Thermodynamics, Buoyancy, and Vertical Motion

Temperature, Pressure, and Density

Buoyancy and Static Stability

Adiabatic “Lapse Rates”

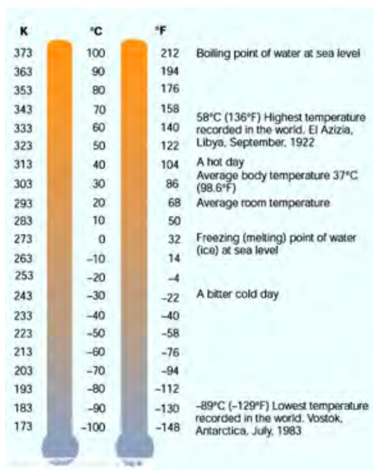
Dry and Moist Convective Motions

What is Air Temperature?

- Temperature is a measure of the kinetic (motion) energy of air molecules
  - K.E. = $\frac{1}{2}$ 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



Atmospheric Soundings

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

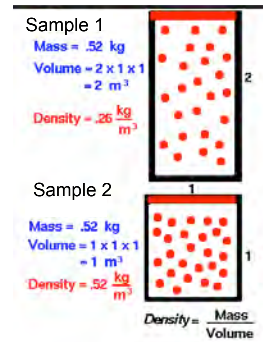
These document temperature, pressure, humidity, and winds aloft

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!

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 ($kg\ m^{-3}$)

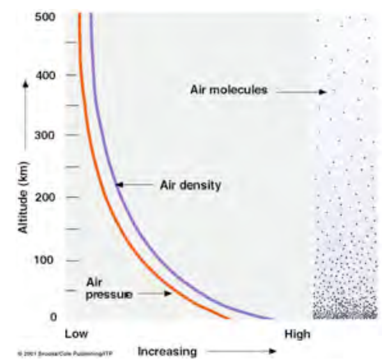
"gas constant" ($J\ K^{-1}\ kg^{-1}$)

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.

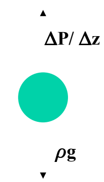
  -Think of a hollow plastic ball submerged under water. What happens when you release it?

Hydrostatic Balance

What keeps air from always moving downwards due to gravity?

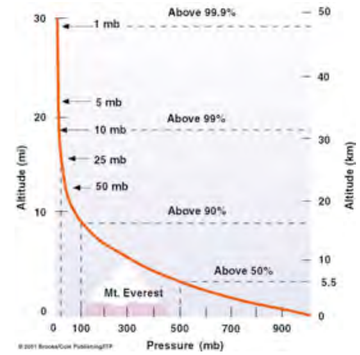
A balance between gravity and the pressure gradient force.

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



The "pressure gradient force?"

Pushes from high to low pressure.



Buoyancy

An air parcel rises in the atmosphere when its density is less than its surroundings

Let ρ_{env} be the density of the environment.

From the Ideal Gas Law

$\rho_{env} = P/RT_{env}$

Let ρ_{parcel} be the density of an air parcel. Then

$\rho_{parcel} = P/RT_{parcel}$

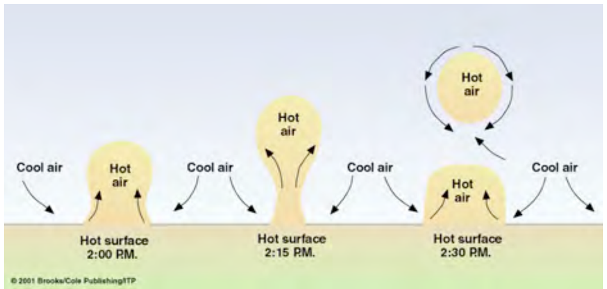
Since both the parcel and the environment at the same height are at the same pressure

- 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

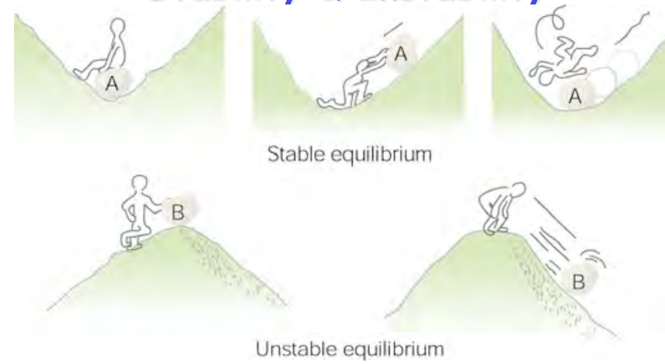
- *Radiation* - The transfer of heat by radiation does not require contact between the bodies exchanging heat, nor does it require a fluid between them.
- *Conduction* - molecules transfer energy by colliding with one another.
- *Convection* - fluid moves from one place to another, carrying it's heat 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.

