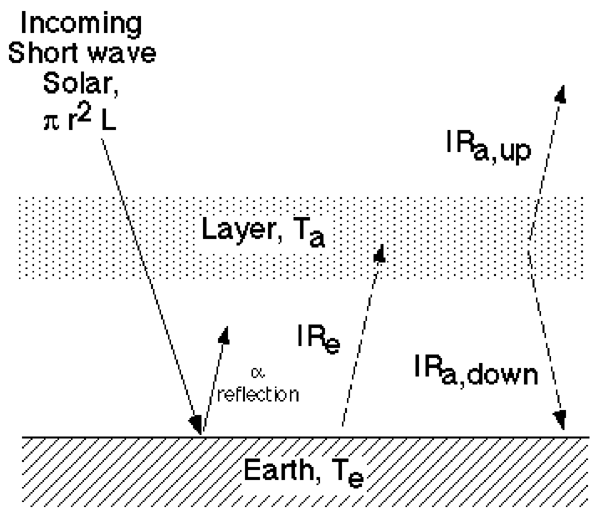
Lecture 3 – Earth surface temperature

ALBEDO

- Albedo: reflection coefficient can range from 0 (no reflection) to 1 (100% reflection).
- On average earth has an albedo of 0.3 in the visible range.
- A (visible) = 0.3: 1/3rd from earth's surface, 2/3rd from atmosphere.
- A (IR) ~ 0

Simplified scheme of the Earth radiation balance



L – solar constant (1367 W/m^2)

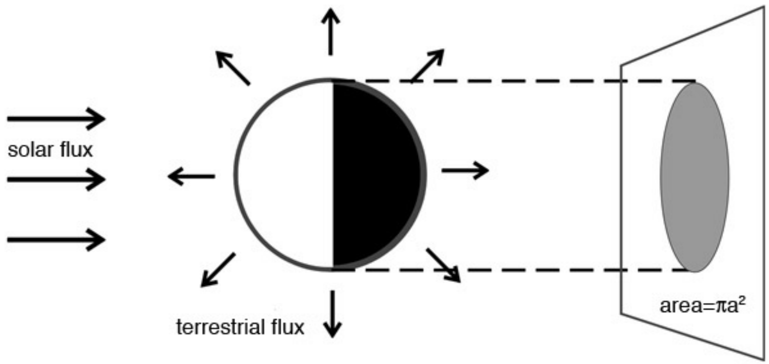
Solar constant

- Solar flux density: amount of solar power per unit area on the surface of a sphere centered at the sun
- Luminosity of sun= 3.9x10^26 W
- Area of a sphere = $4\pi r^2$
- So,
- Solar flux density = Luminosity/ Area of sphere

  = 3.9x10^26 W/ 4xπx(1.5x10^11 m)

  = 1367 W/m^2 =“solar constant”

Earth receives energy from sun and emits infrared light out

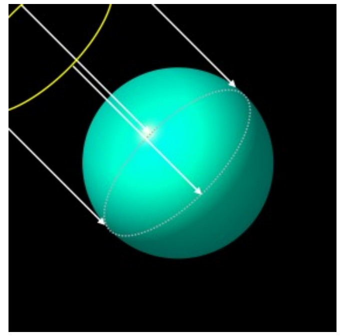


The spinning Earth is imagined to intercept solar energy over a disk of radius 'a' and radiate terrestrial energy away isotropically from the sphere.

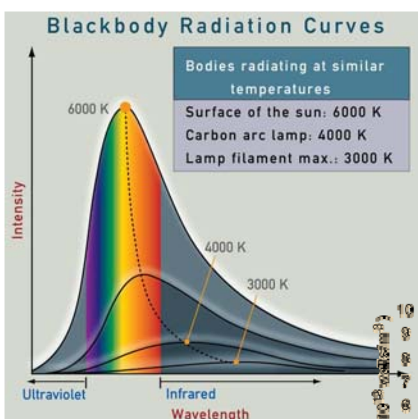
EARTH AS A BLACK BODY (Zeroth Order Model)

- Solar Flux Ω = 1,372 W/m^2 (at a point directly under the sun)
- Average Flux = $\Omega/4$ (Average over day and night and over all latitudes)
- Surface area: $4\pi R^2$; Perpendicular are (disc) = πR^2
- Stefan-Boltzman Law describes the relationship between temperature of black bodies and their rate of radiation
- $F = \sigma T^4$
  F is radiant energy output (units energy per unit time per unit area)
  T is the absolute temperature of the object in Kelvins
  $\sigma = 5.67 \times 10^{-8}$ J/m^2 sec K^4
- $F_{in} = \Omega/4$; $F_{out} = a\Omega/4 + \sigma T^4$
- $T^4 = (1-a)\,\Omega/4\sigma$
- Black body temperature of the earth, T_o = 255K

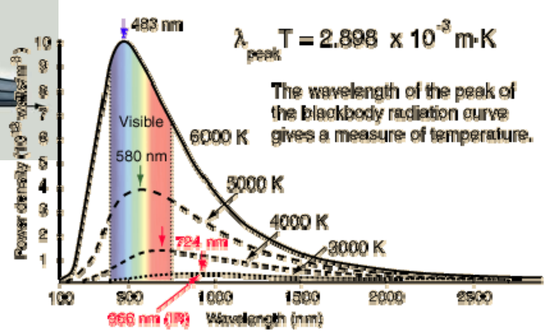
Why is it one quarter?



