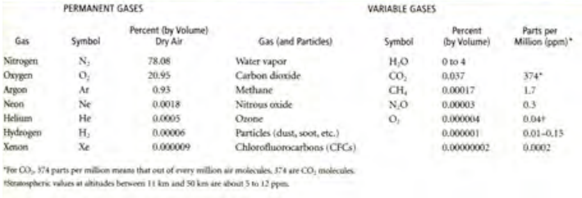
Thermodynamics, Buoyancy, and Vertical Motion

Temperature, Pressure, and Density
Buoyancy and Static Stability
Adiabatic "Lapse Rates"
Dry and Moist Convective Motions

Present Atmospheric Composition



PERMANENT GASES			VARIABLE GASES			
Gas	Symbol	Percent (by Volume) Dry Air	Gas (and Particles)	Symbol	Percent (by Volume)	Parts per Million (ppm)*
Nitrogen	N_2	78.08	Water vapor	H_2O	0 to 4	
Oxygen	O_2	20.95	Carbon dioxide	CO_2	0.037	374*
Argon	Ar	0.93	Methane	CH_4	0.00017	1.7
Neon	Ne	0.0018	Nitrous oxide	N_2O	0.00003	0.3
Helium	He	0.0005	Ozone	O_3	0.000004	0.04†
Hydrogen	H_2	0.00006	Particles (dust, soot, etc.)		0.000001	0.01–0.15
Xenon	Xe	0.000009	Chlorofluorocarbons (CFCs)		0.00000002	0.0002

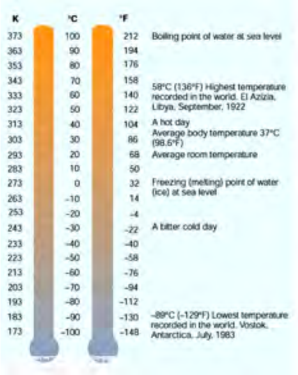
*For CO_2, 374 parts per million means that out of every million air molecules, 374 are CO_2 molecules.
†Stratospheric values at altitudes between 11 km and 50 km are about 5 to 12 ppm.

What is Air Temperature?

- Temperature is a measure of the kinetic (motion) energy of air molecules
  - K.E. = ½ mv^2 m = mass, v = velocity
  - So…temperature is a measure of air molecule speed
- The sensation of warmth is created by air molecules striking and bouncing off your skin surface
  - The warmer it is, the faster molecules move in a random fashion and the more collisions with your skin per unit time

Temperature Scales

- In the US, we use Fahrenheit most often
- Celsius (centigrade) is a scale based on freezing/boiling of water
- Kelvin is the “absolute” temperature scale



How do we measure temperature?

- Conventional thermometry
  - *Liquid in glass.*
- Electronic thermometers
  - *Measures resistance in a metal such as nickel.*
- Remote sensing using radiation emitted by the air and surface (by satellites or by you in this class!).

What is the coldest possible temperature? Why?

Atmospheric Soundings

Helium-filled weather balloons are released from over 1000 locations around the world every 12 hours (some places more often)

These document temperature, pressure, humidity, and winds aloft

Pressure

- Pressure is defined as a force applied per unit area
- The weight of air is a force, equal to the mass m times the acceleration due to gravity g
- Molecules bumping into an object also create a force on that object, or on one another
- Air pressure results from the weight of the entire overlying column of air!

How do we measure pressure?

Sea Level Value (average)	Units of Pressure:
1	atmosphere
760	mm. of mercury
29.92	in. of mercury
33.9	ft. of water
1013.25	millibars

Why does pressure decrease with altitude?

Remember:

Pressure = mass*gravity/unit area

As you go higher, you have less mass above you.

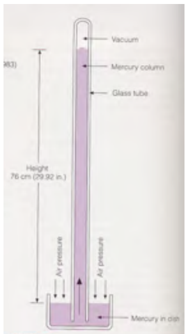


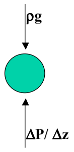
FIGURE 9.5
The mercury barometer. The height of the mercury column is a measure of atmospheric pressure.

