Chapter 4: A Simple Climate Model

Feb 11 & 16

- 4.1. The Source of Energy for Our Climate System
- 4.2. Energy Loss to Space
- 4.3. The Greenhouse Effect
- ~~4.4. Testing Our Theory with Other Planets~~
- Terms
- Problems

Basics:

- Area of a circle and a sphere
- COS function

Chapter 4: A Simple Climate Model

Introduction

Scientists have studied Earth climate for nearly 200 years (e.g., Chapter 13).

We use physics to explain how greenhouse gases warm Earth and why temperature of Earth is what it is.

You will better understand why scientists have high confidence that adding greenhouse gases to atmosphere warms our planet.

4.1. The Source of Energy for Our Climate System

- Understanding climate requires energy balance (unit: W or W/m^2)

Energy-in (Ein) - Energy-out (Eout)

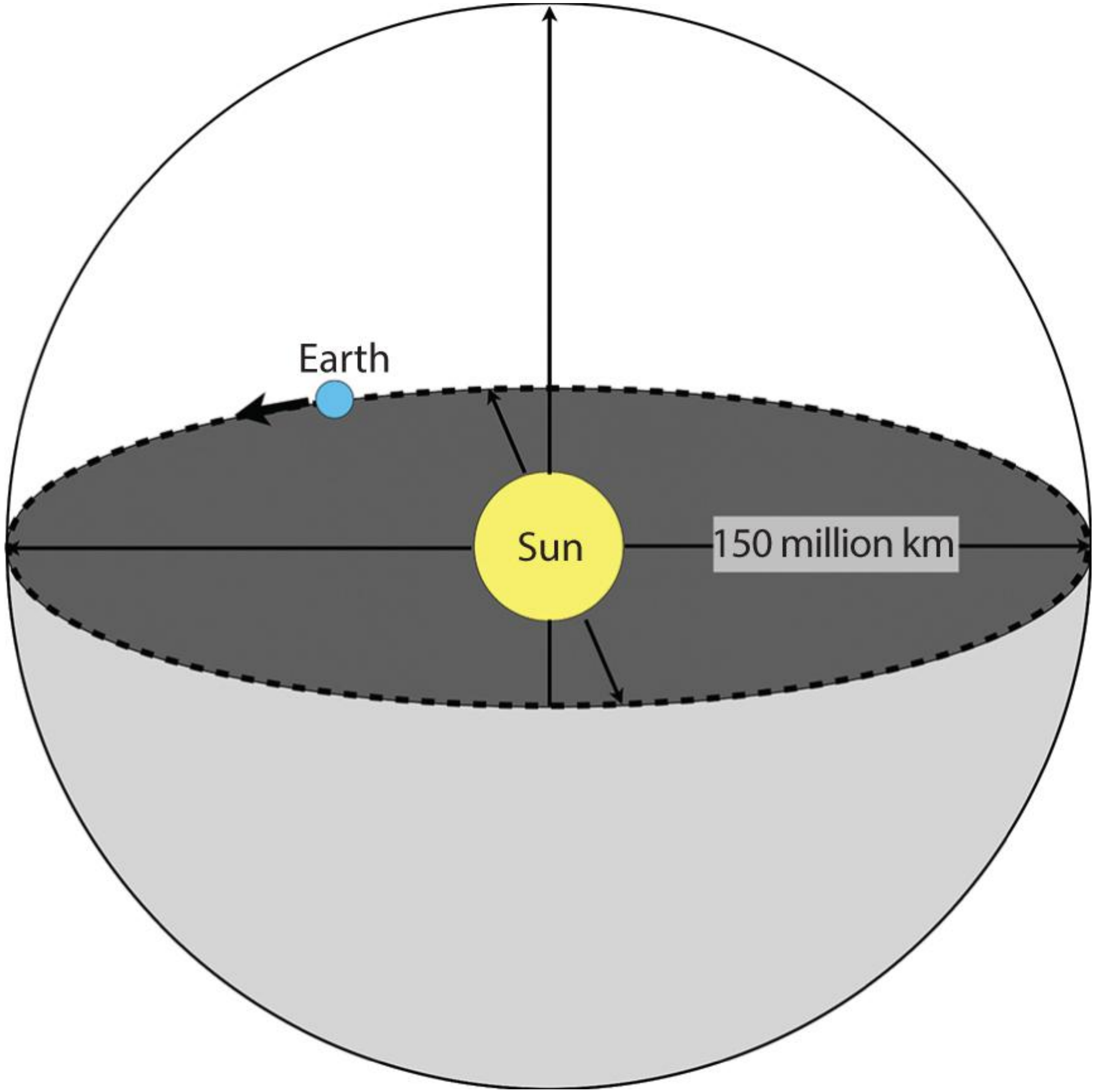
How is this number estimated?