This is because the full energy does not vertically hit the full Earth surface, but only the cross section of the Earth. We know that half of the Earth is always in the night and the sun radiation under a low angle is weaker. Since the cross section of a sphere is one fourth of the surface of a sphere the total energy on the Earth surface is R = 1/4 L = 342 W/m^2.



Wien's law



Wien's displacement law, an equation that describes the relationship between the temperature of an object and the peak wavelength or frequency of the emitted light

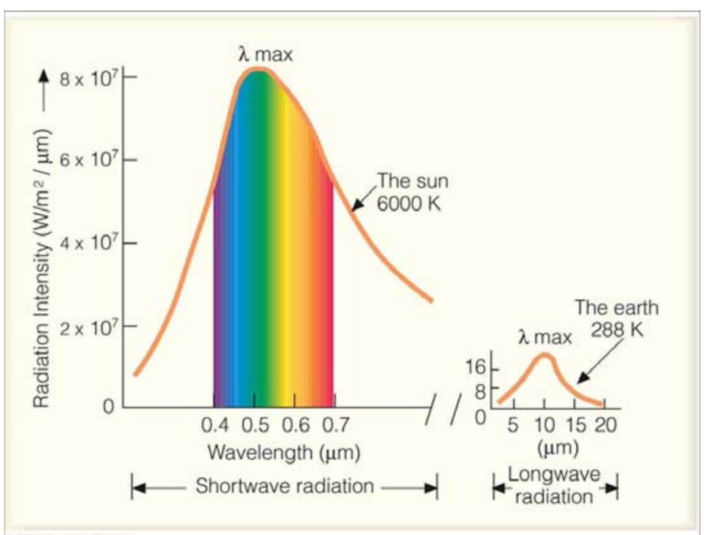
Wiens Law

- Most objects emit radiation at many wavelengths
- However, there is one wavelength where an object emits the largest amount of radiation
- This wavelength is found with Wiens Law:

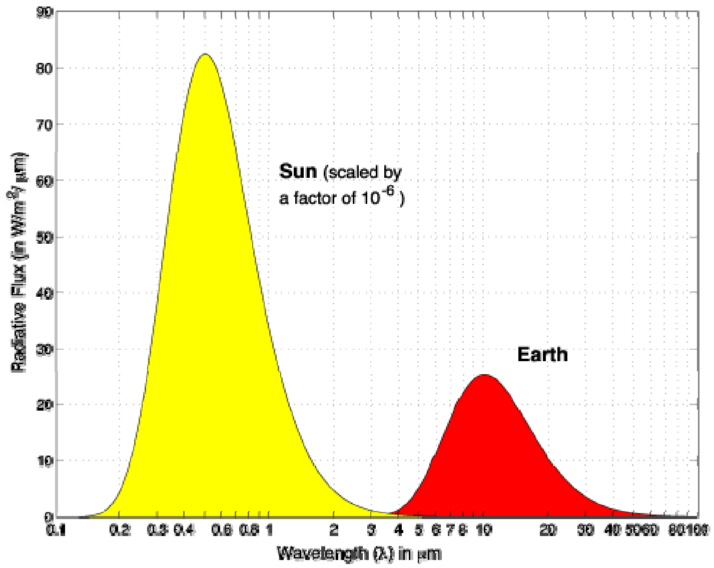
  λ_{max} = 2897 mm / T(K)
- Q: At what wavelength does the sun emit most of its radiation?
- **ANSWER: 0.5 micrometer [shortwave radiation]**
- Q: At what wavelength does the earth emit most of its radiation?
- **ANSWER: 10.0 micrometer [longwave radiation]**

Radiation curves for the Sun and Earth

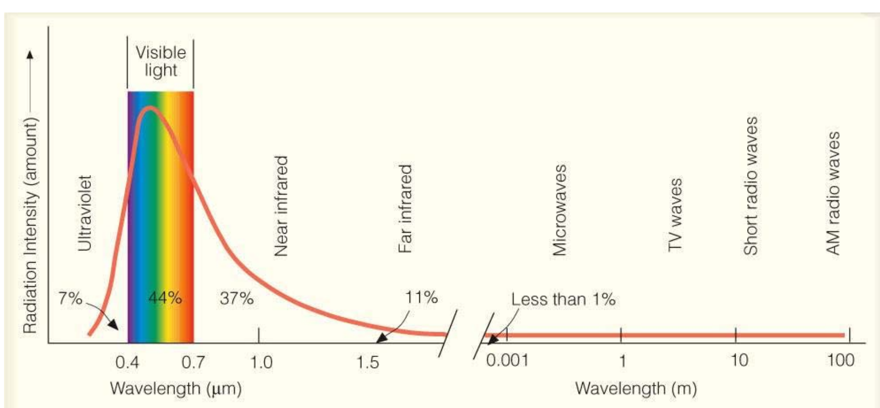
Q: What are the similarities and differences between the Sun and Earth radiation curves?



