TUESDAY: air & water & clouds

Stability, Buoyancy, Convection

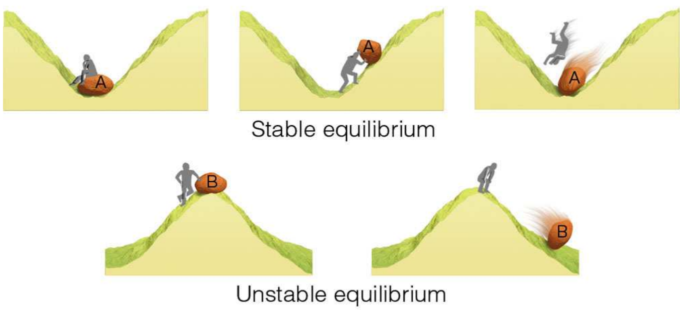
- Why does hot air rise?
- Convection & cloud formation

Why do clouds form in some occasions and not in others?

For example, why did this cloud form, whereas the sky was clear 4 hours ago?

One likely explanation relates to the concept of atmospheric (in)stability.

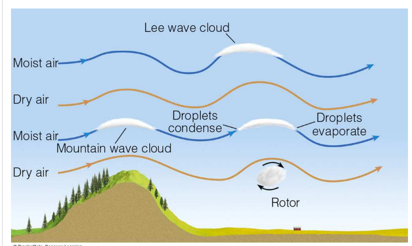
The Concept of Stability



A rock, like a parcel of air, that is in stable equilibrium will return to its original position when pushed.

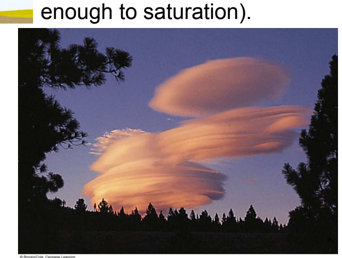
If the rock instead accelerates in the direction of the push, it was in unstable equilibrium.

Stable Atmosphere: Example



Stability tends to force waves in the atmosphere, because air oscillates back and forth around its equilibrium point.

Lenticular clouds tend to form in the wake of mountains, due to waves forced within the atmospheric flow (if close enough to saturation).



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Unstable Atmosphere: Example

As (warm) air parcels rise, they keep accelerating upward, eventually bumping into a stable layer (likely the stratosphere).

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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

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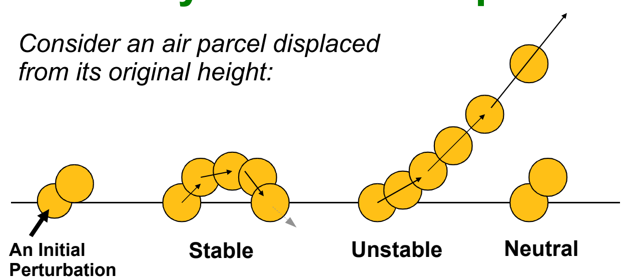
Stability in the Atmosphere

Consider an air parcel displaced from its original height:



This air parcel is considered to be:

STABLE if it returns to its original height (oscillatorily)
UNSTABLE if it accelerates upward because it is buoyant
NEUTRAL if it stays at the place to which it was displaced

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Why is stability important?

- Vertical motions in the atmosphere are a critical part of energy transport and strongly influence the hydrological cycle
- Without vertical motion there would be no precipitation, no mixing of pollutants away from ground level – weather as we know it would not exist
- There are two types of vertical motion:
  - Forced motion such as forcing air up over a hill, over colder air; or from horizontal convergence
  - Buoyant motion in which air rises because it's less dense than its surroundings – **stability** is especially important here

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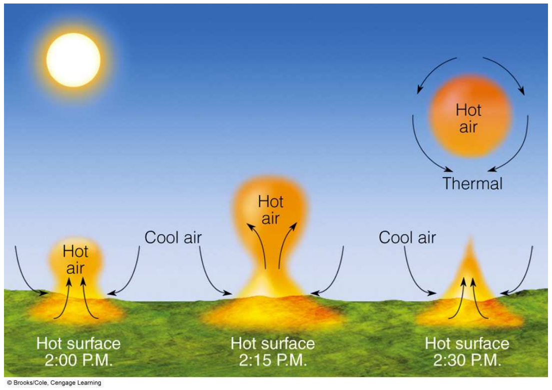
Convection ("warm air rises")



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

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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

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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)**

