adding water vapor and condensation start to happen

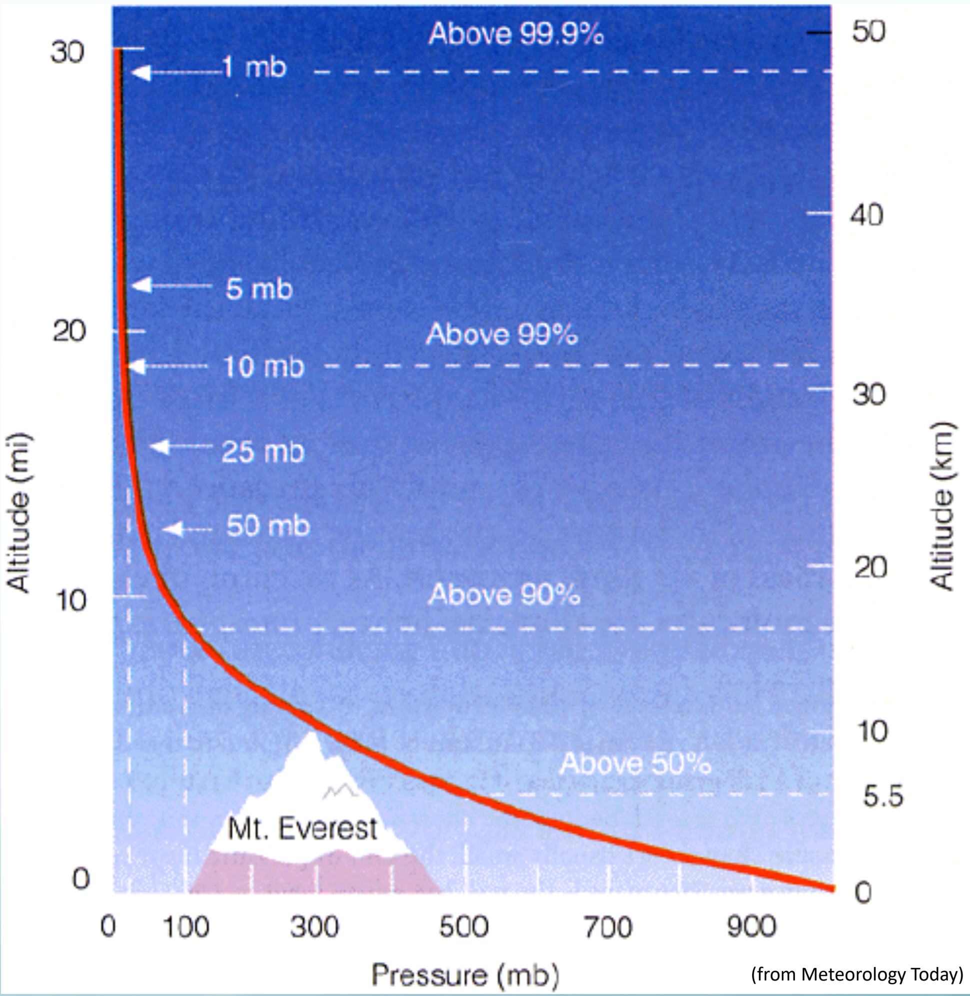
Condensation

- Clouds from when air is cooled to saturation (RH = 100%)
- The cooling occurs as the air rises



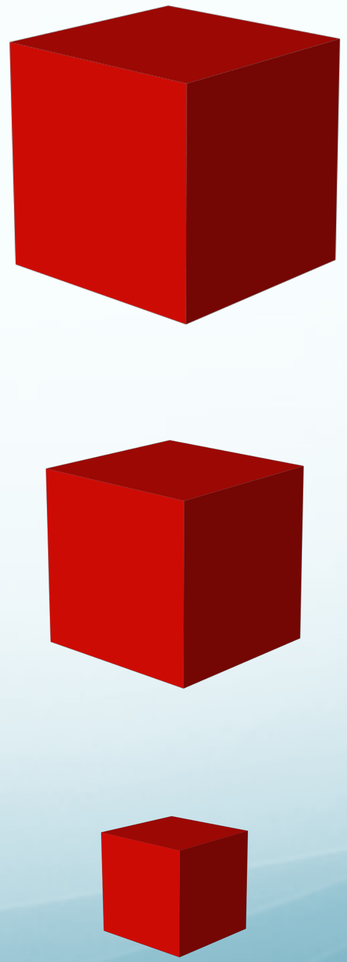
Why does rising air cool?

- Rising air cools due to changes in its pressure.
- Pressure decreases with height in the atmosphere.



Why does rising air cool?

- Rising air cools due to changes in its pressure.
- Pressure decreases with height in the atmosphere.
- When you lift an air parcel…
  - Parcel expands
  - The temperature drops



Why does rising air cool?

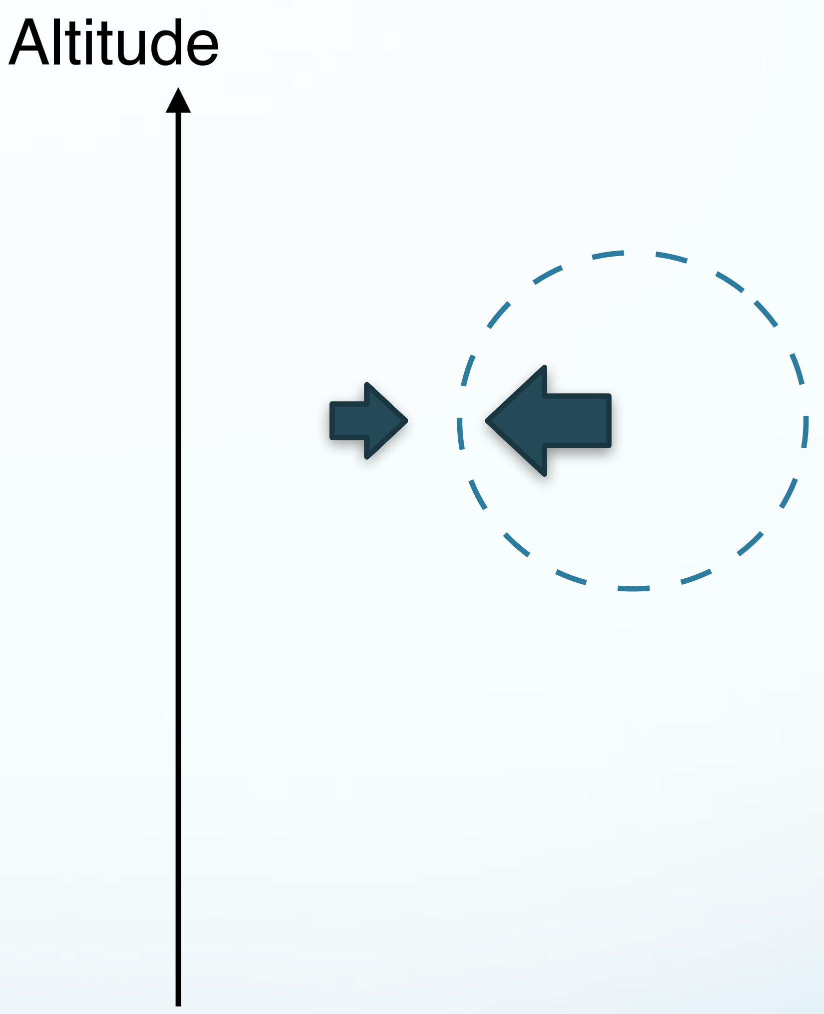
Air Parcel

- Think about blobs of air moving relative to the background atmosphere.
- Pressure inside the parcel is equal to that outside

Why does rising air cool?

Rising Air Parcel

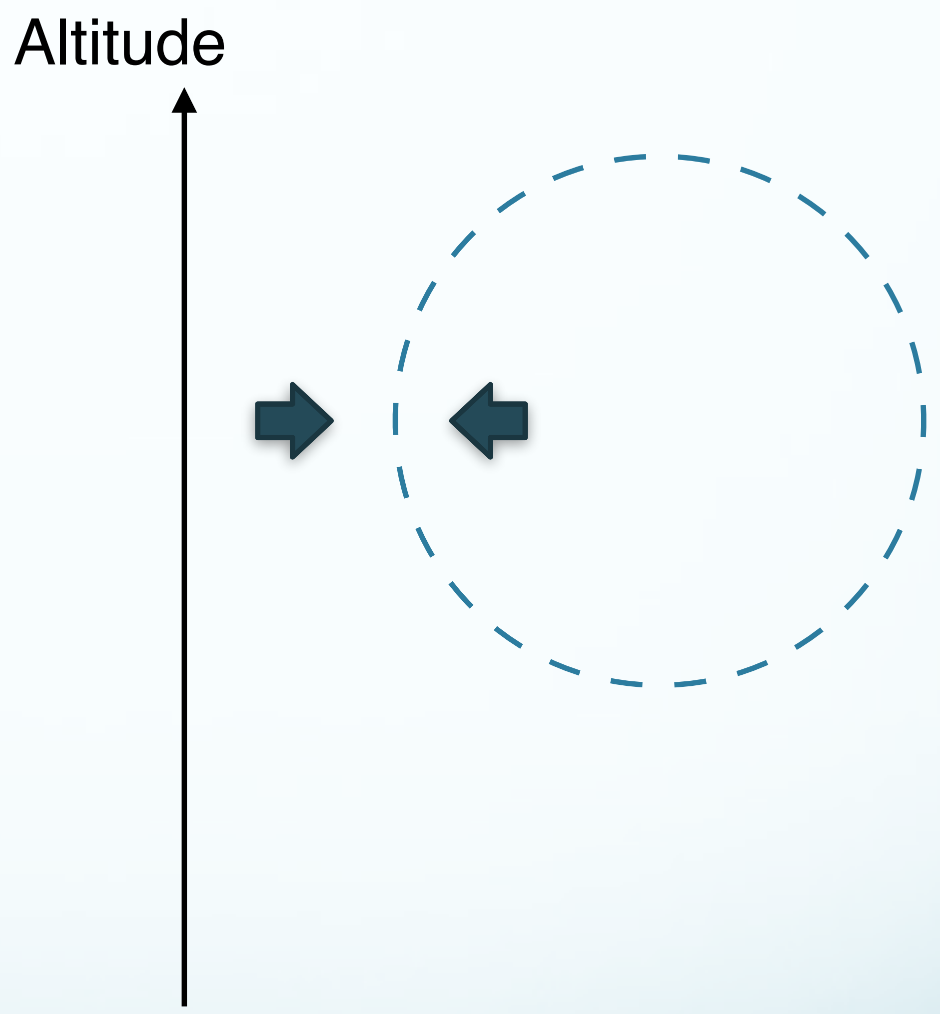
- An air parcel near ground heated by the sun can become warm enough to rise like a hot air balloon.
- The pressure pushing in on the 'surface' of the air parcel decreases as it rises.



Why does rising air cool?

Rising Air Parcel

- An air parcel near ground heated by the sun can become warm enough to rise like a hot air balloon.
- The pressure pushing in on the 'surface' of the air parcel decreases as it rises.
- The parcel expands until the pressure inside the parcel becomes the same as the outside pressure again



- Air molecules move more slowly as they bounce off the expanding 'surface' of the parcel
- Parcel temperature (proportional to the speed of the molecules) drops

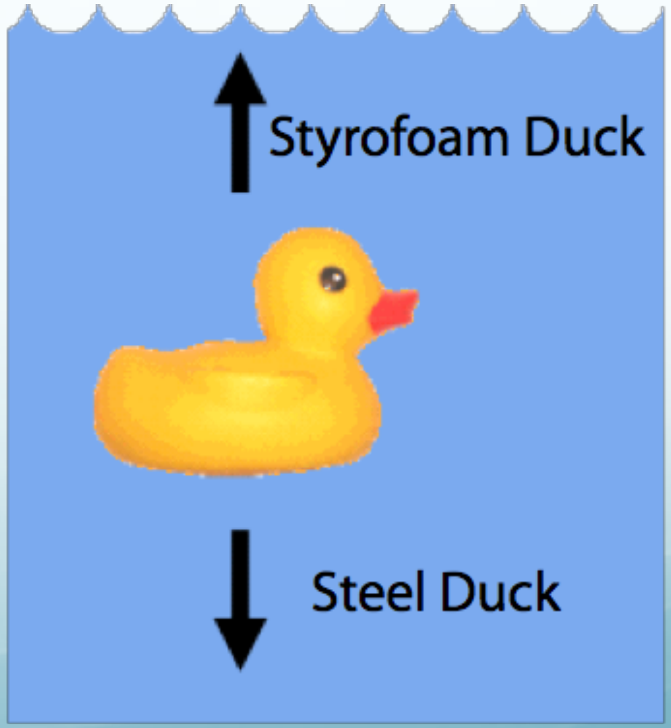
Why does rising air cool?

- Rising air cools due to changes in its pressure.
- Pressure decreases with height in the atmosphere.
- When you lift an air parcel…
  - Parcel expands
  - The temperature drops -the cooling rate is called lapse rate (more about this later)

When does an air parcel rise?

when its density is lower than the surrounding air

- *Density* and *Buoyancy*
- Objects (or fluid parcels)
  - *Less dense* than surrounding fluid *float upward*.
  - *More dense* than surrounding fluid *sink downward*



How is temperature related with density and buoyancy?

- *Warmer, Less dense, positively buoyant*
- *Colder, more dense, negatively buoyant*

- Gas law

$$p = \rho RT$$

pressure — density — temperature

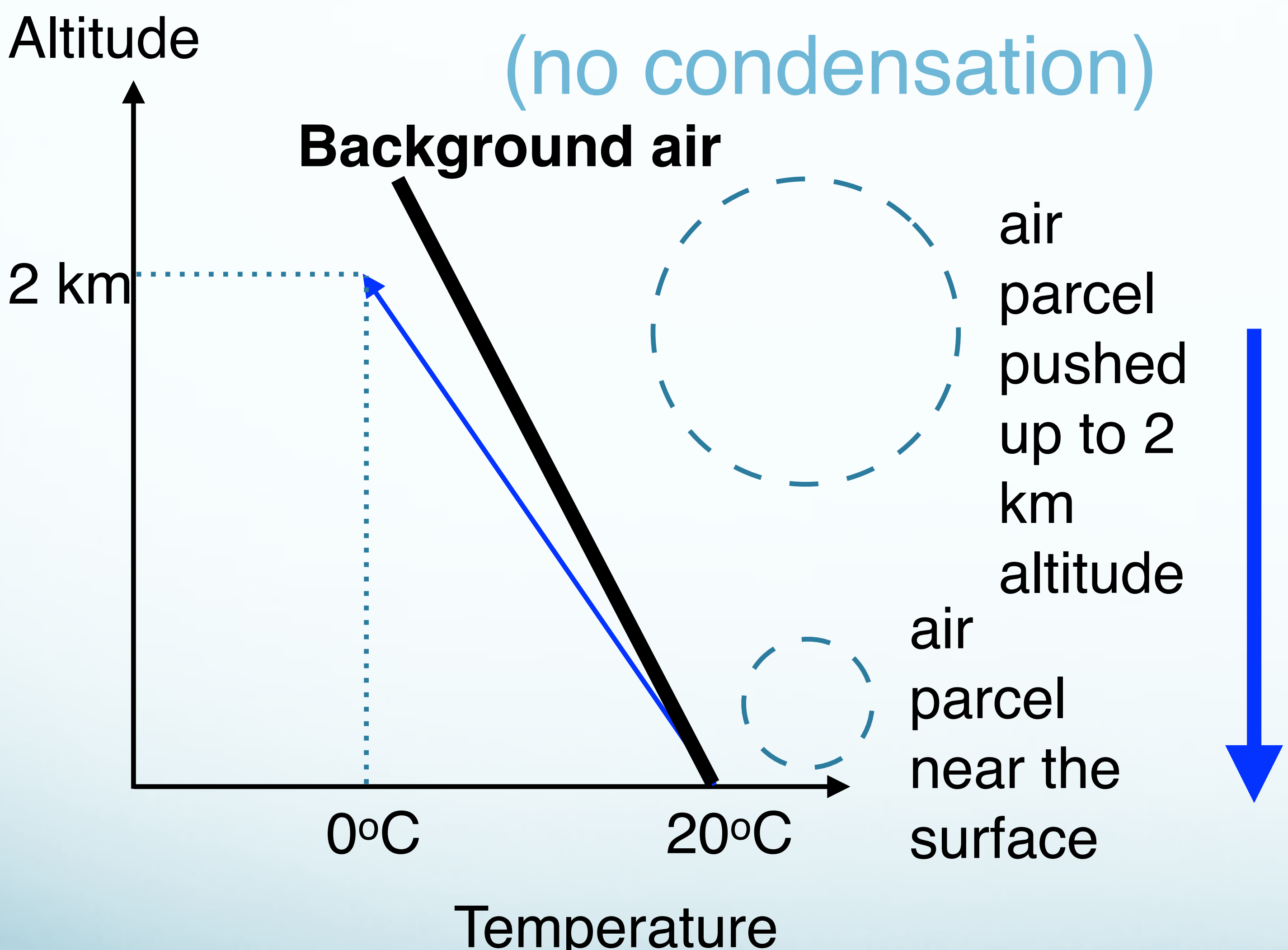
- When pressure of an air parcel matches that of the surrounding air, the air parcel is positively buoyant when its temperature is higher than the surrounding air