Black Body Emission Curves of the Sun and Earth



Radiation curve for the Sun - a closer look



Stefan–Boltzmann law:

- the total energy radiated per unit surface area of a black body in unit time is proportional to the fourth power of the thermodynamic temperature.
- $\sigma = 5.670373(21) \times 10^{-8}$ W m^{-2} K^{-4}

- The Stefan-Boltzman law relates the total amount of radiation emitted by an object to its temperature:
- $E = \sigma T^4$
- where:
- E = total amount of radiation emitted by an object per square meter (Watts m^{-2})
- σ is a constant called the Stefan-Boltzman constant = 5.67 x 10^{-8} Watts m^{-2} K^{-4}
- T is the temperature of the object in K

Consider the earth and sun

- Sun: T = 6000 K

  so E = 5.67 x 10^{-8} Watts m^{-2} K^{-4} (6000 K)^4 = 7.3 x 10^7 Watts m^{-2}
- Q: Is this a lot of radiation??? Compare to a 100 Watt light bulb.....
- Earth: T = 288K

  so E = 5.67 x 10^{-8} Watts m^{-2} K^{-4} (288 K)^4 = 390 Watts m^{-2}
- Q: If you double the temperature of an object, how much more radiation will it emit?
- Answer: It will emit 16 more radiation

Zeroth Order Model

Not a bad model !

$\Lambda_{max} \times T_o$ = constant

Ω ά $1/d^2$

	T_o calc	T_o meas	Tsurf
Earth	255	255	290
Venus	227	230	750
Mars	216	220	
Jupiter	98	130	

Factors that influence climate

- There are a great many theories about the natural causes of climatic change and about how human activity may be modifying Earth's future climate.
- Climate is influenced by numerous factors including
  - the intensity of the sun's radiation;
  - the geometry of Earth's orbit round the sun;
  - the tilt of Earth's axis; the amount of water vapor, cloud, carbon dioxide, dust, and other substances in the atmosphere;
  - the ratio of land to sea area, the location of the continents; and.
  - the types of covering, such as vegetation, on the continental surfaces. Phenomena such as volcanic eruptions, deforestation, fossil fuel burning, and nuclear war can alter some of the factors and thereby alter climate.

MULTI LAYER MODEL

Each zone (layer) contains one radiation thickness of air, i.e. the thickness of air molecules in which quantum of IR will, on the average, be absorbed only once, the reradiation passing through an adjacent zone.

For a layer,

$\Omega = 2*\sigma T^4$. The equation is valid after the layer warm up.

$\Omega/4 = a\,\Omega/4 + \sigma T_o^4$ ………………………..(1)

$2*\sigma T_o^4 = \sigma T_1^4$ ……………………………...(2)

$2*\sigma T_1^4 = \sigma T_o^4 + \sigma T_2^4$ ………………………(3)

$2*\sigma T^4_{n-1} = \sigma T^4_{n-2} + \sigma T_s^4$ ……………………(4)

Ts is the surface temperature.

From Eq 2, $T_1 = 2^{1/4}\, T_o$

From Eq 3, $T_2 = 3^{1/4}\, T_o$

$Ts = (n+1)^{1/4}\, T_o$

Value of n ?

Based on the measured concentration of IR absorbing substances (water vapor, CO_2, ozone) and their effectiveness, n = 2.

$Ts = 3^{1/4}\, To = 3^{1/4}(255K) = 336K > 290K$ which is the actual temperature.