Hydrostatic Balance

What keeps air from always moving downwards due to gravity?

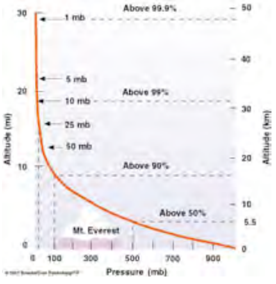
A balance between gravity and the pressure gradient force.

$\Delta P/\Delta z = \rho g$



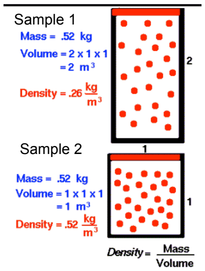
What is the "pressure gradient force?"

Pushes from high to low pressure.



Density (mass/volume)

- Same number of molecules and mass
- Sample 1 takes up more space
- Sample 2 takes up less space
- Sample 2 is more dense than sample 1



Equation of State (a.k.a. the "Ideal Gas Law")

$$p = \rho R T$$

pressure (N m^{-2})

density (kg m^{-3})

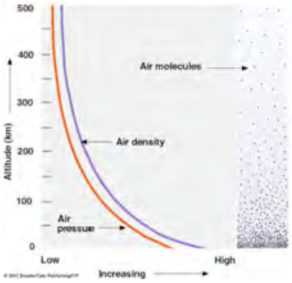
"gas constant" (J K^{-1} kg^{-1})

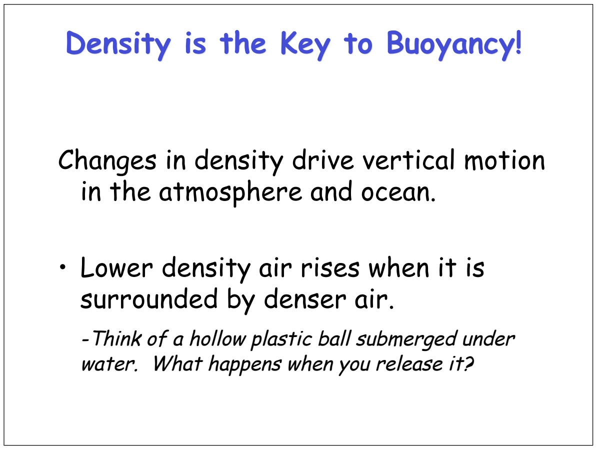
temperature (K)

- Direct relationship between density and pressure
- Inverse relationship between density and temperature
- Direct relationship between temperature and pressure

Pressure and Density

- Gravity holds most of the air close to the ground
- The weight of the overlying air is the pressure at any point



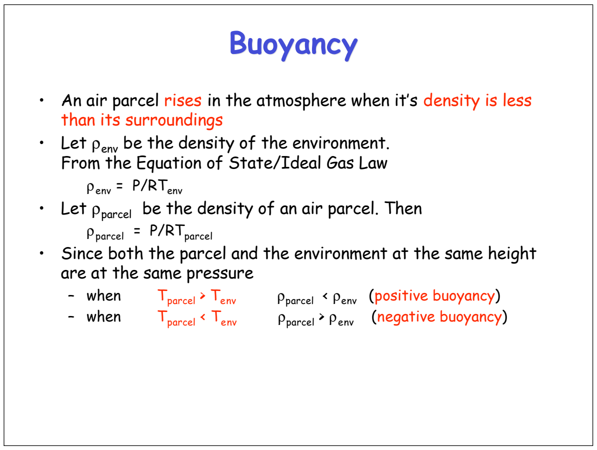


Density is the Key to Buoyancy!

Changes in density drive vertical motion in the atmosphere and ocean.

