SL IB Physics

Your notes

Greenhouse Effect

Contents

Your notes

Albedo & Emissivity

Emissivity

- Stars are good approximations to a black body, whereas planets are not
  - This can be quantified using the emissivity
- Emissivity, e, is defined as

  The the ratio of the power radiated per unit area by a surface compared to that of a black body at the same temperature

- It can be calculated using the equation

$$e = \frac{\text{power radiated by an object}}{\text{power emitted by a black body}}$$

- Calculations of the emissivity assume that the black body:
  - Is at the same temperature as the object
  - Has the same dimensions as the object
- For a perfect black body, emissivity is equal to 1
- When using the Stefan-Boltzmann law for an object which is not a black body, the equation becomes:

$$P = e\sigma AT^4$$

- Where:
  - P = total power emitted by the object (W)
  - e = emissivity of the object
  - σ = the Stefan-Boltzmann constant
  - A = total surface area of the object black body (m^2)
  - T = absolute temperature of the body (K)

Examiner Tip

You will be expected to remember that a perfect black body has an emissivity of 1 - this information is **not** included in the data booklet!

Your notes

Albedo

- Albedo, *a*, is defined as

  The ratio of the total scattered power to the total incident power of radiation that is reflected by a given surface

- It can be calculated using the equation

$$a = \frac{\text{total scattered power}}{\text{total incident power}}$$

- More specifically, the albedo of a **planet** is defined as

  The ratio between the total scattered, or reflected, radiation and the total incident radiation of that planet

- Earth's albedo is generally taken to be 0.3, which means 30% of the Sun's rays that reach the ground are reflected, or scattered, back into the atmosphere
- An albedo of 1 represents a surface that scatters all the incident radiation
- Earth's albedo varies daily and depends on:
  - **Cloud formations** and **season** – the thicker the cloud cover, the higher the degree of reflection
  - **Latitude**
  - **Terrain** – different materials reflect light to different degrees
  - **Incident angle** of radiation
- It is useful to know the albedo of common materials:
  - Fresh asphalt = 0.04
  - Bare soil = 0.17
  - Green grass = 0.25
  - Desert sand = 0.40
  - New concrete = 0.55
  - Ocean ice = 0.50 - 0.70
  - Fresh snow = 0.85
- Albedo has no units because it is a **ratio** (or fraction) of power

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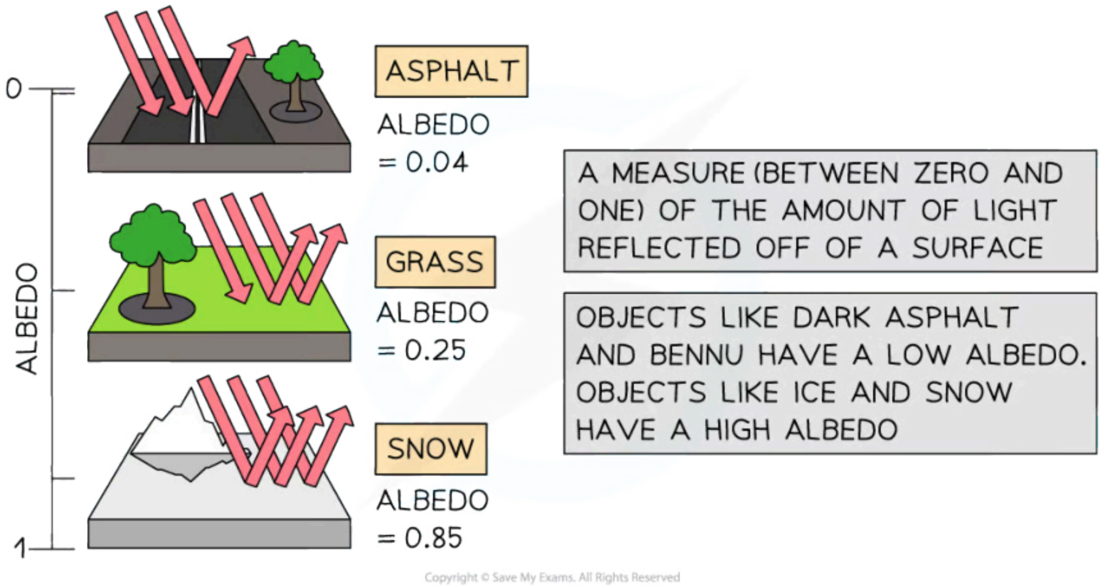


Worked example

The average albedo of fresh snow is 0.85

Calculate the ratio $\frac{\text{energy absorbed by fresh snow}}{\text{energy reflected by fresh snow}}$

Answer:

Step 1: Define albedo

- Albedo = the proportion of radiation that is reflected
- Therefore, the energy reflected by fresh snow = 0.85

Step 2: Identify the proportion of radiation that is absorbed

- If 85% of the radiation is reflected, we can assume that 15% is absorbed
- Therefore, the energy absorbed by fresh snow = 1 – 0.85 = 0.15