- Ultimate source of energy is Sun, which emits ~3.8×10^{26} W (380 trillion trillion) outwards in all directions.
- Earth captures small fraction of solar output.
- Imagine sphere surrounding Sun with radius equal to distance from Sun to Earth.

4.1. The Source of Energy for Our Climate System

Fig. 4.1: Solar constant calculation:

Hypothetical sphere (gray) surrounding Sun with radius equal to Earth's orbit (dashed line); all radiation emitted by Sun (black arrows) falls on this sphere.



4.1. The Source of Energy for Our Climate System

Surface area of a sphere: $a = (4 \times \pi \times r^2)$.

where, r = distance from Sun to Earth (~150 mil km)

$a = 4 \times 3.1415926 \times (1.5 \times 10^{11}\ m)^2 = \sim 2.8 \times 10^{23}\ m^2$

Divide total solar power output (P) by area of sphere (a):

- $P/a = (\sim 3.8 \times 10^{26}\ W) / (\sim 2.8 \times 10^{23}\ m^2) = \sim \mathbf{1360\ W/m^2}$.

SOLAR CONSTANT (S): *intensity of solar radiation at Earth orbit*

4.1. The Source of Energy for Our Climate System

Next, determine Sunlight striking Earth:

- Imagine Earth with screen placed behind it, so that Earth casts circle shadow with radius of Earth (R).
- Shadow area: $\pi \times R^2$, where R = ~6400 km = ~6.4×10^6 m.
- Sunlight striking shadow area =

  $3.1415926 \times (6.4 \times 10^6)^2)$ m^2.
- Total energy

  = ~$1360 \times (3.14 \times (\sim 6.4 \times 10^6)^2)$

  = ~1.75×10^{17} W = ~175,000 TW.

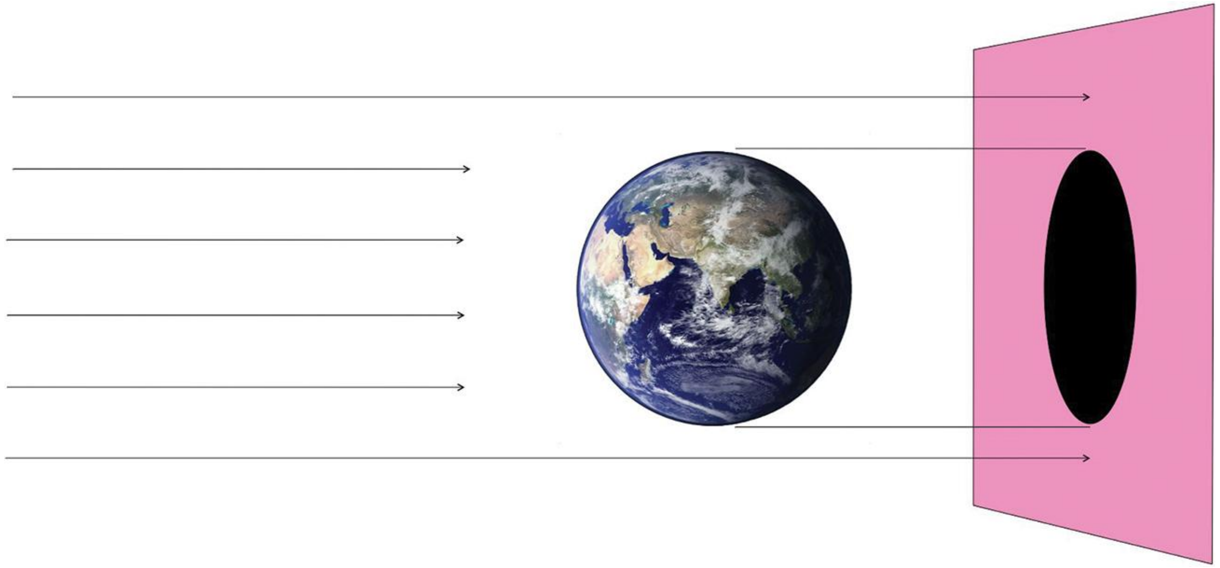


Fig. 4.2: Earth casting shadow on screen placed right behind it because it blocks sunlight. Total sunlight falling on Earth same as what would have fallen into shadow area.

