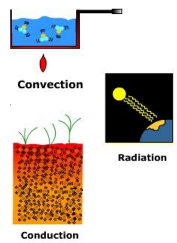
Lecture Ch. 3a

- Types of transfers
- Radiative transfer and quantum mechanics
  - Kirchoff's law (for gases)
  - Blackbody radiation (simplification for planet/star)
  - Planck's radiation law (fundamental behavior)
  - Wien's displacement law (wavelength dependence)
  - Stefan-Boltzmann law (amount of energy)

Curry and Webster, Ch. 3 pp. 74-85
For Monday: Read Ch. 3 and Ch. 12 pp. 331-337

What are the 3 ways heat can be transferred?



- **Radiation**: transfer by electromagnetic waves.
- **Conduction**: transfer by molecular collisions.
- **Convection**: transfer by circulation of a fluid.

Curry and Webster:
- Energy
  - Radiation
  - Conduction
  - Advection
- Scalars
  - Diffusion
  - Advection

Image from: http://www.uwsp.edu/geo/faculty/ritter/geog101/uwsp_lectures/lecture_radiation_energy_concepts.html#Radiation

Scalar Transport

- Mass conservation
  - A continuity equation expresses a conservation law by equating a net flux over a surface with a loss or gain of material within the surface.
  - Continuity equations often can be expressed in either integral or differential form.

The conservation of mass is expressed by the *continuity equation*

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j) = 0 \qquad (3.7)$$

- Transport

$$\frac{\partial C}{\partial t} + u_j \frac{\partial C}{\partial x_j} = \frac{1}{\rho} S_C \qquad (3.11)$$

Energy Transport

- Thermodynamic changes with time

The time variation of temperature can be written from (2.18b) as

$$c_p \frac{dT}{dt} = \frac{dq}{dt} + v \frac{dp}{dt} \qquad (3.1)$$

Using the definition of potential temperature (2.63) for the atmosphere or (2.73) and (2.74) for the ocean, (3.1) becomes

$$c_p \frac{T}{\theta} \frac{d\theta}{dt} = \frac{dq}{dt} \qquad (3.2)$$

- Thermodynamic changes with transport

$$\frac{\partial \theta}{\partial t} + u_j \frac{\partial \theta}{\partial x_j} = \frac{1}{c_p} \frac{\theta}{T} \frac{dq}{dt} \qquad (3.6)$$

Radiation Transport in the Atmosphere

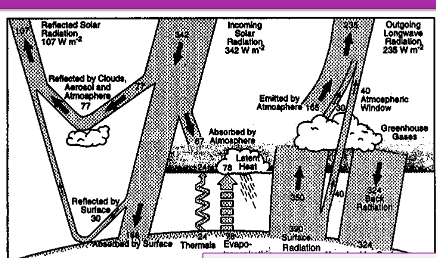
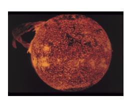
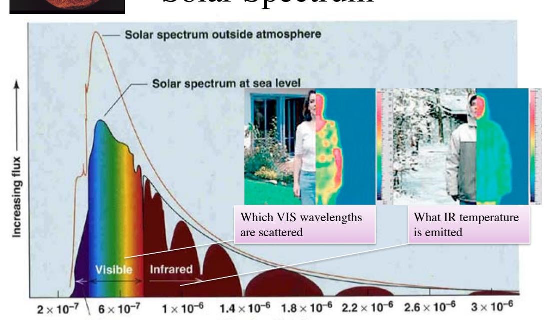


Figure 12.2 Estimated annual mean glob[...] (Kiehl and Trenberth, 1997).

What do we need to know to calculate the temperature of the atmosphere and Earth?

Solar Spectrum





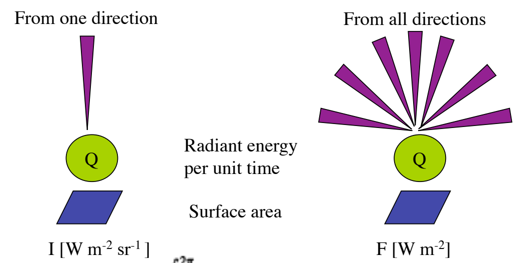
Which VIS wavelengths are scattered

What IR temperature is emitted

Radiation

- At one or a range of wavelengths
- May be incident on a surface at one or over a range of directions
- Direct or diffuse
  - Direct
    - Parallel beam
    - One direction
  - Diffuse
    - Isotropic
    - All directions