A story for a rising air parcel

- An air parcel rises when it is lighter than the surrounding air
- A rising air parcel expands and cools down
- The cooling from expansion alone will push the parcel back down
- If the parcel contains enough moisture, the latent heat from condensation counteracts the cooling and help the parcel keep rising

A story for a rising air parcel without condensation

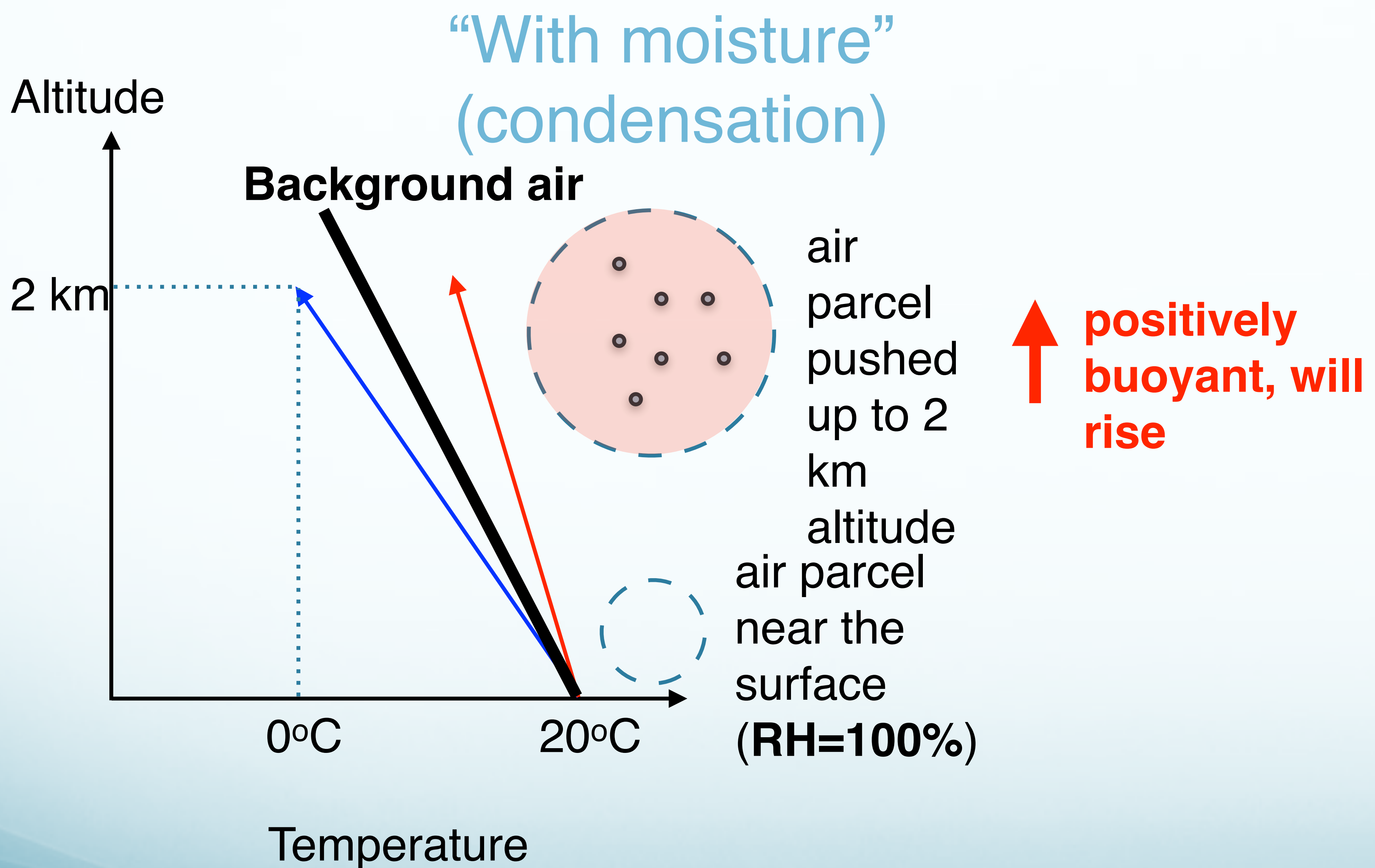
"Without moisture"
(no condensation)



negatively buoyant (colder than environment), will sink

A story for a rising air parcel

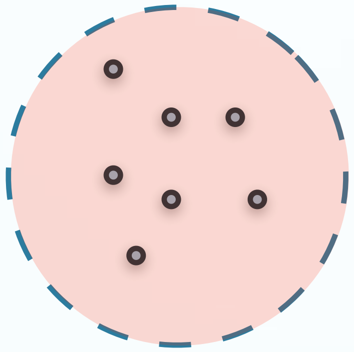
If condensation occurs while being pushed up



A story for a rising air parcel

If condensation occurs while being pushed up

air parcel raised up



air parcel near the surface

(Latent) Heat → **Warm the air nearby**

↑

Condensation (bonds build)

Water vapor → **Liquid**

The warming from the latent heat release partly cancels out the cooling from expansion!!

Latent heat is released as water vapor condenses to form cloud droplets.

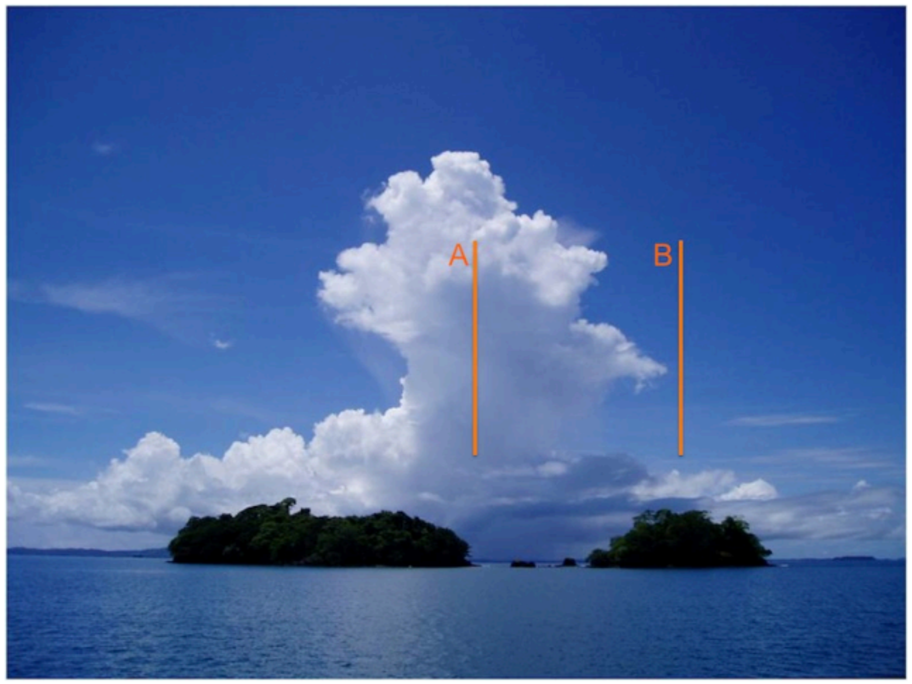
Latent heat powers thunderstorms

Attempts: 148 out of 149

+0.28

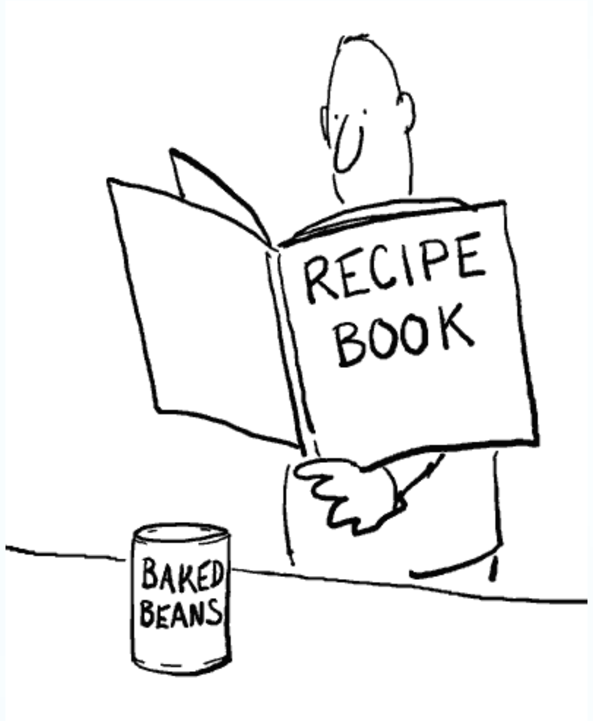
Discrimination Index ?

In which column, A (inside the cloud) or B (outside the cloud), is the air likely colder?



Column A	27 respondents	18 %	
Column B	116 respondents	**78 %**	✓
The two are likely the same temperature	4 respondents	3 %	
Impossible to tell	1 respondents	1 %	
No Answer	1 respondents	1 %	

What Shapes the Clouds?

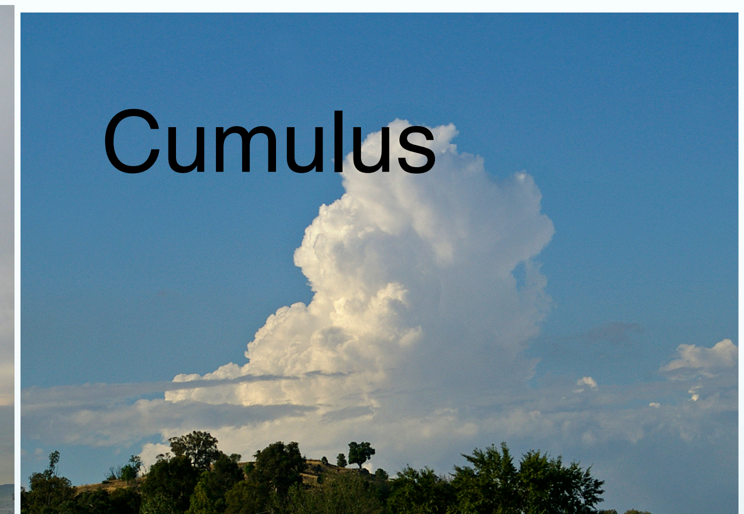


- Key factor: *atmospheric stability*
  - *Stable: Stratus clouds* form
  - *Unstable: Cumulus clouds*
  - *Conditional Unstable: Thunderstorm*

Ingredients for making a cloud

- Water vapor
- Cooling
- CCN

All the air rises at the same rate.



Some air goes up very fast

Some air goes down

How do we measure atmospheric stability?

Compare the environmental lapse rate with dry/moist lapse rate

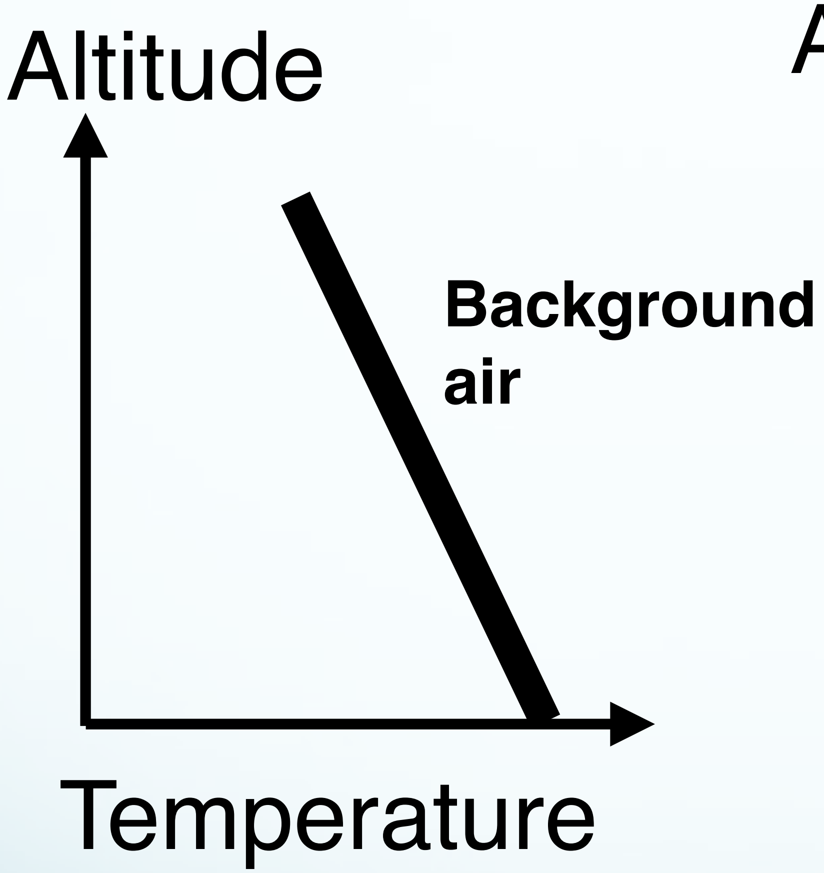
Lapse rate: the rate at which temperature drops with height

- Environmental (or background) lapse rate
- Dry adiabatic lapse rate
- Moist adiabatic lapse rate

Note:
adiabatic means no heat is added or removed from the air parcel

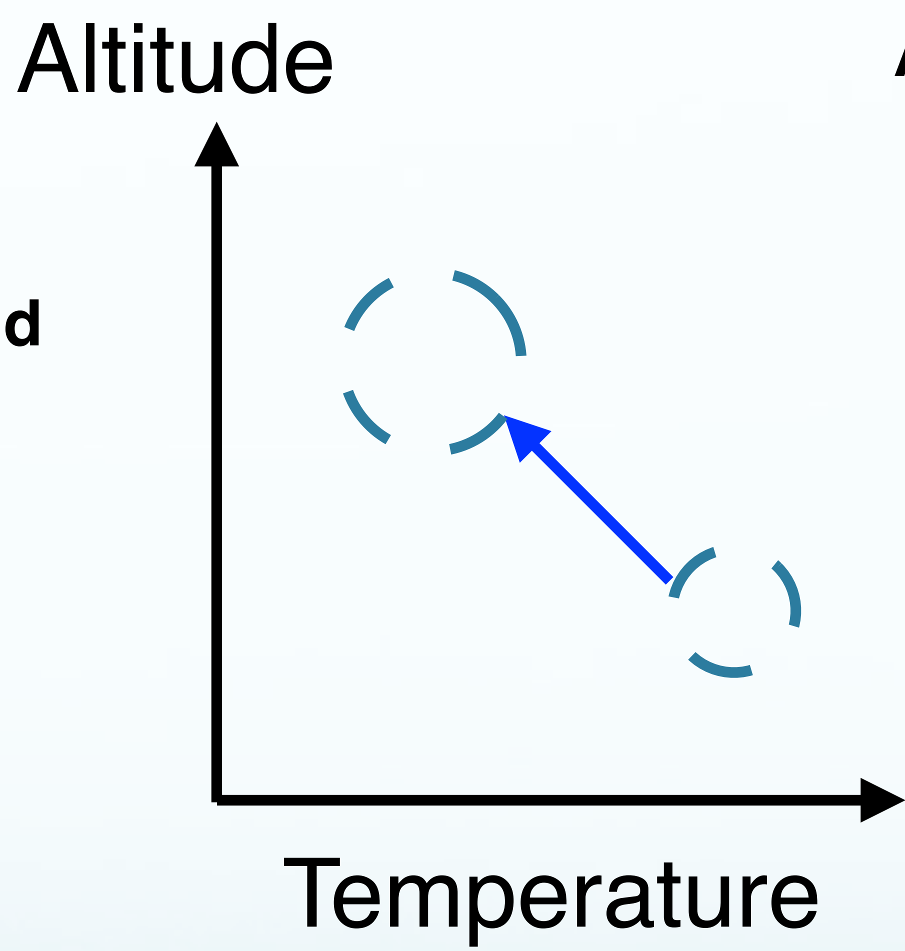
Lapse rate

Environmental lapse rate(varies)



