

THEME B · THE PARTICULATE NATURE OF MATTER

SL & HL ≈ 30 min read

IB Physics B.2 Greenhouse Effect — Notes (SL & HL)

Written by Evan Kotronis for the IB Diploma Physics course (first assessment 2025). B.2 is identical for SL and HL: there is no additional higher level content. It builds directly on the radiation laws of B.1 (Stefan–Boltzmann and Wien), so revise those first if they are not secure.

 SL B.2 questions HL B.2 questions Flashcards Greenhouse effect simulation Black-body & Wien's law simulation

What this page covers

- ✓ Applying conservation of energy to a planet: in equilibrium, power absorbed = power emitted
- ✓ Emissivity: how a real surface compares with a black body at the same temperature
- ✓ Albedo: the fraction of incident power that a planet or surface scatters back
- ✓ Why the Earth's albedo changes from day to day and with latitude
- ✓ The solar constant S , and why the mean incoming intensity over the whole Earth is $S/4$
- ✓ The four main greenhouse gases — CH_4 , H_2O , CO_2 and N_2O — and their natural and human sources
- ✓ How greenhouse gases absorb infrared radiation (molecular energy levels) and re-emit it in all directions
- ✓ Explaining the greenhouse effect with a resonance model and with molecular energy levels
- ✓ The enhanced greenhouse effect caused by human activity, mainly the burning of fossil fuels

- ✓ Energy-balance calculations: equilibrium temperatures with albedo and emissivity, including exchange between the surface and the atmosphere

In one minute

- A planet's temperature settles where the power it absorbs equals the power it radiates (conservation of energy).
- Emissivity $e = \frac{\text{power radiated per unit area}}{\sigma T^4}$, so a real surface radiates $P = e\sigma AT^4$. A black body has $e = 1$.
- Albedo $\alpha = \frac{\text{total scattered power}}{\text{total incident power}}$. The Earth's mean albedo is about 0.30, but it changes with cloud cover, latitude, ice and season.
- The Earth intercepts sunlight over a disc πR^2 but radiates from a sphere $4\pi R^2$, so the mean incoming intensity is $S/4 = 340 \text{ W m}^{-2}$; it absorbs $(1 - \alpha)S/4$.
- Without an atmosphere, $(1 - \alpha)\frac{S}{4} = \sigma T^4$ gives 255 K. The real mean surface temperature is about 288 K: the 33 K difference is the greenhouse effect.
- Greenhouse gases are transparent to the Sun's short-wave radiation but absorb the Earth's long-wave infrared, then re-emit it in all directions — part of it back to the surface. Adding more of them (mainly CO₂ from burning fossil fuels) is the **enhanced** greenhouse effect.

Contents

- | | |
|--|--|
| 1. Energy balance and black-body radiation | 6. The main greenhouse gases |
| 2. Emissivity | 7. Absorption: molecular energy levels |
| 3. Albedo and why it varies | 8. The resonance model |
| 4. The solar constant and $S/4$ | 9. The greenhouse effect step by step |
| 5. Equilibrium temperature of a planet | 10. Surface–atmosphere energy-balance models |

11. The enhanced greenhouse effect

12. Exam tips

13. Common misconceptions

14. How this topic connects

15. Key equations

16. Check your understanding

How does conservation of energy decide a planet's temperature?

Treat the Earth as a **system**. Energy arrives as radiation from the Sun and leaves as radiation emitted by the Earth. Space is (almost) empty, so conduction and convection cannot carry energy away — radiation is the only route in and out.

A planet is in thermal (radiative) equilibrium when the power it absorbs equals the power it emits. Its temperature is then constant.

- If the absorbed power is greater than the emitted power, the internal energy of the planet increases and its temperature rises.
- A hotter planet radiates more ($P \propto T^4$), so the emitted power rises until the two match again. The equilibrium is **self-correcting**: this is why any change to the incoming or outgoing power leads to a *new* equilibrium temperature, not to endless heating.
- Everything in B.2 is an application of this one idea: **power in = power out**, applied to the whole planet, to the surface, or to the atmosphere.

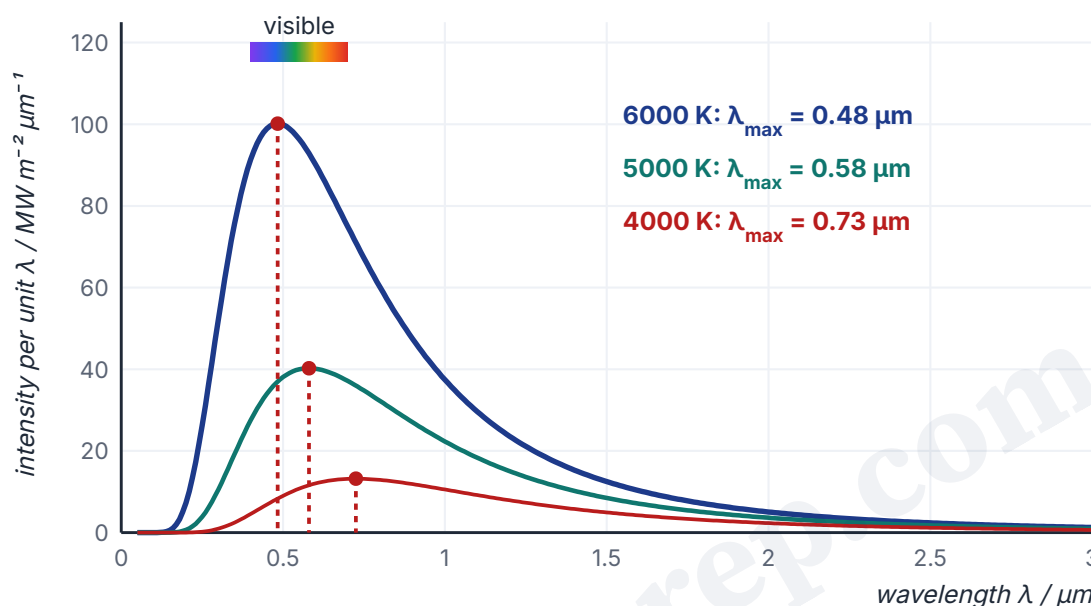
Recap from B.1: black-body radiation

A **black body** absorbs all the radiation that falls on it and emits the maximum possible power for its temperature. You need two B.1 laws:

$$L = \sigma AT^4 \qquad \lambda_{\max}T = 2.9 \times 10^{-3} \text{ m K}$$

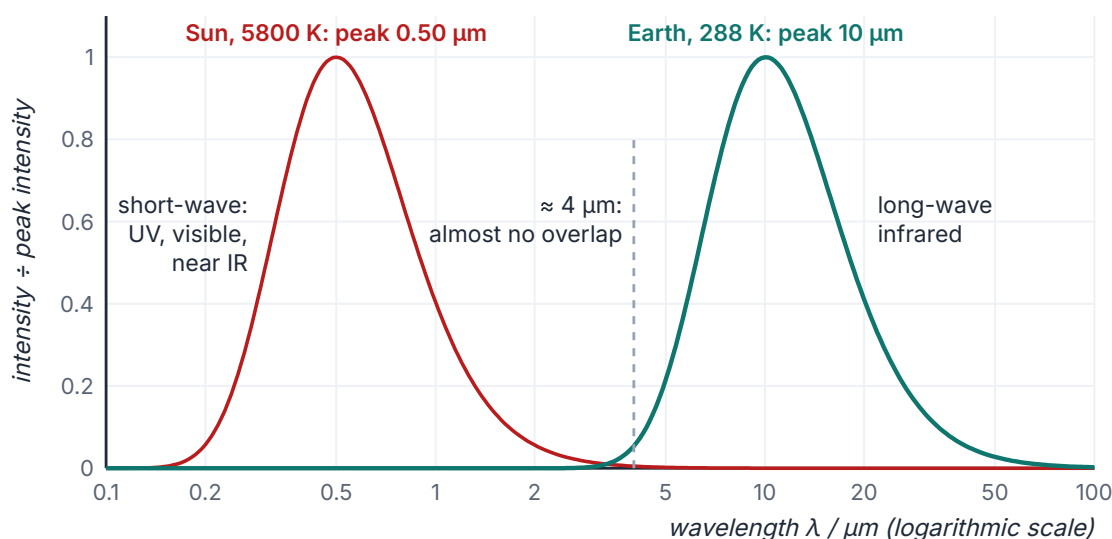
- L = total power emitted (luminosity) (W), σ = Stefan–Boltzmann constant $5.67 \times 10^{-8} \text{ W m}^{-2}\text{K}^{-4}$, A = surface area (m^2), T = absolute temperature (K). Both equations are in the data booklet (B.1).