Step 3: Calculate the ratio

$$\frac{\text{energy absorbed by fresh snow}}{\text{energy reflected by fresh snow}} = \frac{0.15}{0.85} = 0.18$$

The Solar Constant

Your notes

The Solar Constant

- Since life on Earth is entirely dependent on the Sun's energy, it is useful to quantify how much of its energy reaches the top of the atmosphere
  - This is known as the solar constant, *S*
- The solar constant is defined as:

The intensity of the Sun's radiation arriving perpendicularly to the Earth's atmosphere when the Earth is at its mean distance from the Sun

- The **average** value of the solar constant is 1.36×10^3 W m^{-2}
- The value of solar constant varies year-round because:
  - The Earth is in an **elliptical orbit** around the Sun, meaning at certain times of year the Earth is closer to the Sun, and at other times of year it is further away
  - The **Sun's output varies** by about 0.1% during its 11–year sunspot cycle
- Calculations of the solar constant assume that:
  - This radiation is incident on a **plane perpendicular** to the Earth's surface
  - The Earth is at its **mean distance** from the Sun
- The intensity of solar radiation received by different planets in the Solar System **varies** depending on distance from the Sun
  - For example, the intensity of solar radiation incident on Venus' atmosphere is **higher** than Earth's because it is **closer** to the Sun

Incoming Radiative Power

- The surface area of a planet, with radius *r*, equals the surface area of a sphere, $4\pi r^2$
- A planet's radiative intensity covers a cross-sectional area of πr^2
- So the mean value of the radiative power or intensity is:

$$S \times \left(\frac{\pi r^2}{4\pi r^2}\right) = \frac{S}{4}$$

Your notes

Worked example

The Sun emits 4×10^{26} J in one second. The mean distance of the Earth from the Sun is 1.5×10^{11} m.

Using this data, calculate the solar constant.

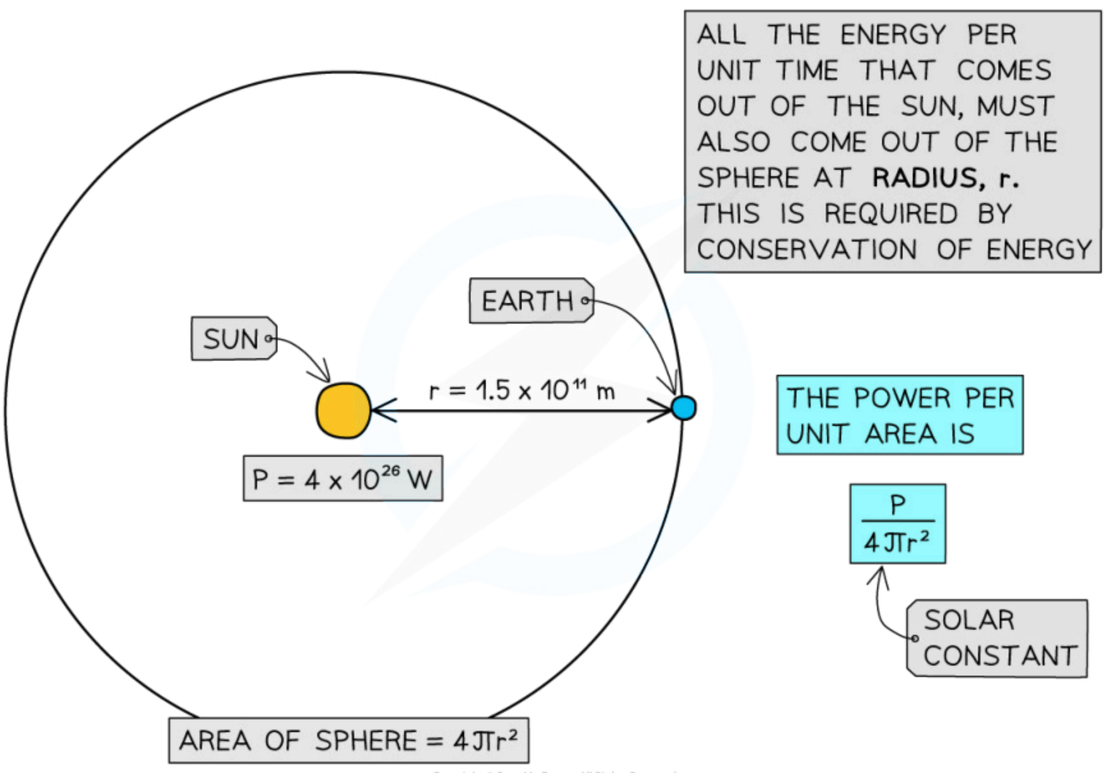
Answer:

Step 1: List the known quantities

- Power output of Sun, $P = 4 \times 10^{26}$ W
- Distance between the Earth and Sun, $r = 1.5 \times 10^{11}$ m

Step 2: Model the scenario using geometry

- As light leaves the surface of the Sun, it begins to spread out uniformly through a spherical shell
- The surface area of a sphere = $4\pi r^2$
- The radius r of this sphere is equal to the distance between the Sun and the Earth



Step 3: Write an equation to calculate the solar constant

$$\text{Solar constant} = \frac{P}{4\pi r^2}$$

Step 4: Calculate the solar constant

$$\text{Solar constant} = \frac{4 \times 10^{26}}{4\pi(1.5 \times 10^{11})} = 1415 \text{ W m}^{-2}$$

Solar constant = **1.4 kW m^{-2}** (2 s.f)

Examiner Tip

When defining the solar constant, it is important to say that the radiation arrives above the Earth's atmosphere and **not at the Earth's surface**.