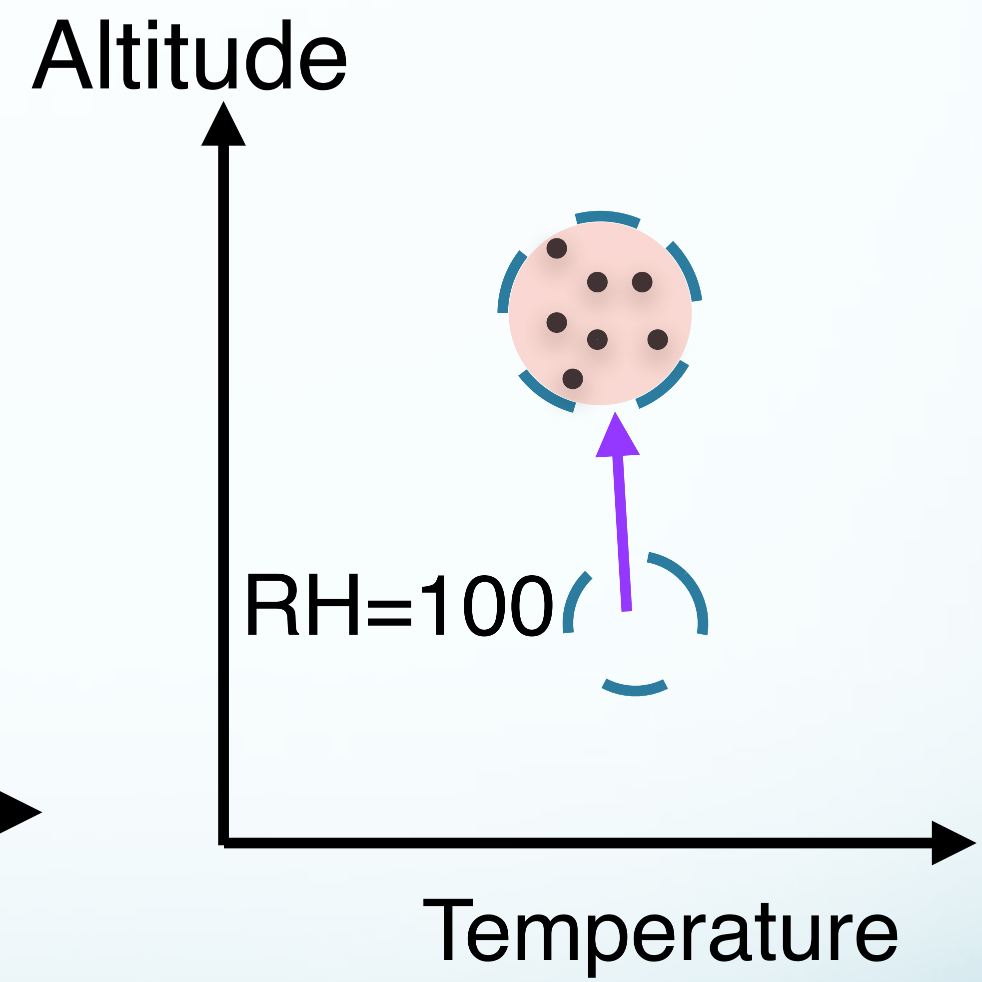
Environmental lapse rate: the rate at which background air temperature drops with height (varies depending on where you are)

Dry adiabatic lapse rate(10 °C/km)



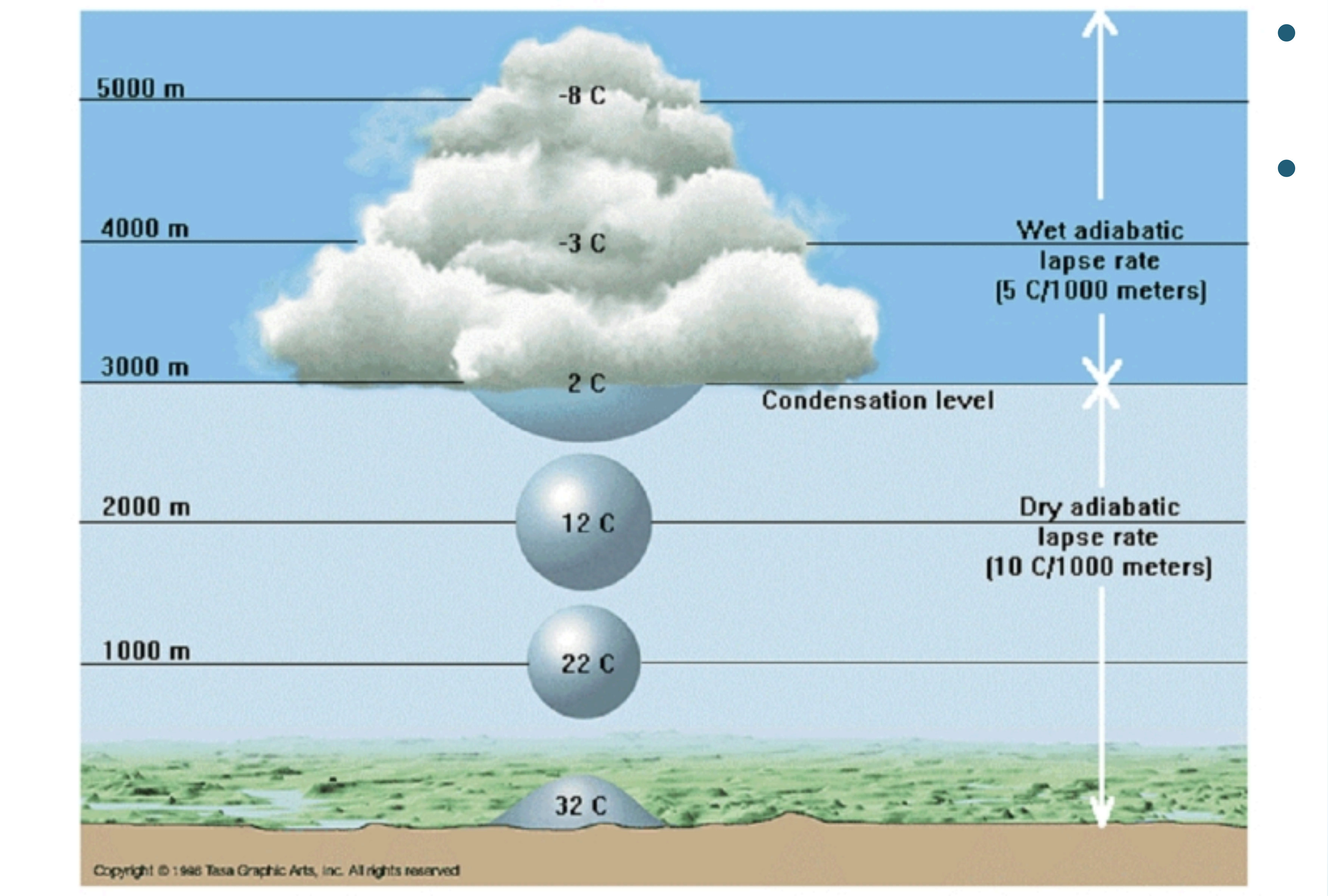
Dry adiabatic lapse rate: the rate at which temperature drops in an air parcel as it is adiabatically raised up (always 10 °C/km)

Moist adiabatic lapse rate(varies)



Moist adiabatic lapse rate: the rate at which temperature drops in a saturated parcel as it is adiabatically raised up (varies depending on the amount of water vapor, less than 10 oC/km)

Dry vs. moist adiabatic lapse rate



- *Latent heat is released* as the vapor condenses.
- Latent heat partially offsets the cooling accompanying the parcel's expansion as it encounters lower pressures aloft.

Moist adiabatic lapse rate < Dry adiabatic lapse rate

Attempts: 146 out of 149

+0.39

Discrimination Index ?

Which of the following is NOT true about adiabatic cooling process of a air parcel

No extra heat is added or removed from the air parcel	10 respondents	7 %
The expansion of the air parcel results in cooling	7 respondents	5 %
For a dry air parcel, as it cools adiabatically, its relative humidity will increase	49 respondents	33 %
For a saturated air parcel, its relative humidity will increase	80 respondents	**54 %** ✓
No Answer	3 respondents	2 %

Attempts: 146 out of 149

+0.47

Discrimination Index ?

If an air parcel is lifted from the surface to 2km, start to form clouds at 2km, and continue to rise to 3km. The temperature of this air parcel decreases by 10°C per km between surface and 2km. Which of the following are NOT true

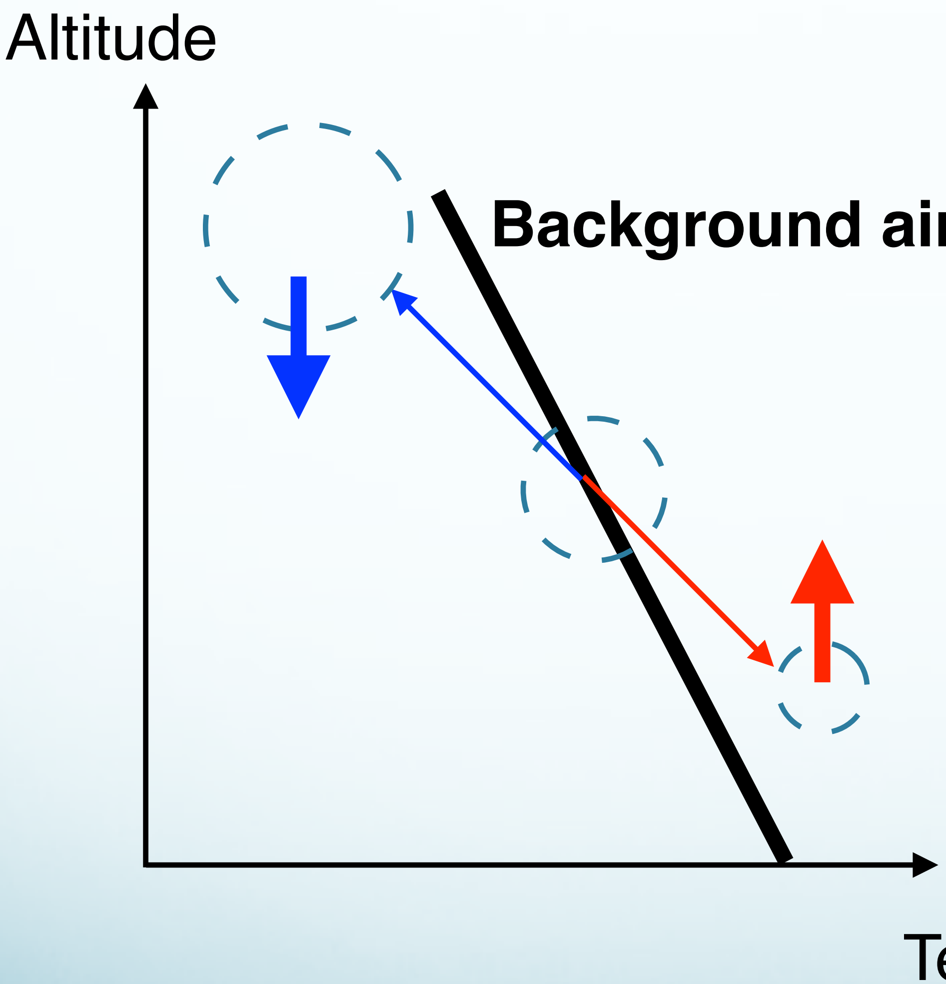
When air parcel rises from 2km to 3km, latent heat is released.	13 respondents	9 %
When air parcel rises from 2km to 3km, the temperature of this air parcel cools at a rate lower than 10°C per km.	29 respondents	19 %
When air parcel rises from 2km to 3km, the temperature of this air parcel increases with height because of the latent heat released.	104 respondents	**70 %** ✓
No Answer	3 respondents	2 %

70% answered correctly

How do we measure atmospheric stability?

Compare the environmental lapse rate with dry/moist lapse rate

“Stable”



Very Stable Air

Thunderstorm anvil from space

thunderstorms “stop rising” when they reach the tropopause because stratosphere is stable

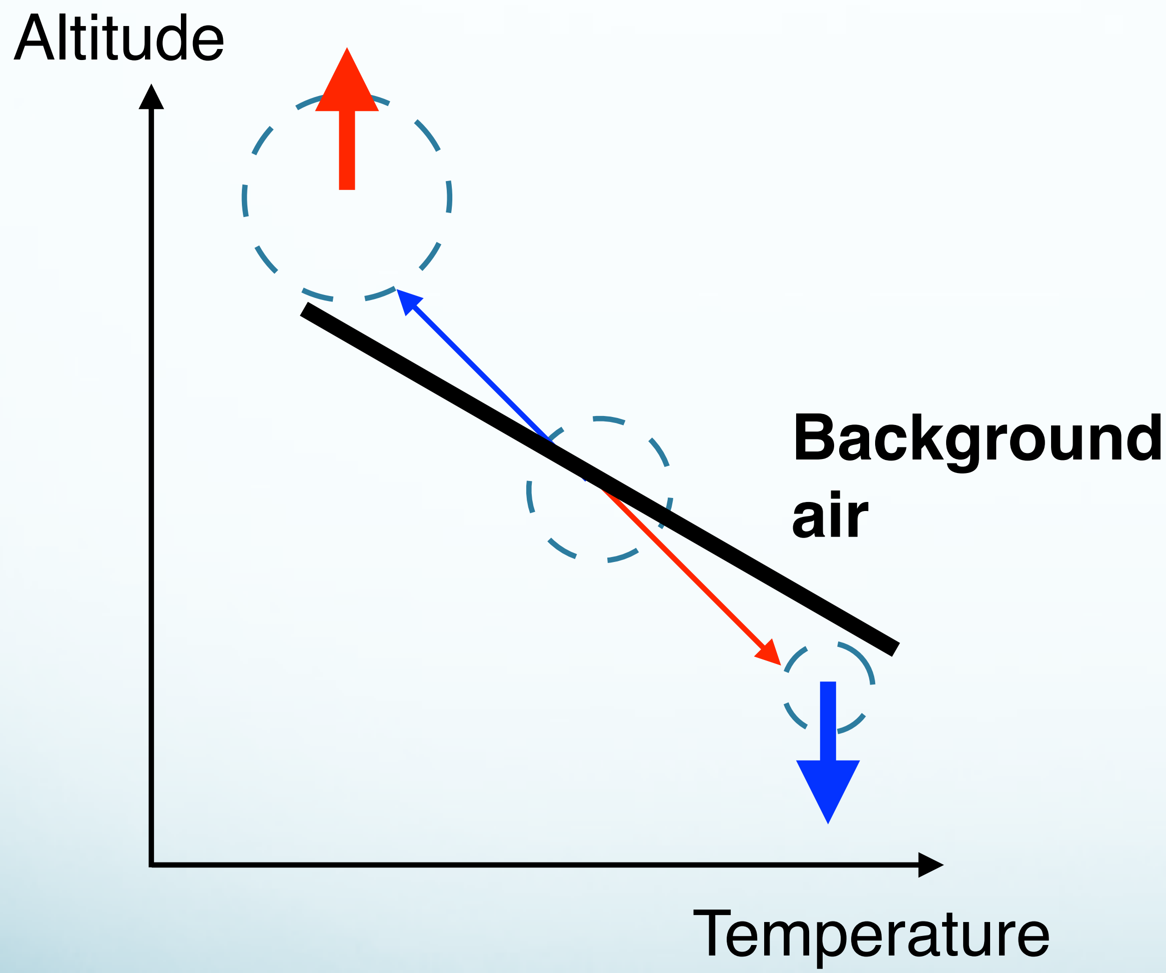
When the parcel is pushed *up* a bit, it becomes slightly *colder* than its surrounding & *sinks* back down (and oscillates about its original position).