- $\lambda_{\max}$ = wavelength at which the emitted intensity is greatest (m). Hotter bodies peak at shorter wavelengths (Wien's displacement law).
- The power radiated **per unit area** by a black body is σT^4 (W m^{-2}).



Black-body spectra calculated for 4000 K, 5000 K and 6000 K. As T rises the peak moves to shorter wavelength ($\lambda_{\max} T$ is constant) and the area under the curve — the power per unit area, σT^4 — grows very rapidly.

The Sun's surface (about 5800 K) and the Earth's surface (about 288 K) are both close to black bodies, but at very different temperatures. Wien's law gives their peaks: $\lambda_{\max} = \frac{2.9 \times 10^{-3}}{5800} = 0.50 \mu\text{m}$ (visible) for the Sun and $\frac{2.9 \times 10^{-3}}{288} = 10 \mu\text{m}$ (infrared) for the Earth.



The Sun's and the Earth's spectra, each scaled to its own peak and plotted on a logarithmic wavelength axis. The Sun sends short-wave radiation; the Earth emits long-wave infrared. The two hardly overlap — the key to the greenhouse effect.

TRY IT YOURSELF

B.2 Black-body & Wien's law simulation: change the temperature and watch the peak wavelength and the area under the curve change.

What is emissivity?

Emissivity is the ratio of the power radiated per unit area by a surface to the power radiated per unit area by an ideal black surface at the same temperature: $e = \frac{\text{power radiated per unit area}}{\sigma T^4}$.

$$e = \frac{\text{power radiated per unit area}}{\sigma T^4} \implies P = e\sigma AT^4$$

- e = emissivity (no unit), $0 \leq e \leq 1$. A black body has $e = 1$; every real surface has $e < 1$.
- The definition is in the data booklet (B.2). $P = e\sigma AT^4$ is not printed — it follows from the definition (multiply by A).
- Compare at the **same temperature**. A body with $e = 0.5$ radiates half as much as a black body of the same size and temperature.

- Good emitters are good absorbers: a surface with high emissivity at some wavelength also absorbs strongly at that wavelength. Matt black surfaces have $e \approx 1$; polished metals have small e .
- A body whose emissivity is less than 1 but the same at every wavelength is sometimes called a *grey body*.

WORKED EXAMPLE 1 Easy · Calculate

The flat top surface of a hot plate has an area of 0.020 m^2 and a temperature of 500 K . It radiates energy at a rate of 50 W .

(a) Calculate the power that a black body of the same area and temperature would radiate. (b) Calculate the emissivity of the surface.

$$\text{(a)} P_{\text{black}} = \sigma AT^4 = 5.67 \times 10^{-8} \times 0.020 \times 500^4 = \mathbf{70.9 \text{ W}}$$

$$\text{(b)} e = \frac{P}{\sigma AT^4} = \frac{50}{70.9} = \mathbf{0.71} \text{ (0.705, no unit)}$$

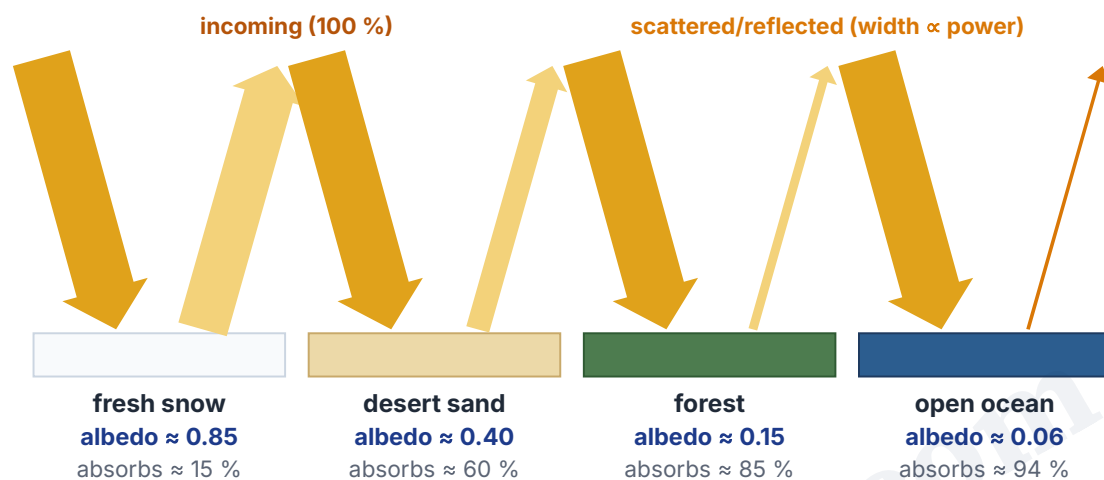
Equivalently, using the per-unit-area definition: $\frac{50}{0.020} = 2500 \text{ W m}^{-2}$ and $\sigma T^4 = 3544 \text{ W m}^{-2}$, giving the same ratio.

What is albedo, and why does the Earth's albedo vary?

Albedo is a measure of the average fraction of incident energy scattered back (reflected) by a macroscopic system: $\alpha = \frac{\text{total scattered power}}{\text{total incident power}}$.

- α has no unit and lies between 0 (absorbs everything) and 1 (scatters everything). The equation is in the data booklet (B.2).
- The fraction **absorbed** is $1 - \alpha$. This is the number you need in energy-balance calculations.
- The Earth's mean albedo is about **0.30**: roughly 30 % of the incoming sunlight is scattered back to space by clouds, the atmosphere and the surface, without ever warming the planet.

- Albedo refers to the incoming (mainly short-wave) solar radiation. Do not confuse it with emissivity, which describes what a body emits at its own temperature.



Typical albedos of four surfaces. Each incoming arrow carries the same power; the width of each reflected arrow is drawn to scale. Snow scatters most of the sunlight; the ocean absorbs almost all of it.

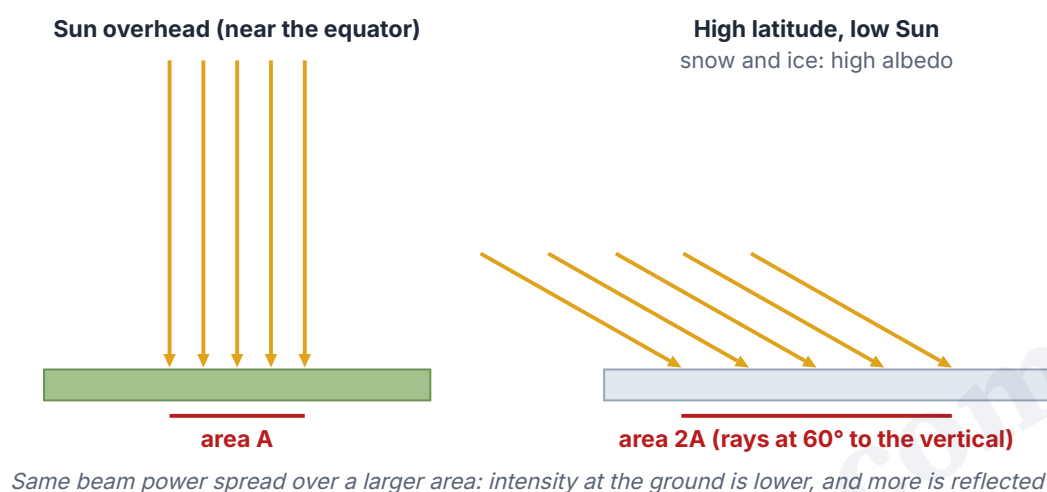
Surface	Typical albedo	Comment
Fresh snow	0.80–0.90	highest of natural surfaces
Thick cloud	0.60–0.90	depends on cloud type and thickness
Sea ice	0.50–0.70	lower when wet or melting
Desert sand	0.30–0.40	
Grassland, forest	0.10–0.25	dark vegetation absorbs strongly
Open ocean	≈ 0.06 (Sun high)	rises sharply when the Sun is low
Earth as a whole	≈ 0.30	global, yearly average

Why the Earth's albedo changes

- Cloud formations.** Clouds are the biggest single influence. Cloud cover changes from hour to hour and day to day, so the Earth's albedo varies **daily**.
- Latitude.** At high latitudes the ground is often covered by snow and ice (high albedo), and the Sun is low in the sky, so the rays strike at a grazing angle;

water and ice reflect much more at grazing incidence.

