Simple Climate models

UNIT-2

Simple Climate models

Source of energy

Energy loss

Greenhouse effect

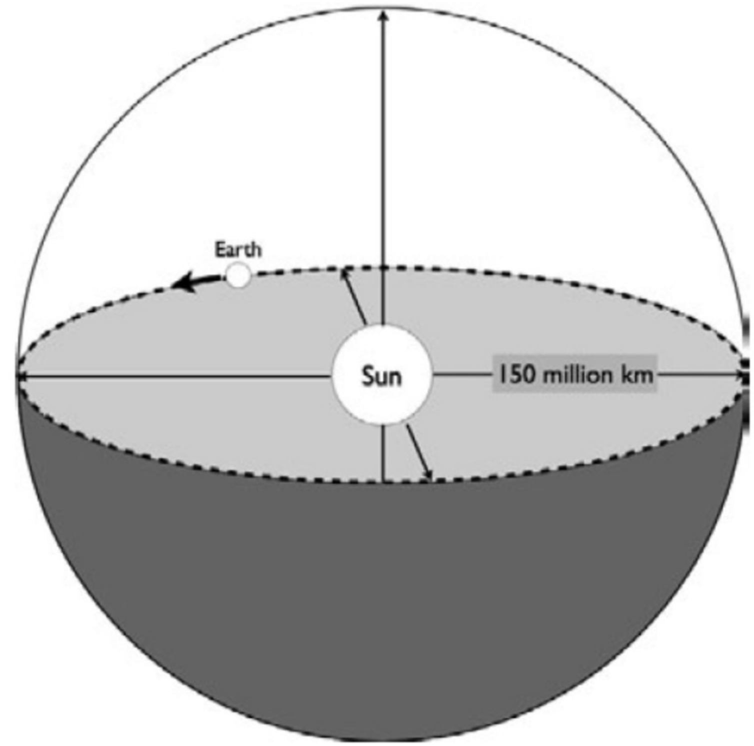
Carbon cycle

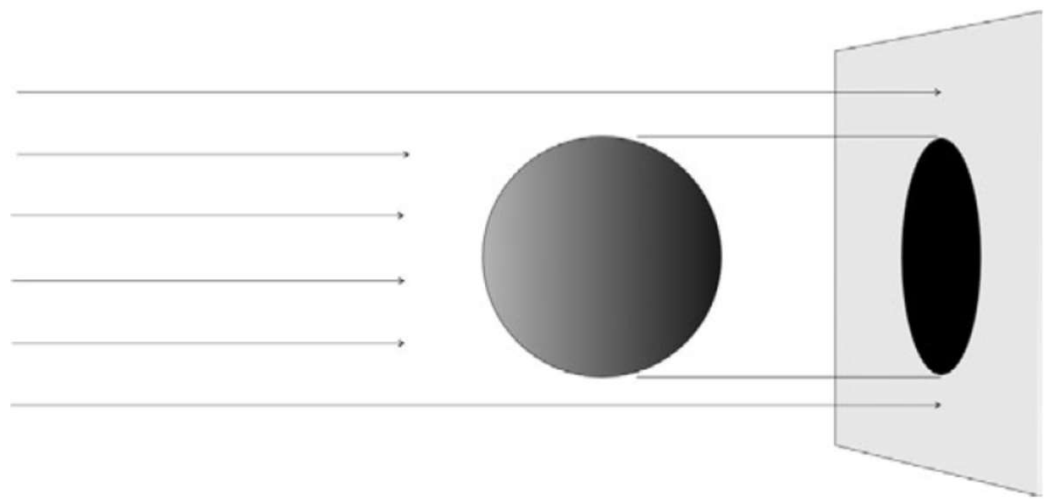
atmosphere–land-biosphere–ocean carbon exchange

The source of energy for our climate system

Source of energy

- The first step to understanding the climate is to do an energy budget calculation: What is the energy in and energy out for the Earth?
- Ultimate source of energy - 3.8×10^{26} W
- The surface area of the sphere is $4\pi r^2 = 4\pi(150 \text{ million km})^2 = 2.8 \times 10^{17} \text{ km}^2 = 2.8 \times 10^{23} \text{ m}^2$.
- This means that the energy emitted by the Sun falling on a 1-m^2 surface of the sphere is 1,360 W/m^2 - *solar constant* for the Earth
- Solar energy is falling on the Earth at a rate of 1.8×10^{17} W or 180,000TW