$T_1 = 2^{1/4}\, To = 2^{1/4}\,(255K) = 303K$

Multi-layer model

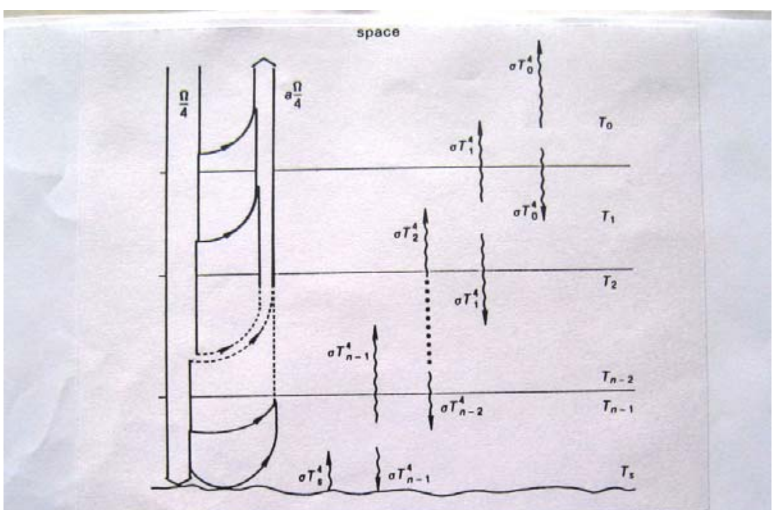


Figure III-5 The flow of energy in an n-layer atmosphere. The solar flux is Ω/4, a is the albedo, and the σT⁴ terms are infrared radiation fluxes (adapted from Goody and Walker, 1972).

EARTH AS A BLACK BODY (First Order Model)

Need to explain why $T_{surface}$ > To
With multiple layers:
$T_s = (n+1)^{1/4}$ To

With 2 absorbing layers:

$T_s = 3^{1/4}$ To	336K
$T_1 = 2^{1/4}$ To	303K
$T_o = 1^{1/4}$ To	255K

Corrective factors we need to put in are:
1. Vertical upliftment of convective heat
2. Latent heat
3. Sunlight absorbed in air
4. Earth is not a perfect black body (some IR passes through atmosphere)

$\sigma T_s^4 = 3(1\text{-a})\ \Omega/4 - (F_c + 1.5F_e + 1.7F_s + 2F_w)$
Answer will come close to 290K

FEEDBACK

2 x CO_2 level = 550 ppm; [275 ppm x 2 = 550 ppm]
ΔTs = 1.4 to 5.8°C (this big range because of feedback)
Feedback
Output = Input + $g^1! + g^2! + g^3! \ldots = 1/(1\text{-}g)$
If g > 1 instability
If g < 0, 0 < 1. If g > 0,) > 1.
Major +ve feedback impacts:
- Water vapor (major GHG). Warmer it gets more water vapor
- Ice-albedo. Warmer, less ice, decrease albedo.
- CO2 from oceans. Higher temperature more outgassing.
- Clouds not understood and reason for large uncertainty.

Two layer model

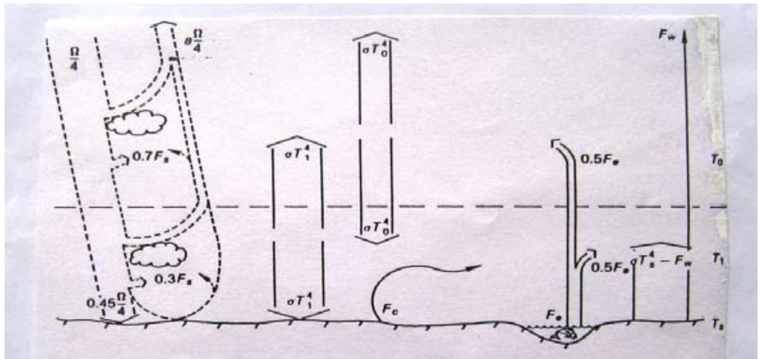


Figure III-6 Energy flows among Earth's surface, atmosphere, and space. The horizontal dashed line separates the two zones of the atmosphere (see text). T_0 and T_1 are the temperatures of these zones, and T_s is the surface temperature. The top of the diagram represents outer space. $\Omega/4$ is the incoming solar radiation (343 W/m²), a is the albedo (≈ 0.3), and F_s is the portion of the solar flux absorbed in the atmosphere (≈ 86 W/m²). The 0.7 F_s and the 0.3 F_s terms include all the absorption, from the beam of reflected solar flux as well as from the incoming beam; multiple scattering is not shown explicitly in the diagram. The solid arrows represent heat flows. σT_0^4, σT_1^4, and σT_s^4 are the IR fluxes in and out of the zones; F_c is the convective heat transfer from the surface to the atmosphere (≈ 17 W/m²); F_e is the flow of latent heat from evaporating surface water (≈ 80 W/m²); and F_w is the IR flux that goes directly from surface to space (≈ 20 W/m²). T_0, T_1, and T_s are determined by energy conservation (Eqs. 12-14).

EARTH'S SURFACE TEMPERATURE

Corrective factors we need to put in are:

1. Vertical upliftment of convective heat (Fc) – loaded fully into the lower zone
2. Latent heat (Fe) – 50% lower and 50% upper region.
3. Sunlight absorbed in air (Fs) – 70% in upper atmosphere and 30% in lower.
4. Some IR passes through atmosphere (Fw).

   These factors reduce the surface temperature since they either reduce heat input or increase its rate of removal.

