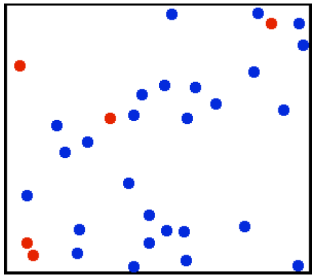
TUESDAY: stability/buoyancy, convection, clouds

Temperature, Pressure, Force Balance

- Molecules in a Box – Ideal Gas Law
- Hydrostatic Force Balance
- Adiabatic Expansion / Compression

Molecular View of a Gas



http://en.wikipedia.org/wiki/File:Translational_motion.gif

What is Atmospheric Pressure?

- Atmospheric pressure is force per unit area of a column of air above you (extending all the way to the top of the atmosphere)
- It arises from gravity acting on a column of air
- $p = F / A = m*g / A$

  (g – acceleration due to gravity)
- That is, pressure is the weight of the column of air above you – a measure of how hard this column of air is pushing down

Question

How much do you carry on your “shoulders”?

or

What's the approximate mass of the column of air above you (~ 1 ft^2 ~ 0.1 m^2)?

A) ~ 20 lb (~ 9 kg)

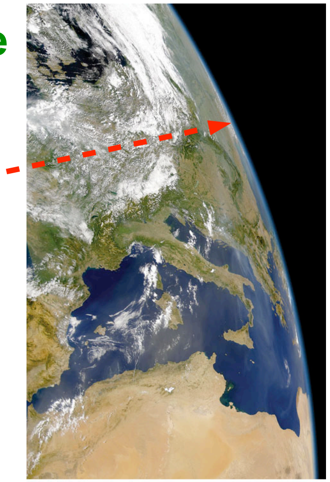
B) ~ 200 lb (~ 90 kg)

C) ~ 2,000 lb (~ 900 kg)

D) ~ 20,000 lb (~ 9,000 kg)

Vertical Structure

- **the atmosphere is very thin!**
- 99% of mass within 30 km (~19 mi) of the surface
- Gravity holds most of the air close to ground
- The weight of the overlying air is the pressure at any point



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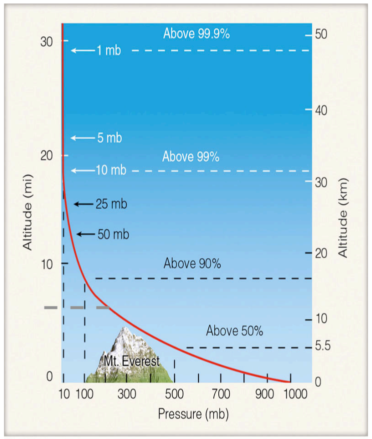
Vertical Structure

- In Fort Collins, 15% of the mass of the total atmosphere is below our feet
- At the top of Long's Peak, you are above 40% of the total atmosphere's mass
- You are closer to outer space than to Colorado Springs!
- Commercial aircraft max out at about 7 mi (~ 250 mb) → 75% of mass of atmosphere is below them (cabins are pressurized to about 750 mb)



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Equation of State
a.k.a. the Ideal Gas Law

- Relates fundamental thermodynamic quantities of air with each other:

$p = \rho R T$ *or* $\rho = p / (RT)$

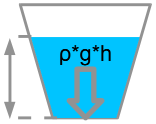
pressure (p) equals the product of density (ρ), universal gas constant (R) and absolute temperature (T)

- T constant (isothermal): pressure and density are directly proportional ($p \sim \rho$)
- p constant (isobaric): density and temperature are inversely proportional ($\rho \sim 1/T$)
- ρ constant: pressure and temperature are directly proportional ($p \sim T$)

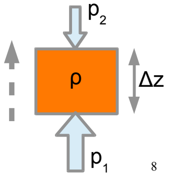
Hydrostatic Pressure & “Pressure Gradient Force”

- Pressure of a fluid column of height h and constant density:

$p = F / A = m*g / A = \rho*V*g / A = \rho*g*h$



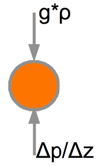
- Hydrostatic pressure does not depend on surface area (“hydrostatic paradox”)
- Pressure gradient: $(p_2 - p_1)/\Delta z = \Delta p/\Delta z$, accelerates fluid parcels from high to low pressure