Environmental lapse rate < Dry adiabatic lapse rate

How do we measure atmospheric stability?

Compare the environmental lapse rate with dry/moist lapse rate

“Unstable”



Fair-weather cumulus

Clouds formed by rising motions in an unstable environment near the ground created by solar heating.

When the parcel is pushed *up* a bit, it becomes slightly *warmer* than its surrounding & continues to *rise.* It becomes even warmer than its surrounding. And rising even faster.

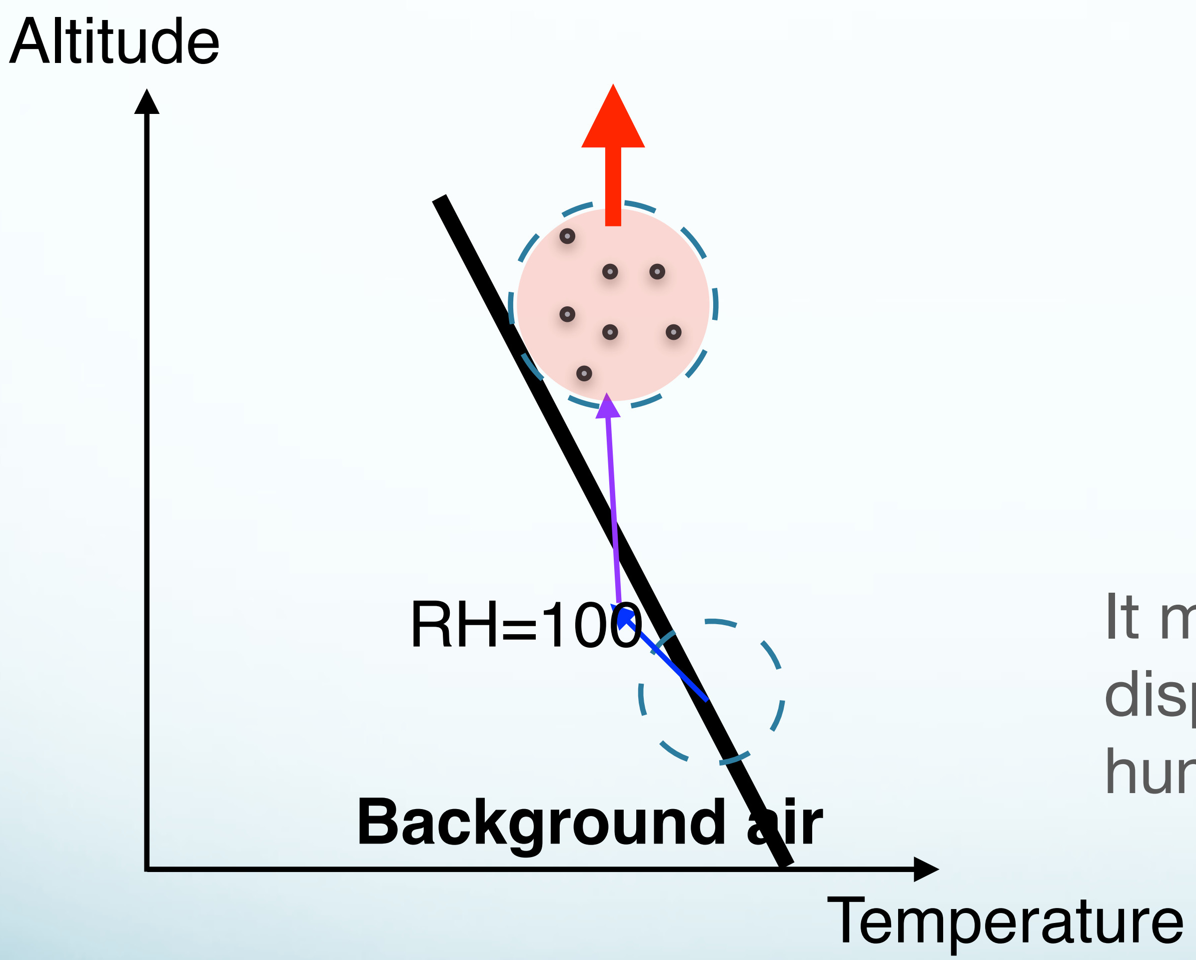
Environmental lapse rate > Dry adiabatic lapse rate

How do we measure atmospheric stability?

Compare the environmental lapse rate with dry/moist lapse rate

“Conditionally unstable”

(thunderstorms develop under this condition!)

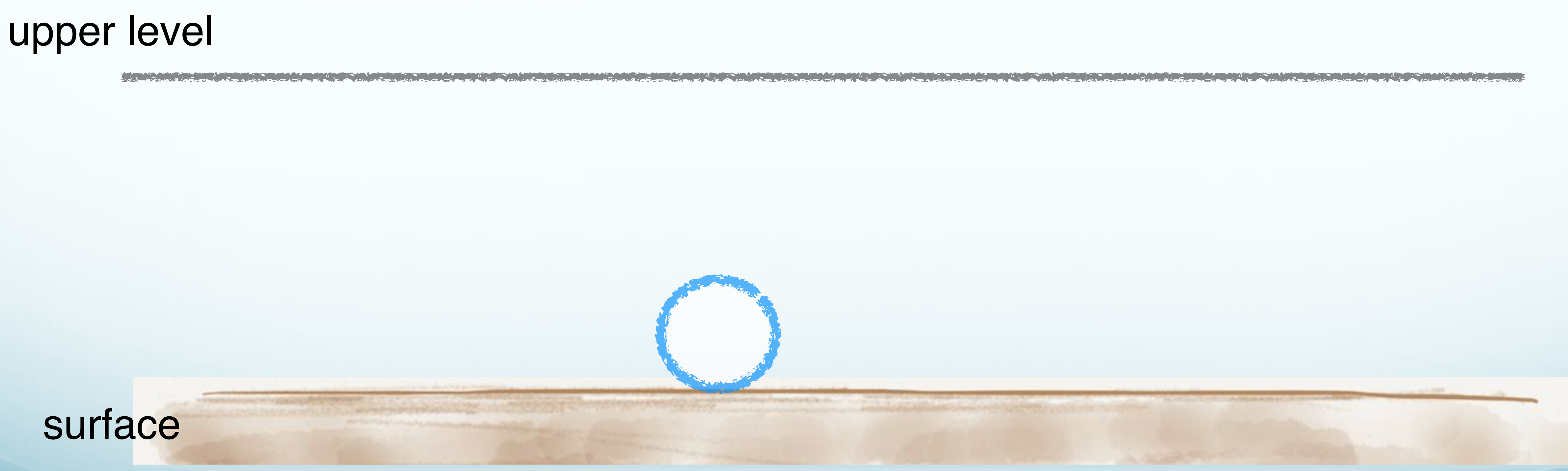


Thunderstorm

It means stable for dry air with small vertical displacement, but unstable for saturated/humid air with large vertical movement

Moist adiabatic lapse rate < Environmental lapse rate < Dry adiabatic lapse rate

How do we measure atmospheric stability?

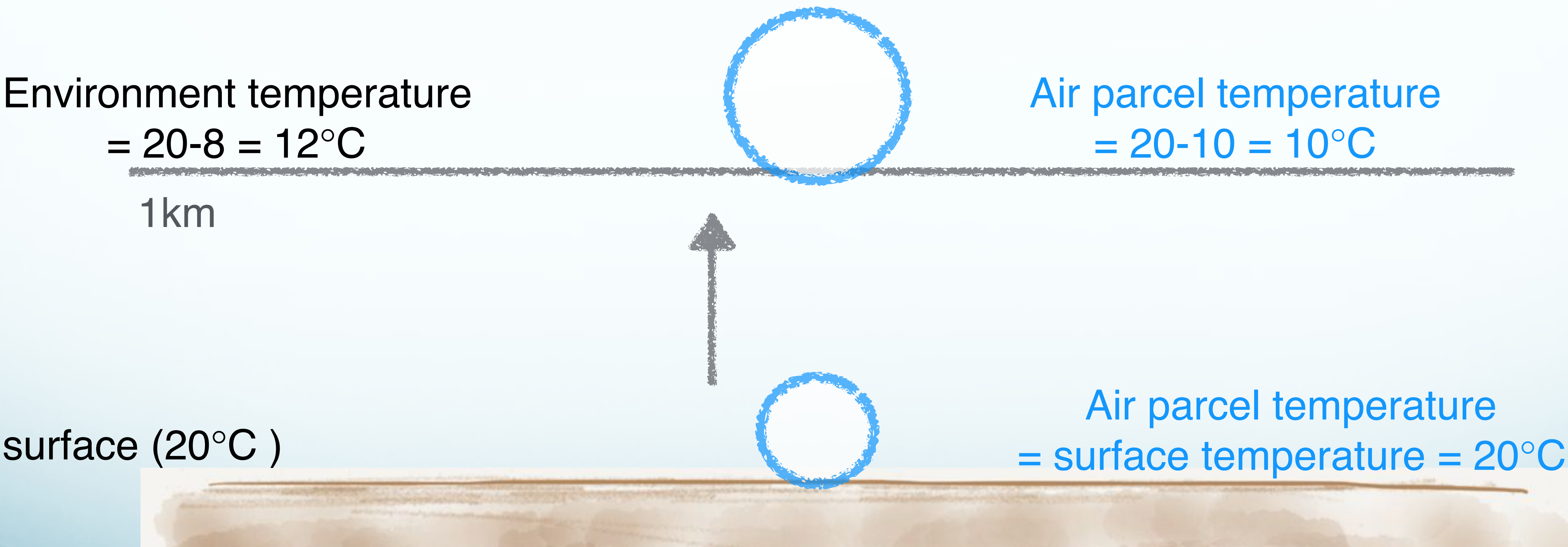


How do we measure atmospheric stability?

If rising air parcel is NOT saturated

Example 1: Environment lapse rate = 8°C/km

stable!

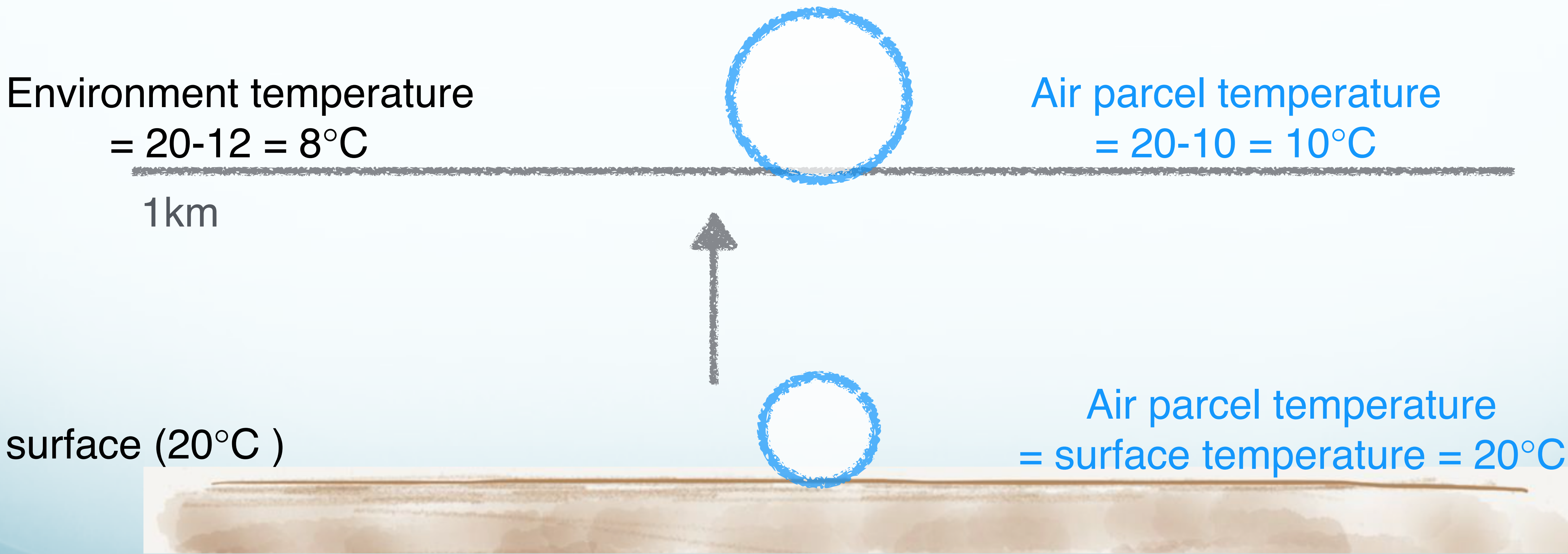


How do we measure atmospheric stability?

If rising air parcel is NOT saturated

Example 2: Environment lapse rate = 12°C/km

unstable!



Attempts: 30 out of 30

Which of the following environmental lapse rates can be conditionally unstable?

A: 11°C/km

B: 9 °C/km

Ingredients for making thunderstorms

- 1. A suitable lapse rate

conditional instability

- 2. Adequate low-level moisture
  - RH can't be too low.
  - Dew points can't be too low.
- 3. Trigger

Lifts the low-level air

Thunderstorm ingredients

- 1. A suitable lapse rate

conditional instability

- 2. Adequate low-level moisture
  - RH can't be too low.
  - Dew points can't be too low.
- 3. Trigger