- **Season and land use.** Snow cover, sea ice and vegetation change through the year; deforestation, agriculture and urban areas also change the local albedo.



Latitude matters twice. A beam that arrives at 60° to the vertical spreads over twice the area ($\cos 60^\circ = 0.5$), so the intensity at the ground is halved — and at high latitudes much of that light falls on snow and ice, which scatter most of it back.

What is the solar constant, and why is the mean intensity $S/4$?

The solar constant S is the intensity of the Sun's radiation at the mean Earth–Sun distance, measured above the atmosphere on a surface perpendicular to the rays. $S = 1.36 \times 10^3 \text{ W m}^{-2}$ (data booklet).

- S is simply the apparent brightness of the Sun at the Earth: $S = b = \frac{L}{4\pi d^2}$ (B.1). It follows an **inverse square law**, so a planet twice as far from the Sun receives a quarter of the intensity.
- It is not the intensity at the ground: clouds, the atmosphere and the angle of the rays all reduce that.

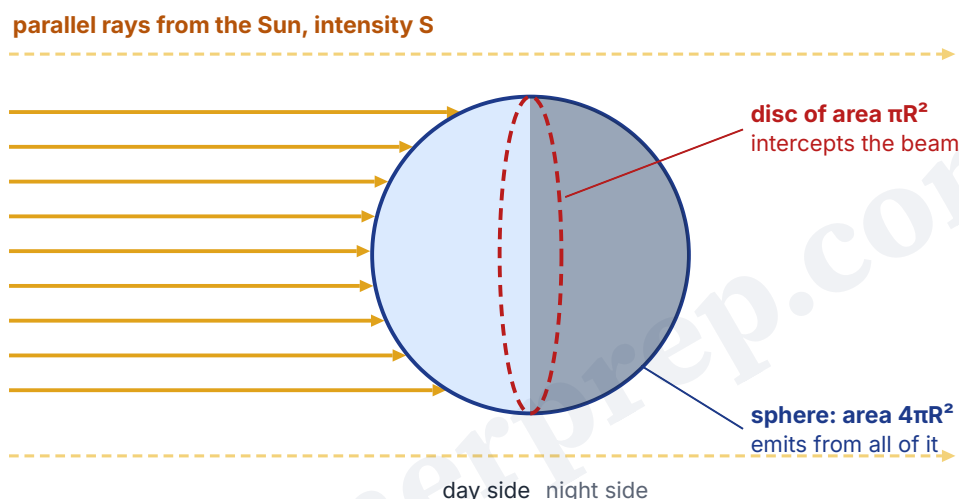
The factor of 4

The incoming radiative power depends on the area the planet presents to the Sun's rays — its **projected** area, a disc of radius R :

$$P_{\text{in}} = S \times \pi R^2$$

But this power is shared, on average, over the **whole surface** of the rotating sphere, $4\pi R^2$ — day side and night side, equator and poles. So the mean incoming intensity is

$$\bar{I}_{\text{in}} = \frac{S\pi R^2}{4\pi R^2} = \frac{S}{4} = \frac{1.36 \times 10^3}{4} = 340 \text{ W m}^{-2}$$



$$\text{mean incoming intensity} = S\pi R^2 \div 4\pi R^2 = S/4$$

The Earth intercepts a cylinder of sunlight of cross-section πR^2 , but it radiates (and spreads the incoming energy) over its whole surface $4\pi R^2$. The ratio of the areas gives the factor 4.

- The 4 is purely geometric: a factor 2 because half the planet is in darkness at any moment, and another factor 2 because the day side is curved, so most of it is not perpendicular to the rays.
- Allowing for albedo, the mean intensity **absorbed** is $(1 - \alpha)\frac{S}{4} = 0.70 \times 340 = 238 \text{ W m}^{-2}$ for the Earth, and $\alpha\frac{S}{4} = 102 \text{ W m}^{-2}$ is scattered back to space.
- $S/4$ is not printed in the data booklet. You must know where it comes from.

WORKED EXAMPLE 2 Medium · Calculate / Determine

Mars orbits the Sun at 1.52 times the Earth's orbital radius. Its albedo is 0.25. Assume Mars has no atmosphere and radiates as a black body at a uniform temperature.

(a) Calculate the solar constant at the orbit of Mars. (b) Determine the equilibrium temperature of Mars.

(a) Intensity follows an inverse square law: $S_{\text{Mars}} = \frac{S}{1.52^2} = \frac{1.36 \times 10^3}{2.31} = 589 \text{ W m}^{-2}$

(b) Mean intensity absorbed = $(1 - \alpha) \frac{S_{\text{Mars}}}{4} = 0.75 \times \frac{589}{4} = 110 \text{ W m}^{-2}$.

Equilibrium: $\sigma T^4 = 110 \Rightarrow T = \left(\frac{110}{5.67 \times 10^{-8}} \right)^{1/4} = 210 \text{ K}$ (about -63°C)

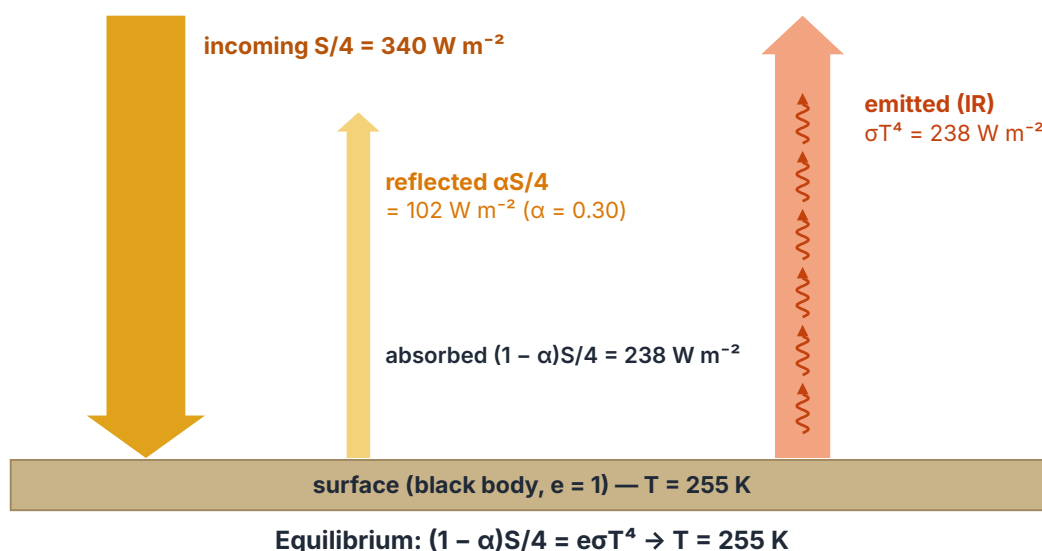
Mars has a very thin atmosphere, so this simple estimate is close to its observed mean surface temperature.

How do you calculate a planet's equilibrium temperature?

Write power in = power out **per square metre of the planet's surface** (both sides refer to the same area $4\pi R^2$, so it cancels):

$$(1 - \alpha) \frac{S}{4} = e \sigma T^4 \quad \Rightarrow \quad T = \left(\frac{(1 - \alpha)S}{4e\sigma} \right)^{1/4}$$

- α = albedo, S = solar constant at the planet (W m^{-2}), e = emissivity of the planet, T = equilibrium temperature (K).
- This equation is **not** in the data booklet: build it from the energy balance each time. Exam questions may also give a different star or a different "constant" — the method is identical.
- Temperature depends on the **fourth root**: doubling the absorbed power raises T by a factor $2^{1/4} = 1.19$, not 2.