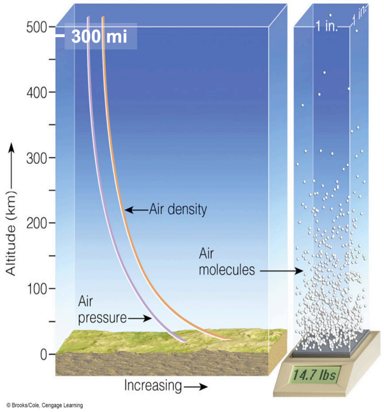
Hydrostatic Balance

- A balance between gravity and the "pressure gradient force":

$\Delta p/\Delta z = -g*\rho$



- remember the "pressure gradient force" causes an acceleration from high to low pressure



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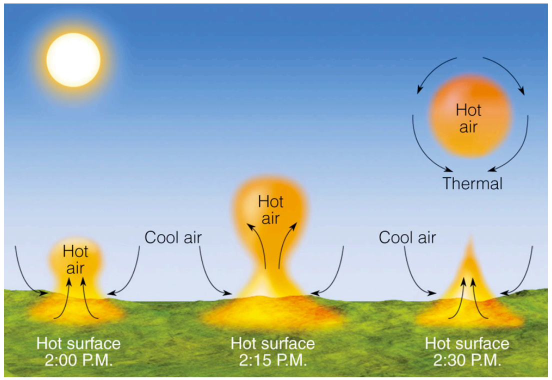
Air Parcel Concept

- **Imaginary blob/volume of air** of given composition and mass (in almost all cases it is assumed that its mass and basic composition do not change)
- All basic thermodynamic properties, temperature, pressure, and density, are allowed to change

- Most prominent application: vertical displacement and subsequent evolution (e.g. rising air expands and cools)
- Consider *adiabatic processes* (of some sort) = no heat exchange with surrounding air (environment), i.e. all change in heat content of parcel is due to internal processes

Convection ("warm air rises")



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Heating of the earth's surface during daytime causes the air to mix

Buoyancy

- An air parcel rises in the atmosphere when its density is less than that of its surroundings
- Hot air has fast-moving molecules that spread out and occupy more space (volume) – so it's less dense!
- Cold air has slow-moving molecules that pack more closely together & take up less space – it's more dense!
- So air that is warmer than it's surroundings rises, air that is colder than it's surroundings sinks

Trading Height for Heat

We can think of two *kinds* of energy in the air:

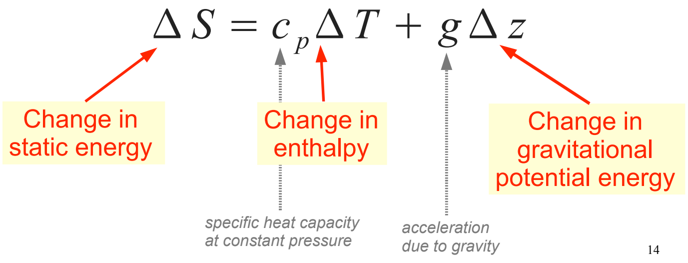
- **potential energy** (due to its height)
- **internal energy** (due to the motions of the molecules that make it up)

- Air can trade one kind of energy for the other, but **conserves the overall total (potential + internal)**

When air rises, it gains height but loses heat (cools) … when it sinks it loses height but gains heat (warms)

Trading height for heat

For an unsaturated air parcel (no latent heat effects), there are two contributions of “static” energy that we need to keep track of: potential energy (due to its height) and enthalpy (due to the motions of the molecules that make it up):



$$\Delta S = c_p \Delta T + g \Delta z$$

Change in static energy

Change in enthalpy

Change in gravitational potential energy

specific heat capacity at constant pressure

acceleration due to gravity

Trading height for heat (cont'd)

Suppose a parcel exchanges no energy with its surroundings (neither gaining nor loosing energy) → adiabatic process

$$\begin{aligned} 0 &= c_p \Delta T + g \Delta z \\ c_p \Delta T &= -g \Delta z \end{aligned}$$

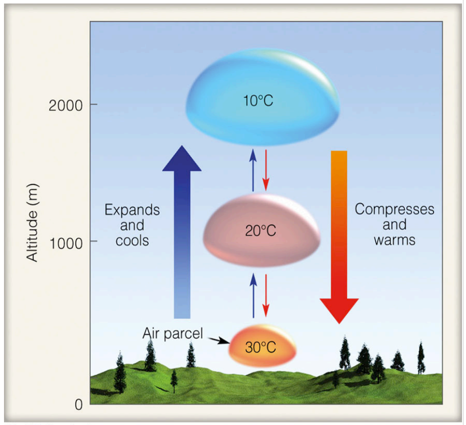
$$\frac{\Delta T}{\Delta z} = -\frac{g}{c_p} = -\frac{9.81\,\mathrm{m/s^2}}{1004\,\mathrm{J/(kg\,K)}} = \underline{-9.8\,\mathrm{K/km}}$$

“Dry adiabatic lapse rate”

Unsaturated adiabatic expansion/compression

As unsaturated air rises, it expands and cools at ~10º C per kilometer (0.5 F per 100 ft).