Your notes

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Greenhouse Gases

The Main Greenhouse Gases

- The main greenhouse gases have both natural and human-generated origins
- In order of decreasing contributions, these are:
  - **Water vapour (H_2O)** - evaporation from the oceans / seas and plants
  - **Carbon dioxide (CO_2)** - volcanic eruptions, wildfires and respiration
  - **Methane (CH_4)** - emission from oceans and soils as part of decomposition, termites also emit methane
  - **Nitrous oxide (N_2O)** - soils and oceans
- When radiation from the Sun hits the Earth, it is radiated back from the Earth's surface as long-wave radiation
- A greenhouse gas is a gas that absorbs this re-radiated radiation, trapping it in the Earth's atmosphere so that it is not lost to space
  - Greenhouse gases in the atmosphere have a similar effect to the glass in a greenhouse, hence the term greenhouse gas
- There are many greenhouse gases, and those that contribute most to the greenhouse effect are:
  - Carbon dioxide (CO_2)
  - Water vapour (H_2O)
- These have the most significant impact on the greenhouse effect
- There are other greenhouse gases which have a lesser effect, such as:
  - Ozone (O_2 and O_3)
  - Methane
  - Nitrous oxides

Examiner Tip

You may have heard of a separate environmental concern, described as the 'hole in the ozone layer'; this is **not** something that you need to know about. Ozone is an atmospheric gas that absorbs harmful UV radiation before it reaches earth, but any concerns about ozone depletion have nothing to do with the greenhouse effect. The problem of ozone depletion is one that has improved significantly due to measures taken to reduce certain types of emissions; humans can get it right sometimes!

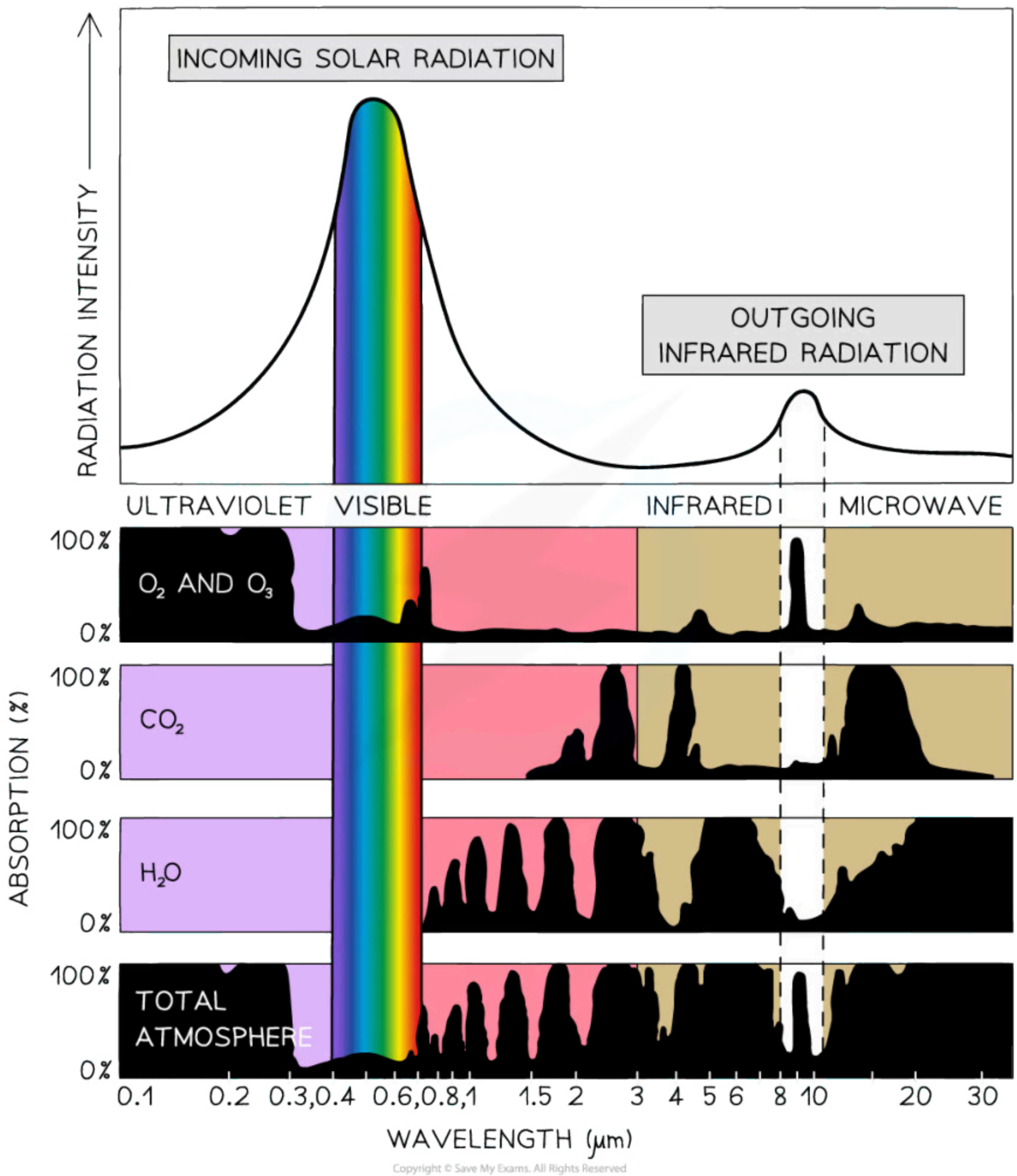
You do not need to know the specific sources of each type of greenhouse gas – all you need to know is that each greenhouse gas has both natural and man-made origins