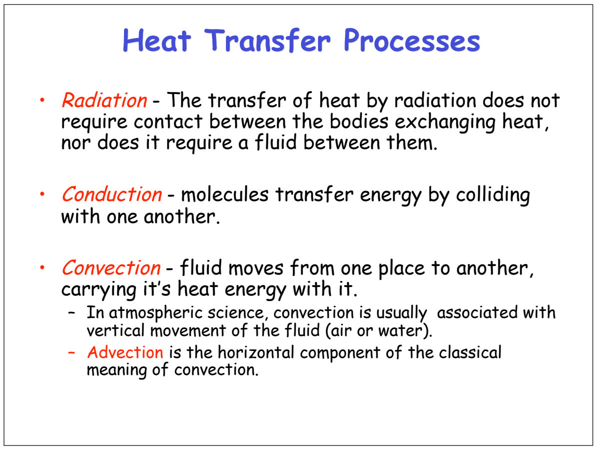
- Lower density air rises when it is surrounded by denser air.

  -Think of a hollow plastic ball submerged under water. What happens when you release it?



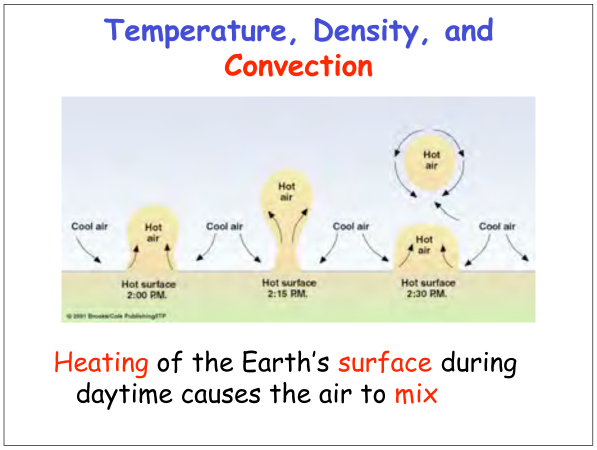
Buoyancy

- An air parcel rises in the atmosphere when it's density is less than its surroundings
- Let ρ_{env} be the density of the environment. From the Equation of State/Ideal Gas Law
  $\rho_{env} = P/RT_{env}$
- Let ρ_{parcel} be the density of an air parcel. Then
  $\rho_{parcel} = P/RT_{parcel}$
- Since both the parcel and the environment at the same height are at the same pressure
  - when $T_{parcel} > T_{env}$ $\rho_{parcel} < \rho_{env}$ (positive buoyancy)
  - when $T_{parcel} < T_{env}$ $\rho_{parcel} > \rho_{env}$ (negative buoyancy)



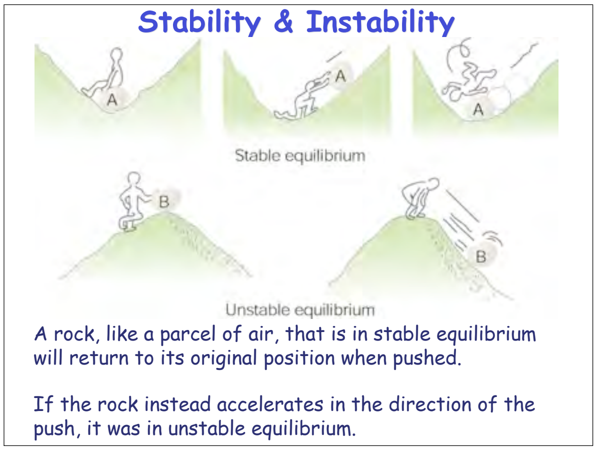
Heat Transfer Processes

- *Radiation* - The transfer of heat by radiation does not require contact between the bodies exchanging heat, nor does it require a fluid between them.
- *Conduction* - molecules transfer energy by colliding with one another.
- *Convection* - fluid moves from one place to another, carrying it's heat energy with it.
  - In atmospheric science, convection is usually associated with vertical movement of the fluid (air or water).
  - Advection is the horizontal component of the classical meaning of convection.