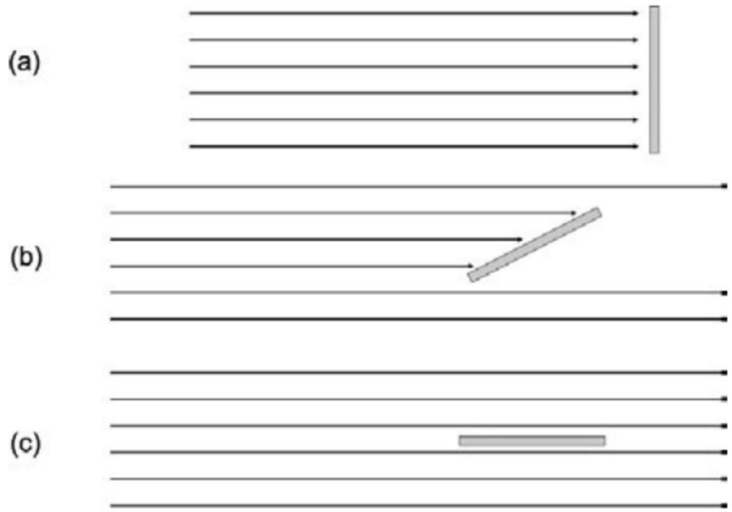
Source of energy

- Humans today consume approximately 15 TW - 0.01% of the solar energy falling on the Earth
- The reflectivity of a planet is called the *albedo*, from the Latin word for "whiteness."
- The total rate of energy in (E_{in}) for the Earth is

$$E_{in} = S(1 - \alpha)\pi R^2$$

- α is the fraction of photons that are reflected, so $1 - \alpha$ is the fraction of photons that are absorbed. For the Earth, $\alpha = 0.3$, meaning that about 126,000 TW are absorbed by the Earth system and the other 54,000 TW of solar photons are reflected back to space.

Source of energy



Schematic showing how the amount of energy falling on a surface is dependent on the angle between the surface and the incoming beams of light: (a) perpendicular, (b) rotated away from perpendicular, and (c) parallel.

The total rate of energy per m^2 for the Earth

$$\frac{E_{\text{in}}}{\text{area}} = \frac{S\,(1-\alpha)\,\pi R^2}{4\pi R^2} = \frac{S\,(1-\alpha)}{4}$$

- The amount of solar energy absorbed varies widely across the planet
- During daytime, the amount of sunlight falling on a square meter is determined by the orientation of that square meter with respect to the incoming beams of sunlight.
- The amount of sunlight received is at maximum if the surface is oriented perpendicular to the incoming beam.
- As the surface rotates away from perpendicular to the beam of photons, the amount of solar energy intercepting the surface decreases, eventually reaching zero for a surface parallel to the incoming beam

Source of energy

- More solar energy falls on the tropics than on higher latitudes, mid-latitudes receive less solar radiation per square meter than the tropics
- Finally, the polar regions receive even less solar energy
- The tropics are mainly open ocean, therefore has a low albedo. Combined with the large amount of solar energy per square meter, the tropics therefore experience far more solar heating than anywhere else on the planet.
- A simple but fundamentally correct explanation of why the tropics tend to be the warmest place on the planet.
- The high latitudes are frequently covered by ice, giving them a high albedo indicating amount of solar heating and therefore tend to be the coldest place on the planet.

Energy loss to space

Why doesn't the Earth heat up until it is the same temperature as the Sun?

- Earth is losing energy at a rate equal to the rate at which it is receiving energy from the Sun
- Earth loses energy back to space by means of blackbody radiation

$$P/a = \sigma T 4$$

$$\frac{S(1-\alpha)}{4} = \sigma T^4$$

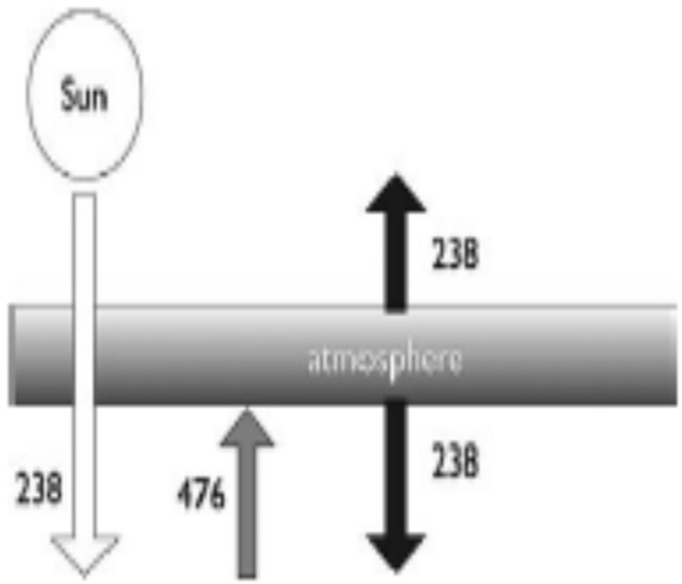
- Plugging S = 1,360 W/m^2 and α = 0.3 into above equation yields a temperature T of 255 K (−18 ◦C).
- The actual average temperature of the Earth is closer to 288 K (15 ◦C), so our estimate of the Earth's temperature is too cold
- The heating of the planet by the Earth's atmosphere, which is frequently referred to as the *greenhouse effect*