Greenhouse Gases & Infrared Radiation

Your notes

- While only around 25% of the (mostly short wavelength) solar radiation is absorbed by the **atmosphere** on its way to Earth, around 80% of the (long wavelength) re-emitted radiation from Earth is **absorbed** on its way back into the atmosphere
  - For example, incoming UV radiation is absorbed by **ozone**
  - Re-emitted **infrared** radiation is absorbed by the main greenhouse gases
- This absorbed radiation keeps Earth at a **habitable** temperature
  - However, if there is an imbalance in the chemical composition of the atmosphere, this can lead to fluctuations in the Earth's mean surface temperature

- The relative significance of a greenhouse gas depends on its concentration in the Earth's atmosphere and how much the gas can absorb specific wavelengths of radiation



The degree of absorption for a particular molecule varies depending on the wavelength of the radiation. The dark parts show the percentage of radiation that is absorbed by each type of greenhouse gas.

Ozone (O_3)

- Ozone absorbs close to 100% of the Sun's incoming ultraviolet rays

- It also strongly absorbs the wavelengths of the outgoing infrared radiation leaving the Earth's atmosphere, between 9 μm and 10 μm
- However, it is not a significant contributor to the greenhouse effect as it is found in much smaller concentrations in the atmosphere

Carbon dioxide (CO_2)

- Carbon dioxide is a good absorber of infrared radiation with wavelengths between 1.5 - 30 μm
- In particular, it strongly absorbs radiation with a wavelength of 15 μm
- The increasing concentration of carbon dioxide in the atmosphere makes it one of the most significant contributors to the greenhouse effect

Water vapour (H_2O)

- Water vapour is the best absorber of infrared radiation with wavelengths between 0.8 - 35 μm
- The concentration of water vapour in the atmosphere increases as the air becomes warmer

Total atmosphere

- Overall, most of the ultraviolet, infrared and microwave radiation is absorbed by the atmosphere
- The atmosphere is mostly transparent to incoming visible radiation, which means that the gases in the atmosphere do not absorb or emit much visible radiation