Temperature, Density, and Convection

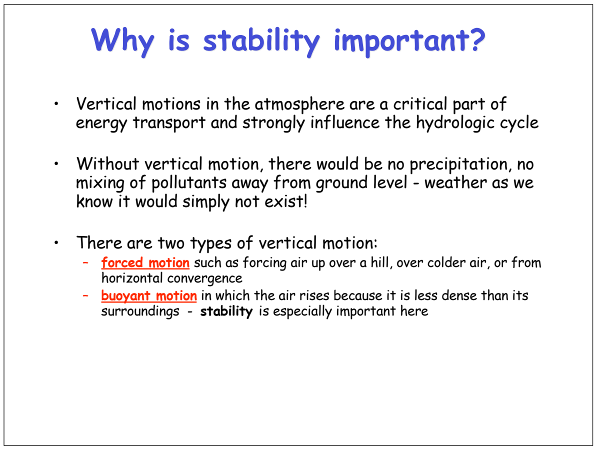
Heating of the Earth's surface during daytime causes the air to mix



Stability & Instability

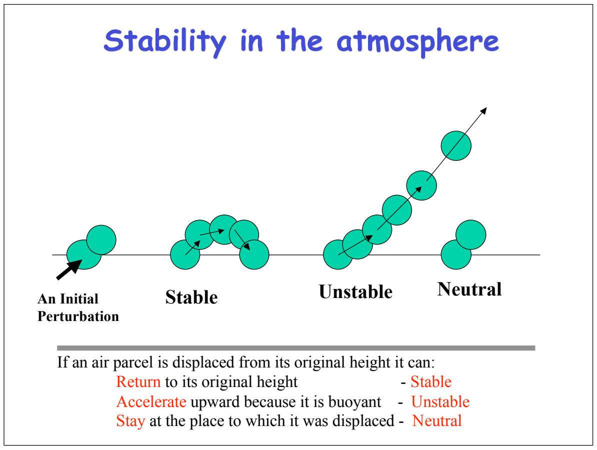
A rock, like a parcel of air, that is in stable equilibrium will return to its original position when pushed.

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



Why is stability important?

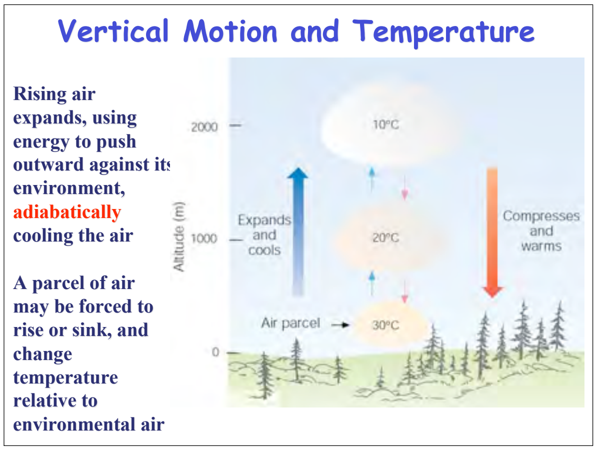
- Vertical motions in the atmosphere are a critical part of energy transport and strongly influence the hydrologic cycle
- Without vertical motion, there would be no precipitation, no mixing of pollutants away from ground level - weather as we know it would simply not exist!
- There are two types of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



Stability in the atmosphere

If an air parcel is displaced from its original height it can:

Return to its original height - Stable
Accelerate upward because it is buoyant - Unstable
Stay at the place to which it was displaced - Neutral



Vertical Motion and Temperature

Rising air expands, using energy to push outward against its environment, adiabatically cooling the air

A parcel of air may be forced to rise or sink, and change temperature relative to environmental air

"Lapse Rate"

- The lapse rate is the change of temperature with height in the atmosphere
- Environmental Lapse Rate
  - The actual vertical profile of temperature (e.g., would be measured with a weather balloon)
- Dry Adiabatic Lapse Rate
  - The change of temperature that an air parcel would experience when it is displaced vertically with no condensation or heat exchange

Trading Height for Heat

There are two kinds of "static" energy in the parcel: 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

Trading Height for Heat (cont'd)

- Suppose a parcel exchanges no energy with its surroundings … we call this state adiabatic, meaning, "not gaining or losing energy"