The greenhouse effect

One-layer model

To understand the impact of the atmosphere on our planet's temperature, let's make the following assumptions.

- The Earth's atmosphere is transparent to visible photons emitted by the Sun (which have wavelengths from 0.3–0.8 µm)
- The atmosphere is opaque to infrared photons emitted by the surface (wavelengths from 4–20 µm), and so all these photons are absorbed by the atmosphere.
- The atmosphere also behaves like a blackbody, so it emits photons based on its temperature.
- Half of these emitted photons are emitted in the upward direction, toward space. These photons escape to space and carry energy away from the Earth.
- The other half are emitted downward, and these photons are all absorbed by the surface.



Schematic of energy flow on a planet with a one-layer atmosphere. The atmosphere is represented by a single layer that is transparent to visible photons but absorbs all infrared photons that fall on it. The arrows show global average energy flows with values in W/m2.

One-layer model

To calculate the surface temperature in this model

- The temperatures on the planet are not changing
- The solar constant and albedo for this planet have the same values as for the Earth.
- Energy into the planet is coming entirely from the Sun. Energy out to space is coming entirely from the atmosphere

The energy in from the Sun is 238 W/m^2

The atmosphere must be radiating 238 W/m^2 upward to space

Atmosphere is also radiating 238 W/m^2 back toward the Earth's surface

Consider energy balance for the surface

- Energy in for the surface is 238W/m^2 from the Sun + 238 W/ m^2 from the atmosphere, for a total of 476 W/m^2.
- This means that the surface has to be emitting 476 W/ m^2 upward

Energy balance for the atmosphere

- Energy in comes from the surface, which is emitting 476 W/m^2.
- Energy out comes from emission of 238 W/m^2 upward to space and 238 W/m^2 downward to the surface, for a total energy out of 476 W/m^2.

What is the temperature of the surface?

Stefan–Boltzmann equation

$E_{out} = P/a = \sigma T^4$

$\sigma T^4 = 476\ \text{W/m}^2$

T = ???

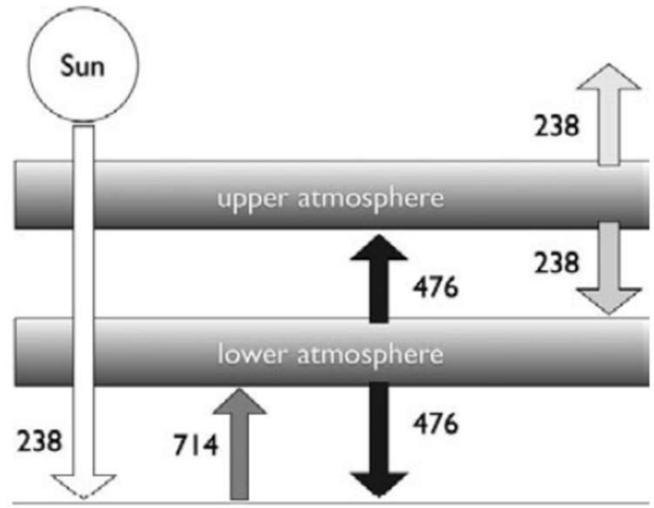
Surface temperature of 303 K (30 ◦C), which is 48 ◦C warmer than that for the planet without an atmosphere.

- The addition of an atmosphere that is opaque to infrared radiation has significantly warmed the planet's surface
- The surface of the planet with an atmosphere is heated not just by the Sun but also by the atmosphere
- One cannot see the atmosphere heating the Earth's surface because the photons it emits are not visible, but they still carry energy
- The greenhouse effect - It is the heating of the surface by the atmosphere to which scientists are referring (above phenomenon)
- Alternative way to think about the greenhouse effect is that the atmosphere warms the surface by making it harder for the surface to lose energy to space
- A planet with an atmosphere must have a warmer surface than a planet without an atmosphere.