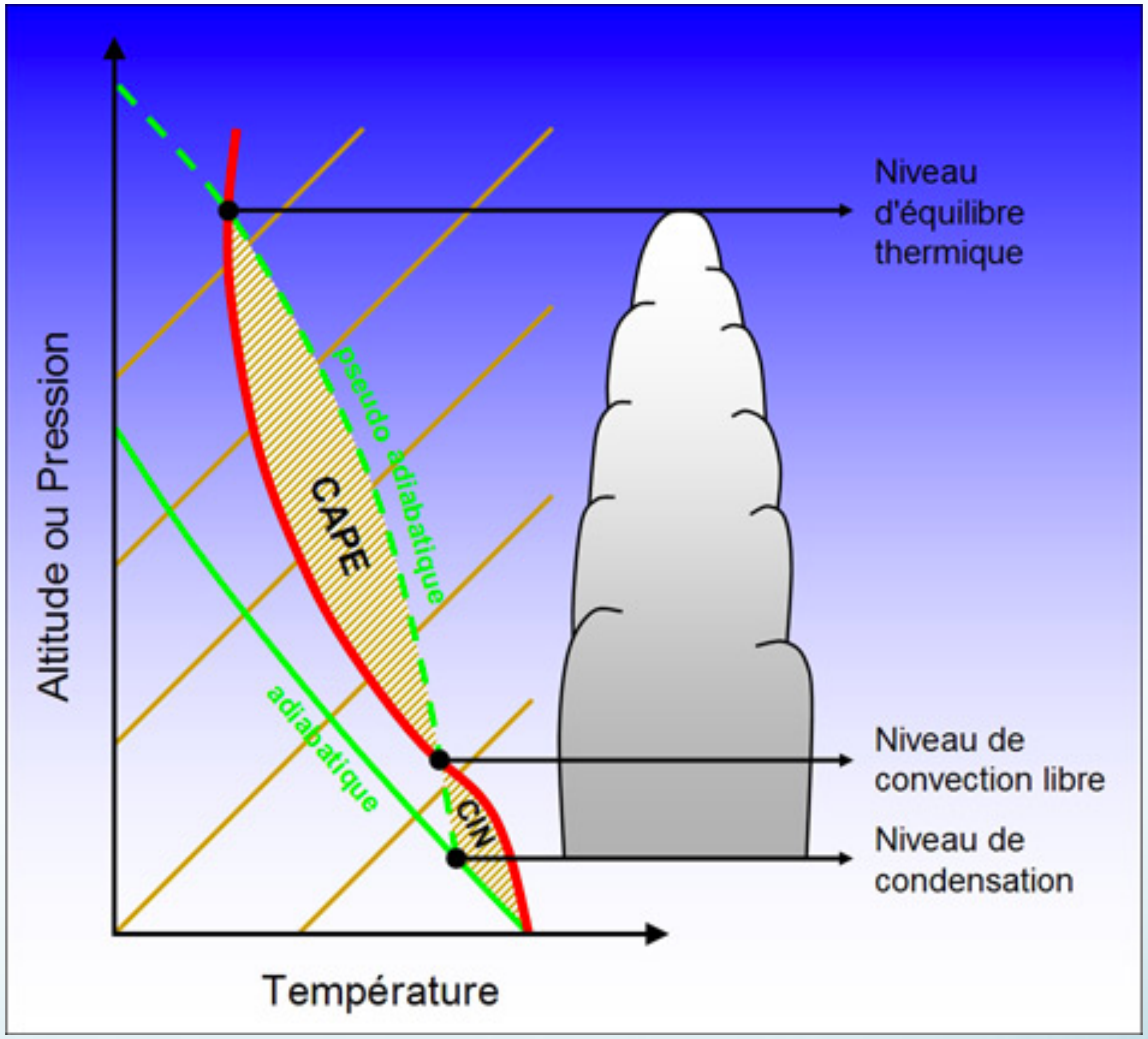
Lifts the low-level air

1 + 2 determines

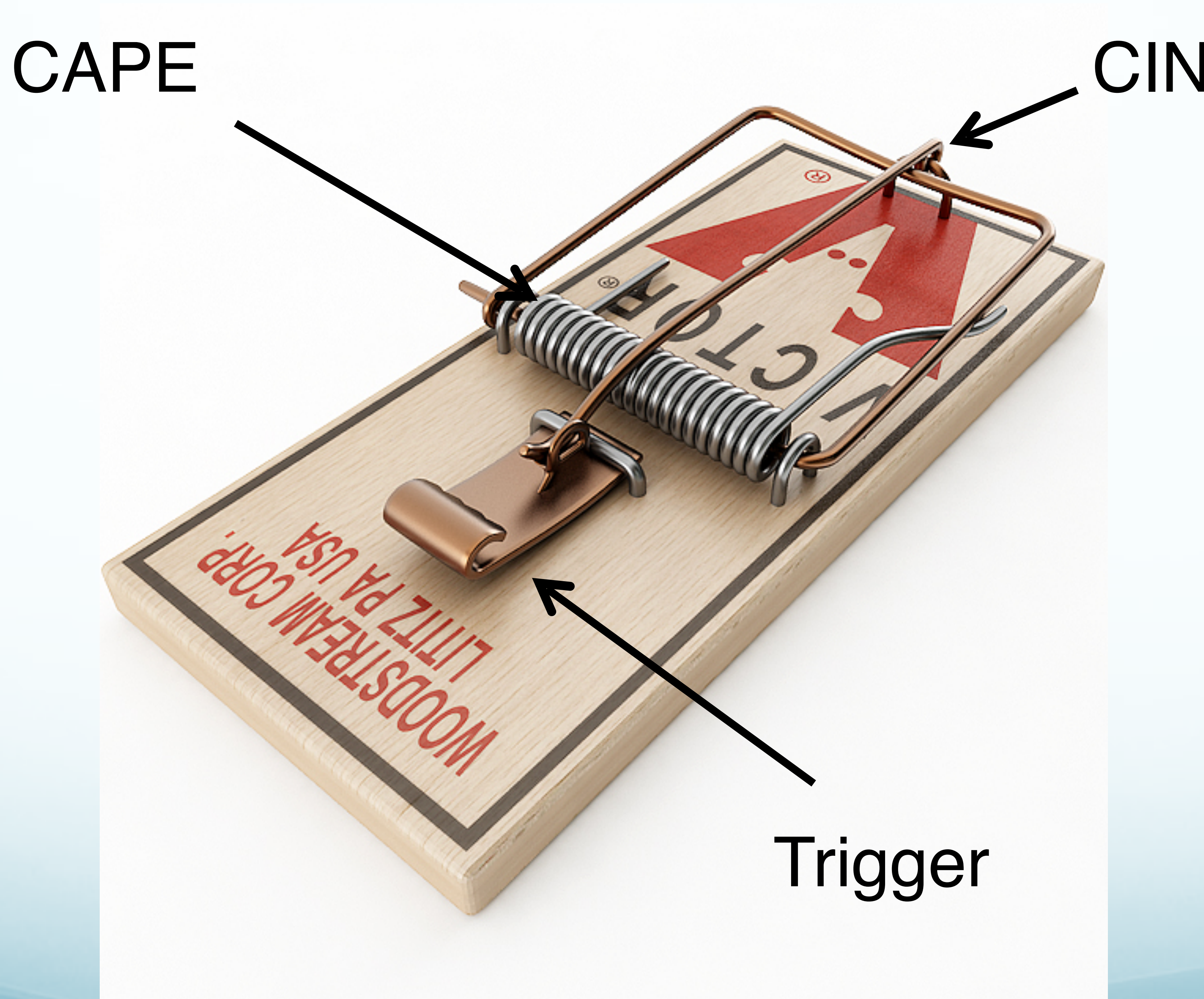
CAPE
CIN

Thunderstorm ingredients

- CAPE (Convective Available Potential Energy)
  - The total energy that can be released while a rising air parcel is warmer than its environment.
- CIN (Convective InhibitioN)
  - The cap that allows lots of CAPE to build up until conditions are ripe for a thunderstorm.
- A trigger that lifts the low-level air (overcomes the CIN)
  - Surface Heating
  - Lifting at a weather front
  - Lifting of ascending air by mountains



Thunderstorm ingredients



What determines type of thunderstorm?

- CAPE:

The amount by which rising air parcels become warmer than their environment

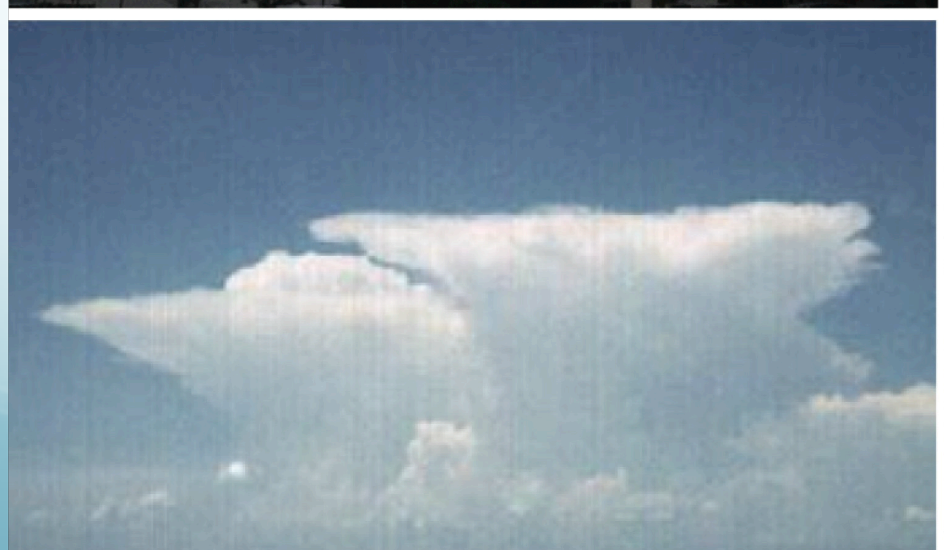
- Low-level Wind Shear

The change with height in the wind's speed and direction in the lowest 5 km above the ground.

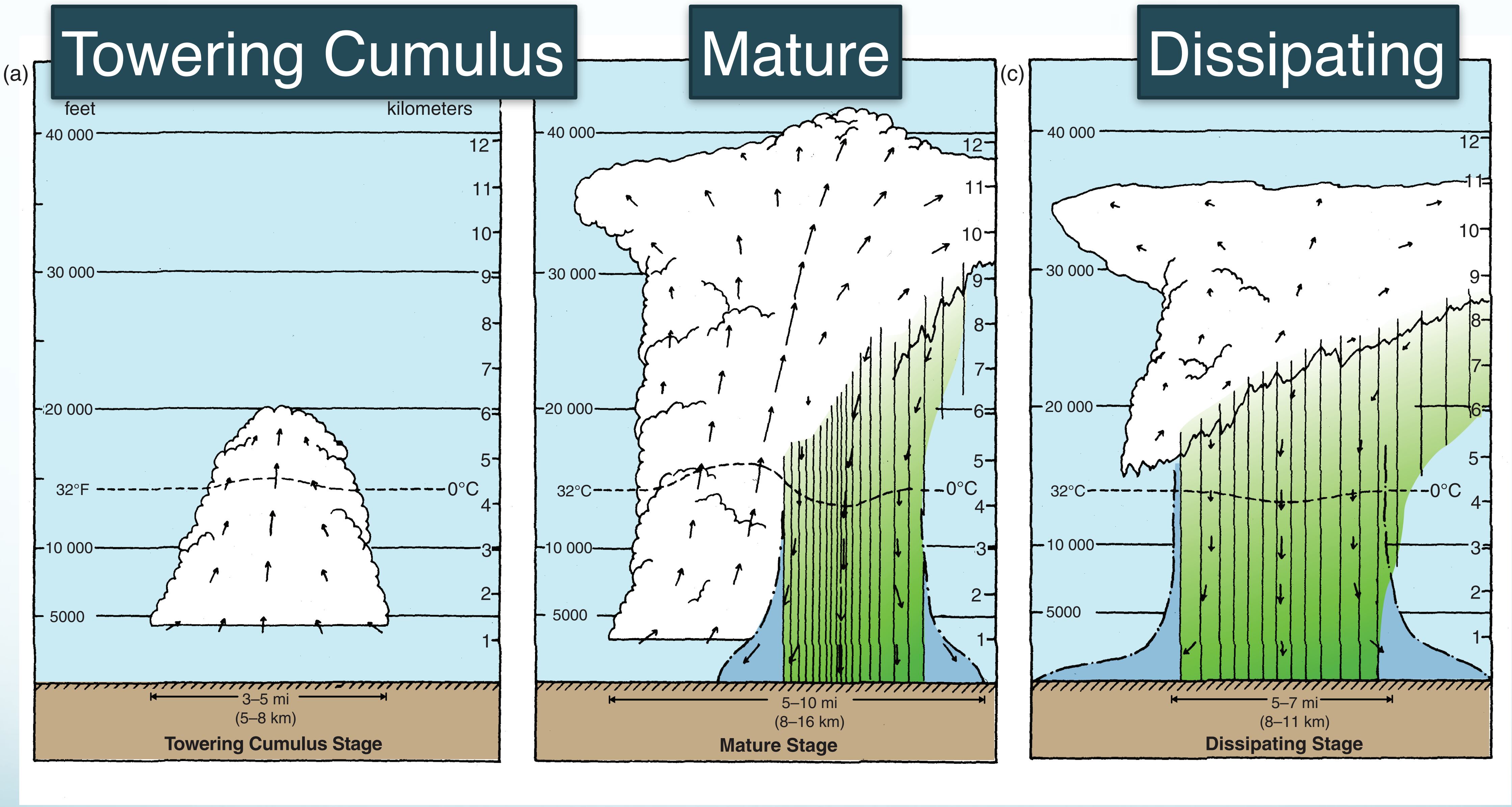
Kinds of thunderstorms

Midterm1

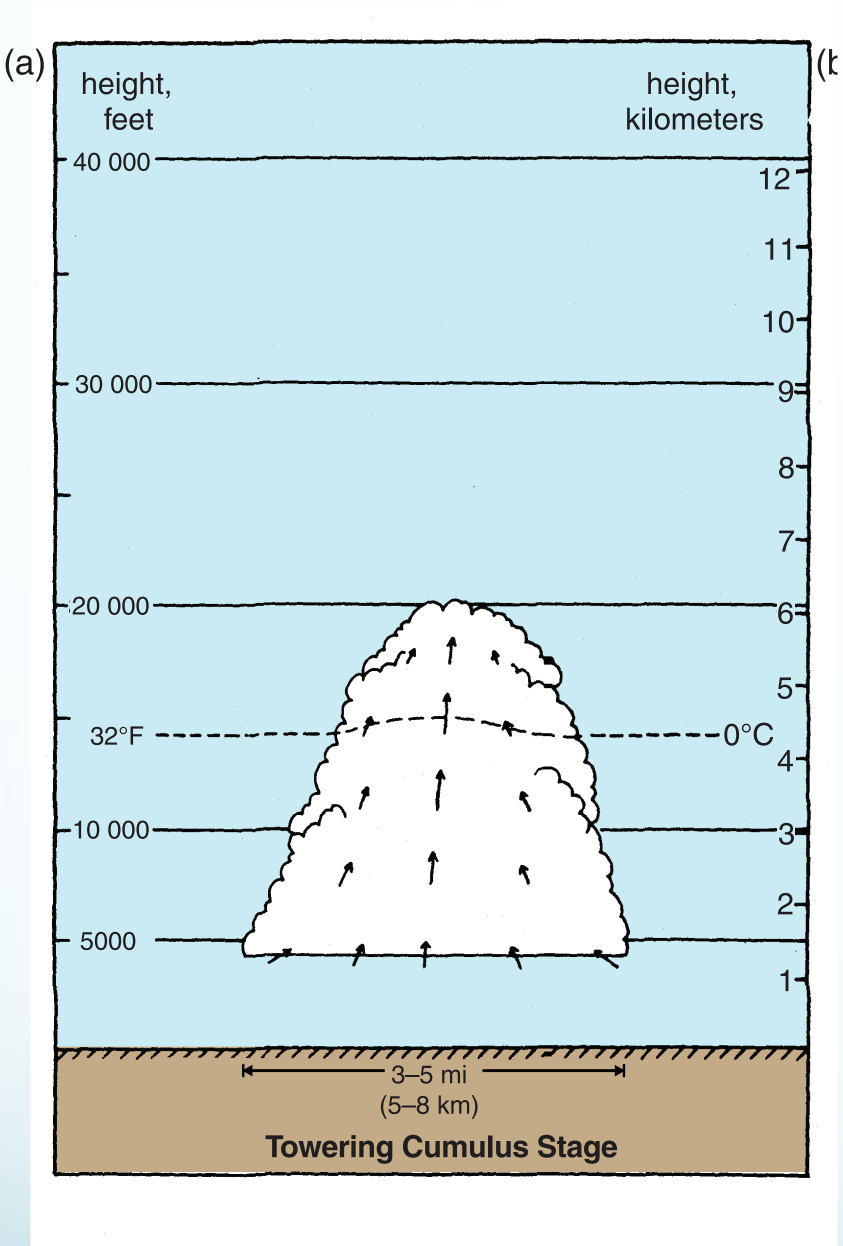
- Single cell
  - "Ordinary" or "air mass" thunderstorm
  - Generates lightning, heavy rain, downbursts.



Life Cycle of a Single Cell



Stage I: Towering cumulus



Updrafts!

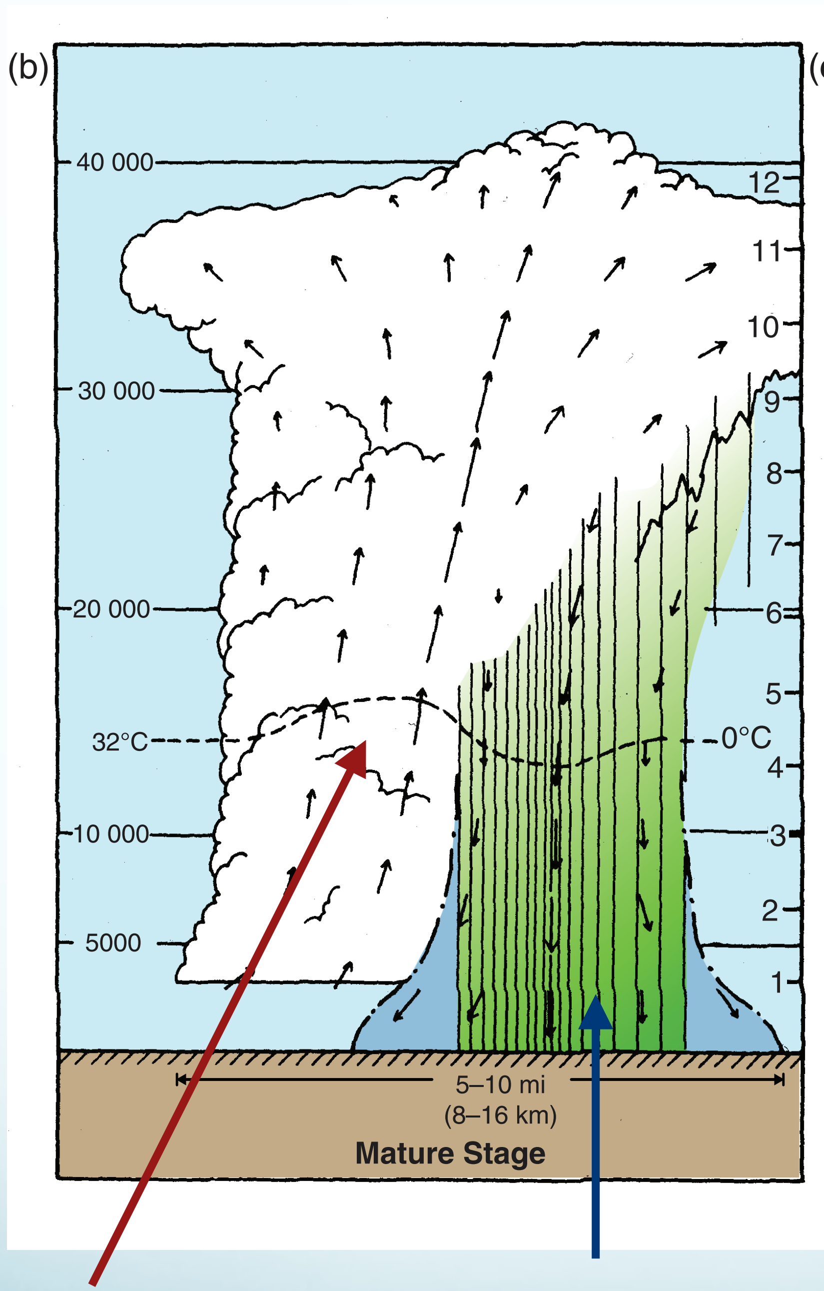
- The trigger makes parcels rise…
- cool to saturation…
- continue rising, freely…
- until reaching stable layer

One More Hurdle: Entrainment

- *Entrainment* occurs when unsaturated air at the edge of the cloud mixes with the rising air.
- We have ignored this in our previous arguments about hypothetical “air parcels”.