Radiance and Irradiance



$$F = \int_0^{2\pi} I \cos Z \, d\omega \qquad (3.12)$$

Wavelength Dependence

Since the radiant energy is distributed over a spectrum of wavelengths, we define *monochromatic* radiance, I_λ, and irradiance, F_λ, as

Over a range of wavelengths

$$I = \int_0^\infty I_\lambda \, d\lambda \quad \text{and} \quad F = \int_0^\infty F_\lambda \, d\lambda \qquad (3.14)$$

At one wavelength λ

- Range may be either
  - Shortwave
    - Solar
    - Wavelengths 0.3-4 µm
  - Longwave
    - Terrestrial
    - Wavelengths 4-200 µm

Blackbody Radiation

- Maximum possible emission of radiation

If a body emits the maximum amount of radiation at a particular temperature and wavelength, or equivalently absorbs all of the incident radiation, it is called a *black body*. For a black body, $\mathcal{A}_\lambda = 1$ and $\mathcal{R}_\lambda = \mathcal{T}_\lambda = 0$ for all wavelengths. *Black-body radiation* is characterized by the following properties:

1. The radiant energy is determined uniquely by the temperature of the emitting body.
2. The radiant energy emitted is the maximum possible at all wavelengths for a given temperature.
3. The radiant energy emitted is isotropic.

Radiation Laws - Black Body Radiation

• Several physical laws describe the properties of electromagnetic radiation that is emitted by a perfect radiator, a so-called black body.

• By definition, at a given temperature, a black body absorbs all radiation incident on it at every wavelength and emits all radiation at every wavelength at the maximum rate possible for a given temperature;

• No radiation is reflected.

• A blackbody is therefore a perfect absorber and a perfect emitter.

Radiation Laws - Black Body Radiation

•The term black body can be misleading because the concept does not refer to color.

•Objects that do not appear black may none the less be be blackbodies, perfect radiators.

• Most gases are not blackbodies (see instead Kirchoff's Law)

•Both the Sun and the Earth closely approximate perfect radiators, so that we can apply blackbody radiation laws to them.

•We'll discuss 2 laws for blackbody radiation,

1) Wien's displacement law

2) Stefan-Boltzmann law.

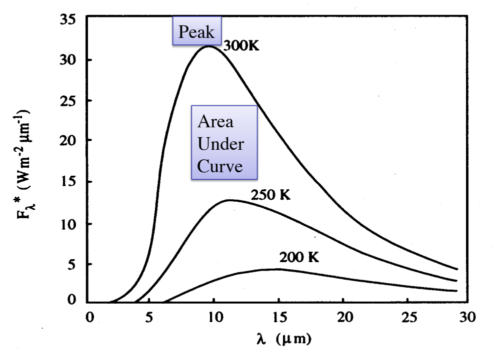
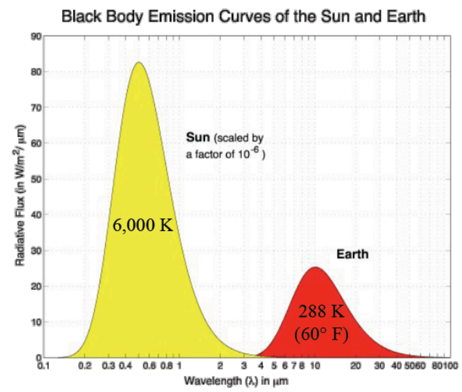


Figure 3.1 Black-body irradiance curves for terrestrial temperatures.



Wien's Displacement Law

- Inverse dependence of wavelength on temperature

The wavelength of maximum emission for a black body is found by differentiating Planck's law (3.19) with respect to the wavelength, equating to zero, and solving for the wavelength. This yields *Wien's displacement law*:

$$\lambda_{max} = \frac{2897.8}{T}$$

This is the location of the peak!

where T is in K and λ_{max} is in μm. Evaluation of Wien's displacement law at $T = 6000$ K and $T = 300$ K shows that $\lambda_{max}(6000) = 0.48\ \mu$m and $\lambda_{max}(300) = 9.66\ \mu$m. Thus the wavelength of peak emission from the sun lies in the visible portion of the electromagnetic spectrum, while that from the Earth lies in the infrared.