Two-layer model

Consider a planet with a thicker atmosphere

- photons emitted by the surface are absorbed in the lower atmosphere.
- Photons emitted by the lower atmosphere in the upward direction are absorbed by the upper atmosphere.
- If they are emitted by the upper atmosphere in the upward direction, then they escape to space.
- Photons emitted in the downward direction by the lower atmosphere are absorbed by the surface
- While photons emitted in the downward direction by the upper atmosphere are absorbed by the lower atmosphere.



Schematic of energy flow on a planet with a two-layer atmosphere, with values in W/m^2.

Two-layer model

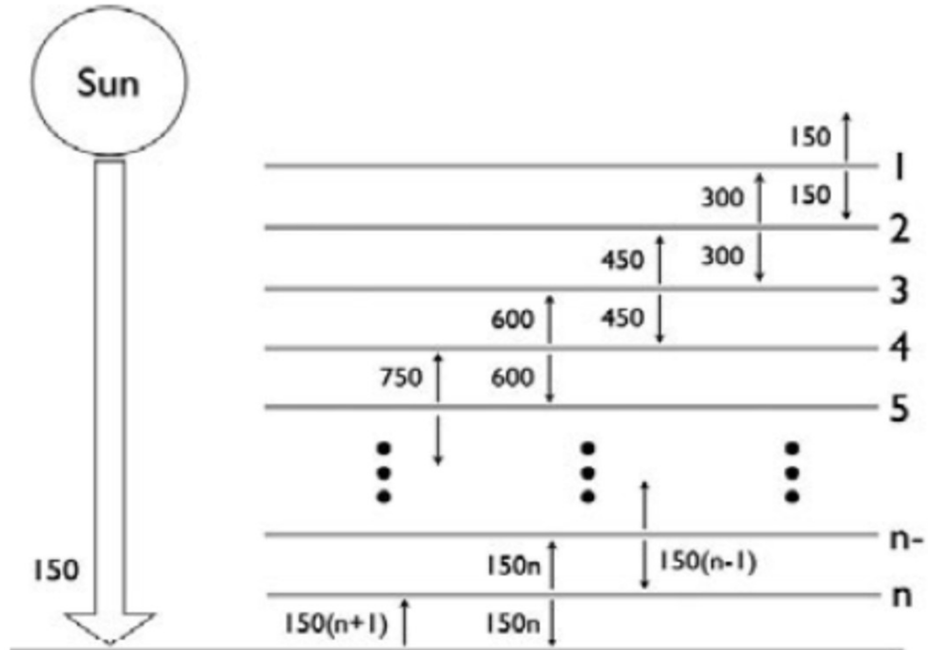
Applying energy balance for the planet as a whole

- Energy emitting from the sun = 238 W/m^2
- Energy emitting from upper layer towards sun (space) = 238 W/m^2
- Total Energy emitting from upper layer (both directions) = 238 + 238 = 476 W/m^2
- Energy received by upper layer = Energy emitting from lower atmosphere = 476 W/m^2
- Total Energy emitting from lower layer (both directions) = 476 + 476 = 952 W/m^2
- Total Energy emitting from the surface of the earth = 952 W/m^2 (238 W/m^2 from sun + 714 W/m^2 from the earth's surface)
- **The surface to be emitting 714 W/ m^2, the surface temperature must be 335 K (62 ◦C), which is 32 ◦C warmer than the planet with a thinner one-layer atmosphere.**