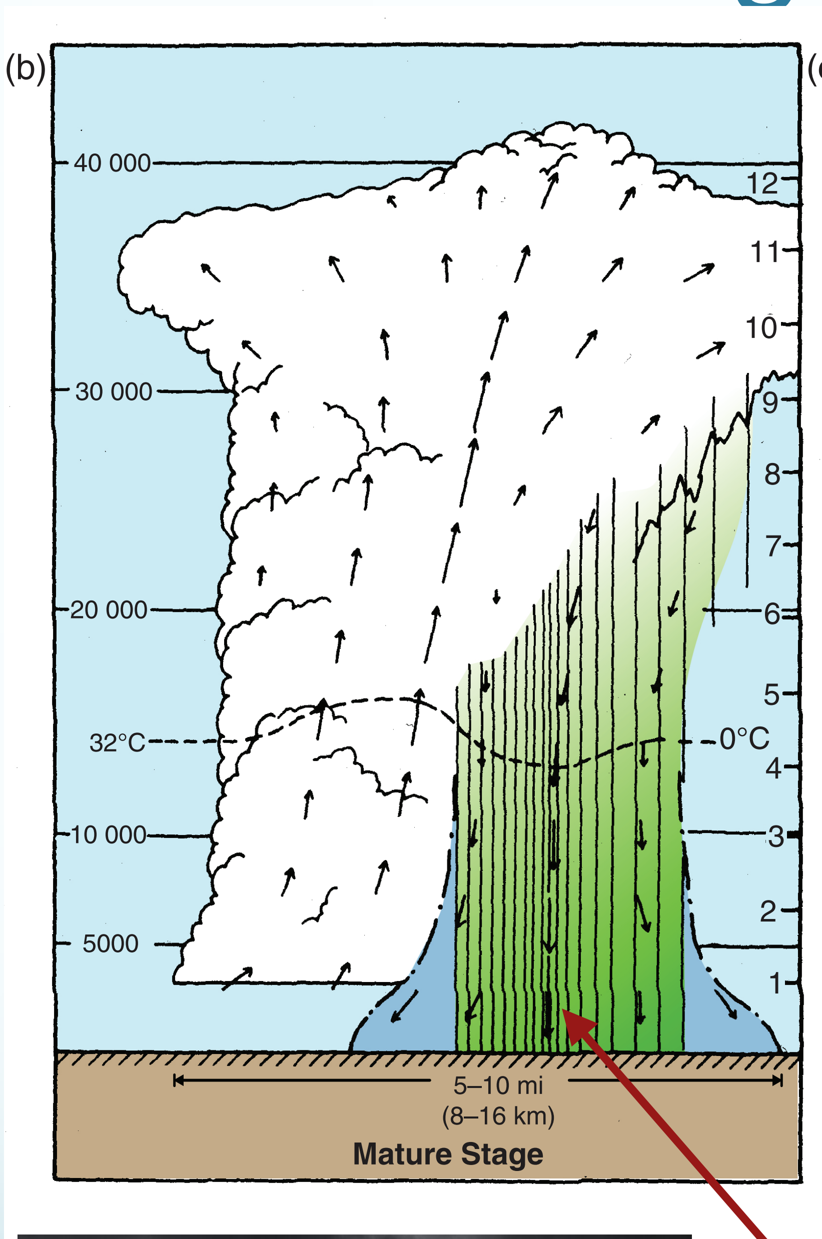
- Cloud droplets evaporate
- After entraining unsaturated air, the mixture
  - Has less liquid water
  - Has been cooled by the evaporation of cloud droplets.

Stage II : Mature stage



- Both updrafts and downdrafts
- rain, thunder and lightning have developed

Stage II : Mature stage



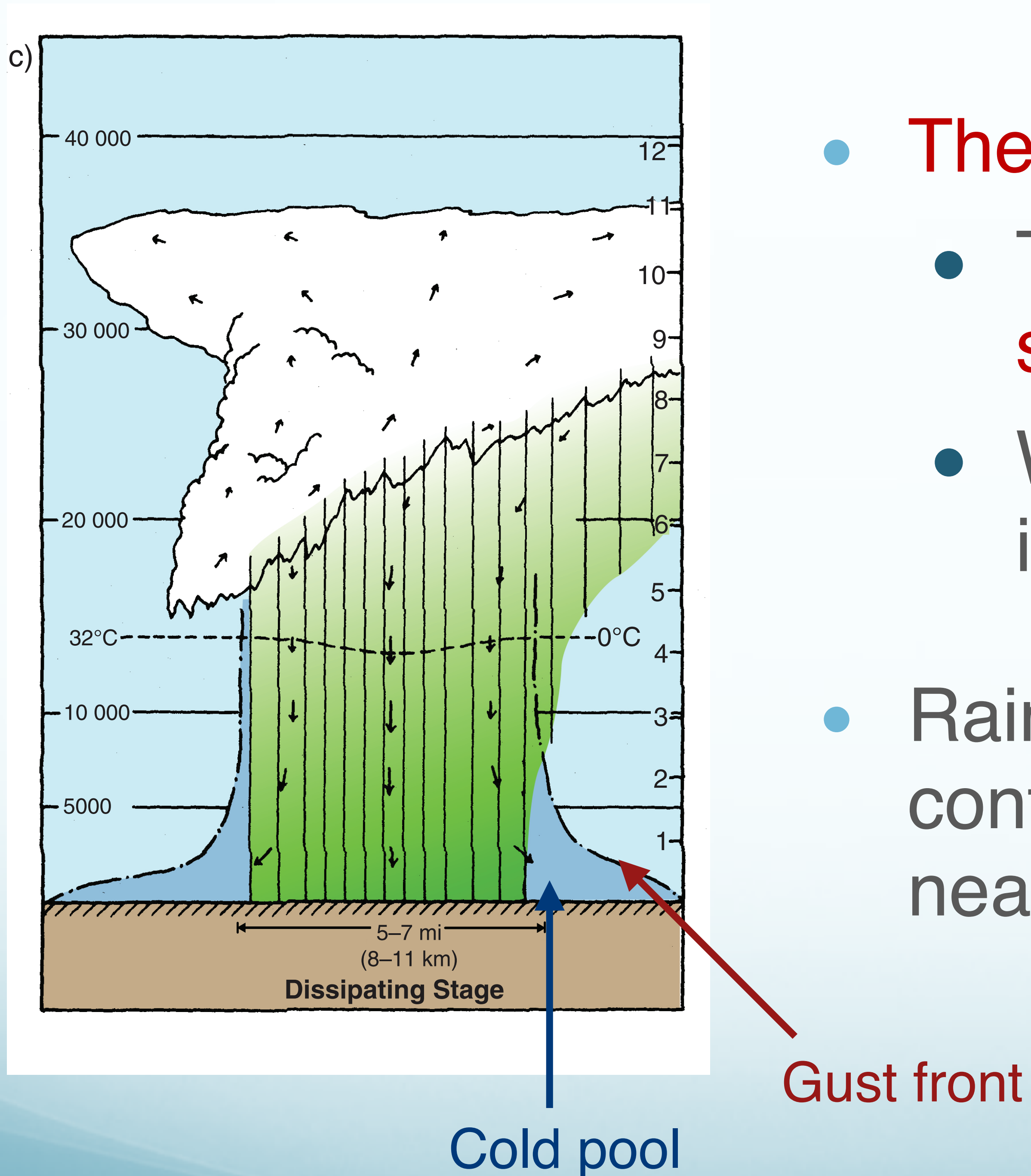
Downdrafts

- The upward transport of air needs to be balanced by an equal downward transport.
- Most of the compensating subsidence (descent) actually happens in the clear air around the cloud.

What produced downdrafts?

- Aerodynamic drag
- The entrainment of dry air through the sides of the cloud, which is cooled as cloud droplets evaporate.
- Evaporation of precipitation also cools downdrafts below cloud base.

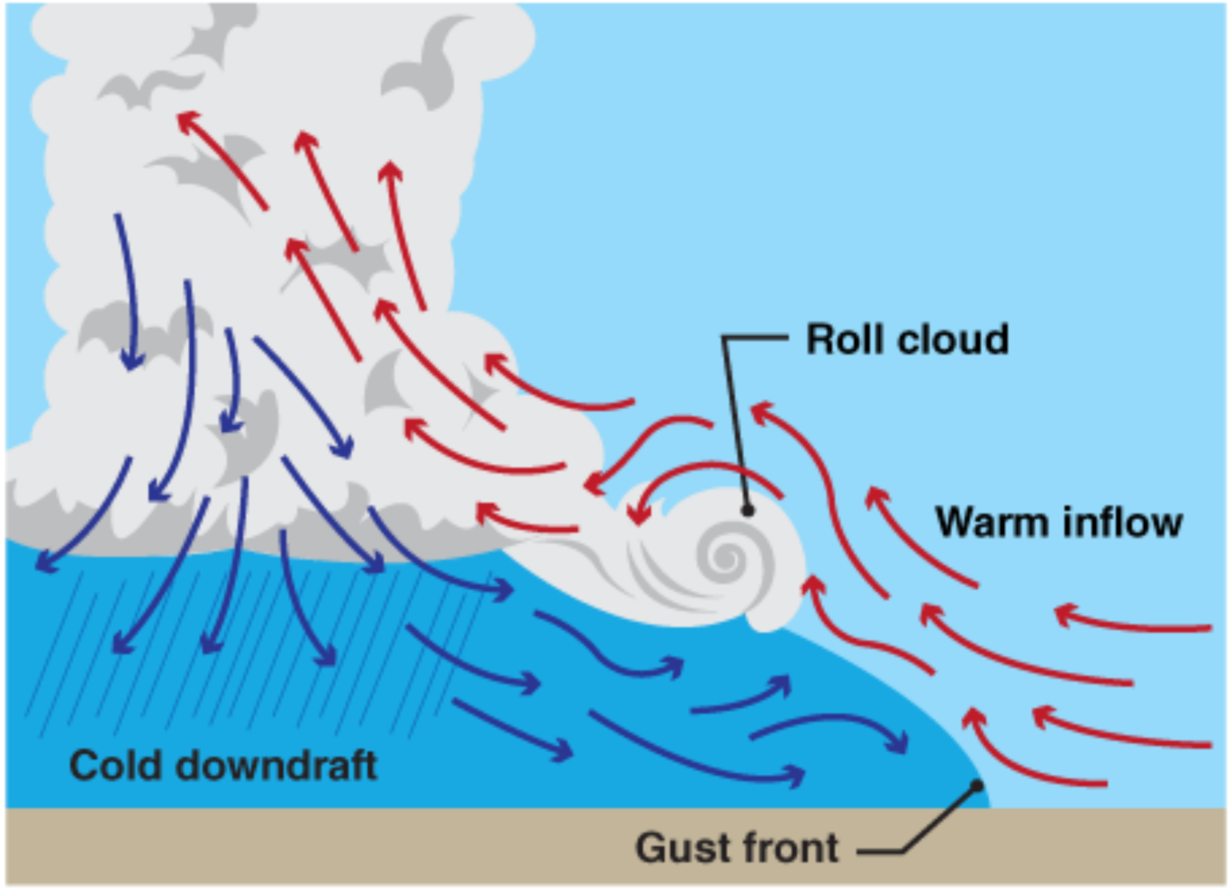
Stage III: Dissipating stage



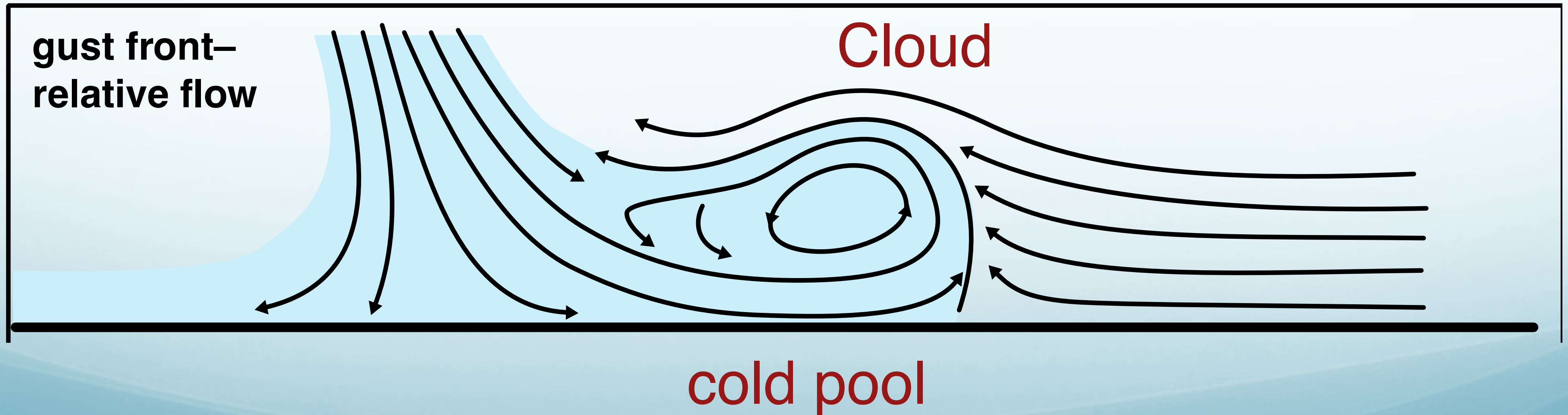
- The updrafts are gone.
  - They have been cutoff by the spreading cold pool.
  - Warm moist air is no longer flowing into the cloud.
- Rain, thunder and lightning may continue for a while, but the end is near.