4.1. The Source of Energy for Our Climate System

However, not all photons strike Earth are absorbed.

Some photons reflected by clouds, ice, and other reflective elements of Earth system.

Albedo (α) = Reflectivity of planet:

- Value ranges from 0.0-1.0 with no units.

- α = the fraction of incoming photons reflected back to outer space (Earth = 0.3).

- Absorption = fraction of photons absorbed by the Earth = $1-\alpha$ (~0.7).

4.1. The Source of Energy for Our Climate System

Energy-in (E_{in}) for Earth is:

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

where for Earth,

- S = ~1360 W/m^2.
- α = ~0.3.
- π = 3.14…
- $R = 6.4 \times 10^6$ m.
- E_{in} = ? W

Rather than work with power (W), we often want to work in power per unit area (W/m^2). *With surface area of Earth = 4 x π x R^2*

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

The energy received per m^2 is: **~238 W/m^2**

E_{in} = ~1.23×10^{17} W
= ~123,000 TW

4.1. The Source of Energy for Our Climate System

Varies locally depending on time of day, time of year, latitude, and albedo:

- Amount of Sunlight maximized if surface oriented perpendicular to incoming beam (**Fig. 4.3a**).
- As surface rotates away from perpendicular, amount of energy intercepting surface decreases (**Fig. 4.3b**).
- Amount of energy intercepting surface eventually reaching zero for surfaces parallel to incoming beam (**Fig. 4.3c**).