Radiation Laws - Wien's Displacement Law

•Although all known objects emit all forms of electromagnetic radiation, the **wavelength of most intense radiation is inversely proportional to the T.** (1/T)

•Implications:
- Sun emits @ ~ 6000 deg Kelvin
- Earth emits @ ~ 288 deg Kelvin,

•Which will emit radiation at the longer wavelength?
  •Earth

•The peak of Solar output is in the visible (light, shorter) part of the electromagnetic spectrum while the Earth, emits most of its energy in the infrared (heat, longer) portion of the electromagnetic spectrum

Radiation Laws - Wien's displacement law

•What does this mean in terms of the Earth and the Sun?

• **Warm objects,** Sun (6000°K) emit peak radiation at relatively short wavelengths (0.5 micrometers (1 millionth of a meter) = yellow-green visible)

• **Colder objects** Earth-atmosphere (average T of 288 °K, 15°C, 59°F) emit peak radiation at longer wavelengths (10 microns – infrared part of the spectrum)

• Most of the **sun's energy** is emitted in a spectrum from 0.15 µm to 4 µm. 41% of it is visible, 9% is uv, 50 % infra-red.

• **Earth's radiant energy**, stretches from 4 to 100µm, with maximum energy falling at about 10.1 µm (infrared).

Planck's Radiation Law

- Direct consequence of quantum theory

The theory of black-body radiation was developed by Planck in 1900. Planck determined a semi-empirical relationship that included the concept that energy is quantized. Planck showed from quantum theory that the black-body irradiance, F_λ^*, is given by

$$F_\lambda^* = \frac{2\pi hc^2}{\lambda^5\left[\exp\left(\frac{hc}{k\lambda T}\right) - 1\right]} \tag{3.19}$$

where h is *Planck's constant* and k is Boltzmann's constant. Equation (3.19) is known as *Planck's radiation law.*

Radiation Laws - Stefan-Boltzmann law

•Would you expect the same amount of electromagnetic radiation to be emitted by the Earth and Sun?

•No. The total energy radiated by an object is proportional to the fourth power of it's absolute T

•F = k (T^4) = Stefan-Boltzmann law.
•F (rate of energy emitted)
•k = Stefan-Boltzmann constant (5.67 x 10^{-8} Wm-2 K^{-4})

•Sun radiates at a much higher temperature than Earth.-

•Sun's energy output/m^2 = 160,000 that of Earth

Stefan-Boltzmann Law

- Describes T^4 dependence of emission

Integration of (3.19) over all wavelengths gives

This is the area under the curve!

$$F^* = \int_0^\infty F_\lambda^* \, d\lambda = \sigma T^4 \qquad (3.20)$$

where $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4} is called the *Stefan–Boltzmann constant*. Equation (3.20) is referred to as the *Stefan–Boltzmann law*, whereby the irradiance emitted by a black body varies as the fourth power of the absolute temperature. Evaluation of the Stefan–Boltzmann law at $T = 6000$ K (the approximate emission temperature of the sun) and $T = 300$ K (the approximate emission temperature of the Earth's surface) shows that $F^*(6000) = 7.35 \times 10^7$ W m^{-2} and $F^*(300) = 4.59 \times 10^2$ W m^{-2}, a difference of five orders of magnitude.

Summary: Solar Radiation

- Luminosity of the sun $L_0 \sim 3.9\times10^{26}$ W (p. 331)
- Irradiance F=Luminosity/Area=$L_0/(4\pi r^2)$= 6.44×10^7 W/m^2
  - r_{sun}=6.96×10^8 m [p. 437]
- Estimate blackbody radiation $T_{BB,sun}$=$(F/\sigma)^{0.25}$~ 5800K
  - σ=5.67×10^{-8} W m^{-2} K^{-4} [p. 437]

$$F^* = \int_0^\infty F_\lambda^* \, d\lambda = \sigma T^4 \qquad (3.20)$$

- Use Wien's law to evaluate λ_{sun} ~ 0.5 µm (visible)

$$\lambda_{max} = \frac{2897.8}{T} \qquad (3.21)$$

- Similarly, λ_{earth} ~ 10 µm (infrared) for T_{earth} ~ 300K

Radiative Transfer

- Absorption, Transmission, Reflection

the matter. The fraction of the incident radiation that is absorbed (*absorptivity*, $\mathcal{A}_\lambda$), transmitted (*transmissivity*, $\mathcal{T}_\lambda$), and reflected (*reflectivity*, $\mathcal{R}_\lambda$) must add up to unity, so that

$$\mathcal{A}_\lambda + \mathcal{T}_\lambda + \mathcal{R}_\lambda = 1 \qquad (3.15)$$