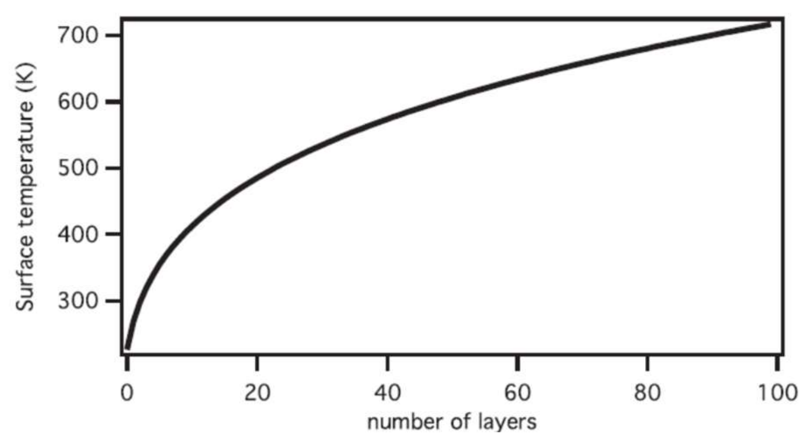
n-layer model

Let's derive the surface temperature for a planet with *n* layers

- let's assume that the planet has a solar constant of S = 2,000 **and** albedo of $\alpha = 0$
- Energy in for this planet is $S(1 - \alpha)/4$ = 150 W/m^2
- Upward emissions from the topmost layer of the atmosphere (Layer 1) must also be 150 W/m^2.
- This layer is also emitting 150 W/m^2 downward
- So that total energy out for this layer is 300 W/m^2
- Energy in for Layer 1 must also be 300 W/m^2
- Layer 2 must therefore be emitting 300 W/m^2 upward.



Schematic of energy flow on a planet with an *n*-layer atmosphere; layers are numbered from 1 to *n* (topmost to bottommost layers)



Surface temperature for the *n*-layer planet, as a function of the number of layers. Here $S(1-\alpha)/4$=150 W/m2.

n-layer model

- Layer 2 must be emitting 300 W/ m^2 downward, for a total energy out of 600 W/m^2
- Energy in for Layer 2 comes from downward emissions of Layer 1 and upward emissions of Layer 3 and must total 600 W/ m^2
- Downward emissions from Layer 1 are 150 W/m^2, which means that upward emissions from Layer 3 must be 450 W/m^2
- Layer 3 must be emitting 450 W/m2 both upward and downward, for a total energy out of 900 W/ m^2. Energy in from downward emissions from Layer 2 is 300 W/m^2, meaning that upward emissions from Layer 4 must be 600 W/m^2
- Extrapolating to the bottommost layer, layer *n*. For layer *n*, both upward and downward emissions are 150*n*.
- It means that the surface is receiving 150*n* emitted from the bottommost layer and 150 W/m^2 from the Sun
- The surface must be emitting $150(n + 1)$ W/m^2 upward.
- Setting $150(n + 1) = \sigma T^4$,

$$T = \sqrt[4]{\frac{150\,(n+1)}{\sigma}}$$

- The surface temperature as a function of *n*,

n-layer model

- The surface temperature of the planet is basically determined by three parameters: the number of layers in the atmosphere (*n*), the solar constant (*S*), and the albedo (α)

What the “number of layers” physically represents ???

- The *greenhouse gases* in our atmosphere that absorb infrared photons
- The number of layers is equivalent to the amount of greenhouse gas in the atmosphere
- An increase in the greenhouse gas in the atmosphere corresponds to an increase in the number of layers – and a warming climate.

Testing our theory with other planets

n-layer model – Drawbacks

- not all energy transport on a planet is by radiation (some is transported by atmospheric motions, such as deep convective thunderstorms)
- The model assumes an infinitely fast horizontal energy transport
- The model assumes that the atmosphere absorbs all infrared photons
- This means that you should not expect the model to produce quantitatively accurate surface temperatures

The model is successful in making qualitative projections of planetary temperatures

Data on the four inner planets in our solar system

Planet	Solar constant (W/m^2)	Albedo	Observed surface temperature (K)	Inferred n
Mercury	10,000	0.1	452	0.052
Venus	2,650	0.7	735	82
Earth	1,360	0.3	289	0.65
Mars	580	0.15	227	0.22

Testing climate model theory with other planets

- Mercury is the planet closest to the Sun, yet Venus, twice as far from the Sun as Mercury, has a surface temperature that is approximately 300 K warmer
- Because of its high albedo, the energy in for Venus, $S(1 - \alpha)/4 = 200$ W/m^2, is more than a factor of 10 smaller than that for Mercury (2,250 W/m^2)
- The inferred n for Mercury is near zero, suggesting it has almost no greenhouse effect. Mercury has essentially no atmosphere
- For Mars, inferred $n = 0.22$. Mars has a thin atmosphere containing carbon dioxide, so it does have some greenhouse effect. However, the Martian atmosphere has fewer greenhouse gases than the Earth's atmosphere, so the greenhouse effect on Mars is expected to be weaker than that on Earth.
- Venus has inferred $n = 82$, has a massive greenhouse effect. The surface pressure on Venus is 90 times that of Earth (1,300 psi, or pounds per square inch, compared with 14.5 psi here on Earth), and the atmosphere is mainly composed of carbon dioxide.

Thank you