Energy balance of an Earth with no atmosphere (intensities in W m^{-2} , widths to scale). The surface absorbs 238 W m^{-2} and must emit the same, which needs $T = 255 \text{ K}$.

WORKED EXAMPLE 3 Medium · Show that / Suggest

The Earth has an albedo of 0.30. (a) Show that, if the Earth had no atmosphere and radiated as a black body, its equilibrium temperature would be about 255 K. (b) The observed mean surface temperature is 288 K. Suggest why the two values differ.

(a) Absorbed: $(1 - 0.30) \times \frac{1.36 \times 10^3}{4} = 238 \text{ W m}^{-2}$.

$$\sigma T^4 = 238 \Rightarrow T = \left(\frac{238}{5.67 \times 10^{-8}} \right)^{1/4} = \mathbf{254.5 \text{ K}} \approx 255 \text{ K}$$

(b) The real Earth has an atmosphere containing greenhouse gases. They absorb some of the infrared emitted by the surface and re-radiate part of it back down, so the surface receives more power than the 238 W m^{-2} from the Sun alone and settles at a higher temperature — about **33 K** warmer. This is the (natural) greenhouse effect.

Another way to say the same thing: seen from space, the Earth at 288 K emits only 238 W m^{-2} instead of $\sigma(288)^4 = 390 \text{ W m}^{-2}$, so it behaves like a body of effective emissivity $238/390 \approx 0.61$.

Which are the main greenhouse gases?

A greenhouse gas is a gas in the atmosphere that absorbs and emits infrared radiation. The main greenhouse gases are methane CH_4 , water vapour H_2O , carbon dioxide CO_2 and nitrous oxide N_2O .

Every one of them has both **natural** origins and origins in **human activity**:

Gas	Natural sources	Sources from human activity
Water vapour, H_2O	evaporation from oceans, lakes and soil; transpiration from plants	small direct effect (irrigation, combustion); mainly indirect — a warmer atmosphere holds more water vapour
Carbon dioxide, CO_2	respiration, decay of organic matter, volcanoes, wildfires, release from the oceans	burning fossil fuels (coal, oil, natural gas), cement making, deforestation
Methane, CH_4	wetlands, termites, decay without oxygen	cattle and other livestock, rice paddies, landfill sites, leaks from gas extraction and coal mines
Nitrous oxide, N_2O	bacteria in soils and oceans	nitrogen fertilisers, manure, some industrial processes and combustion

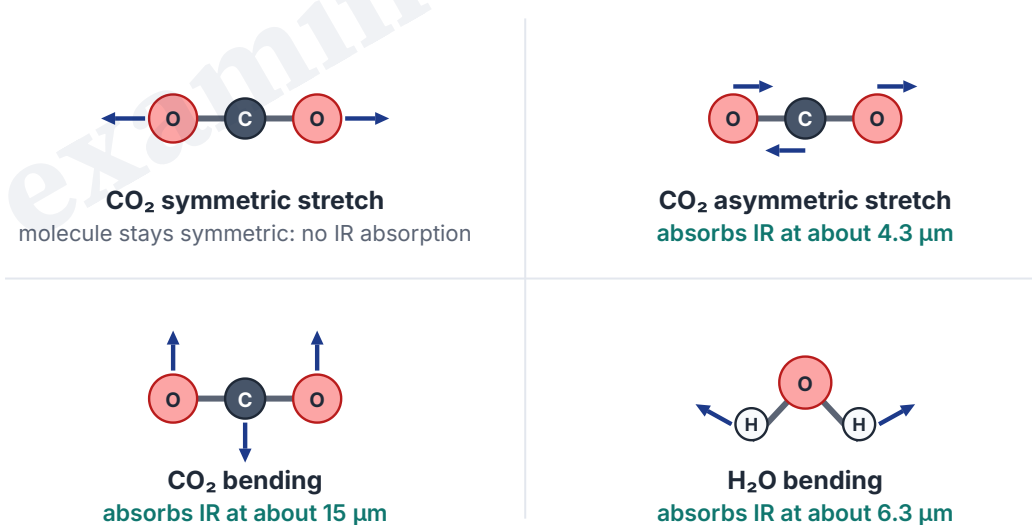
- Water vapour makes the largest contribution to the natural greenhouse effect; CO_2 is the largest contributor to the *enhanced* effect.
- Nitrogen (N_2) and oxygen (O_2) make up about 99 % of dry air but absorb almost no infrared, so they are not greenhouse gases.

How do greenhouse gases absorb infrared radiation?

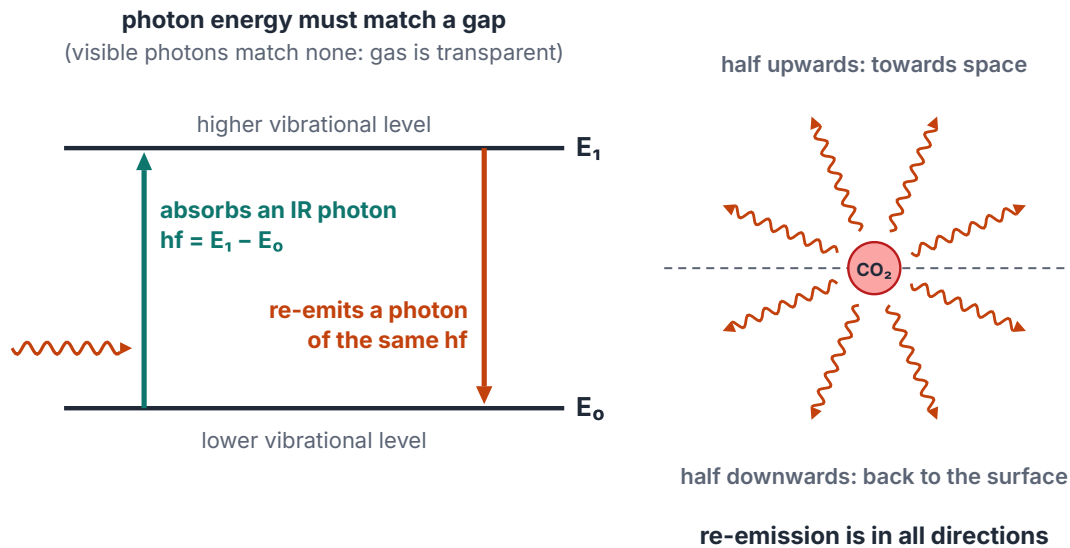
The atoms in a molecule are joined by bonds that can stretch and bend. Like every other quantum system, a molecule can only have certain **discrete vibrational energies** — its molecular energy levels.

A greenhouse-gas molecule absorbs a photon of infrared radiation when the photon's energy hf equals the difference between two of its vibrational energy levels. It later emits a photon of the same energy, in a random direction.

- The gaps between vibrational levels are small — typically about 0.06–0.3 eV — which matches photons of infrared wavelength (about 4–20 μm). Most of the Earth's own emission (peak $\approx 10 \mu\text{m}$) lies in this range, although the peak itself falls in the 8–13 μm "atmospheric window", where absorption is weak (see the spectrum below).
- Visible photons (about 1.8–3.1 eV) do not match any vibrational gap, so greenhouse gases are almost **transparent** to the Sun's short-wave radiation.
- The molecule spends only a short time in the excited state. It then re-emits — or shares its energy with neighbouring molecules in collisions, warming the air. Re-emission occurs in **all directions** equally, so roughly half heads back down towards the surface.