As unsaturated air sinks, it compresses and warms at ~10º C per km. (helps to explain why it's often warm here in winter during wind storms)



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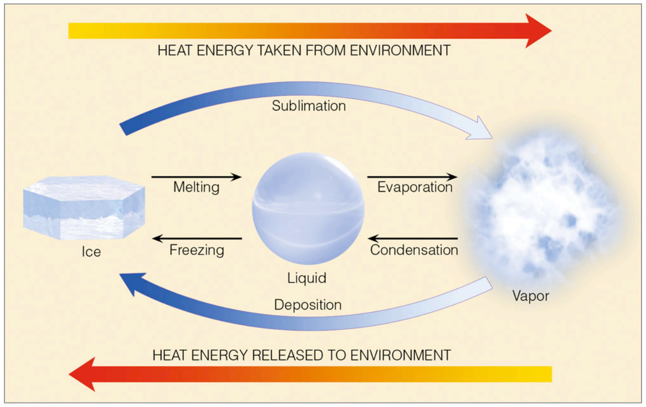
Saturated Air Parcels

- When a rising air parcel cools, its vapor content needed for saturation decreases (relative humidity increases) → eventually saturation can be reached (100% relative humidity).
- As the, now saturated, air parcel continues to rise, its vapor content needed for saturation further decreases, and water vapor in excess of the saturated amount therefore condenses into cloud droplets.
- CONDENSATION RELEASES LATENT HEAT. Therefore, the rate of temperature decrease with height is less for a saturated air parcel than for an unsaturated air parcel (saturated air cools down less strongly under adiabatic expansion).

Latent heat due to water phase changes

(latent = hidden)



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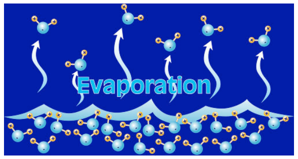
When water vapor condenses to form clouds, the surrounding air is heated.

Latent Heat due to Water Phase Changes

- Energy is required to break bonds between molecules of H_2O in solid ice
- Adding energy to ice causes molecules to vibrate faster in the crystal structure
- Adding enough molecular energy overcomes crystal bonds, releasing the molecules as liquid
- When water freezes into ice, this “hidden” (latent) energy is released as sensible heat
- Even more energy is released when water vapor (gas) condenses to form liquid water!

Evaporation vs Condensation

- **Evaporation cools:** (heat) energy is needed to break up bonds between molecules (similar for sublimation)
- **Condensation warms:** (heat) energy / internal energy from freely moving molecules is released as molecules bond with each other (similar for deposition)



Sublimation: evaporation of ice directly to water vapor

- Take one gram of ice at zero degrees Celcius
- Energy required to change the phase of one gram of ice to water vapor:
  - Add 80 calories to melt ice
  - Add 100 calories to heat up to 100 C
  - Add 540 calories to evaporate the liquid
- Total energy ADDED for sublimation of 1 gram of ice:
  - **80 + 100 + 540 = 720 calories!**

Deposition: convert water vapor directly to ice

- Take one gram of water vapor at 100 degrees C
  - Release 540 calories to condense
  - Release 100 calories to cool down to 0 C
  - Release 80 calories to freeze water
- Total energy RELEASED for deposition of 1 gram of ice:
  - **80 + 100 + 540 = 720 calories!**

Saturated vs Unsaturated Air

- When lifting saturated air parcels, their temperature decreases at roughly 6° C per km, this is called the Moist Adiabatic Lapse Rate, although it's not technically a constant.
- Compare:
  - Moist adiabatic lapse rate = 6° C per km (saturated air parcel)
  - Dry adiabatic lapse rate = 10° C per km (unsaturated air parcel)

Questions for Thought

- Why is the moist adiabatic lapse rate always smaller than the dry adiabatic lapse rate?
- Why does the moist adiabatic lapse rate approach the dry adiabatic lapse rate as we go high up in the troposphere?