Sun's energy is emitted in the form of electromagnetic radiation (Radiant Energy)

- Radiant energy can interact with matter in 3 ways.
- Most often its behavior is a combination of two or more of these modes
- **Reflection** - there is no change in the matter because of the radiant energy that strikes it and it does not let the energy pass through it (i.e. it is opaque to the radiant energy), then it ***reflects*** the energy. Reflection only changes the direction of the beam of radiant energy, not its wavelength or amplitude.
- **Transmission** - matter allows radiant energy to pass through it unchanged. Again, there is no change in any of the properties of the radiant energy.
- **Absorption** –energy is transferred from the radiant beam to the matter resulting in an increase in molecular energy of the matter

Reflectivity = Albedo

- Reflected Energy/ Incident Energy
- Higher reflectivity = brighter, shinier surface (snow, ice)
- Lower reflectivity = darker, rougher surface (soil, sand)
- Water – depends on the angle of the sun
- Average albedo for Earth = 30
- Average albedo for moon = 7

Image from: http://www.fourmilab.ch/earthview/vplanet.html

Kirchoff's Law

- Molecules absorb and emit radiation
  - Wavelength determined by quantum mechanics (discrete)

When matter exists as a dilute gas, it absorbs radiation at discrete wavelengths. These spectral lines are characteristic of the gas and correspond to jumps in the quantum energy levels (electronic, vibrational, roatational) of the gas molecule as photons are either emitted or absorbed. For matter in the liquid or solid state, molecules are so close to each other that liquids and solids tend to emit and absorb in extended continuous regions of the spectrum rather than in discrete spectral lines and bands.

A molecule that absorbs radiation of a particular wavelength can also emit radiation at the same wavelength. The rate at which emission takes place depends only on the temperature of the matter and the wavelength of the radiation. *Kirchoff's law* states that

$$\frac{F_\lambda}{\mathcal{A}_\lambda} = f(\lambda, T) \qquad (3.16)$$

Kirchoff's Law

- For example, if an atmospheric layer absorbs just 70% of what a black body would, then the layer will emit 70% of what a black body would.

$$\epsilon_\lambda = \mathcal{A}_\lambda \qquad (3.18)$$

which states that the emissivity is equal to the absorptivity. This equation also states that emission can only occur at wavelengths where absorption occurs. If the absorption varies with wavelength, so will the emission. Kirchoff's law is applicable only under conditions of *local thermodynamic equilibrium,* which occurs when a sufficient number of collisions take place between molecules and the translational, rotational, and vibrational energy states are in equilibrium. In the atmosphere, conditions of local thermodynamic equilibrium are not met at heights above about 50 km.

Absorption and Emission

Note that whereas the disposition of solar radiation is dominated by absorption and scattering, thermal radiation is dominated by emission and absorption.

The rate of transfer of energy by electromagnetic (em) radiation is called *radiant flux* (units are joules per second, $J s^{-1}$, or watts, W). The radiant flux incident on a unit area is called the *irradiance* ($W m^{-2}$), denoted by E. The irradiance per unit wavelength interval, centered on wavelength λ, is denoted by E_λ ($W m^{-2} \mu m^{-1}$).

- Emissivity – the irradiance from the body divided by the irradiance from a blackbody at the same temperature
- Absorptivity – the amount of irradiance absorbed divided by that absorbed by a blackbody (perfect absorber).

Absorption by Molecules

- Occurs only when incident photon has same energy as difference between two energy states
  - States may differ in rotation, vibration or electronic
  - Result may not be chemical, e.g. heating (GHGs)

Consequences of Absorption

- Molecules may lose absorbed photon's energy by several mechanisms
  - Dissociation (breaks apart)
  - Direct reaction (excited molecule reacts with other molecule)
  - Isomerization (internal rearrangement of bonds to make more stable)
  - Collision (losing energy to other molecules w/o chemical changes)
  - Internal energy transfer
  - Luminescence (fluorescence or phosphorescence: emission of a photon)
  - Photoionization (ejection of an electron to form an ion)

Photolysis -- general word describing chemical changes from reactions initiated by light, regardless of the detailed mechanism