Your notes

The Greenhouse Effect

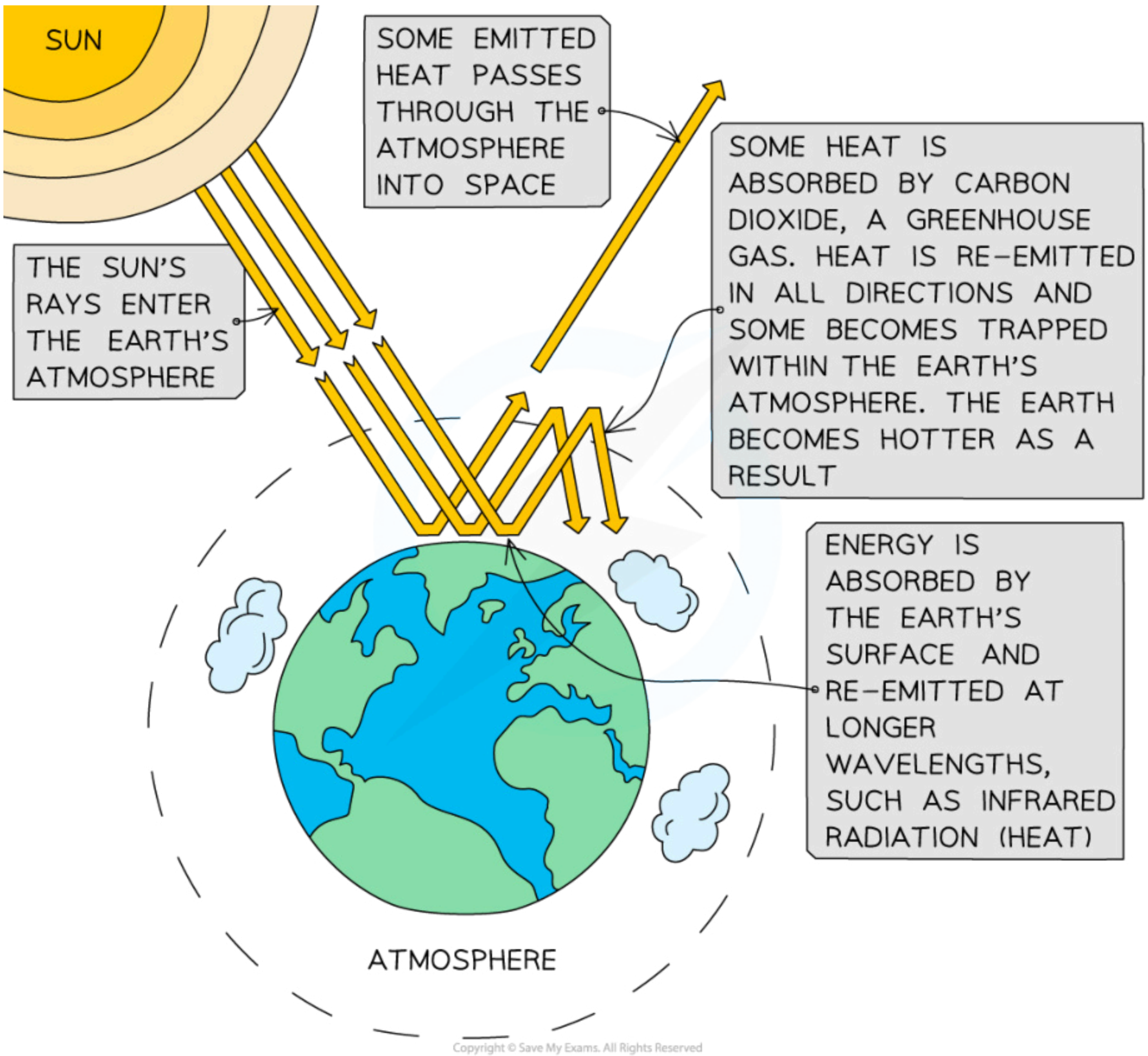
Your notes

The Greenhouse Effect

- While only around 25% of the (primarily **short wavelength**) solar radiation is absorbed by the atmosphere on its way to Earth, around 80% of the (**long wavelength**) re-emitted radiation from Earth is absorbed on its way back into the atmosphere
  - For example, incoming UV radiation is absorbed by ozone
  - Re-emitted infrared radiation is absorbed by greenhouse gases
- This absorbed radiation keeps Earth at a habitable temperature
  - However, if there is an imbalance in the chemical composition of the atmosphere, this can lead to fluctuations in the Earth's mean surface temperature

Resonance Model of Global Warming

- Incoming radiation from the Sun predominantly takes the form of ultraviolet and visible radiation
- Visible light is not absorbed by the atmosphere, instead, it is absorbed by the Earth's surface
- At night, the **Earth re-radiates** this radiation as infrared
- Some of this radiation is **absorbed** by the **Earth's atmosphere** and some of the radiation is reflected back into space
- The greenhouse gases present in the atmosphere absorb infrared radiation and reflect it back towards the Earth's surface
  - The higher the concentration of greenhouse gases present, the more infrared radiation there is remaining in the Earth's surface-atmosphere system
- Therefore, heat energy becomes trapped inside Earth's atmosphere and accumulates
  - This leads to the greenhouse effect and an increase in average mean temperatures on Earth

