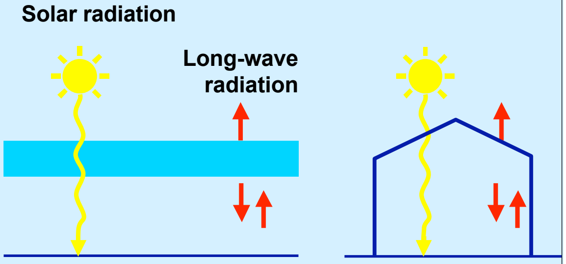
Climate Sciences: Atmospheric Thermodynamics

Instructor: Lynn Russell, NH343
http://aerosol.ucsd.edu/courses.html
Text: Curry & Webster

The Greenhouse Effect



Solar radiation

Long-wave radiation

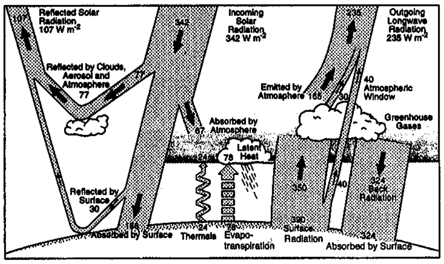
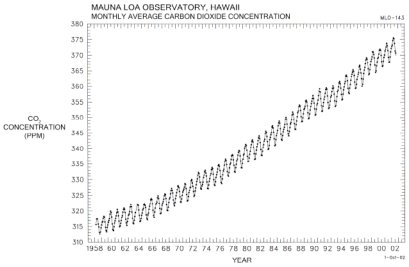
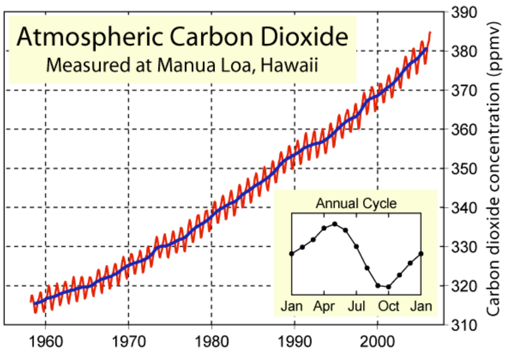


Figure 12.2 Estimated annual mean global energy balance for the Earth. Units are W m^{-2} (Kiehl and Trenberth, 1997).





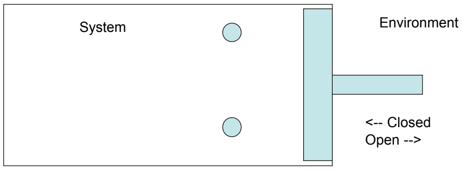
Review from Ch. 1

- Thermodynamic quantities
- Composition
- Pressure
- Density
- Temperature
- Kinetic Theory of Gases

Curry and Webster, pp. 1-17
Feynman, Book I, ch. 39

Thermodynamic Quantities

- Classical vs. Statistical thermodynamics
- Open/closed systems
- Equation of state f(P,V,T)=0
- Extensive/intensive properties
- Thermal, engine, heat/work cycles



Intensive quantities: P, T, v, n
Extensive quantities: V, N

Concentration: n=N/V
Volume: v=V/N

Composition

- Structure
  - Comparison to other planets
- N_2, O_2, Ar, CO_2, H_2O: 110 km constitute 99%
- Water, hydrometeors, aerosol

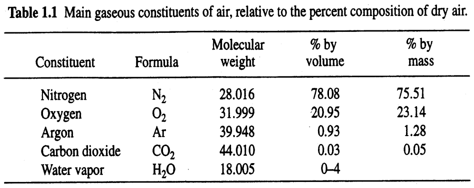
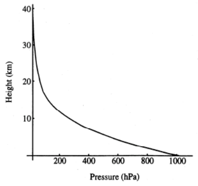


Table 1.1 Main gaseous constituents of air, relative to the percent composition of dry air.

Constituent	Formula	Molecular weight	% by volume	% by mass
Nitrogen	N_2	28.016	78.08	75.51
Oxygen	O_2	31.999	20.95	23.14
Argon	Ar	39.948	0.93	1.28
Carbon dioxide	CO_2	44.010	0.03	0.05
Water vapor	H_2O	18.005	0–4	

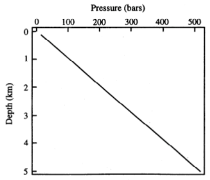
Pressure

- Force per unit area
- 1 bar = 10^5 Pa; 1 mb = 1 hPa; 1 atm = 1.013 bar
- Atmosphere vs. Ocean



Atmosphere

Ocean



Density

- Specific volume: $v=V/m$
- Density: $\rho=m/V$
  - 1.29 kg/m3
- Mean free path
  - frequency of intermolecular collisions

Temperature

- “Zeroeth” Law of Thermodynamics
  - Equilibrium of two bodies with third
  - Allows universal temperature scale
- Temperature scale
  - Two fixed points: Kelvin, Celsius
  - Thermometer
- Lapse Rate $\Gamma = -\partial T/\partial z$
  - Change in temperature with altitude
  - Typically Γ=6.5 K/km
- Temperature inversion $\Gamma<0$
  - Boundary layer “cap”
  - Tropopause between troposphere and stratosphere