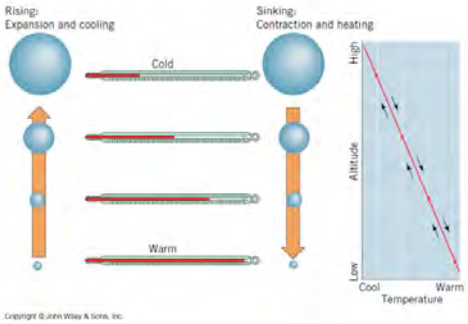
$$0 = c_p \Delta T + g \Delta z$$

$$c_p \Delta T = -g \Delta z$$

$$\frac{\Delta T}{\Delta z} = -\frac{g}{c_p} = -\frac{(9.81 ms^{-2})}{(1004 J\, K^{-1}\, kg^{-1})} = -9.8\, K\, km^{-1}$$

"Dry adiabatic lapse rate"

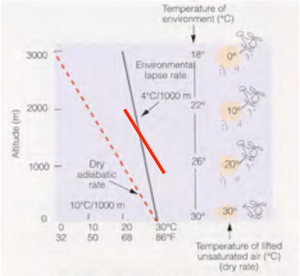
Dry Adiabatic Lapse Rate



Warming and Cooling due to changing pressure

Stability and the dry adiabatic lapse rate

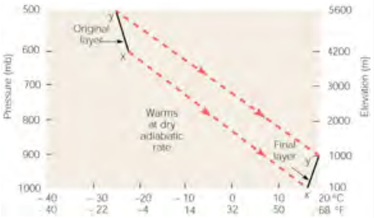
- Atmospheric stability depends on the environmental lapse rate
  - A rising unsaturated air parcel cools according to the dry adiabatic lapse rate
  - If this air parcel is
    - warmer than surrounding air it is less dense and buoyancy accelerates the parcel upward
    - colder than surrounding air it is more dense and buoyancy forces oppose the rising motion



(a) Lifted, unsaturated air at each level is colder and heavier than the air around it. If given the chance, the parcel would return to its original position

What conditions contribute to a stable atmosphere?

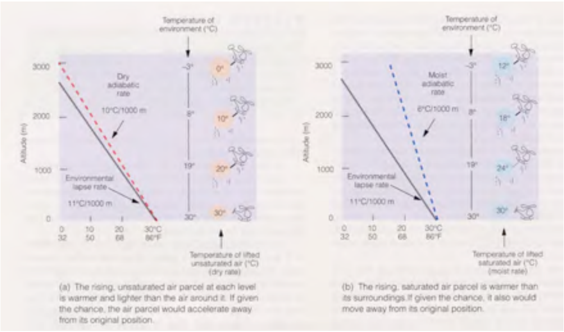
- Radiative cooling of surface at night
- Advection of cold air near the surface
- Air moving over a cold surface (e.g., snow)
- Adiabatic warming due to compression from subsidence (sinking)



Absolute instability

- The atmosphere is absolutely unstable if the environmental lapse rate exceeds the moist and dry adiabatic lapse rates
- This situation is not long-lived
  - Usually results from surface heating and is confined to a shallow layer near the surface
  - Vertical mixing can eliminate it
- Mixing results in a dry adiabatic lapse rate in the mixed layer, unless condensation (cloud formation) occurs (in which case it is moist adiabatic)

Absolute instability (examples)

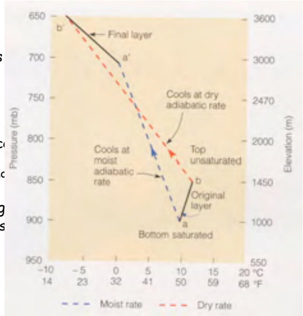


(a) The rising, unsaturated air parcel at each level is warmer and lighter than the air around it. If given the chance, the air parcel would accelerate away from its original position.

(b) The rising, saturated air parcel is warmer than its surroundings.If given the chance, it also would move away from its original position.

What conditions enhance atmospheric instability?