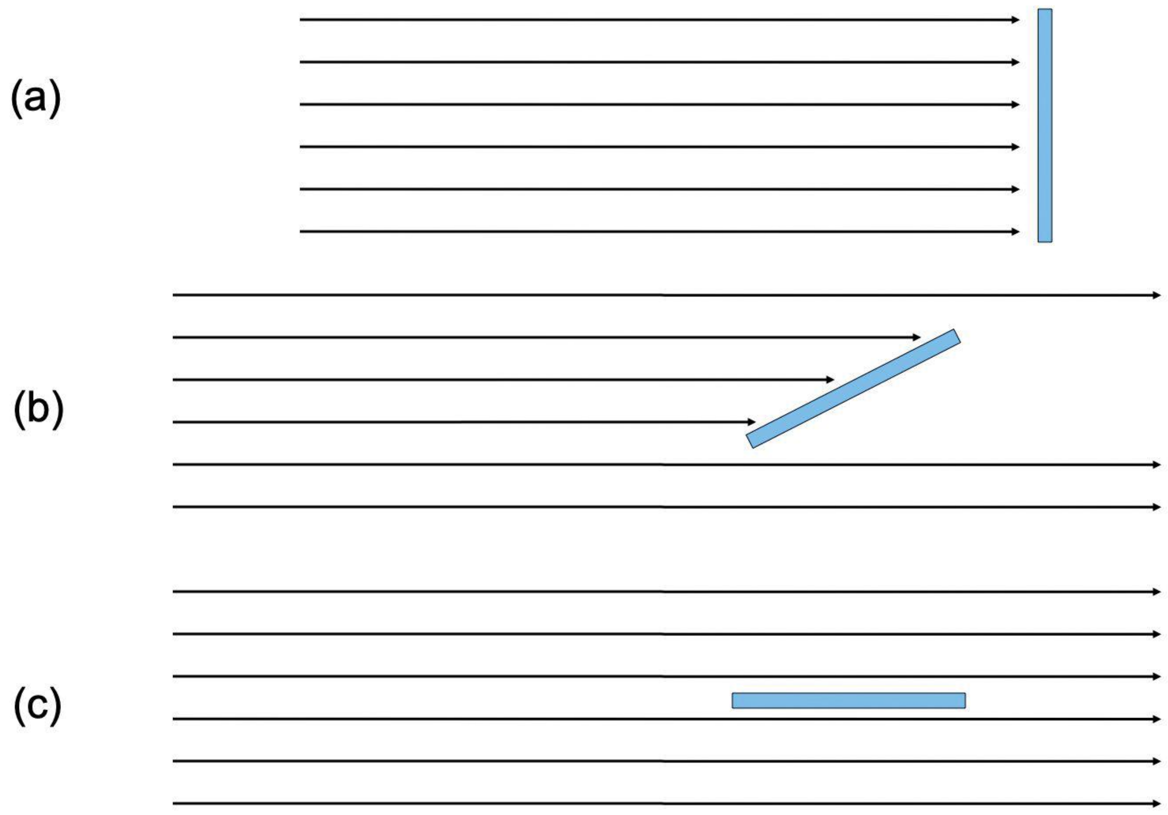


Fig. 4.3: Schematic showing how amount of power falling on surface dependent on angle between surface and incoming beams of light: (a) perpendicular, (b) rotated away from perpendicular, & (c) parallel.

4.1. The Source of Energy for Our Climate System

Amount of solar energy falling on Earth varies with latitude when averaged over a year:

- In tropics, surface of Earth is perpendicular to incoming solar light beams (Fig. 4.3a).
- In mid-latitudes, surface of Earth at moderate angle to incoming solar light beams (Fig. 4.3b).
- In polar regions, surface of Earth at large angle to incoming solar light beams (Fig. 4.3c).

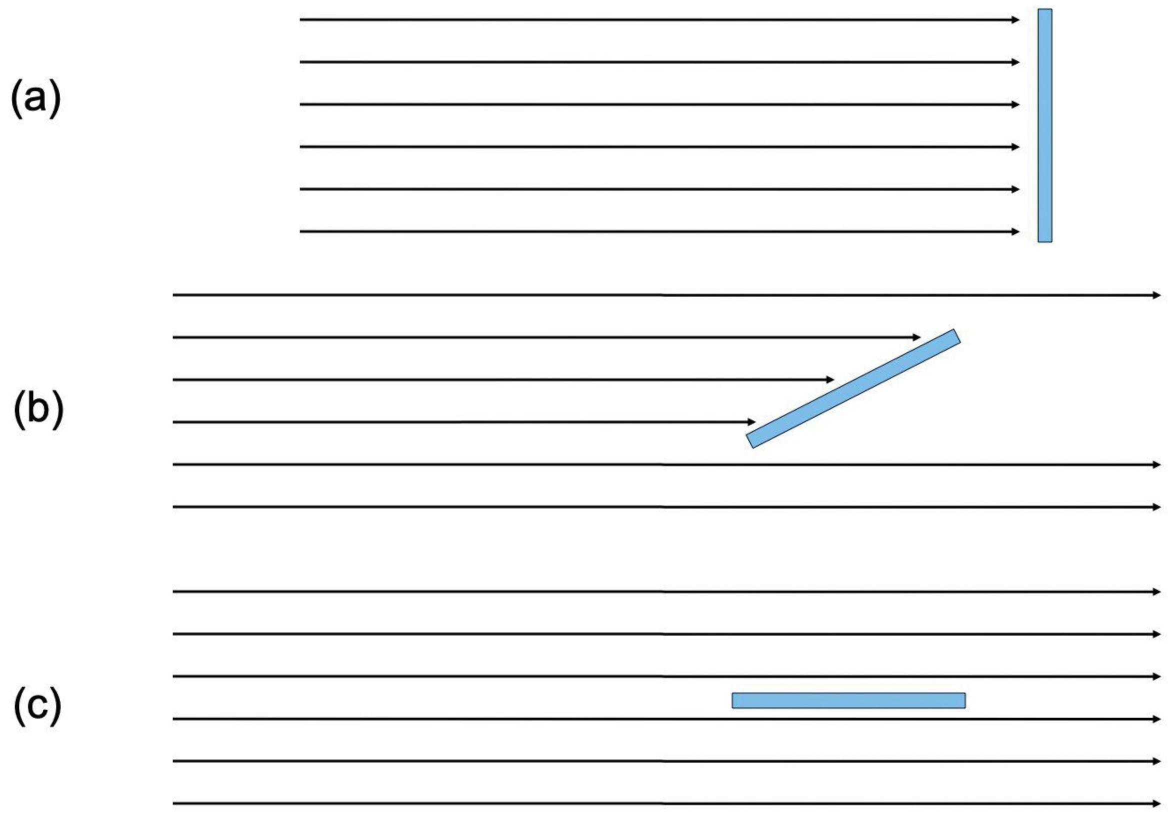


Fig. 4.3: Schematic showing how amount of power falling on surface dependent on angle between surface and incoming beams of light: (a) perpendicular, (b) rotated away from perpendicular, & (c) parallel.