Atmospheric (environmental) Temperature Profile

- The fact that air parcels cool when the gain altitude (or warm when losing altitude) makes life complicated. In order to determine whether a parcel is buoyant relative to its environment at the same pressure, you have to compare its new temperature after rising or sinking to that of the atmosphere around it.
- We will examine examples of how different atmospheric temperature profiles affect stability.

"Lapse Rate"

- The Lapse Rate describes the rate of **change (decrease) of temperature with height** in the atmosphere
- There are two kinds of lapse rates:
  - Environmental Lapse Rate
    - what you would measure with a weather balloon
  - Parcel Lapse Rate
    - The change of temperature that an air parcel would experience when displaced vertically
    - This is assumed to be an *adiabatic process* (no heat exchange occurs across parcel boundary)

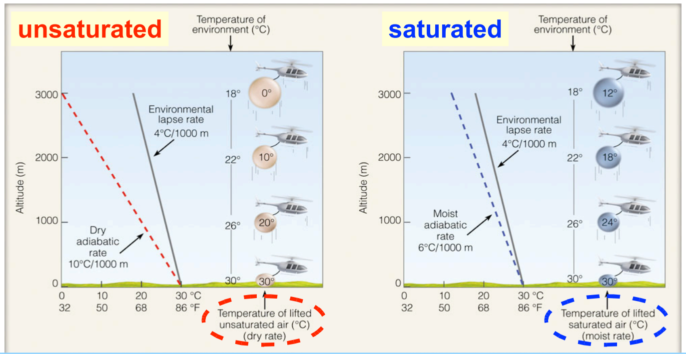
Key points to remember

- The temperature change of a rising air parcel and the temperature change of the environmental air around the parcel are considered separately
- A parcel of air if lifted will change temperature at a different rate than its environment
- Environmental air can be expected to have a temperature profile that is fixed relative to rising parcels

Stability in the Atmosphere

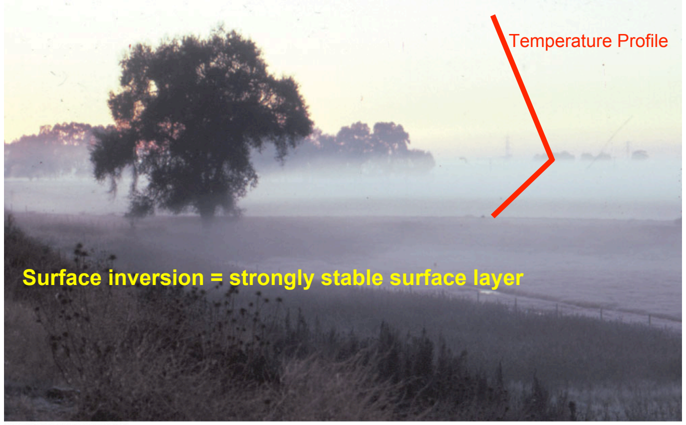
- when examining stability in the atmosphere we need to compare the lapse rate of the environmental air (LR_{env}) to the dry adiabatic (LR_{dry} = 10°C/km) and moist adiabatic lapse rates (LR_{moist} = 6°C/km)
- **Absolutely stable air:** $LR_{env} < LR_{moist} < LR_{dry}$
- **Absolutely unstable air:** $LR_{env} > LR_{dry} > LR_{moist}$
- **Conditionally stable air:** $LR_{env} < LR_{dry}$, but $LR_{env} > LR_{moist}$

An ***absolutely stable*** atmosphere



In this example, LR_{env} = 4ºC/km → as an unsaturated air parcel **OR** a saturated air parcel is lifted it becomes colder (more dense) than its environment. It will therefore tend to sink back down. Likewise, an air parcel pushed down will tend to come back up.

Fog can form in an absolutely stable atmosphere



Surface inversion = strongly stable surface layer

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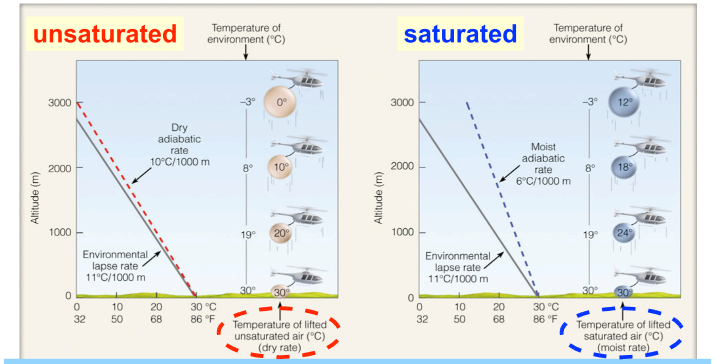
An ***absolutely unstable*** atmosphere