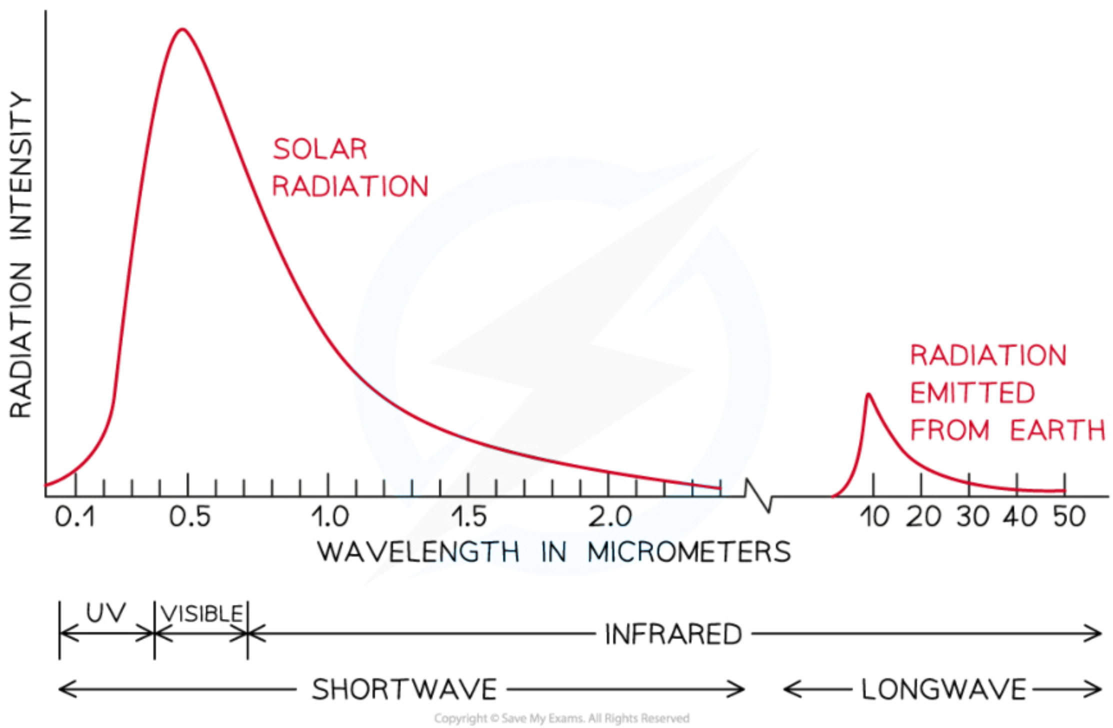


Greenhouse gases absorb the long-wave radiation emitted by Earth, warming the atmosphere

Your notes

Molecular Energy Level Model

- The greenhouse effect occurs due to the particular molecular structure of greenhouse gases
  - High-frequency UV light is energetic and able to break bonds within molecules
  - Infrared light, on the other hand, causes atoms to vibrate
- The greenhouse gases have a **natural frequency** that falls in the infrared region
  - This means when they absorb infrared light, they begin to resonate, causing the molecules to heat up
  - They absorb the infrared radiation and subsequently emit it back towards the Earth's surface



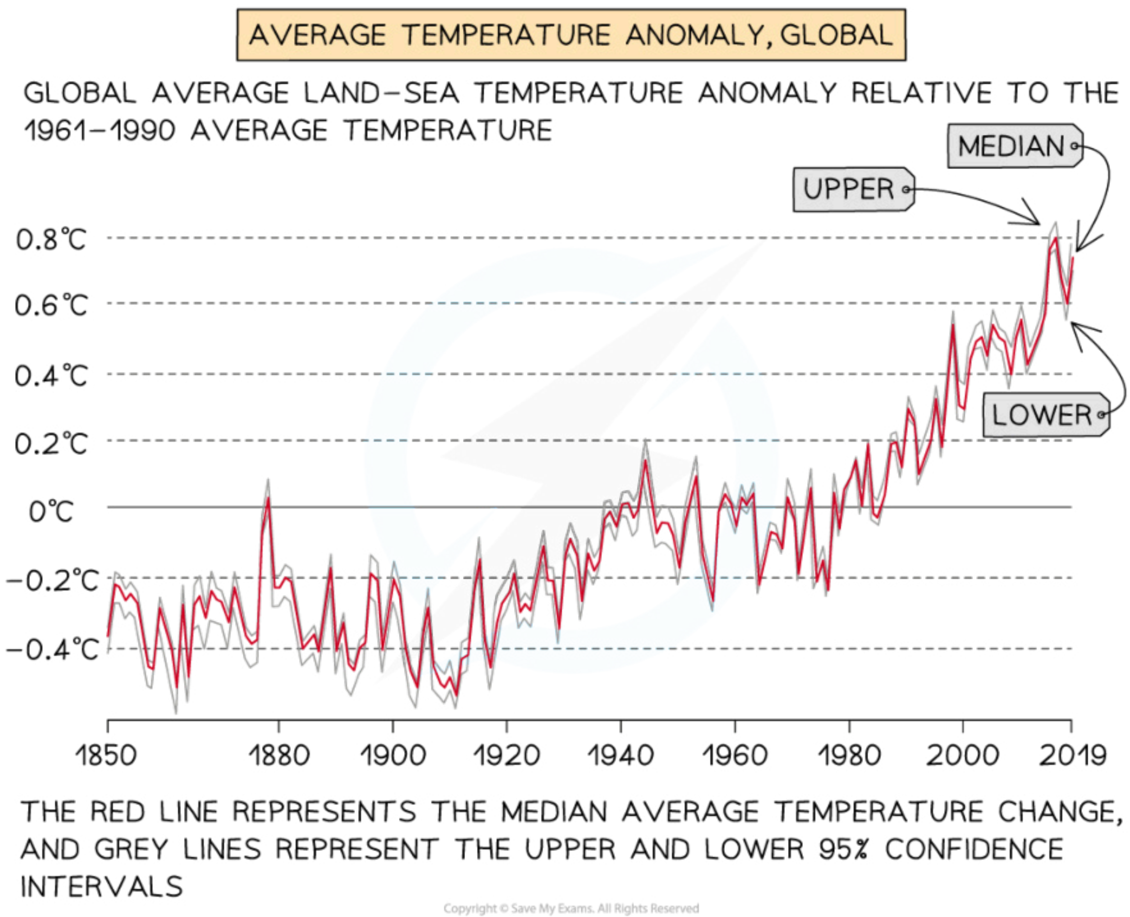
Solar radiation is primarily short-wave, while the radiation that is re-emitted by earth is long-wave radiation