4.1. The Source of Energy for Our Climate System

- Because tropics mostly ocean and polar regions mostly ice, albedo generally increases as latitude increases

- Overall, land has a higher albedo (0.1-0.3) than the oceans (<0.1)

- Explaining why tropics is warmer; polar regions are cooler.

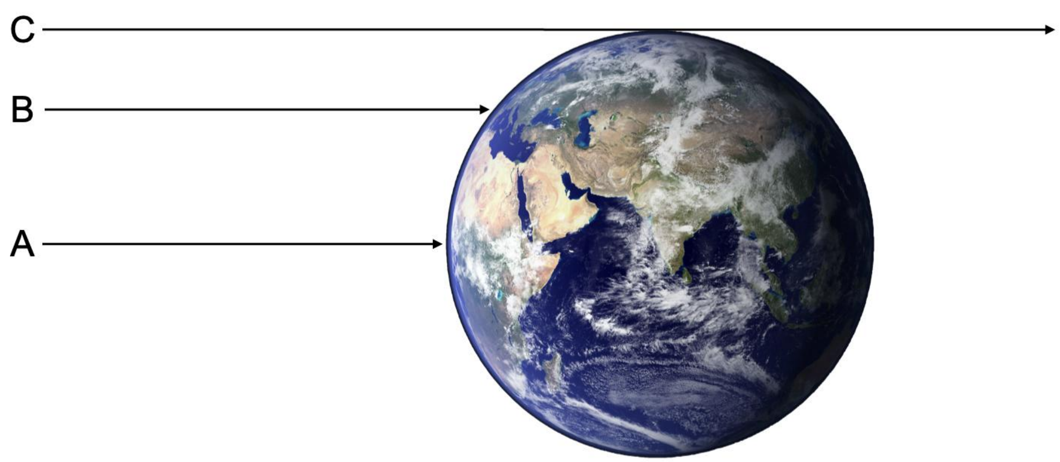


Fig. 4.4: Schematic showing how amount of solar power falling on square meter of Earth surface determined by latitude.

4.2. Energy Loss to Space: E_{out}

- In early 1800s Joseph Fourier asked, if Earth always absorbing power from Sun, why does Earth not heat up until Earth T = Sun T?
- **Answer**: Earth always emitting power at rate approximately equal to rate at which it is absorbing power.
- Earth emits power outwards to space by means of blackbody radiation (Stephen-Boztman's Law)(Eqn. 3.2),
- If $E_{in} = E_{out}$, then we get Eqn. 4.3a:

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

4.2. Energy Loss to Space: E_{out}

- Eqn. 4.3a solved for T yields Eqn. 4.3b:

$$T = \sqrt[4]{\frac{S(1-\alpha)}{4\sigma}}$$

- Plugging in S = 1360 W/m^2 and α = 0.3 into Eqn. 4.3b yields Earth T without atmosphere of ~255 K (~-18 ^{o}C).
- However, Earth T with atmosphere is ~15 ^{o}C, which is ~33 K higher!
- Eqn. 4.3b neglects heating by Earth atmosphere: greenhouse effect.
- Greenhouse Effect: (buffering) heating of planet by its atmosphere.

4.3. The Greenhouse Effect

4.3.1. One-layer Model

Four assumptions help us understand atmosphere impact on planet T:

1) Earth atmosphere transparent to visible photons emitted by Sun (wavelength = 0.4-0.8 microns), so these photons pass through atmosphere and (partially) absorbed by surface.
2) Earth atmosphere opaque to infrared photons emitted by Earth (wavelengths > 4 microns), so these photons absorbed by atmosphere.
3) Earth atmosphere acts as blackbody, emitting photons based on its T, approximately equal in upward and downward directions.
4) Photons emitted by Earth atmosphere in upward direction escape to space, carrying energy away from Earth, while photons emitted downward absorbed by Earth surface.