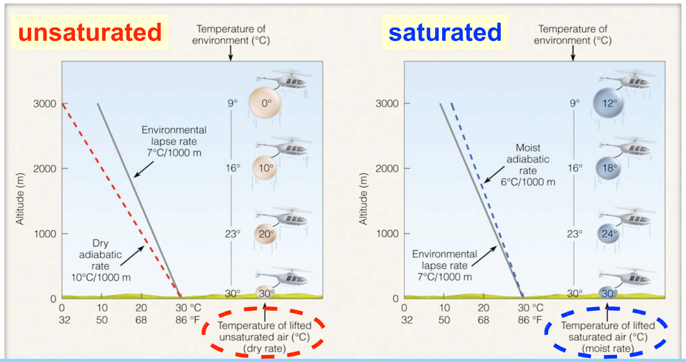


In this example, LR_{env} = 11ºC/km → as an unsaturated air parcel **OR** a saturated air parcel is lifted it becomes warmer (less dense) than its environment. It will therefore tend to accelerate further up. Likewise, an air parcel pushed down will tend to accelerate further.

A ***conditionally unstable*** atmosphere

- What happens when a rising *saturated* air parcel becomes warmer than its environment and is accelerated further up, but a rising *unsaturated* air parcel becomes colder than its environment and wants to sink back down?
- In this case the atmosphere is described to be ***conditionally unstable***
- The *condition* to produce instability is to somehow saturate the air, say by lifting it sufficiently high (to the “lifting condensation level”)
- *(you might also refer to the atmosphere being conditionally stable: if you somehow unsaturate the air it becomes stable)*

A *conditionally unstable* atmosphere



In this example, LR_{env} = 7ºC/km → A lifted unsaturated air parcel becomes colder (less dense) than its environment and will tend to sink back down. A lifted saturated air parcel, however, becomes warmer than its environment and will tend to accelerate further up.

(Conditional) Instability in the Atmosphere generates Convection

Most severe convection that is observed occurs under conditional instability.

The tropical atmosphere in general is conditionally unstable.

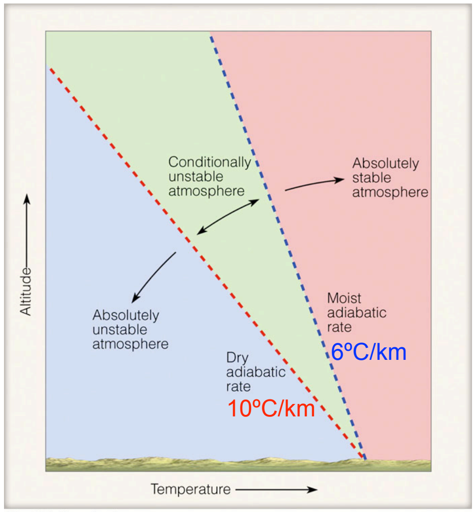
Understanding only German, Fritz was unaware that the clouds were becoming threatening.

Summary

Absolutely stable: LR_{env} < 6ºC/km < 10ºC/km

Absolutely unstable: LR_{env} > 10ºC/km > 6ºC/km

Conditionally unstable: 6ºC/km < LR_{env} < 10ºC/km



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Interesting application of dry adiabatic lapse rate:

Conventional jet airliners tend to fly at an altitude of ~12 km (~40,000 ft), corresponding to ~200 mb pressure. Bringing in outside air and compressing it to cabin pressure (~750 mb, corresponding to ~2 km altitude), will warm that air by:

10ºC/km x (12 km – 2 km) = 100ºC !!

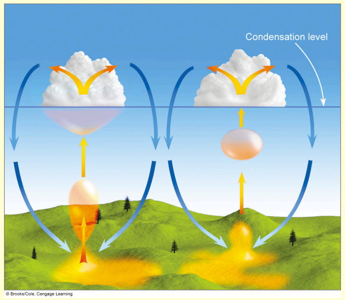
So, if outside temperature is –60ºC (–76ºF), compressing the air to cabin pressure results in a temperature of +40ºC (104ºF)!! The AC system will actually have to cool the air, despite the cold temperatures outside.