- Cooling of air aloft
  - Cold advection aloft
  - Radiative cooling of air/clouds aloft
- Warming of surface air
  - Solar heating of ground
  - Warm advection near surface
  - Air moving over a warm surfac (e.g., a warm body of water)
    - Contributes to lake effect sn
- Lifting of an air layer and associated vertical “stretching
  - Especially if bottom of layer is moist and top is dry

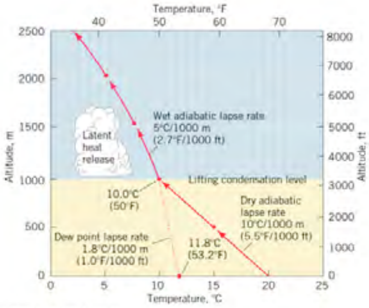


Phase Changes and Latent Heat

A saturated rising air parcel cools less than an unsaturated parcel

- If a rising air parcel becomes saturated condensation occurs
- Condensation warms the air parcel due to the release of latent heat
- So, a rising parcel cools less if it is saturated
- Define a moist adiabatic lapse rate
  - ~ 6 C/1000 m
  - Not constant (varies from ~ 3-9 C)
  - depends on T and P

Moist Adiabatic Lapse Rate

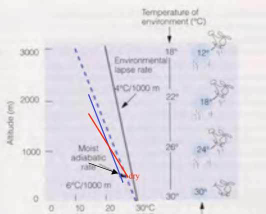


Copyright © John Wiley & Sons, Inc.

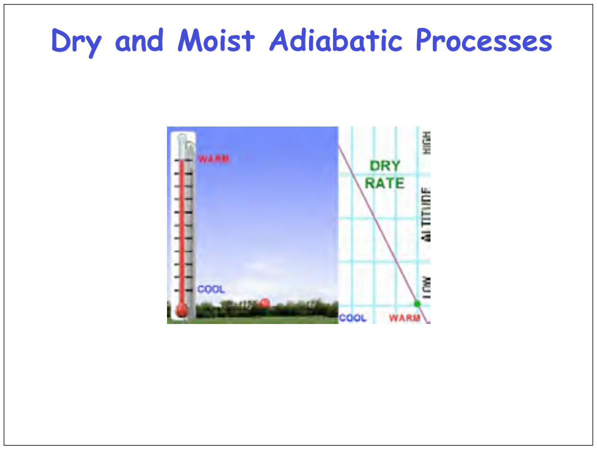
Warming and cooling due to both changes in pressure and latent heat effects

Stability and the moist adiabatic lapse rate

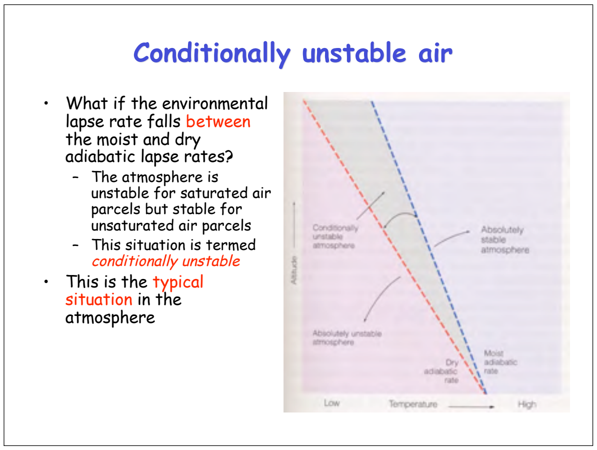
- Atmospheric stability depends on the environmental lapse rate
  - A rising saturated air parcel cools according to the moist adiabatic lapse rate
  - When the environmental lapse rate is smaller than the moist adiabatic lapse rate, the atmosphere is termed *absolutely stable*
    - Recall that the dry adiabatic lapse rate is larger than the moist
  - What types of clouds do you expect to form if saturated air is forced to rise in an absolutely stable atmosphere?



(b) Lifted, saturated air at each position is colder and heavier than the air surrounding it. If released, the parcel would return to its original position.



Dry and Moist Adiabatic Processes



Conditionally unstable air

- What if the environmental lapse rate falls between the moist and dry adiabatic lapse rates?
  - The atmosphere is unstable for saturated air parcels but stable for unsaturated air parcels
  - This situation is termed *conditionally unstable*
- This is the typical situation in the atmosphere