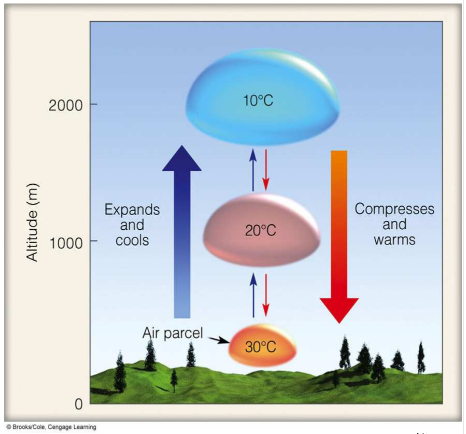
When air rises, it gains height but loses heat (cools) … when it sinks it loses height but gains heat (warms)

Vertical Motion and Temperature

Rising air expands (recall pressure decreases with height), using energy to push outward against its environment, adiabatically cooling the air.

Sinking air ...

A parcel of air maybe forced to rise or sink, and change temperature relative to environmental air.



"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)

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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

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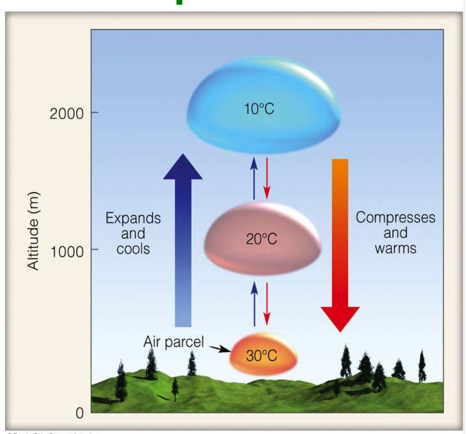
Adiabatic expansion/compression

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

As (non-cloudy) 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)



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.

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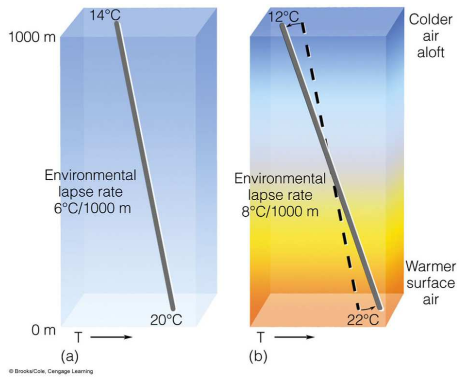
How to decrease Stability?

Starting from a profile that is stable ...

instability can be produced by heating the surface and/or cooling aloft.

This is why convective storms tend to form in the afternoon.



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Convection induced by Forest Fires

The lowest layers of the atmosphere are heated by the fire.

Hot surface air becomes positively buoyant and forms convective plumes.

As the air parcels rise and cool they may eventually reach saturation and form clouds.

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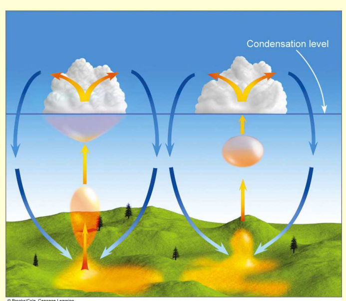
Cloud Development

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

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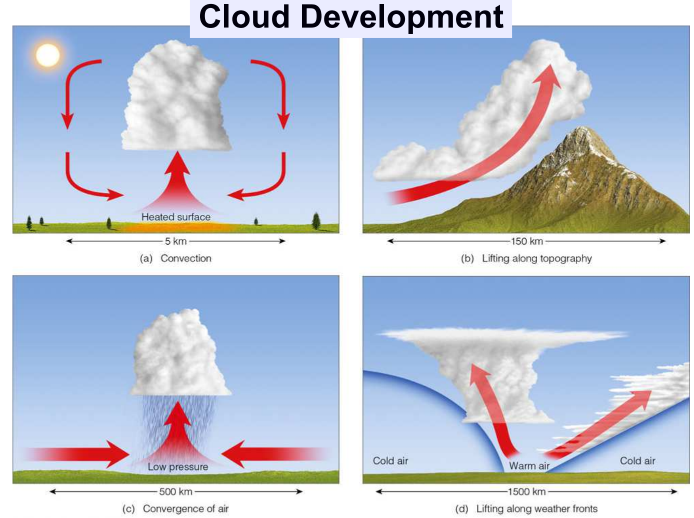
Cloud Development



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