The Gust Front

- Downdraft air spreads out along the surface, producing
  - a cold pool under the thunderstorm
  - a gust front at the edge of the spreading cold pool

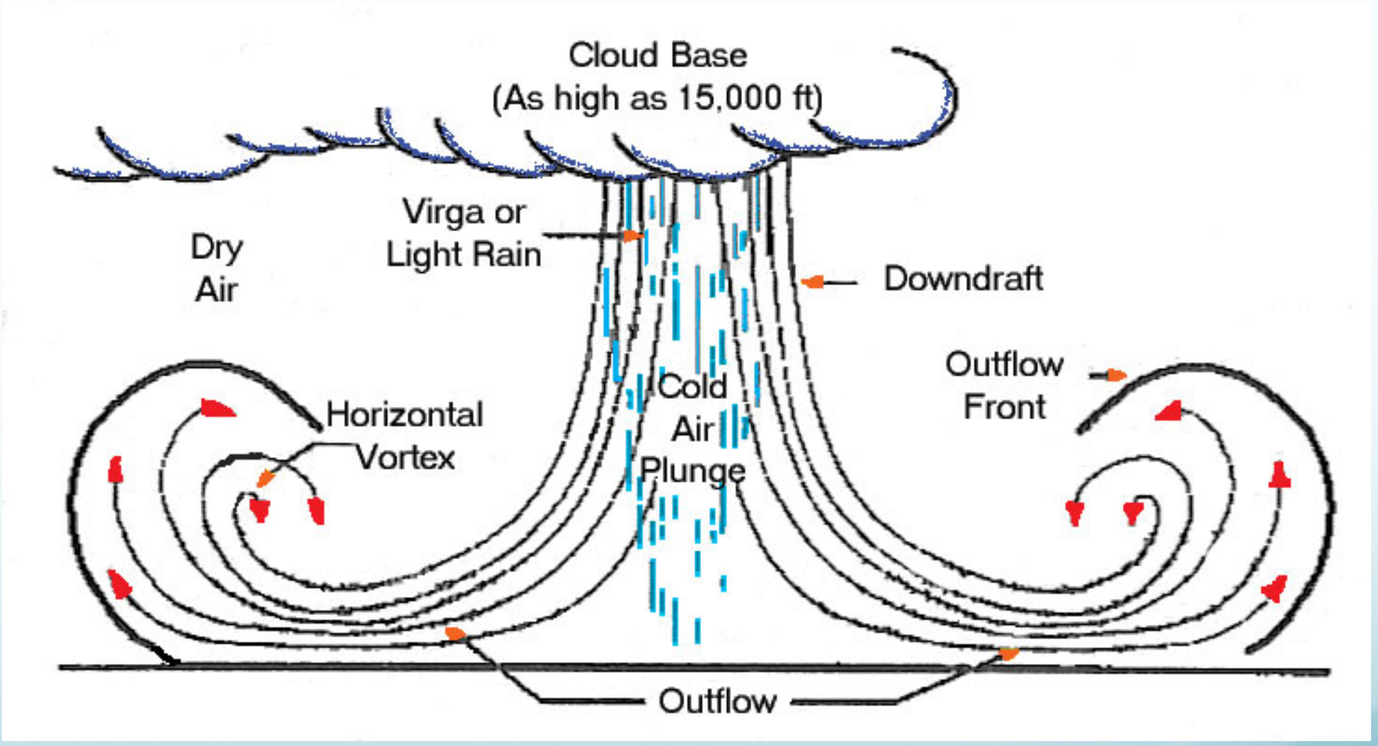


Gust Front diagram



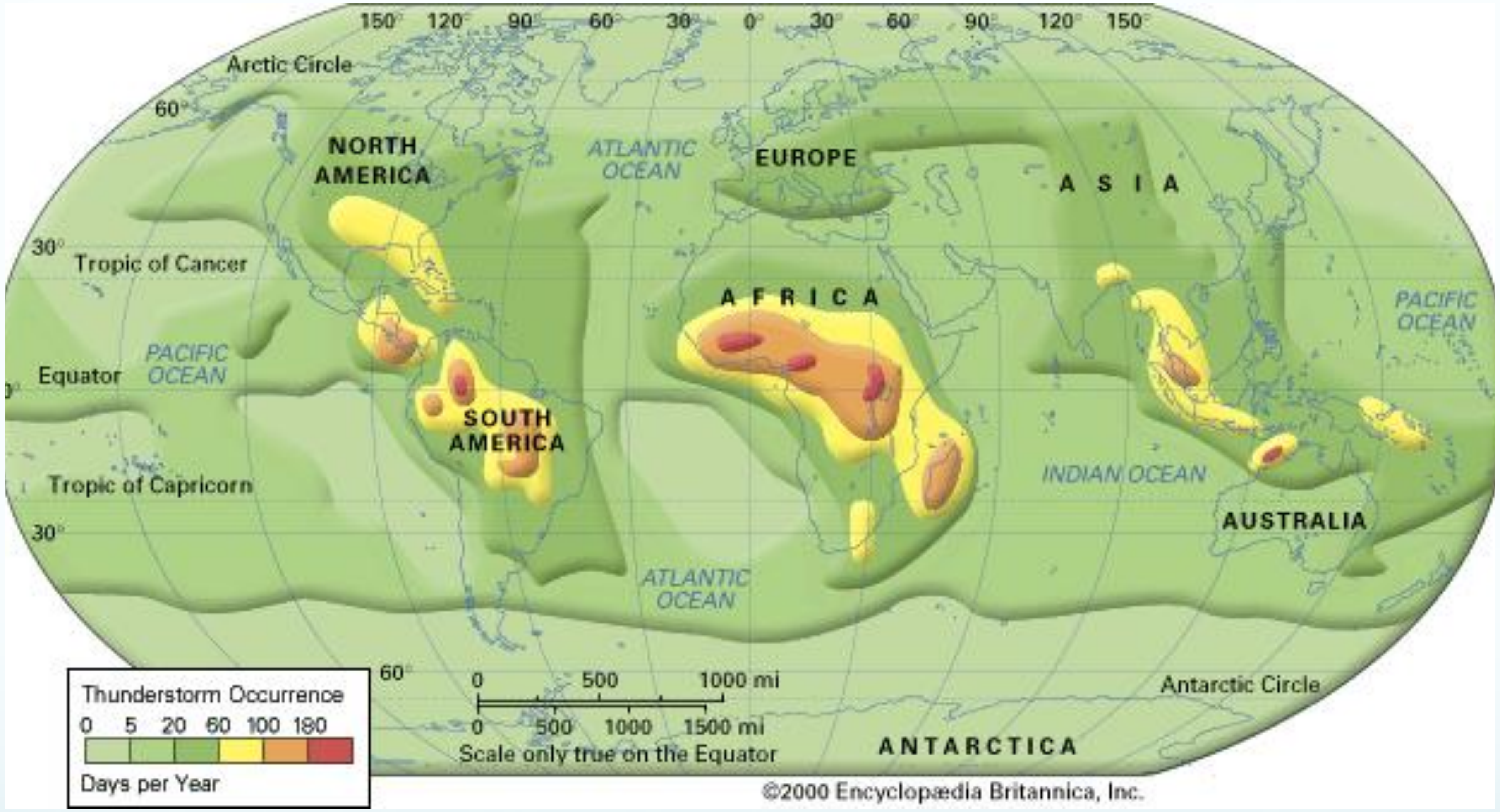
Hazards from single cell

- Lightning
- Downdrafts and the spreading gust front create microbursts, an aviation hazard.
- Flash floods



- June 24, 1975: Eastern Airlines Flight 66 was on its final approach into New York Kennedy when it encountered microbursts.

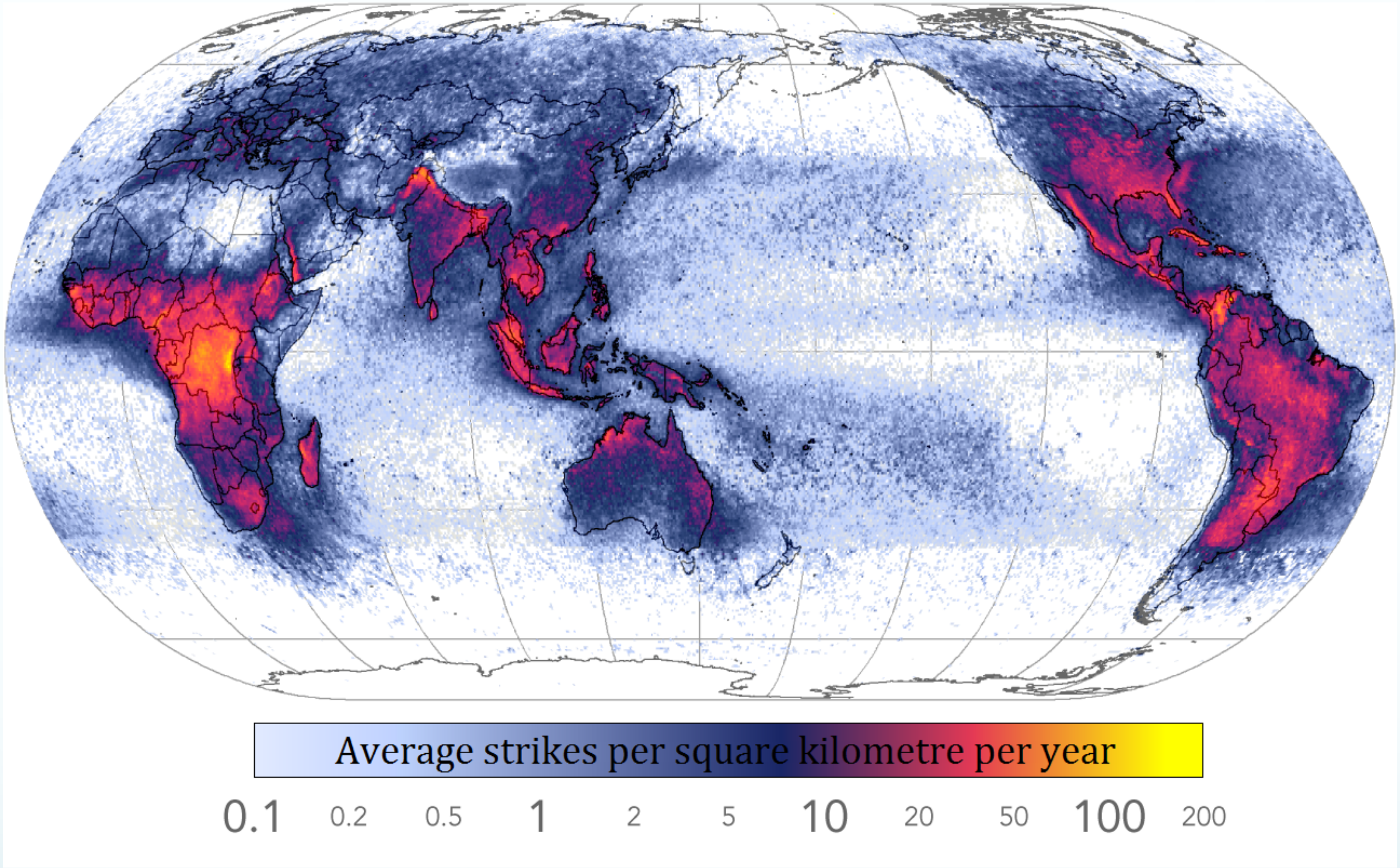
Thunderstorm Frequency



Hazards from single cell

- Lightning
- Downdrafts and the spreading gust front create microbursts, an aviation hazard.
- Flash floods

Global Lightning Frequency



- Globally, more common over land than over ocean
- In US, Florida!

Ingredients for making lighting

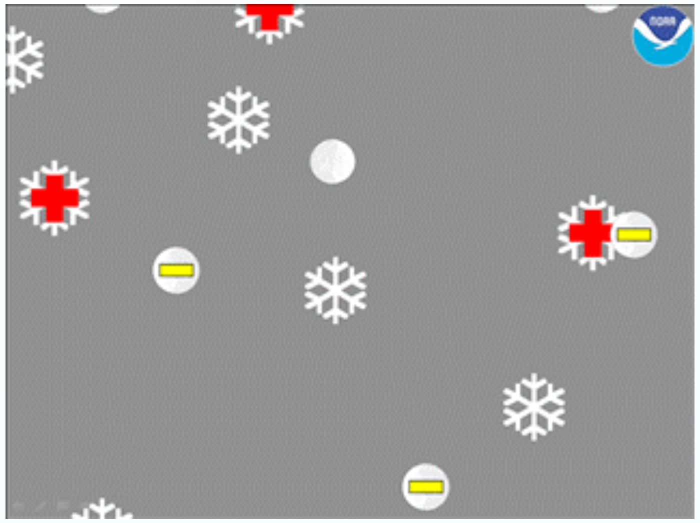
- Generate separate regions of positive and negative charge.
- Trigger a bolt (an avalanche of electrons) between these regions
  - Maybe relates to cosmic rays
  - Maybe ?

Lightning & Safety

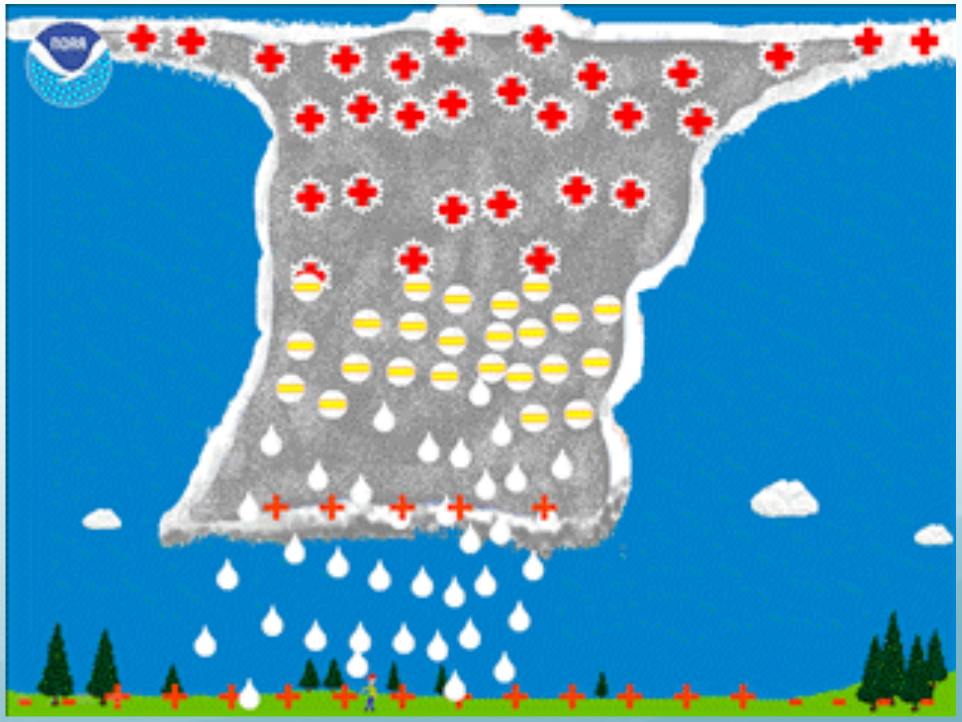
Creating and separating the charges

- Falling graupel and hail collide with rising ice crystals
  - Graupel and hail become negative
  - Ice crystals become positive

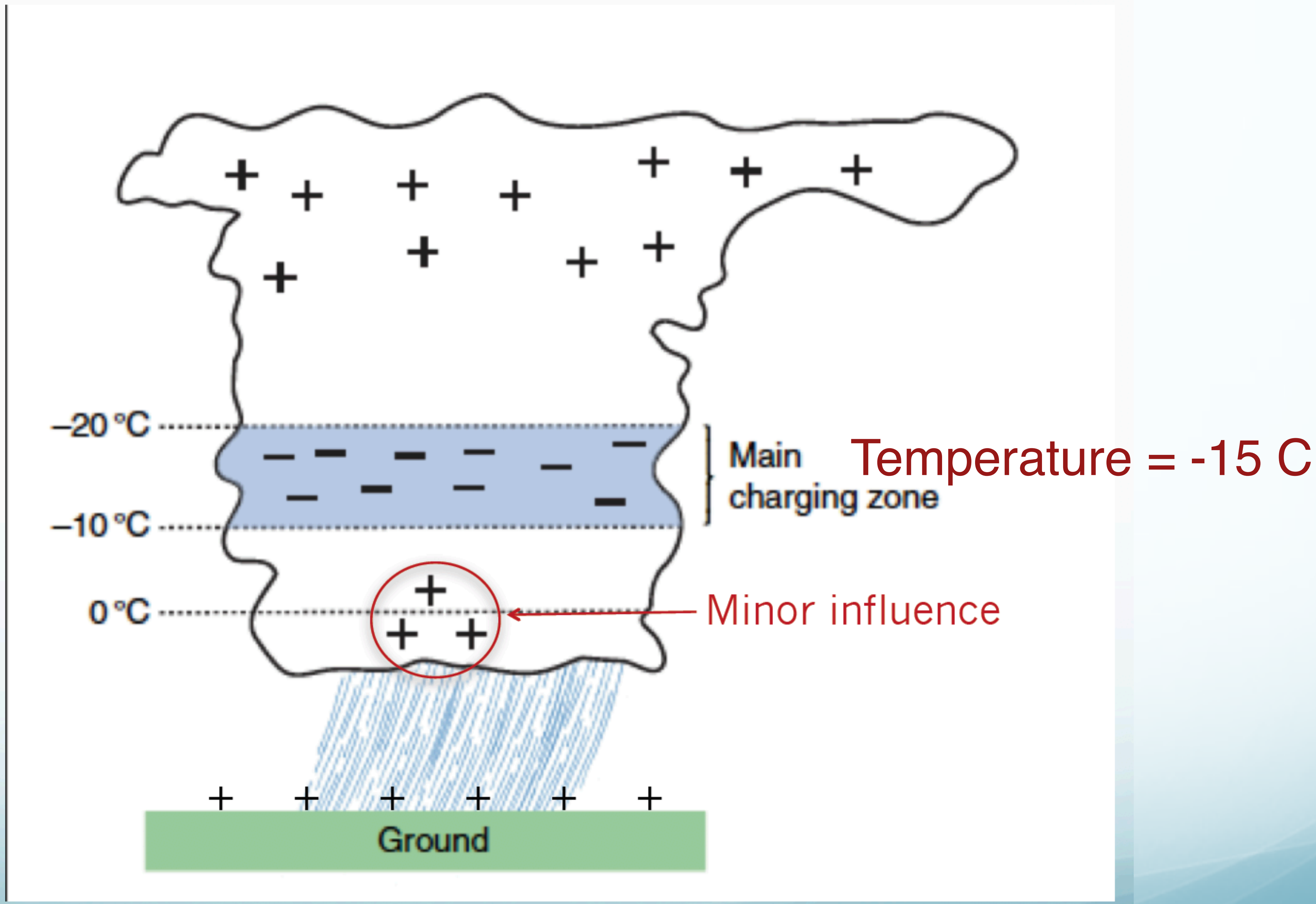
ice plays a key role in electrification.