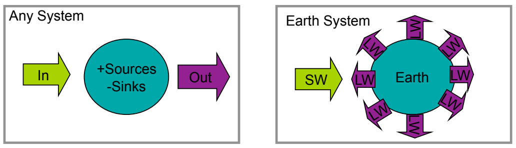
Lecture Ch. 3b

- Simplified climate model
  - Assumptions
  - Calculations
  - Cloud sensitivity
  - Effect of an atmosphere
- Absorption coefficient
- Optical thickness
- Heat transport

Curry and Webster, Ch. 3; Ch. 12 pp. 331-337; also Liou, 1992
Read Ch. 4

Energy Balance

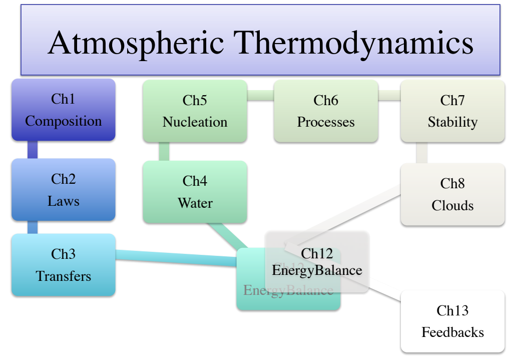
Energy In = Energy Out + Sources - Sinks



- As a 1st approximation, there are no continuous sources or sinks of energy on Earth (only temporary storage, e.g. ocean)
  - Energy In (Shortwave) = Energy Out (Longwave)

Thermal Equilibrium is the name of this assumption

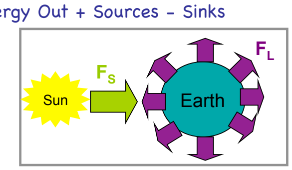
Atmospheric Thermodynamics



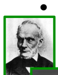
Textbook "Energy Balance"

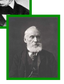
Energy In = Energy Out + Sources - Sinks

$F_S = F_L$



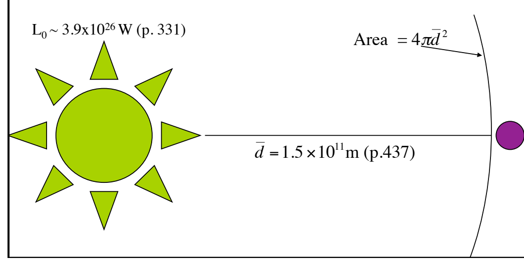
- How do we know this?
  - First Law of Thermodynamics
    - Rudolf Clausius 1850
    - William Thompson (Lord Kelvin) 1848



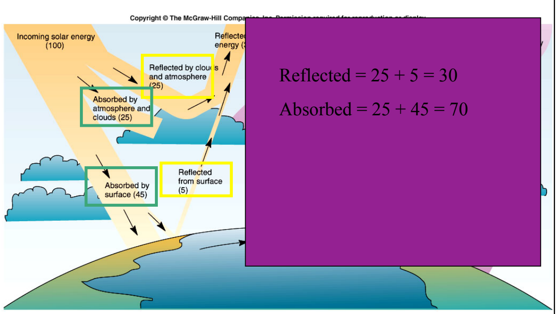


Solar Constant

- Luminosity of the sun
- Irradiance at earth $S_0 = L_0/(4\pi d^2) = 1.4\mathrm{x}10^3$ W/m^2



Energy Balance



From Cunningham & Cunningham, 2004, Fig. 9.2

Simplified Climate Model: First 2 Assumptions

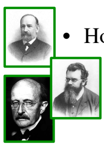
- Atmosphere described as one layer
  - Albedo $\alpha_p \sim 0.31$: reflectance by surface, clouds, aerosols, gases
  - Shortwave flux absorbed at surface $F_s = 0.25 * S_0 (1 - \alpha_p)$
- Earth behaves as a black body
  - Temperature T_e: equivalent black-body temperature of earth $F_L = \sigma T_e^4$
  - Longwave flux emitted from surface

Textbook "Radiation"

More Infrared Radiation = Higher Temperature

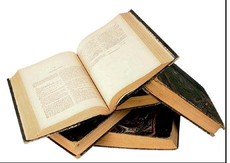
$F_L = \sigma T_{surf}^4$

It's the same law that night vision goggles use!



- How do we know this?