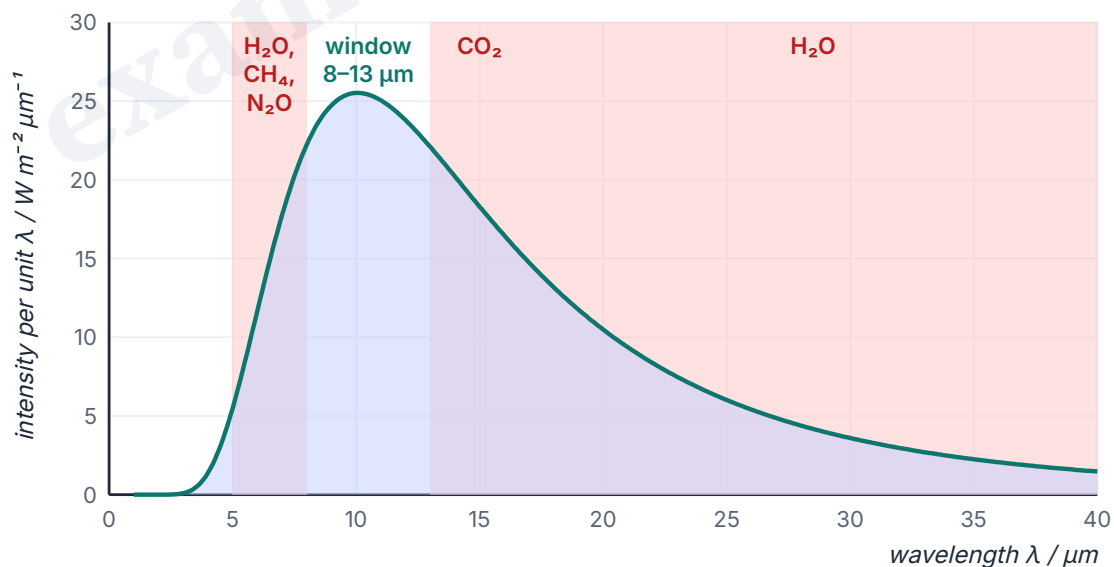


Ways in which CO₂ and H₂O molecules vibrate (blue arrows show the motion of the atoms). Vibrations that change the way charge is distributed in the molecule interact with infrared radiation; the symmetric stretch of CO₂ does not.



Molecular energy levels: an infrared photon is absorbed only if hf matches a gap, and the photon that is later emitted can travel in any direction — up to space or back down to the surface.

Quick example. The bending vibration of CO_2 absorbs at $15\ \mu\text{m}$. The photon frequency is $f = \frac{c}{\lambda} = \frac{3.00 \times 10^8}{15 \times 10^{-6}} = 2.0 \times 10^{13}\ \text{Hz}$ and its energy is $E = hf = 6.63 \times 10^{-34} \times 2.0 \times 10^{13} = 1.3 \times 10^{-20}\ \text{J}$ (0.083 eV). ($E = hf$ is in the data booklet under E.1.)



Spectrum emitted by a black body at 288 K, with the regions absorbed strongly by greenhouse gases shaded (band positions approximate). Most of the Earth's emission is absorbed, except in the "atmospheric window" between about $8\ \mu\text{m}$ and $13\ \mu\text{m}$.

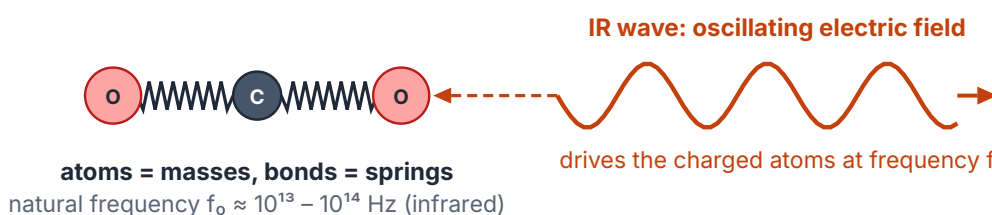
How does the resonance model explain the greenhouse effect?

You need to explain the greenhouse effect in **two** ways. The second is a classical model that links B.2 with simple harmonic motion (C.1) and resonance (C.4).

Resonance model: the bonds in a greenhouse-gas molecule act like springs, so the molecule has natural frequencies of vibration in the infrared. Infrared radiation of the same frequency drives the molecule into resonance, so it absorbs energy strongly; radiation of other frequencies passes through.

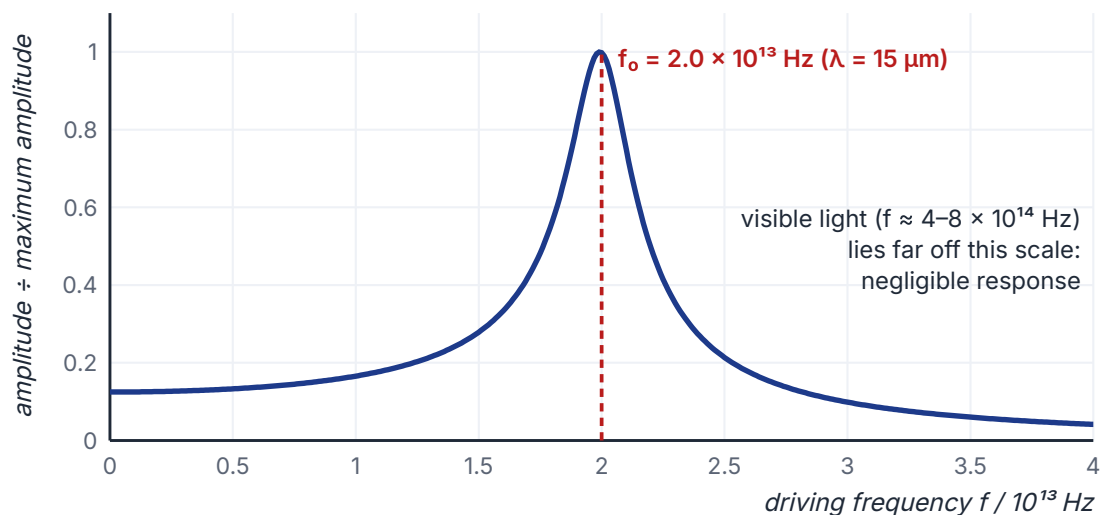
- The atoms carry small charges, so the oscillating electric field of an electromagnetic wave exerts a periodic driving force on them.
- When the driving frequency equals a natural frequency of the molecule, the amplitude of vibration becomes large and energy is transferred efficiently from the radiation to the molecule — absorption.
- The vibrating molecule is an oscillating charge, so it re-radiates at the same frequency, in all directions.
- Visible light has a frequency ($4\text{--}8 \times 10^{14}$ Hz) far above the natural frequencies of these vibrations (about $10^{13}\text{--}10^{14}$ Hz), so it causes almost no response.

$f = f_0 \rightarrow$ resonance: large-amplitude vibration, energy absorbed



$f \neq f_0$ (e.g. visible light) $\rightarrow$ tiny response, radiation passes through

The resonance model: a CO₂ molecule is modelled as masses joined by springs, driven by the oscillating electric field of an infrared wave.



Calculated resonance curve for a lightly damped oscillator with natural frequency $2.0 \times 10^{13} \text{ Hz}$ (the CO_2 bending vibration, $\lambda = 15 \mu\text{m}$). The response is large only near f_0 .