- Ice crystals (+ charge) keep rising and accumulate in the top of the cloud.
- Graupel and hail (– charge) remain lower in the cloud



Basic Charge Distribution

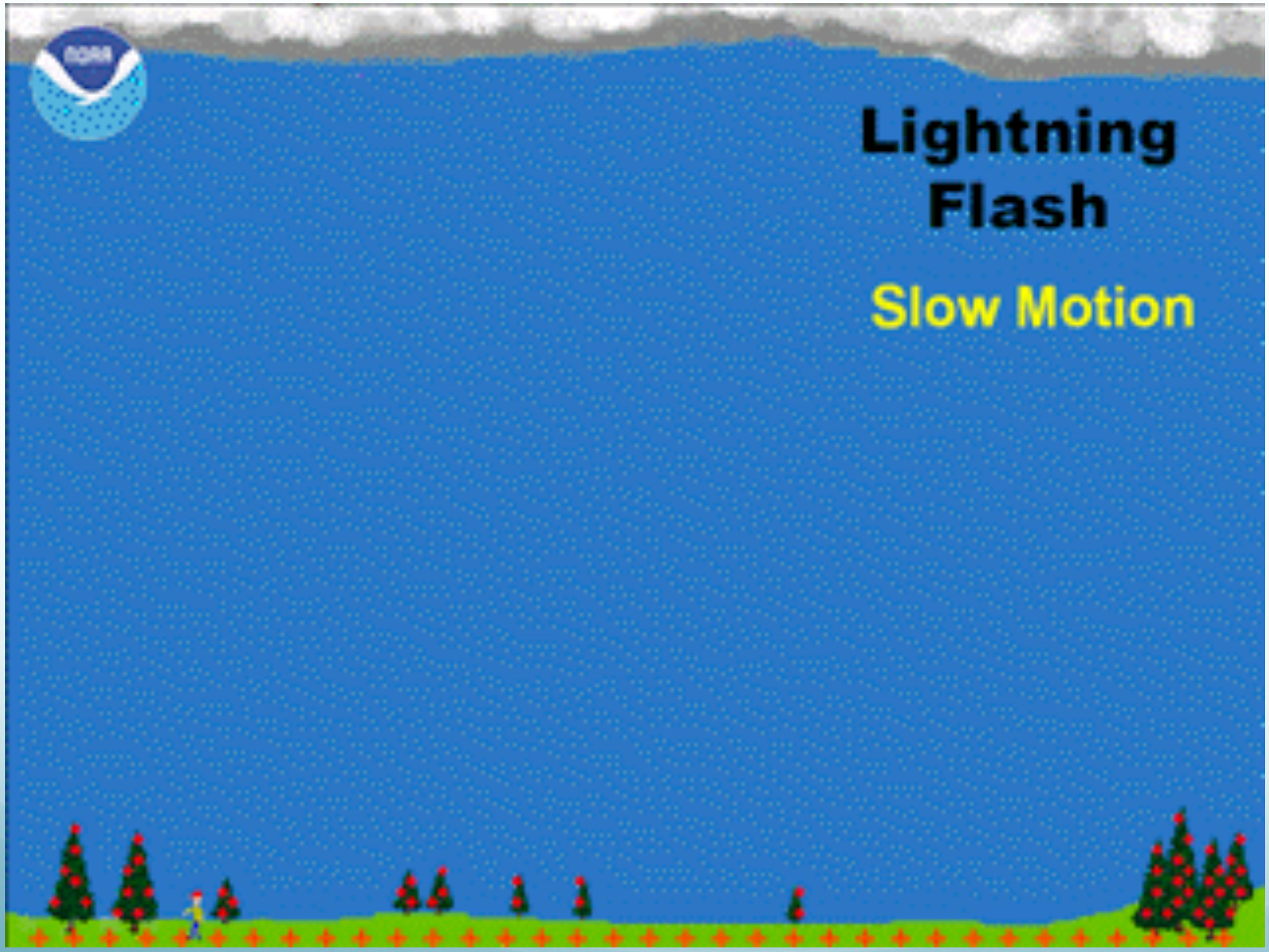


A Cloud-to-ground Lightning Event

- Stepped Leader Initiation & Descends Below Cloud Base (showing charges)
  - Starts by transferring negative charge toward the small region of positive charge near the cloud base
  - Stepped Leader Tries to find the path of least resistance toward the ground in 50-meter segments
- Streamers extend upward from high points on the surface.
- Return stroke caries the main discharge.
  - Stroke moves upward from the surface, but electrons (negatives) flow downward from cloud.
- Dart Leader
  - Flows down from above along the path of the previous discharge.
  - Triggers subsequent return strokes (3-4 total flashes is common)

A Cloud-to-ground Lightning Event

Complete Event – Slow Motion



- Stepped Leader
- Streamers
- Return stroke
- Dart Leader

Thunder

- Thunder is caused by the air expansion when air is heated by a lightning stroke
- Why do you see lightning before hearing thunder?
  - Sound travels much slower than light!

Red sprites

- Occur way above active thunderstorms
- Hard to see from the ground

Lightning Safety

- NO PLACE outside is safe when thunderstorms are in the area

Indoor safety

- Stay off corded phones, computers and other electrical equipment that put you in direct contact with electricity.
- Avoid plumbing, including sinks, baths and faucets.
- Stay away from windows and doors, and stay off porches.
- Do not lie on concrete floors, and do not lean against concrete walls.

Lightning Safety

How People Are Struck By Lightning

1. Direct Strike
2. Side Flash
3. Ground Current
4. Conduction
5. Streamer

How to avoid them?

Flash floods & Raindrops

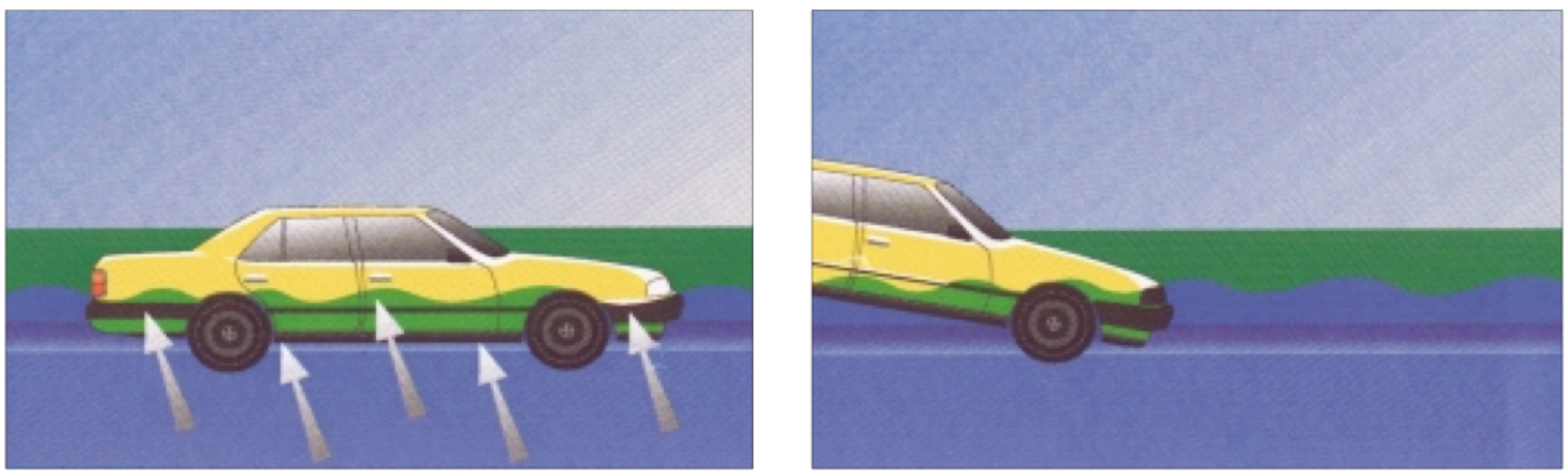
How do raindrops grow?

Hazards from single-cell thunderstorms

- Lightning
- Downdrafts and the spreading gust front create microbursts, an aviation hazard.
- *Flash floods*

Flash floods

- Very fast…
- Two feet of water will carry away most vehicles

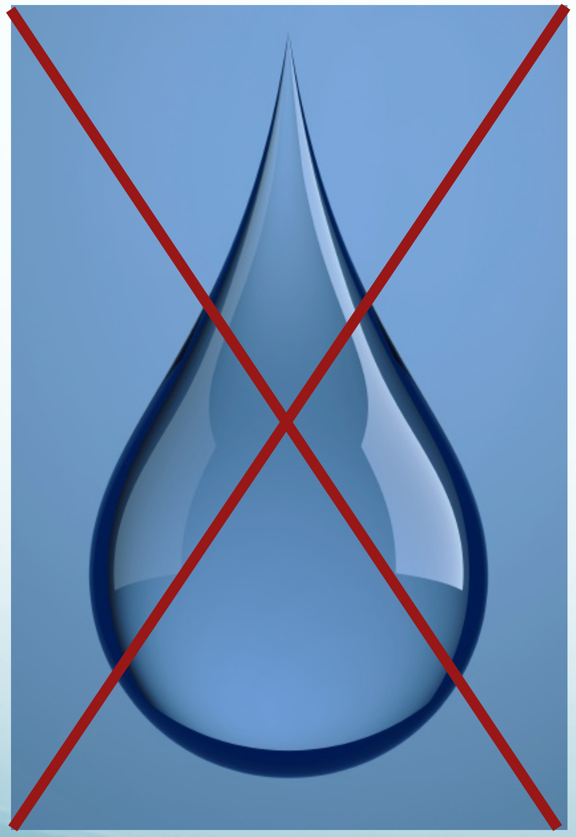


But the biggest factor is buoyancy. For each foot the water rises up the side of the car, the car displaces 1,500 lbs. of water. In effect, the car weighs 1,500 lbs. less for each foot the water rises.

Two feet of water will carry away most automobiles.

About raindrops

- Size:
  - Cloud droplet: 0.02 mm (typical)
  - Raindrop: 0.5 – 8 (?) mm l maximum size is determined by aerodynamics
- Shape



Surface tension
Aerodynamics

Virga is rain that never reaches the ground

Virga is rain (or snow) that evaporates (or sublimates) while falling through dry air before reaching the ground.

Virga is more common when the air below cloud base has low relative humidity.

How do raindrops grow?

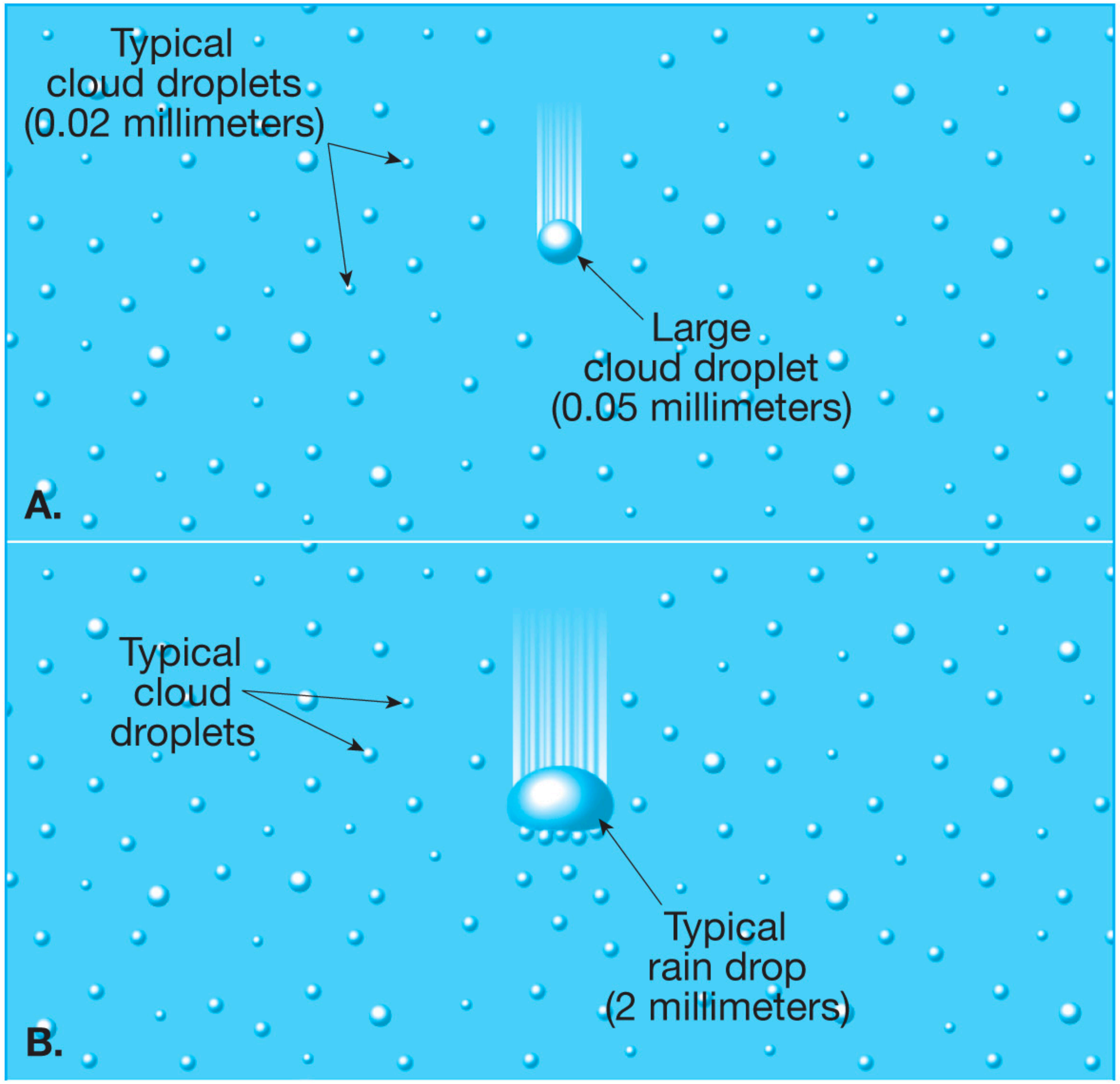
- Condensation

overall is very slow … at least 2 days!

- Collision and coalescence
- A process involving ice crystals[not in mid-term1]

Collision and coalescence

- Large droplets fall faster than small droplets
- The large droplets may collide with smaller droplets in their path
- If collisions result in a merger: the drops coalesce



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Where do the first large drops come from?

- They start large because the form on large CCN.
- Turbulent air motions cause similar sized droplets to collide and coalesce into a few larger droplets.

Thank you