   $\Omega/4 = a\,\Omega/4 + \sigma T_o^4 + Fw$ ……………………………...(5)

   $2^* \sigma T_o^4 = \sigma T_1^4 + 0.5Fe + 0.7Fs$ ……………………..(6)

   $2^* \sigma T_1^4 = \sigma T_o^4 + \sigma T_s^4 - Fw + Fc + 0.5Fe + 0.3Fs$ …(7)

Show for a two layer model that:

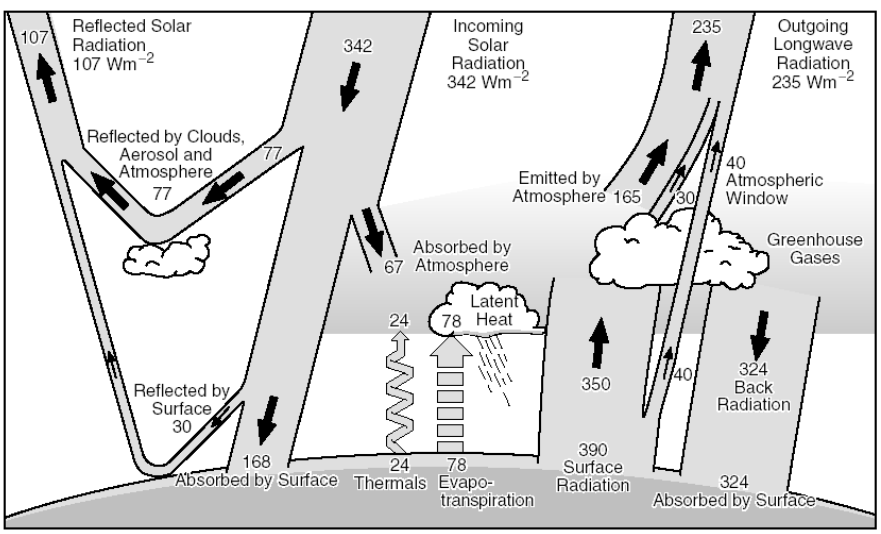
   $\sigma T_s^4 = 3(1\text{-}a)\,\Omega/4 - (Fc + 1.5Fe + 1.7Fs + 2Fw)$ …..(8)

   Calculate the adjusted T_o, T_1, and T_2 using the numbers from Figure "Trapping of heat by GHG".

Answer: Ts = 287K

NUMERICAL VALUES

- Average flux, Ω/4 = 343 W/m^2;
- a is Earth's albedo (0.3);
- Fs is the portion of the solar flux absorbed in the atmosphere (86 W/m^2) [67 W/m^2];
- Fc is the flux of convective heat leaving earth's surface (17 W/m^2) [24 W/m^2];
- Fe is the flux of latent heat leaving Earth's surface (80 W/m^2) [78 W/m^2];
- Fw is the portion of IR emitted from the surface that is radiated in the atmosphere (20 W/m^2) [40 W/m^2].



The Earth's annual and global mean energy balance. Of the incoming solar radiation, 49% (168 Wm-2) is absorbed by the surface. That heat is returned to the atmosphere as sensible heat, as evapotranspiration (latent heat) and as thermal infrared radiation. Most of this radiation is absorbed by the atmosphere, which in turn emits radiation both up and down. The radiation lost to space comes from cloud tops and atmospheric regions much colder than the surface. This causes a greenhouse effect. Source: Kiehl and Trenberth, 1997: Earth's Annual Global Mean Energy Budget, *Bull. Am. Met. Soc.* 78, 197-208.

THE CO_2 "GREENHOUSE" EFFECT

Direct effect of an increase in atmospheric CO_2 and other GHG is increase in amount of IR absorbing materials. In our model this results in the increase in n – the number of IR – absorbing boxes.

Eqn 8 can be rewritten as:

σT_s^4 = (n+1)(1-a) Ω/4 – (Fc + 1.5Fe + 1.7Fs + nFw) ……….(9)

Using the numerical values from "Trapping of heat by GHGs",

Ts = 1/σ [(n+1) (1-a) Ω/4 – 283.2 + n(20)]$^{1/4}$ ………………..(10)

To find the impact of a small change of n on Ts,

dTs/dn =

(1-a) Ω/4σ – 40/σ / [4{(n+1)(1-a) Ω/4 – 283.2 – n(40)}]$^{3/4}$…..(11)

Using eqn (10), this can be rewritten as:

dTs/dn = Ts/ 4(n+1) * (1 + 263.2/ σT_s^4) ……………………..(12)

Using σT_s^4 = 397.1 Wm^{-2}

ΔTs/Ts = 0.42 Δn/(n+1) ………………………………………..(13)

..continued

Simple calculation to find the impact of doubling of CO_2 on Δn:

Each of the GHGs is effective at absorbing IR at a different part of the spectrum. Certain atmospheric trace gases such as CH_4 and O_3 can have a particularly high impact on surface temperature.

Total umber of moles or air = 1.8 x 10^20.