Your notes

The Enhanced Greenhouse Effect

Your notes

- Human activity is increasing the number of greenhouse gases in the atmosphere:
  - **Carbon dioxide (CO_2)** levels in the atmosphere have increased by more than 100 parts per million (ppm) to 420ppm in 2020
- Increased amounts of greenhouse gases have led to the **enhanced greenhouse effect:**
  - Less long-wave radiation (heat) can escape the atmosphere
  - Average global temperatures have increased over 1°C since pre-industrial times



The average global temperature has risen remarkably in the past 100 years

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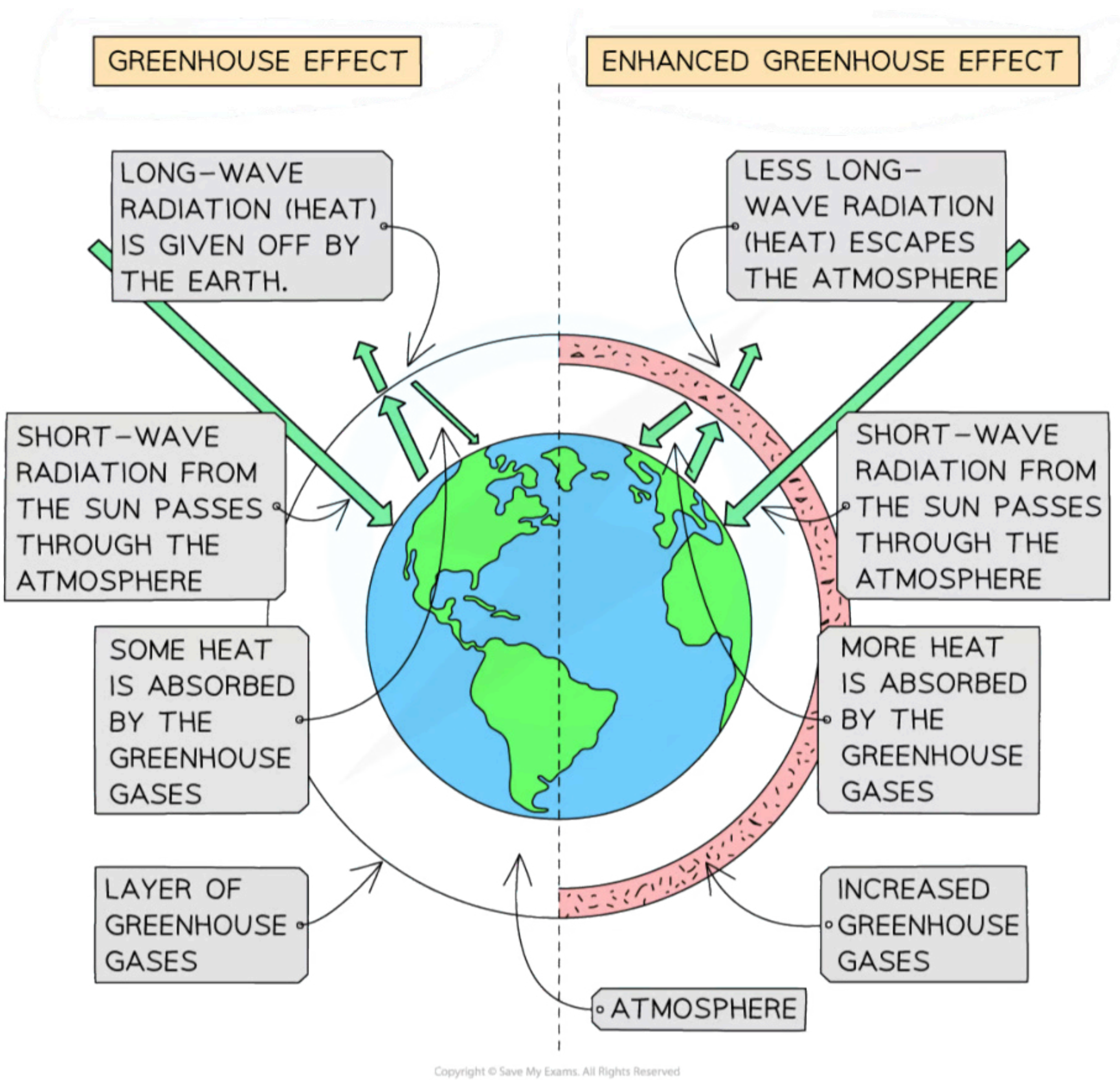

The greenhouse effect arises due to natural causes, but the enhanced greenhouse effect arises due to human activity

Human Sources of Greenhouse Gases

Greenhouse Gas	Sources from human activity
Carbon Dioxide (CO_2)	▪ Burning of fossil fuels - power stations, vehicles ▪ Burning of wood ▪ Deforestation - trees utilise CO_2 in photosynthesis. The fewer trees there are the less CO_2 is removed from the atmosphere

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Methane (CH_4)	▪ Decay of organic matter - manure, waste in landfill, crops
Nitrous Oxide (N_2O)	▪ Artificial fertilisers ▪ Burning fossil fuels

Worked example

Which of the following is the result of the enhanced greenhouse effect?