	Resonance model	Molecular energy-level model
Picture	bonds = springs; classical driven oscillator	quantised vibrational energy levels
Condition for absorption	driving frequency = natural frequency, $f = f_0$	photon energy = gap between levels, $hf = \Delta E$
Why visible light passes	its frequency is far from f_0	its photon energy matches no vibrational gap
Re-emission	oscillating charges radiate in all directions	photon emitted in a random direction
Linked topics	C.1 simple harmonic motion, C.4 resonance	E.1 atomic energy levels, $E = hf$

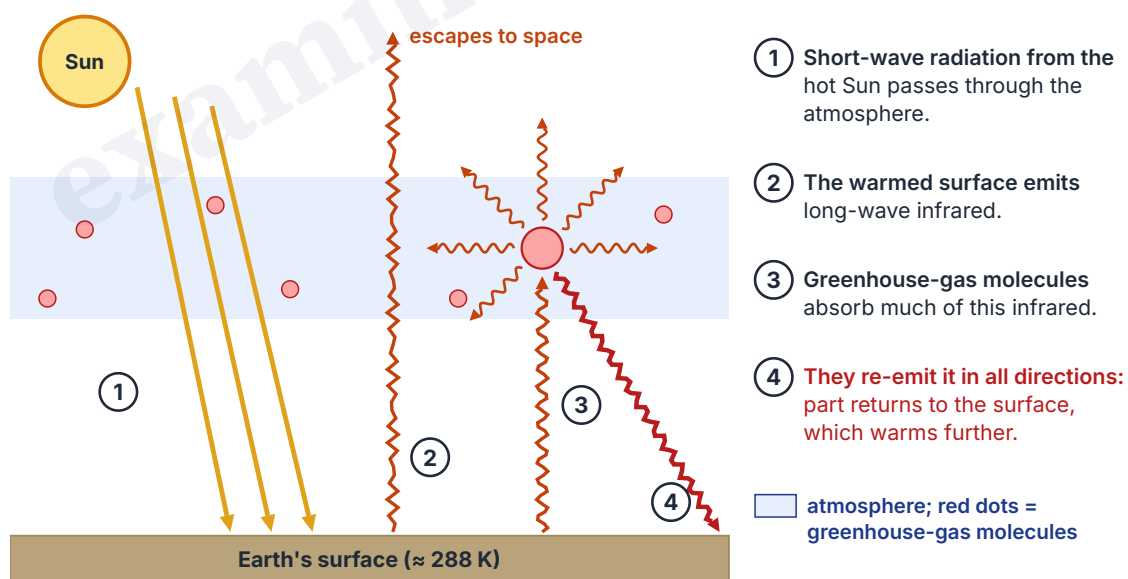
TRY IT YOURSELF

B.2 Greenhouse Effect simulation: add or remove greenhouse gases and clouds and watch the incoming and outgoing radiation and the surface temperature respond.

What is the greenhouse effect?

The greenhouse effect is the warming of a planet's surface above the temperature it would have without an atmosphere, caused by greenhouse gases absorbing the infrared radiation emitted by the surface and re-emitting part of it back towards the surface.

1. Short-wave radiation from the hot Sun (peak $0.50\ \mu\text{m}$) passes through the atmosphere largely unabsorbed. About 30 % is scattered back to space (albedo); the rest is absorbed by the surface.
2. The warmed surface emits long-wave infrared radiation, because it is much cooler (peak $\approx 10\ \mu\text{m}$).
3. Greenhouse-gas molecules absorb much of this infrared: its frequency matches their natural frequencies of vibration (resonance), or its photon energy matches the gaps between their vibrational energy levels.
4. The molecules re-emit infrared in **all directions**. Part returns to the surface, which therefore receives energy from both the Sun and the atmosphere, and reaches a higher equilibrium temperature ($\approx 288\ \text{K}$ instead of $\approx 255\ \text{K}$).



The greenhouse mechanism in four steps. The red wavy arrow is the re-emitted radiation returning to the surface — the extra input that warms it.

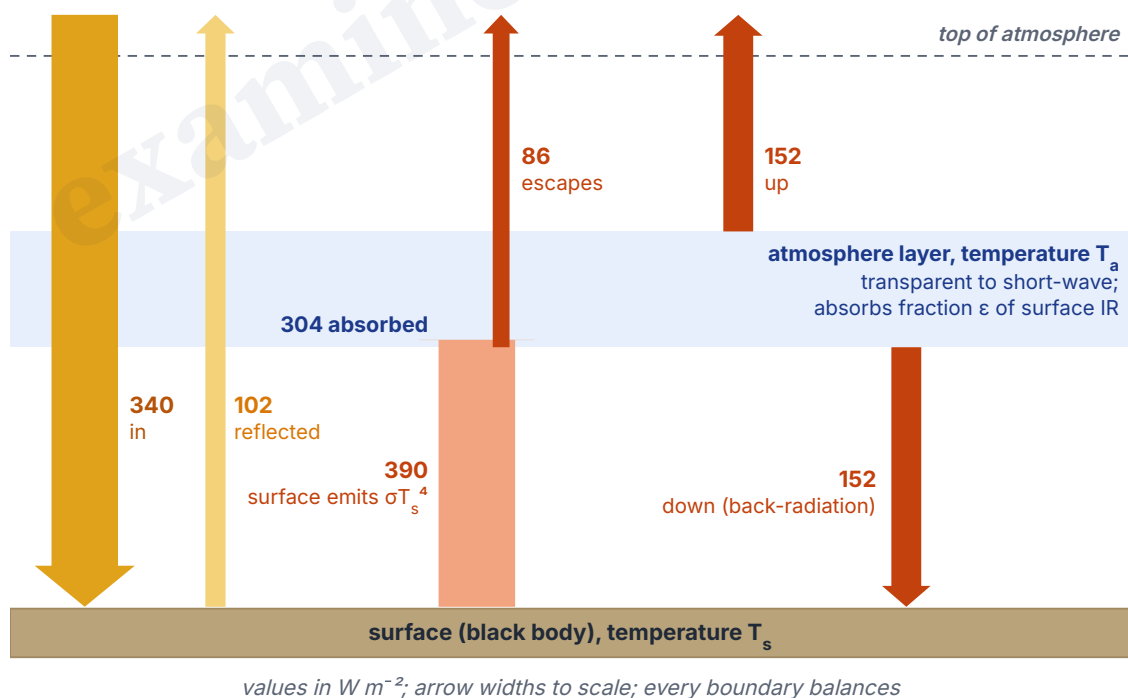
- The natural greenhouse effect is **essential for life**: without it the mean surface temperature would be about $-18\ ^\circ\text{C}$ and most water would be frozen.
- Greenhouse gases do not "trap" or "reflect" heat like a mirror; they **absorb and re-emit**. Energy still leaves the planet — at equilibrium the Earth emits

exactly as much as it absorbs — but it does so from a colder, higher layer of the atmosphere, so the surface must be warmer to keep the balance.

How do energy-balance models include the atmosphere?

Exam questions often give a simplified "energy budget" diagram with intensities in W m^{-2} and ask you to complete it, check it, or find a temperature or an emissivity. The simplest version is the **one-layer model**:

- The atmosphere is a single layer at temperature T_a , transparent to short-wave radiation.
- It absorbs a fraction ε of the infrared emitted by the surface and lets $(1 - \varepsilon)$ through. Since good absorbers are good emitters, its emissivity is also ε : it emits $\varepsilon\sigma T_a^4$ **upwards and the same downwards**.
- The surface (temperature T_s) is treated as a black body, emitting σT_s^4 .



A one-layer energy-balance model of the Earth with global-mean intensities in W m^{-2} (arrow widths to scale). Used in worked example 4.

Apply **power in = power out** to each part of the system in turn (all values per m^2):

$$\text{surface: } (1 - \alpha) \frac{S}{4} + \varepsilon \sigma T_a^4 = \sigma T_s^4$$

$$\text{atmosphere: } \varepsilon \sigma T_s^4 = 2 \varepsilon \sigma T_a^4$$

$$\text{whole planet (top of atmosphere): } (1 - \alpha) \frac{S}{4} = (1 - \varepsilon) \sigma T_s^4 + \varepsilon \sigma T_a^4$$

- Only two of the three equations are independent — the third is a useful check.
- Combining the first two: $\sigma T_s^4 = \frac{(1 - \alpha)S/4}{1 - \varepsilon/2}$. With no absorbing gas ($\varepsilon = 0$) this gives 255 K again; the greater ε , the warmer the surface.
- Real energy budgets also include short-wave absorption in the atmosphere and the transfer of energy from the surface to the air by convection and evaporation (latent heat). Exam diagrams may include these as extra arrows: the rule "in = out for each part" still applies.

WORKED EXAMPLE 4 Hard · Determine (diagram)

Use the energy-balance diagram above (all intensities in W m^{-2}).