Concentration of CO_2 in atmosphere pre-industrial = 275 ppm(v)

Total number of moles of CO_2 = 49.5 x 10^15 ((275/10^6)*1.8*10^20)

Total number of moles of H_2O = 722x10^15 ((1.3*10^19/18)

Ratio of CO_2 to (H_2O+CO_2), **r = 0.064**

Since a mole of any substances contains Avogadro's number of molecules, r is also the ratio of molecules.

An individual molecule of CO_2 is only 0.25 times as effective as a molecules of H_2O in terms of absorbing IR. Therefore r = 0.25 times the earlier value.

Δn = r x % increase in CO_2 x n

Δn = 0.0169 x 1 x n = 0.0338

Substituting in Eq 13

ΔTs = 0.42/3 x 0.0338 = 0.0047Ts

Using the value Ts = 290K, **ΔTs = 1.4K**

What controls earth’s surface temperature ?

- Sun’s luminosity
- Distance from Sun
- Earth’s atmosphere and albedo
- Earth’s temperature
- Greenhouse effect

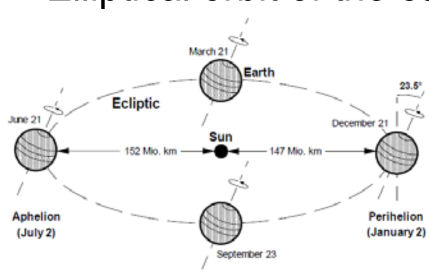
Sun’s luminosity

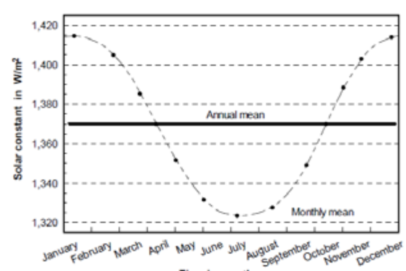
- Over 4.5 billion years, the luminosity of the sun has gradually increased by 30%
- But … there is evidence for liquid water on Earth for most of Earth’s history.
- Sun’s luminosity (power output)=3.865x10^26 Watts
- Sun can be regarded as a black body hypothetically
- A black body is anything that absorbs all light shined upon it and emits a spectrum of light that depends upon its temperature

Energy: electromagnetic radiation

- What emits radiation?
- Everything whose temperature is > 0K

Elliptical orbit of the earth around the sun





The solar constant reaches its maximum in January at almost 1,420 W/m2, due to reaching the shortest distance between the sun and the earth (Perihelion) on January., 2nd . The opposite takes place on June 2nd, when it reaches its minimum with approximately 1,330 W/m2 (Aphelion).

The atmosphere and albedo

- Solar energy above and below the atmosphere
- Solar radiation in the atmosphere
- Albedo: fraction of solar energy reflected away (planetary albedo = 30% or 0.3)
- Why does not Earth get hotter and hotter?

- Solar energy absorbed = Terrestrial energy emitted

Greenhouse effect

- Sun's peak output is visible light
- Earth's atmosphere transmits visible light. The light that reaches Earth's surface is called insolation. It is absorbed and warms the surface.
- Earth's surface is much colder than the sun. Earth's peak output is longer wavelength infrared radiation.
- Atmosphere absorbs infrared (heat). Greenhouse gases trap heat and warm the atmosphere.

Three fundamental ways to change the radiation balance of the Earth

- By changing the incoming solar radiation (e.g., by changes in Earth's orbit or in the Sun itself)
- By changing the fraction of solar radiation that is reflected (called albedo) (e.g., by changes in cloud cover, atmospheric particles or vegetation)
- By altering the longwave radiation from Earth back towards space (e.g., by changing greenhouse gas concentrations)

Climate, in turn, responds directly to such changes, as well as indirectly, through a variety of feedback mechanisms.

Factors affecting temperature

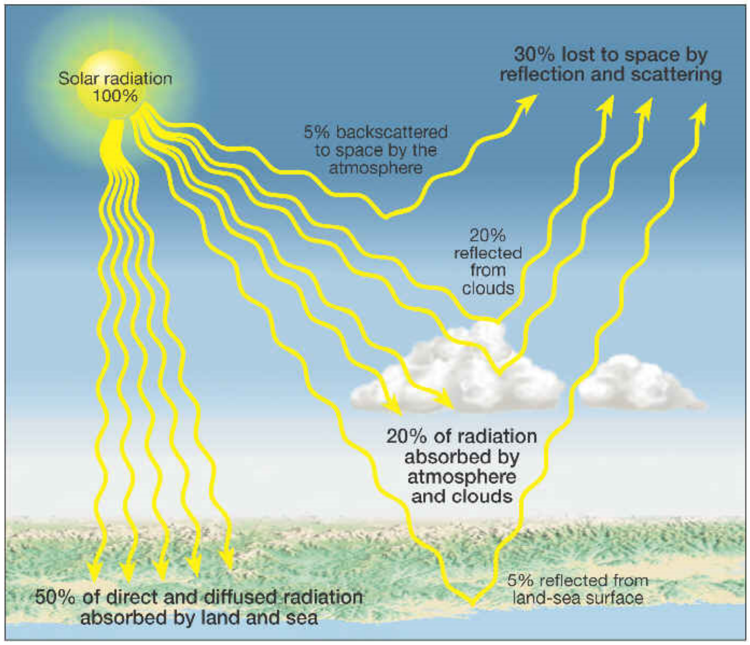
- **Clouds:**
  - Low, thick clouds primarily reflect solar radiation and cool the surface of the Earth.
  - High, thin clouds primarily transmit incoming solar radiation; at the same time, they trap some of the outgoing infrared radiation emitted by the Earth and radiate it back downward, thereby warming the surface of the Earth.
  - Whether a given cloud will heat or cool the surface depends on several factors, including the cloud's height, its size, and the make-up of the particles that form the cloud.
  - The balance between the cooling and warming actions of clouds is very close - although, overall, cooling predominates.
- **Fine particles (aerosols) in the atmosphere:**