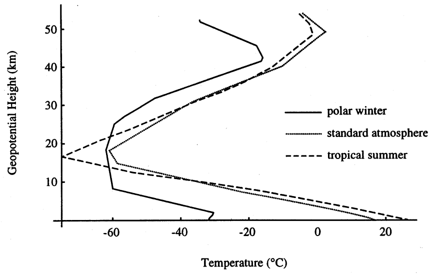


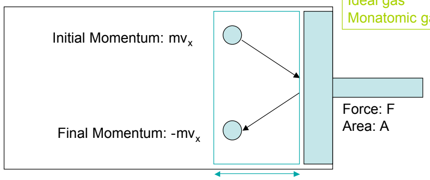
Figure 1.7 Vertical temperature structure in the atmosphere below about 50 km. Temperature decreases with height in the troposphere, except for the polar winter, where surface temperatures are very low, causing a temperature inversion near the surface (U.S. Standard Atmosphere, 1976).

Kinetic Theory of Gases

- Pressure of a gas
- Kinetic energy
- Internal energy
- Temperature of a gas
- Pressure-volume-temperature relationship

- The “fine print”

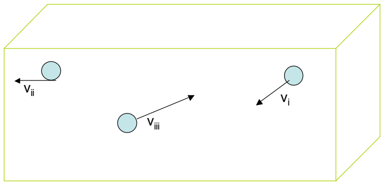
Individual collisions
Perfect reflection
Ideal gas
Monatomic gas



Collision Distance-Per-Time: $v_xt/t=v_x$

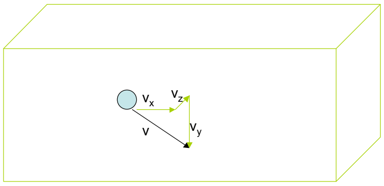
If all atoms had same x-velocity v_x:
Momentum Change for one Atom-Collision: [Initial]-[Final] = $mv_x-(-mv_x) = 2mv_x$
Number of Atom-Collisions-Per-Time: [Concentration]*[Volume] = [n]*[v_xA]
Force = [Number]*[Momentum Change] = [nv_xA]*[$2mv_x$] = $2nmAv_x^2$
Pressure = [Force]/[Area] = $2nmv_x^2$

For atoms with average velocity-squared of $<v_x^2>$:
Pressure = [Force]/[Area] = $nm<v_x^2>$



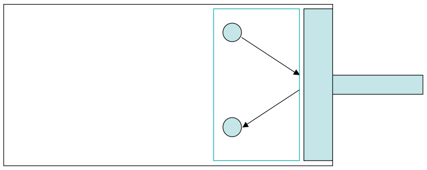
Population-averaged Velocity: $<v^2>=[v_i^2 + v_{ii}^2 + v_{iii}^2 +\ldots+ v_n^2]/n$
Scalar multipliers: $<mv^2/2>=[mv_i^2 + mv_{ii}^2 + mv_{iii}^2 +\ldots+ mv_n^2]/2n$

How many will hit “right” wall? n/2



3D velocity: $<v^2>=<v_x^2>+<v_y^2>+<v_z^2>$
Random motion (no preferred direction): $<v_x^2>=<v_y^2>=<v_z^2>$

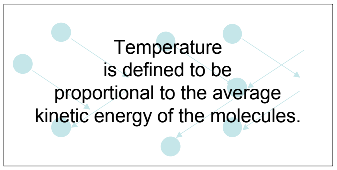
$<v_x^2>= <v^2>/3$



P = $nm<v_x^2>$
$=[2/2]*[nm]*[<v^2>/3]$
$=[2/3]n*<mv^2/2>$
=[2/3]n*[kinetic energy of molecule]

PV $=[2/3]*[N*<mv^2/2>]$
=[2/3]*U
$=[2/3]*E_k$

Concentration: n=N/V
Total “internal” energy: U
Kinetic energy of gas



Temperature
is defined to be
proportional to the average
kinetic energy of the molecules.

PV $=[2/3]*E_k$
E_k =[3/2]* PV

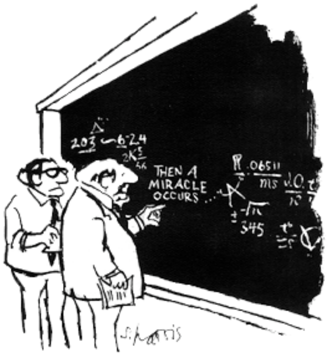
Define $T = f(E_k)$
For scale choose $T=(2/3Nk)*E_k$
E_k =(3/2)*NkT

Then PV = NkT = nR*T

Kinetic energy of gas
RHS is independent of gas
--> so scale can be universal

Mean k.e.: $E_k/N=(3/2)kT$
$k=1.38\times10^{-23}$ J/K

$R^*=N_0k=8.314$ J/mole/K



"I think you should be more explicit here in step two."