A. increasing global average temperature due to natural causes

B. decreasing global average temperature due to human activity

C. increasing global average temperature due to human activity

D. decreasing global average temperature due to natural causes

Answer: **C**

- The enhanced greenhouse effect causes the average global temperature to **increase** and is the result of **human activity**

Your notes

Energy Balance Problems

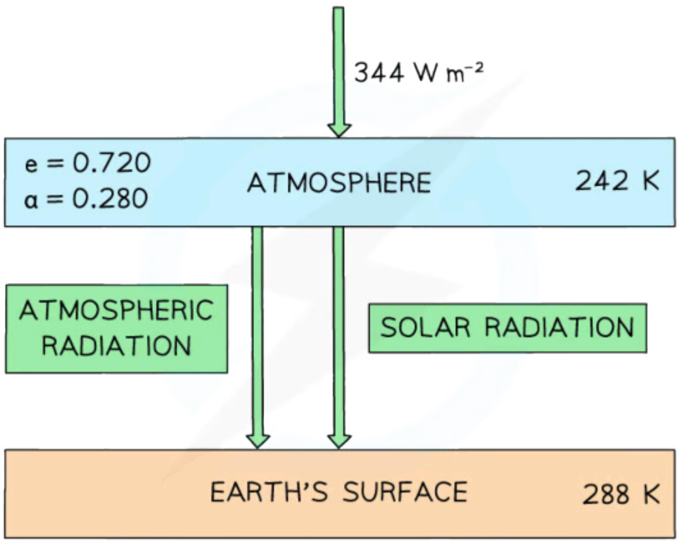
Energy Balance Problems

- It is useful to consider Earth's energy balance in terms of how much incoming energy from the Sun is used and how much is returned to space
- If incoming and outgoing energy are in balance, the Earth's temperature will remain constant
- This can be used to create models which can help climate scientists predict temperature fluctuations based on current and increased concentrations of greenhouse gases
  - At it's simplest, the model involves a one-layer atmosphere above the Earth's surface

Your notes

Worked example

The diagram below shows a simple energy balance climate model in which the atmosphere and the Earth's surface are treated as two bodies.



The Earth's surface receives both solar radiation and radiation emitted from the atmosphere.

At current atmospheric greenhouse gas concentrations, the temperature of Earth's atmosphere is set to increase by 6 K.

Data for this model:

- Current mean temperature of the Earth's atmosphere = 242 K
- Current mean temperature of the Earth's surface = 288 K
- Solar intensity per unit area at top of the atmosphere = 344 W m^{-2}
- Emissivity of the atmosphere, e = 0.720
- Albedo of the atmosphere, a = 0.280

Use this data to estimate the increase in temperature of the Earth's surface.

Answer:

Step 1: List the known quantities

- Solar intensity above atmosphere, I_a = 344 W m^{-2}
- Emissivity of the atmosphere, e = 0.720
- Emissivity of the surface, e = 1
- New temperature of Earth's atmosphere, T_a = 242 + 6 = 248 K

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- Stefan-Boltzmann constant, $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}
- Intensity absorbed at the Earth's surface = I_s
- New temperature of Earth's surface = T_s

Step 2: Calculate the solar intensity absorbed at the Earth's surface

- This can be calculated using the emissivity and the solar intensity above the atmosphere

$$I_s = e \times I_a$$

$$I_s = 0.720 \times 344 = 247.68 = 248 \text{ W m}^{-2}$$

Step 3: Write the equation for the power per unit area emitted by a body

- Since intensity = power per unit area

$$I = e\sigma T^4$$

Step 4: Calculate the new intensity radiated by the atmosphere

$$I = 0.720 \times (5.67 \times 10^{-8}) \times 248^4 = 154.43 = 154 \text{ W m}^{-2}$$

Step 5: Calculate the new intensity absorbed by the Earth's surface

- The intensity absorbed by the Earth's surface is a sum of the solar radiation that reaches the surface plus the intensity radiated by the atmosphere

$$\text{New intensity, } I_s = 248 + 154 = 402 \text{ W m}^{-2}$$

Step 6: Calculate the new temperature of the Earth's surface

- The Earth's surface can be assumed to be a black body, hence e = 1

$$I_s = \sigma T_s^4$$

$$400 = (5.67 \times 10^{-8}) \times T_s^4$$

$$T_s = \sqrt[4]{\frac{400}{5.67 \times 10^{-8}}} = 290 \text{ K}$$

Step 7: Determine the increase in temperature

$$\Delta T = 290 - 288 = 2 \text{ K}$$

Examiner Tip

In simplified climate models, you can generally assume the Earth's surface and the atmosphere:

- Act as black bodies - this means the emissivity of the surface will be equal to 1!
- Remain at a constant temperature