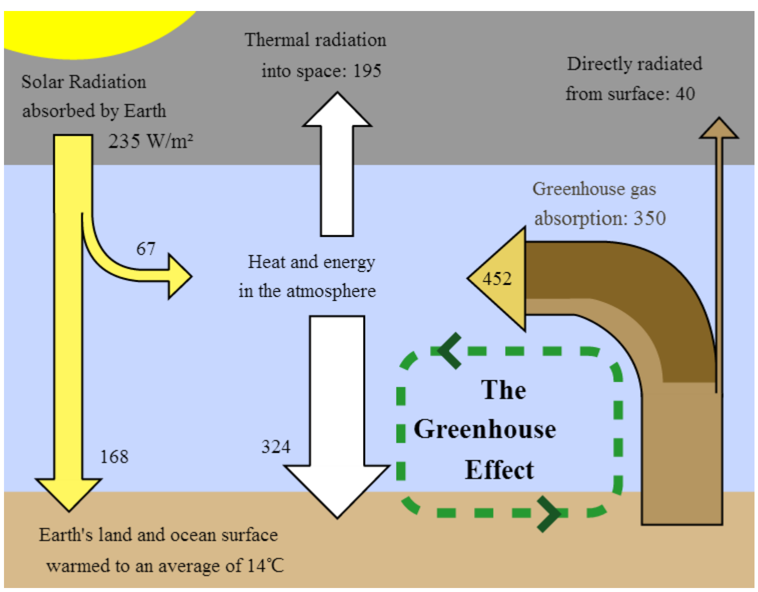
Factors affecting temperature

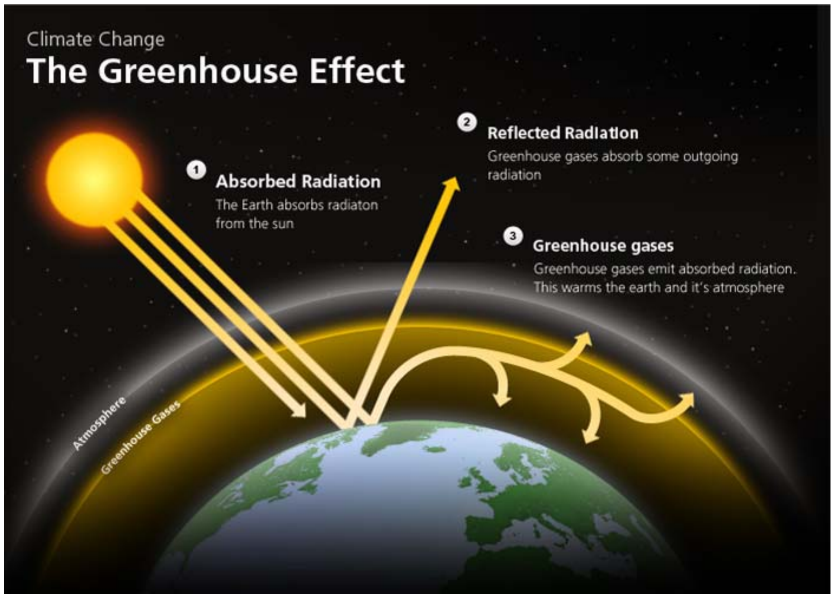
- **Clouds:**
- **Fine particles (aerosols) in the atmosphere:**
  - Atmospheric factors shown in the image below include natural factors such as clouds, volcanic eruptions, natural biomass (forest) burning, and dust from storms. In addition, human-induced factors such as biomass burning (forest and agricultural fires) and sulfate aerosols from burning coal contribute tiny particles that contribute to cooling.
  - Volcanic eruptions of this magnitude can impact global climate, reducing the amount of solar radiation reaching the Earth's surface, lowering temperatures in the troposphere, and changing atmospheric circulation patterns. The extent to which this occurs is an uncertainty.
  - Water vapor is a greenhouse gas, but at the same time, the upper white surface of clouds reflects solar radiation back into space. Albedo—reflections of solar radiation from surfaces on the Earth—creates difficulties in exact calculations. If, for example, the polar icecap melts, the albedo will be significantly reduced. Open water absorbs heat, while white ice and snow reflect it.
- **Ocean (Te ocean conveyor belt):**