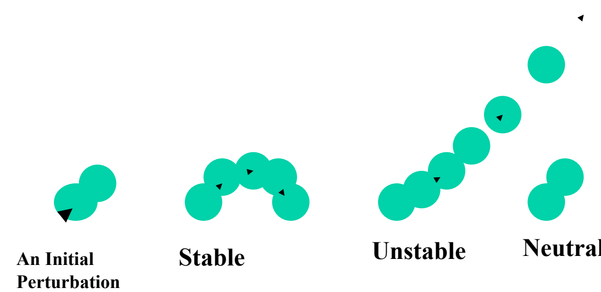
If the rock instead accelerates in the direction of the push, it was in unstable equilibrium.

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 in the atmosphere

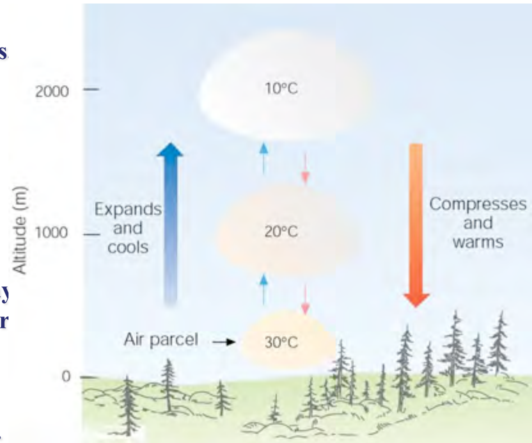


If an air parcel is displaced from its original height it can:
Return to its original height - Stable
Accelerate upward because it is buoyant - Unstable
Stay at the place to which it was displaced - Neutral

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 if it were displaced vertically with no condensation or heat exchange

Trading Height for Heat

Define two kinds of "static" energy in the air:

- potential energy (due to its height)
- 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"

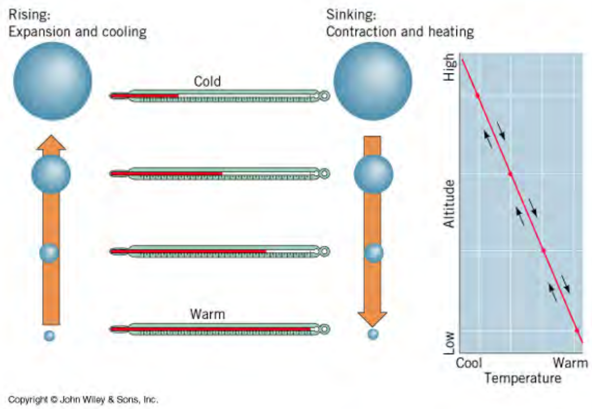
$$0 = c_p \Delta T + g\Delta z$$

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

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

"Dry adiabatic lapse rate"

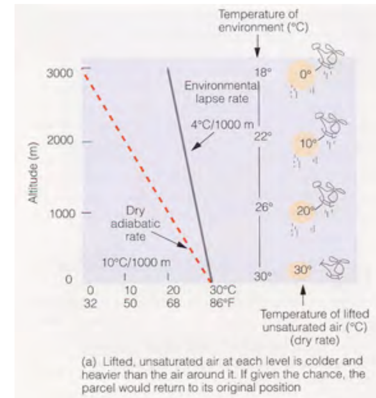
Dry Adiabatic Lapse Rate



Warming and Cooling due to changing pressure

Stability and the Dry Adiabatic Lapse Rate

- A rising 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

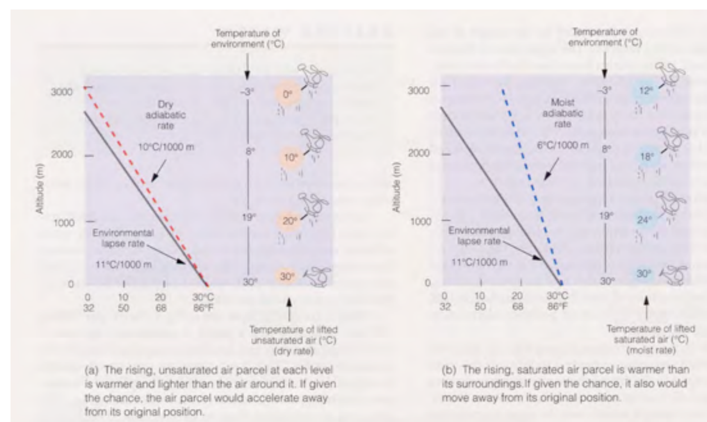


(a) Lifted, unsaturated air at each level is colder and heavier than the air around it. If given the chance, the parcel would return to its original position

Absolute Instability

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

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?

- Warming of surface air
  - Solar heating of ground
  - Warm "advection" near surface
  - Air moving over a warm surface (e.g., a warm body of water)
- Cooling of air aloft
  - Cold "advection" aloft (thunder-snow!)
  - Radiative cooling of air/clouds aloft

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)