4.3. The Greenhouse Effect

- To calculate Earth T, assume Ein = Eout (Fig. 4.5).
- Earth surface absorbs visible photons from Sun (~238 W/m^2).
- Earth atmosphere emits infrared photons upward toward space = ~238 W/m^2 (upward light red arrow).
- Earth atmosphere emits infrared photons downward toward surface = ~238 W/m^2 (downward light red arrow).
- Earth surface absorbs infrared photons from Earth atmosphere = ~238 W/m^2 (downward light red arrow).
- Earth surface must emit infrared photons upward toward Earth atmosphere = ~476 W/m^2 (upward dark red arrow).

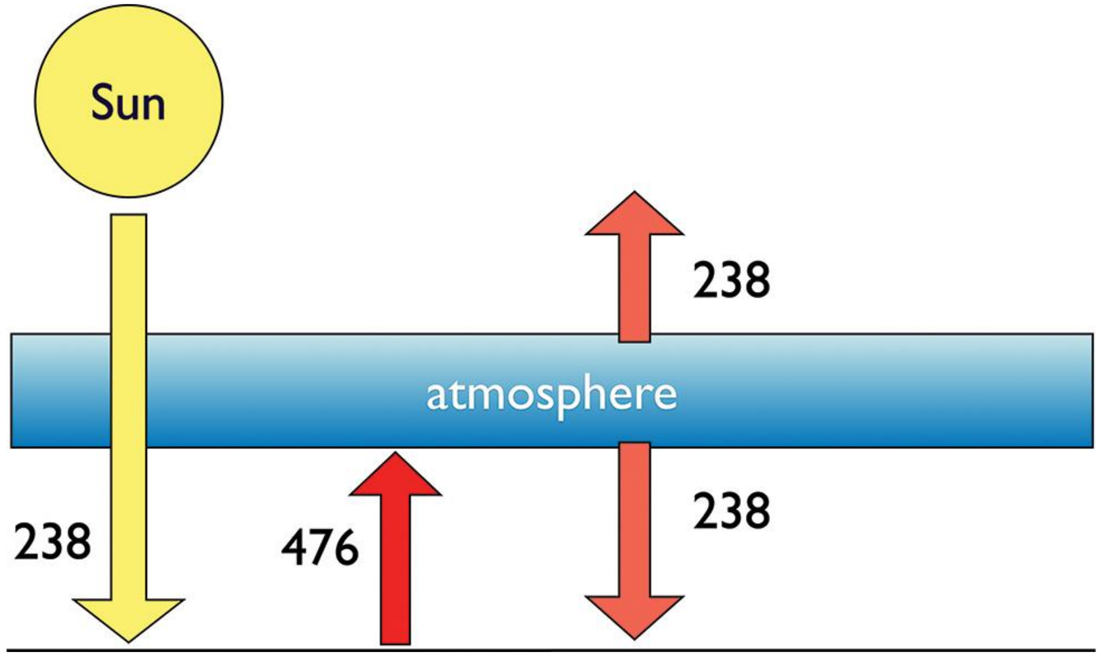


Fig. 4.5: Schematic of energy flow on planet with one-layer atmosphere. Atmosphere represented by single layer transparent to visible photons but absorbs all infrared photons that fall on it. Arrows show Earth average power flows with values in W/m^2, based on Earth values of solar constant & albedo.

4.3. The Greenhouse Effect

- For Earth surface below one-layer atmosphere, $E_{out}/a = P/a = \sigma \times T^4 =$ ~476 W/m^2

- Eqn. 3.2 solved for $T = ((E_{out}/a)/\ \sigma)^{1/4}$

- $T = ((476\ W/m^2)\ /\ (5.67 \times 10^{-8}\ W/m^2/K^4))^{1/4}$

- T = ~303 K.

- However, Earth T = ~303 K is ~48 K warmer than Earth T without atmosphere (~255 K).

4.3. The Greenhouse Effect

- Earth T = ~303 K, ~15 K warmer than observed T with atmosphere (~288 K).

Results:

- Addition of one-layer atmosphere opaque to infrared photons warms planet surface.
- Without atmosphere, all photons emitted to space.
- With one-layer atmosphere, half of photons emitted to space, with other half returned to surface.

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TERMS

Albedo

Greenhouse effect

Solar constant