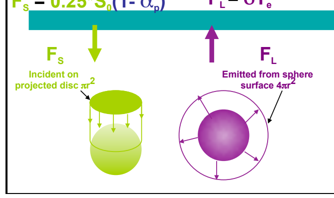
  Stefan-Boltzmann Law
  - Josef Stefan 1874
  - Ludwig Boltzmann 1884
  - Max Planck 1901



Simplified Climate Model

- Incoming shortwave = Outgoing longwave
- Energy absorbed = Energy emitted

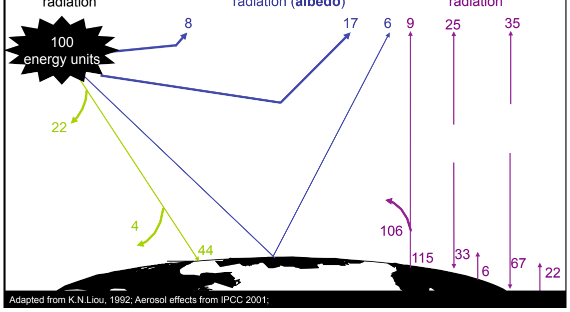
$F_S = 0.25 * S_0(1 - \alpha_p)$ $\quad F_L = \sigma T_e^4$



At "TOA": $F_S = F_L$

Atmospheric Radiation Balance

$F_S = 0.25 * S_0(1 - \alpha_p)$ $\quad F_L = \sigma T_e^4$



Simplified Climate Model

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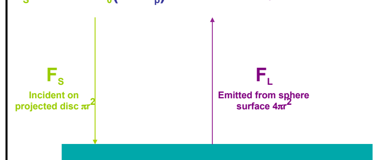


$F_S = F_L$

Simplified Climate Model

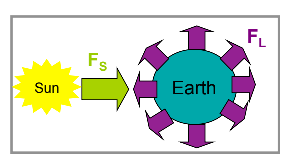
- At thermal equilibrium (what happens if not?)

$$F_S = F_L$$
$$0.25 * S_0(1 - \alpha_p) = \sigma T_e^4$$
$$T_e = [0.25 * S_0(1 - \alpha_p)/\sigma]^{0.25}$$
$$T_e \sim 255K$$

- Observed surface temperature T = 288K
- What's missing?

Balance & Radiation

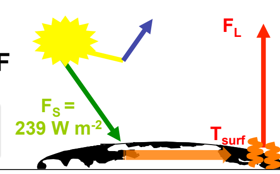
$F_S = F_L$



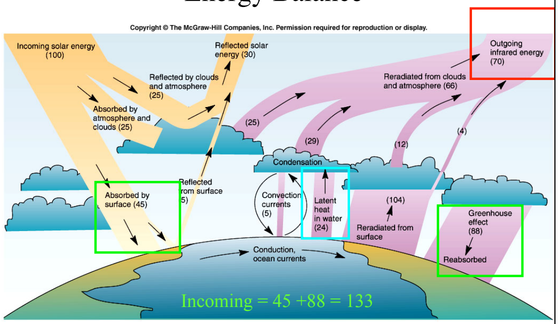
$F_S = \sigma T_{surf}^4$

$T_{surf} \approx$ -18°C or 0°F

That's too cold!
What did we forget?



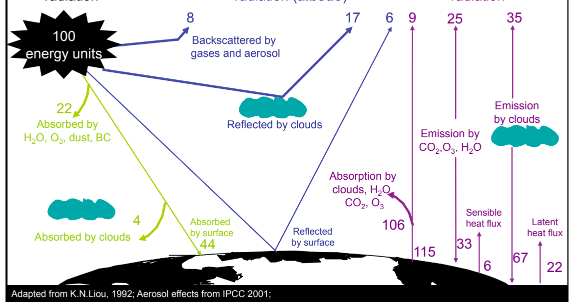
Energy Balance



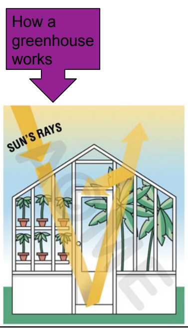
Outgoing = 104 + 24 + 5 = 133

From Cunningham & Cunningham, 2004, Fig. 9.2

Atmospheric Radiation Balance



Earth's Blanket: The Greenhouse Effect



- H_2O and CO_2 in the atmosphere act like the glass windows
  - absorbing infrared energy
  - emitting heat

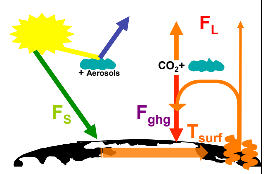
Ch.12! (and 217c)

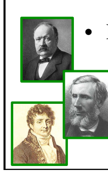
Textbook "Greenhouse Effect"

$F_s + F_{ghg} = \sigma T_{surf}^4$

$T_{surf} \approx$ 15°C or 59°F

Tyndall measured how F_{ghg} increases with CO_2 (and H_2O).