Factors affecting temperature

- **Clouds:**
- **Fine particles (aerosols) in the atmosphere:**
- **Ocean currents (e.g., The ocean conveyor belt):**
  - Oceans play a vital role in the energy balance of the Earth. It is known that the top 10 feet of the oceans can hold as much of the heat as the entire atmosphere above the surface. However, most of the incoming energy is incident on the equatorial region.
  - The water in the oceans in the equatorial regions is warmer and needs to be transported to the northern latitudes. This is done due to natural variations in the temperatures of the water and prevailing winds that cause the disturbances in the surface waters.
  - The Intergovernmental Panel on Climate Change (IPCC) states that even the low end of this warming projection "would probably be greater than any seen in the last 10,000 years, but the actual annual to decadal changes would include considerable natural variability."


Solar radiation 100%
30% lost to space by reflection and scattering
5% backscattered to space by the atmosphere
20% reflected from clouds
20% of radiation absorbed by atmosphere and clouds
5% reflected from land-sea surface
50% of direct and diffused radiation absorbed by land and sea


Solar Radiation absorbed by Earth
235 W/m²
Thermal radiation into space: 195
Directly radiated from surface: 40
Greenhouse gas absorption: 350
67
Heat and energy in the atmosphere
452
The Greenhouse Effect
168
324
Earth's land and ocean surface warmed to an average of 14℃



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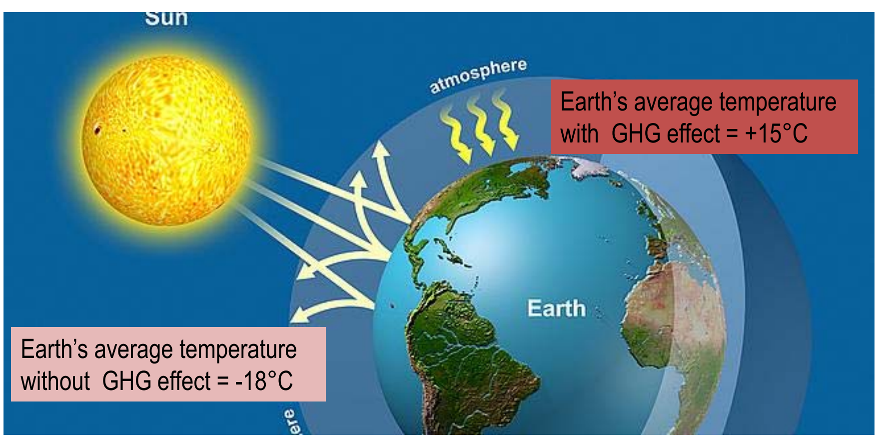
The Greenhouse Effect



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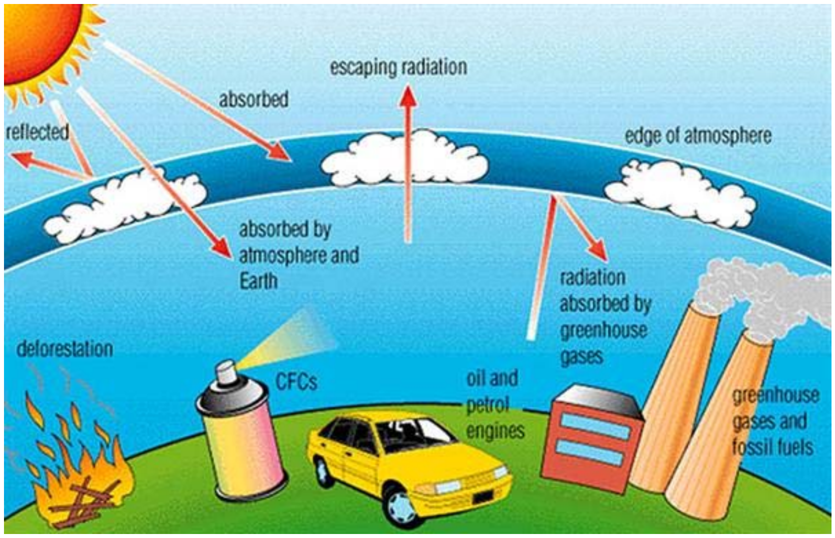
GHG Effect



Conclusions

- Zeroth order model considers the earth as a black body to calculate the surface temperature of the earth.
- Two layer model gives the earth surface temperature close to the measured value.
- There are many factors that influence the earth surface temperature.
- GHG effect is the major culprit of global warming.