Tuesday AM, Explain: Pressure, Temperature, Stability

Cloud Development

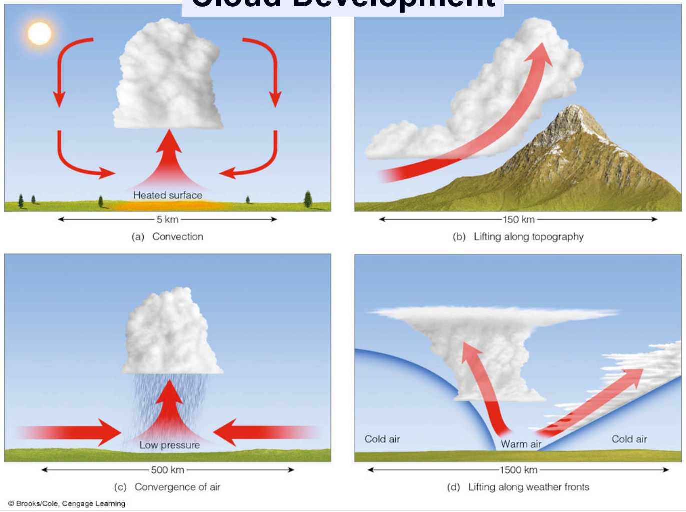
Clouds form as air rises, expands and cools, and eventually saturates

- Fair weather cumulus development:
  - often associated with high-pressure systems
  - rising is strongly suppressed at base of subsidence inversion produced from large-scale sinking motion
  - Why is there sinking air between cloud elements?

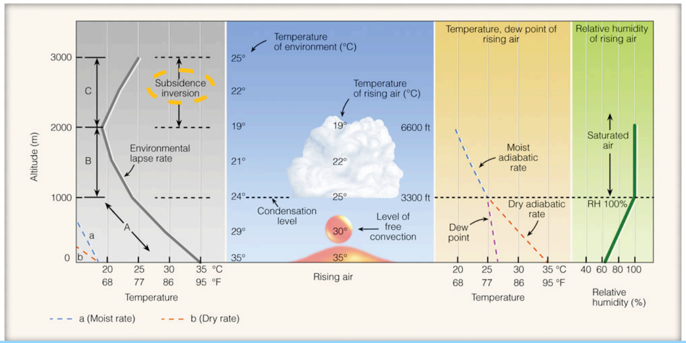


taller cumulus development (deep convection) occurs for less stable atmospheric profiles

Cloud Development

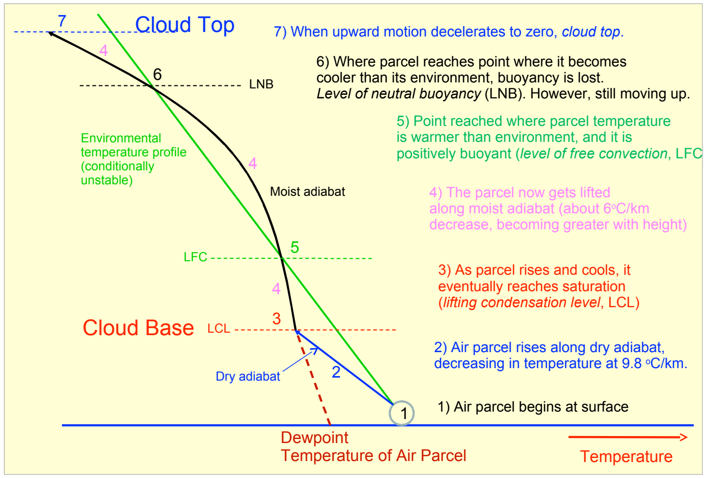


Fair weather cumulus development



Cloud base: unsaturated air cools at 10ºC/km, dew point decreases at ~2ºC/km → air parcel temperature approaches dew point at ~8ºC/km → surface temperature 8ºC higher than the dew point produces cloud base at a height of 1 km

Cumulonimbus Formation



7) When upward motion decelerates to zero, *cloud top*.

6) Where parcel reaches point where it becomes cooler than its environment, buoyancy is lost. *Level of neutral buoyancy* (LNB). However, still moving up.

5) Point reached where parcel temperature is warmer than environment, and it is positively buoyant (*level of free convection*, LFC)

4) The parcel now gets lifted along moist adiabat (about 6°C/km decrease, becoming greater with height)

3) As parcel rises and cools, it eventually reaches saturation (*lifting condensation level*, LCL)

2) Air parcel rises along dry adiabat, decreasing in temperature at 9.8 °C/km.

1) Air parcel begins at surface

Thomas Birner, ATS, CSU