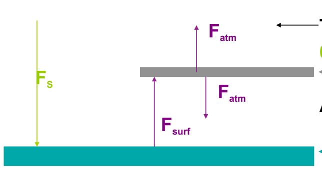




- How do we know this?
  - The Greenhouse Effect of CO_2
    - Joseph Fourier 1824
    - John Tyndall 1858
    - Svante Arrhenius 1896

Add an Atmosphere!

- Atmosphere is transparent to non-reflected portion of the solar beam
- Atmosphere in radiative equilibrium with surface
- Atmosphere absorbs all the IR emission (A=1)



TOA: $F_s = F_{atm}$

$0.25 * S_0 (1-\alpha_p) = \sigma T_{atm}^4$

$T_{atm} = 255K$

Atmos: $F_{surf} = 2F_{atm}$

$\sigma T_{surf}^4 = 2\sigma T_{atm}^4$

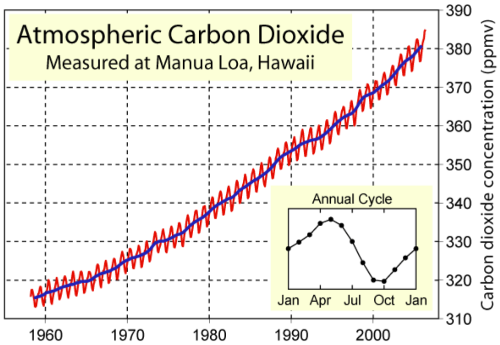
$T_{surf} = 303K$

What's (still) wrong?

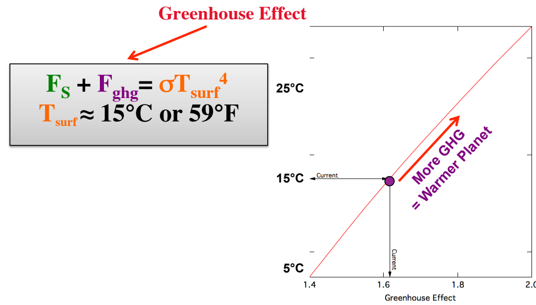
- With no atmosphere, $T_{surf} = 255K$
- With "atmosphere", $T_{surf} = 303K$
- From observations, $T_{surf} = 288K$

- Real atmosphere:
  - Not perfectly transparent to incoming solar (20 unit absorbed by atm.)
  - Not perfectly opaque to infrared (12 unit "window")
  - Not in pure radiative equilibrium with surface (23 units latent heat)

- Three assumptions were wrong -- but we got very close by adding the greenhouse effect of the atmosphere.



The Textbook Equations



Sensitivity to Albedo

- What if albedo changes?

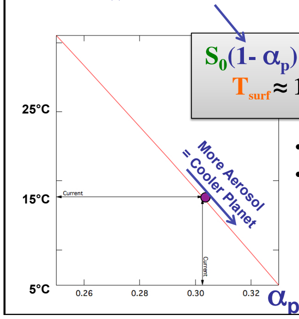
$$T_e = [0.25 * S_0 (1 - \alpha_p)/\sigma]^{0.25}$$
$$\alpha_p = 0.31,\ T_e \sim 255K$$
$$\alpha_p = 0.30,\ T_e \sim ?$$

- 1% decrease in albedo warms temperature 1K
- 1% increase in albedo cools temperature 1K

How Aerosols Keep Planet Cool

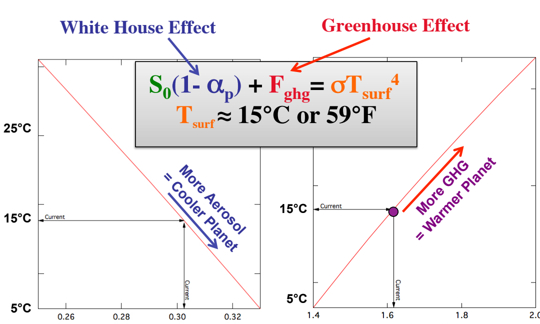
White House Effect

$$S_0(1 - \alpha_p) + F_{ghg} = \sigma T_{surf}^4$$
$$T_{surf} \approx 15°C \text{ or } 59°F$$