(a) Determine the albedo of the planet. (b) Show that the surface is in equilibrium. (c) Determine the surface temperature T_s . (d) Determine the fraction ε of the surface's infrared that the atmosphere absorbs. (e) Hence determine the temperature T_a of the atmosphere layer.

$$\text{(a) } \alpha = \frac{102}{340} = \mathbf{0.30}$$

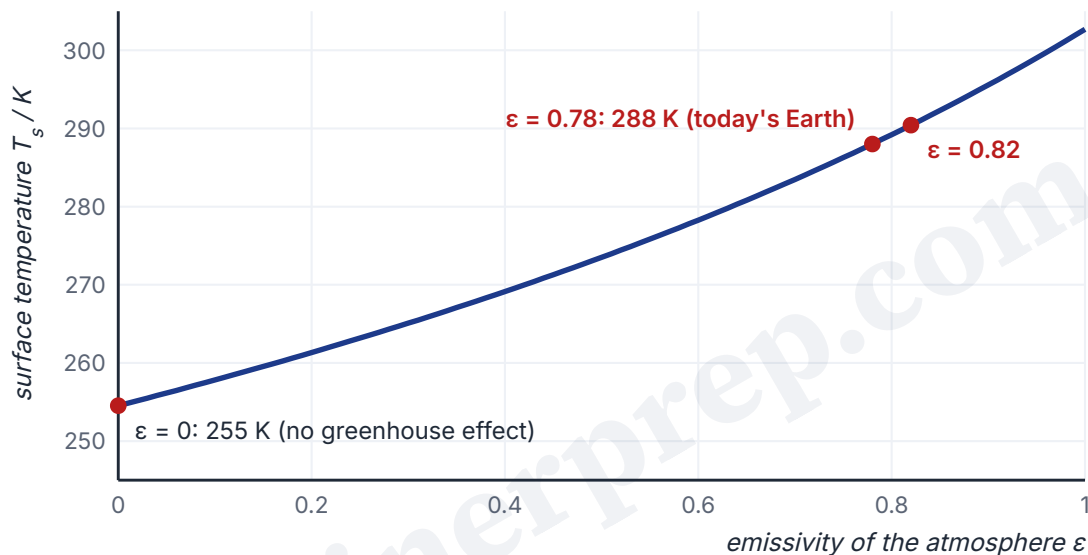
(b) Into the surface: $340 - 102 = 238$ (sunlight) $+ 152$ (from the atmosphere) $= 390 \text{ W m}^{-2}$. Out: 390 W m^{-2} emitted. In = out, so the surface is in equilibrium.

$$\text{(c) } \sigma T_s^4 = 390 \Rightarrow T_s = \left(\frac{390}{5.67 \times 10^{-8}} \right)^{1/4} = \mathbf{288 \text{ K}}$$

$$\text{(d) Absorbed by the atmosphere} = 390 - 86 = 304 \text{ W m}^{-2}, \text{ so } \varepsilon = \frac{304}{390} = \mathbf{0.78}$$

(e) The atmosphere emits $\varepsilon\sigma T_a^4 = 152 \text{ W m}^{-2}$ in each direction: $T_a = \left(\frac{152}{0.78 \times 5.67 \times 10^{-8}} \right)^{1/4} = 242 \text{ K}$

Checks: atmosphere in 304 = out 152 + 152; top of atmosphere in 340 = out 102 + 86 + 152. The cold atmosphere (242 K) radiates far less to space than the warm surface would — that is the greenhouse effect in numbers.



Surface temperature predicted by the one-layer model ($\alpha = 0.30$, $S = 1.36 \times 10^3 \text{ W m}^{-2}$) as the atmosphere absorbs a larger fraction ε of the surface's infrared.

What is the enhanced greenhouse effect?

The enhanced greenhouse effect is the augmentation of the natural greenhouse effect due to human activities, which increase the concentrations of greenhouse gases in the atmosphere.

- The burning of **fossil fuels** — for electricity generation, transport, heating and industry — is the primary cause: it releases CO_2 that was locked away underground for millions of years.
- Other contributions: deforestation (less CO_2 taken up by photosynthesis), cattle farming and rice growing (CH_4), fertilisers (N_2O).
- More greenhouse gas means the atmosphere absorbs a larger fraction of the surface's infrared (ε increases). Less energy escapes to space, so for a while

the Earth absorbs more power than it emits. It warms until a new, higher equilibrium temperature is reached.

- **Feedback** can amplify the change: a warmer atmosphere holds more water vapour (another greenhouse gas), and melting snow and ice lowers the albedo, so more sunlight is absorbed. Both are positive feedbacks.

WORKED EXAMPLE 5 Hard · Show that / Determine / Explain

In the one-layer model, increased greenhouse-gas concentrations raise the fraction of surface infrared absorbed by the atmosphere from 0.78 to 0.82. The albedo (0.30) and the solar constant do not change.

(a) Show that $\sigma T_s^4 = \frac{(1 - \alpha)S/4}{1 - \varepsilon/2}$. (b) Determine the increase in the surface temperature. (c) Explain, in terms of the absorption of radiation, why the surface temperature increases.

(a) Atmosphere in equilibrium: $\varepsilon\sigma T_s^4 = 2\varepsilon\sigma T_a^4$, so the downward emission is $\varepsilon\sigma T_a^4 = \frac{1}{2}\varepsilon\sigma T_s^4$.

Surface: $(1 - \alpha)\frac{S}{4} + \frac{1}{2}\varepsilon\sigma T_s^4 = \sigma T_s^4 \Rightarrow \sigma T_s^4 \left(1 - \frac{\varepsilon}{2}\right) = (1 - \alpha)\frac{S}{4}$, as required.

(b) $(1 - \alpha)S/4 = 238 \text{ W m}^{-2}$.

$$\varepsilon = 0.78: T_s = \left(\frac{238}{5.67 \times 10^{-8} \times 0.61} \right)^{1/4} = 288.0 \text{ K.}$$

$$\varepsilon = 0.82: T_s = \left(\frac{238}{5.67 \times 10^{-8} \times 0.59} \right)^{1/4} = 290.4 \text{ K.}$$

Increase = **2.4 K**

(c) More greenhouse-gas molecules absorb a larger fraction of the infrared emitted by the surface. They re-emit it in all directions, so more is radiated back down: the back-radiation rises from 152 to 165 W m^{-2} . The surface now receives more power than it emits, so its temperature rises until σT_s^4 again equals the total power it receives.

Exam tips for B.2

EXAM TIP 1 — PUT $(1 - \alpha)$ AND THE 4 IN THE RIGHT PLACES

The absorbed intensity is $(1 - \alpha)\frac{S}{4}$. The most common errors are using α instead of $1 - \alpha$, forgetting the 4, or dividing by 2 ("half the Earth is in daylight"). If a question asks what the planet *radiates* in equilibrium, it is the same as what it absorbs — not $\alpha S/4$ and not $S/4$.

EXAM TIP 2 — KELVIN AND THE FOURTH ROOT

Always use kelvin in σT^4 . Find T^4 first, then take the fourth root, and sense-check: planetary temperatures are a few hundred kelvin. Proportional reasoning is quick in multiple-choice questions: $T \propto [(1 - \alpha)S]^{1/4}$, so a 10 % rise in absorbed power raises T by only about 2.4 %.

EXAM TIP 3 — EXPLAIN THE MECHANISM IN FULL

An "explain the greenhouse effect" answer earns marks for distinct steps: short-wave radiation passes through the atmosphere; the surface emits **infrared** (because it is cooler); greenhouse gases **absorb** it (resonance / energy levels); they **re-emit in all directions**, so some returns to the surface, which warms. "The gases trap heat" or "the infrared is reflected back" scores nothing.

EXAM TIP 4 — BALANCE EACH BOUNDARY SEPARATELY

In an energy-budget diagram, check the surface, the atmosphere and the top of the atmosphere one at a time. Remember that the atmosphere radiates **both up and down**; the most common slip is to count its emission once. Show the numbers you add — a bare final value cannot earn method marks if it is wrong.

EXAM TIP 5 — EMISSIVITY ≠ ALBEDO

Albedo describes the incoming sunlight that is scattered without being absorbed; emissivity describes how well a body radiates at its **own** temperature compared with a black body. They appear on opposite sides of the energy-balance equation. When you define emissivity, include "**at the same temperature**".