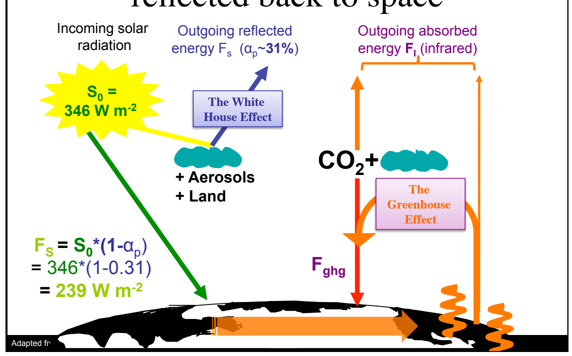


- Now α_p is about 0.31
- If we increase aerosols
  - More sunlight is reflected
  - Less infrared is emitted
  - Temperature decreases

The Textbook "Model"



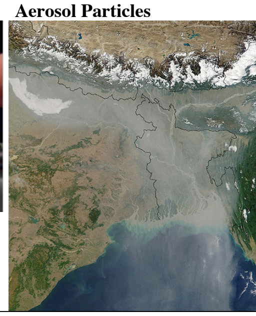
Then 31% of the Sun's energy will be reflected back to space



What are Aerosols?

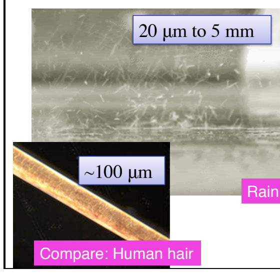
Aerosol Spray Cans

Aerosol Particles



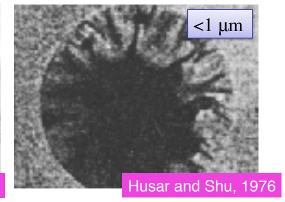
How long do particles stay in the atmosphere?

Rain is big enough to fall



Aerosol particles are too small to fall

- **one-millionth of a meter**



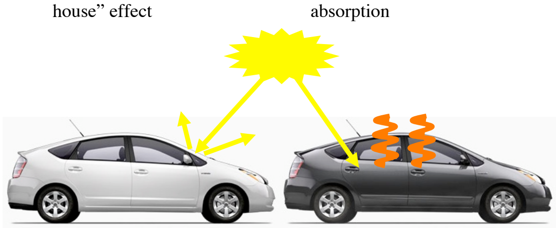
Which one would you like to sit in on a hot day?

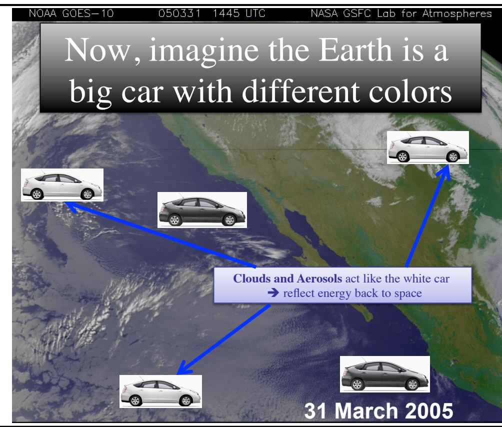
White "Reflects" Energy

- We call this "the white house" effect

Black "Absorbs" Energy

- The less black, the less absorption

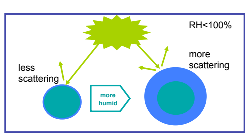


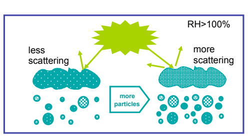


Aerosol Effects on Climate

Aerosol **direct** effect:

Particle scattering → increased albedo





Cloud albedo effect:

More droplets → increased reflectance

Global Warming and Climate

What we know

- CO_2 traps sunlight energy
  - like a blanket
- Atmospheric CO_2 has increased in the 20th century,
  - like a thicker blanket
- Earth's T_{surf} increases
  - like a person under blanket
- Aerosols cause cooling
  - **could it be enough to offset warming?**

What we don't know

- Will temperature increase…
  - In 20 years? In 100 years?
  - In California? In Siberia?
- Will sea level rise?
  - Less sea ice?
- Which species will adapt?
  - What migrations will result?
- **Will aerosol changes cause…**
  - **Less rain? Less snow?**