Common misconceptions

Misconception	Why it is wrong	Correct idea
The greenhouse effect is harmful.	The natural effect keeps the mean surface temperature about 33 K higher than it would otherwise be.	The <i>natural</i> effect is essential for life; the concern is the <i>enhanced</i> effect from human activity.
Greenhouse gases reflect infrared back to the Earth.	Reflection is not the mechanism.	They absorb infrared and re-emit it in all directions; only part returns to the surface.
Greenhouse gases block incoming sunlight.	They are nearly transparent to short-wave radiation.	They absorb the long-wave infrared emitted by the surface.
The mean incoming intensity is $S/2$ because half the Earth is dark.	That ignores the curvature of the day side.	Intercepting area πR^2 ÷ emitting area $4\pi R^2$ gives $S/4$.
CO ₂ is the only (or main) greenhouse gas.	Water vapour contributes most to the natural effect; CH ₄ and N ₂ O also matter.	The four main greenhouse gases are CH ₄ , H ₂ O, CO ₂ and N ₂ O.
The ozone hole causes global warming.	Ozone depletion concerns ultraviolet radiation, a different problem.	Global warming is caused by increased concentrations of infrared-absorbing gases.

How this topic connects

Molecules as springs: oscillations, resonance and the climate

The bonds of a greenhouse-gas molecule behave approximately like springs, so the atoms perform simple harmonic motion with natural frequencies in the infrared (C.1). Infrared from the Earth's surface drives these oscillations; where the driving frequency matches a natural frequency, resonance (C.4) transfers energy strongly to the molecules. Increasing the number of such oscillators in the atmosphere increases the absorption and re-emission of infrared, which is the physical basis of the enhanced greenhouse effect and therefore of climate change.

Power generation choices and the Earth's energy balance

Coal-, oil- and gas-fired power stations release CO₂ (coal the most per unit of energy), and gas extraction can leak methane. These raise the fraction of the surface's infrared absorbed by the atmosphere, so less energy escapes to space and the equilibrium surface temperature rises. Wind, solar, hydroelectric, tidal and nuclear generation release almost no greenhouse gases while operating, so they do not disturb the balance in this way. Thermal power stations (fossil-fuel and nuclear) also release waste thermal energy directly, but this is tiny compared with the absorbed solar power.

Where the resonance picture of the greenhouse effect falls short

The resonance model treats a molecule as a classical spring system that could absorb a continuous range of energies near f_0 . In reality the vibrational energy is quantised, so absorption occurs at definite photon energies, and only certain vibrations (those that change the charge distribution) absorb at all — something the simple spring picture does not predict. It also ignores collisions, by which an excited molecule usually passes its energy to N₂ and O₂ molecules, warming the air, and it says nothing about where in the atmosphere re-emission happens. The energy-level model is needed for a complete explanation.

Tools & inquiry — modelling albedo and the Earth's energy budget (NOS: models)

- **Modelling albedo in the lab:** shine a lamp at a fixed angle onto samples (white paper, sand, soil, leaves, water) and measure the reflected light with a light sensor at a fixed distance. Divide by the reading from a reference white surface to obtain a relative albedo. Repeat at different angles of incidence to model the effect of latitude.
- **Working with databases:** satellite radiation-budget data give monthly maps of incoming, reflected and emitted intensity. Plotting the reflected fraction against latitude, or against month, shows the variation of albedo directly.
- **Models:** the no-atmosphere and one-layer models are deliberately simple. They predict the right size of the greenhouse effect ($\approx 33\text{ K}$) from a few physical ideas, but ignore convection, latent heat, clouds and feedbacks. Climate models used by international bodies such as the IPCC build on the same energy-balance principle with many layers and processes, and are tested against measured data.

Key equations

Equation	Use	In data booklet?
emissivity = $\frac{\text{power radiated per unit area}}{\sigma T^4}$	definition of emissivity	yes (B.2)
$P = e\sigma AT^4$	power radiated by a real surface	no — combine the definition with $L = \sigma AT^4$
albedo = $\frac{\text{total scattered power}}{\text{total incident power}}$	definition of albedo	yes (B.2)
$S = 1.36 \times 10^3 \text{ W m}^{-2}$	solar constant	yes (constants)
$\bar{I}_{\text{in}} = \frac{S}{4}$	mean incoming intensity over a planet	no — learn the derivation
$(1 - \alpha)\frac{S}{4} = e\sigma T^4$	equilibrium temperature of a planet	no — build it from power in = power out
$L = \sigma AT^4, \lambda_{\text{max}}T = 2.9 \times 10^{-3} \text{ m K}$	black-body radiation	yes (B.1)
$b = \frac{L}{4\pi d^2}$	intensity at distance d (inverse square law)	yes (B.1)
$E = hf$	energy of an infrared photon	yes (E.1)

Check your understanding

1. Explain why the mean intensity of solar radiation over the Earth's surface is $S/4$ and not S .

The Earth intercepts the Sun's parallel rays over its projected area, a disc of area πR^2 , so it receives power $S\pi R^2$. Averaged over time this power is

spread over the whole spherical surface, area $4\pi R^2$. Mean intensity = $\frac{S\pi R^2}{4\pi R^2} = \frac{S}{4}$.

2. The intensity of sunlight at Venus is $2.60 \times 10^3 \text{ W m}^{-2}$ and its albedo is 0.76. Estimate the equilibrium temperature of Venus if it radiated as a black body with no greenhouse effect, and comment on the fact that its surface is at about 740 K.

Absorbed: $0.24 \times \frac{2.60 \times 10^3}{4} = 156 \text{ W m}^{-2}$; $T = \left(\frac{156}{5.67 \times 10^{-8}} \right)^{1/4} = 229 \text{ K}$. The actual surface is about 500 K hotter: Venus's very dense CO_2 atmosphere produces an extreme greenhouse effect. (Its high albedo, from thick cloud, means it absorbs less sunlight per m^2 than the Earth.)

3. Calculate the peak wavelengths of the radiation emitted by the Sun (5800 K) and the Earth (288 K), and use them to explain why the atmosphere affects incoming and outgoing radiation differently.

$\lambda_{\text{max}} = \frac{2.9 \times 10^{-3}}{5800} = 5.0 \times 10^{-7} \text{ m}$ (0.50 μm , visible) and $\frac{2.9 \times 10^{-3}}{288} = 1.0 \times 10^{-5} \text{ m}$ (10 μm , infrared). Greenhouse gases have vibrational energy gaps (natural frequencies) that match infrared, not visible, photons — so they let the incoming short-wave radiation through but absorb much of the outgoing long-wave radiation.

4. Calculate the frequency and the photon energy of radiation of wavelength 15 μm , which is absorbed by CO_2 molecules.

$f = \frac{3.00 \times 10^8}{15 \times 10^{-6}} = 2.0 \times 10^{13} \text{ Hz}$; $E = hf = 6.63 \times 10^{-34} \times 2.0 \times 10^{13} = 1.3 \times 10^{-20} \text{ J}$ (0.083 eV).

5. Melting sea ice lowers the Earth's albedo from 0.30 to 0.28. Using the no-atmosphere model, determine the change in equilibrium temperature, and explain why this is called a positive feedback.

$$T_1 = \left(\frac{0.70 \times 340}{5.67 \times 10^{-8}} \right)^{1/4} = 254.5 \text{ K}; T_2 = \left(\frac{0.72 \times 340}{5.67 \times 10^{-8}} \right)^{1/4} = 256.3 \text{ K:}$$

a rise of about **1.8 K**. Warming melts ice, which lowers the albedo, so more sunlight is absorbed and the warming increases further — the effect reinforces its own cause.

Practise B.2 with exam-style questions

Original Paper 1A, 1B and 2 questions on emissivity, albedo, energy balance and the greenhouse effect, with full mark schemes. Tick the questions you want and print them as your own test.

SL B.2 questions

HL B.2 questions

Revise and explore

- **Flashcards** — choose IB Physics and filter to B.2 Greenhouse effect. Free, no sign-up.
- **B.2 Greenhouse Effect simulation**
- **B.2 Black-body & Wien's law simulation**
- **Full IB Physics question bank (all sub-topics, SL & HL)**

← Previous: B.1 Thermal energy transfers · Next: B.3 Gas laws →