MEGA LECTURE

IB DP PHYSICS

Theme B: The Particulate Nature of Matter

B.2 Greenhouse Effect

Revision Notes · Standard and Higher Level

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Original notes prepared for the IB Diploma Programme Physics course (first assessment 2025)

What the syllabus requires

B.2 asks one big question: *what sets the temperature of a planet?* Everything in the topic — the solar constant, albedo, emissivity, black-body radiation and the greenhouse mechanism — is a tool for answering it. Use this list as a final checklist before the exam.

Understanding	You should be able to...
Conservation of energy / radiative balance	Explain that a planet's mean temperature is constant when absorbed solar power equals emitted infrared power.
Solar constant, S	Use $S \approx 1360\ W\ m^{-2}$; explain why the mean intensity over the whole planet is S/4.
Albedo, α	Define albedo as the fraction of incident radiation scattered/reflected; recall that it varies with surface and that Earth's mean is about 0.3.
Emissivity, ε	Define emissivity as the ratio of a surface's emitted power to that of a black body at the same temperature; use $P = \varepsilon\sigma A T^4$.
Equilibrium (bare-rock) temperature	Derive and apply $T = [S(1 – \alpha) / 4\sigma]^{1/4} \approx 255$ K for Earth.
Greenhouse gases	Name CH_4, H_2O, CO_2 and N_2O; explain absorption of infrared by molecular resonance; explain re-radiation in all directions.
Wien's law link (B.1)	Contrast the visible peak of solar radiation with the ~10 µm infrared peak of terrestrial radiation.
Enhanced greenhouse effect	Distinguish the natural effect from the anthropogenic enhancement; describe the evidence (Keeling curve, temperature records).

> **Exam note:** B.2 is common to SL and HL and leans heavily on B.1 (Stefan–Boltzmann law, Wien's law, intensity). Expect 'explain' questions worth 3–4 marks as well as full equilibrium-temperature calculations.

1. Radiative equilibrium: what sets a planet's temperature

A planet in space can exchange energy with its surroundings in essentially one way: **electromagnetic radiation**. It absorbs radiation from its star and, because it has a temperature, it emits infrared radiation from its own surface and atmosphere (every body above 0 K radiates).

- If absorbed power > emitted power, the planet's internal energy and temperature rise.
- A hotter planet radiates more ($P \propto T^4$, Stefan–Boltzmann), so emission grows until it matches absorption.
- At **radiative equilibrium** the two rates are equal and the mean temperature is steady.

power absorbed from the Sun = power radiated to space

This is simply conservation of energy applied to the whole planet. The equilibrium is *stable*: a small warming increases emission more than absorption, pushing the planet back towards balance. The T^4 dependence is what makes the balance self-correcting.

> **Key phrase for explain questions:** “The planet's temperature is constant because the rate of absorption of solar radiation equals the rate of emission of infrared radiation; if they were unequal the temperature would change until they balanced.”

2. The solar constant and the factor of 4

The **solar constant** S is the intensity of solar radiation arriving at the top of Earth's atmosphere, measured on a surface facing the Sun directly:

$$S \approx 1360\ \mathrm{W\ m^{-2}}$$

It follows from the Sun's luminosity spread over a sphere of radius equal to the Earth–Sun distance: $S = L / 4\pi d^2$. For a planet at a different orbital distance, S scales as $1/d^2$ (inverse-square law).

Why intercepted power uses πR^2

Seen from the Sun, the Earth blocks out a **flat disc** of radius R (the planet's radius). The power intercepted is therefore the intensity times the disc area:

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

Why the average received intensity is S/4

That intercepted power is spread, on average, over the planet's entire spherical surface of area $4\pi R^2$ — the planet rotates, and at any instant half of it is in darkness while the illuminated half receives sunlight mostly at a slant. The time-averaged intensity over the whole globe is

$$\text{mean incident intensity} = S\pi R^2 / 4\pi R^2 = S/4 \approx 340\ \mathrm{W\ m^{-2}}$$

The factor of 4 is purely geometric: the ratio of a sphere's surface area to the area of its shadow disc. It has nothing to do with albedo or the atmosphere.

Worked example 1 — mean absorbed intensity

Using $S = 1360\ \mathrm{W\ m^{-2}}$ and a global mean albedo of 0.30, calculate the average intensity (a) arriving at, and (b) absorbed by, each square metre of Earth.

(a) Mean arriving intensity = S/4 = 1360 / 4 = **340 W $\mathrm{m^{-2}}$**.

(b) A fraction $\alpha = 0.30$ is scattered back to space, so the absorbed fraction is 0.70:

absorbed intensity = $(1 - \alpha)S/4 = 0.70 \times 340$ = **238 W $\mathrm{m^{-2}}$** ≈ **240 W $\mathrm{m^{-2}}$**.

This 238 W $\mathrm{m^{-2}}$ is the number the outgoing infrared must match at equilibrium.

3. Albedo

Not all radiation reaching a planet is absorbed. The **albedo** α is defined as

$$\alpha = \text{(total scattered or reflected power) / (total incident power)}$$

It is a dimensionless number between 0 (perfect absorber) and 1 (perfect reflector). Much of the reflection is **diffuse scattering** — clouds, snow and rough surfaces scatter light in all directions rather than reflecting it like a mirror — but the definition only counts what fraction goes back to space, not in which direction.

Surface	Typical albedo	Comment
Fresh snow / ice	0.75–0.90	Excellent reflector; melting it exposes darker ground
Thick cloud	0.6–0.9	Clouds dominate the reflective side of Earth's budget
Desert sand	≈ 0.4	Bright, dry surfaces reflect well
Grassland / soil	0.2–0.3	Intermediate
Forest	0.1–0.15	Dark canopy absorbs strongly
Ocean (high Sun)	0.05–0.1	Very absorbing; covers ~70% of the globe
Earth, global annual mean	**≈ 0.3**	The value to use in calculations unless told otherwise

Albedo varies with season (snow cover), cloudiness, time of day (Sun angle over water), latitude and land use. Quoting Earth's albedo as a single number is already a modelling simplification — a point worth making in evaluate-the-model questions.

> **Common misconception:** Albedo is a ratio of *powers* (or intensities), not a ratio of temperatures, and it applies to the incoming *short-wavelength* radiation. The infrared the Earth emits is a separate story handled by emissivity.

4. Emissivity and grey bodies

A **black body** is a perfect absorber and therefore also a perfect emitter; at temperature T it emits the maximum possible power, $\sigma A T^4$, where $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}. Real surfaces emit less. The **emissivity** compares the two:

ε = (power emitted per unit area by the surface) / (power emitted per unit area by a black body at the same temperature)

$$P = \varepsilon \sigma A T^4 \quad 0 \le \varepsilon \le 1$$

A body with constant $\varepsilon < 1$ across all wavelengths is called a **grey body**. Emissivity can be estimated by comparing the measured radiated power from a sample (using a thermopile or IR sensor) with the theoretical black-body value at the same measured surface temperature and area — the ratio of the two powers is ε.

For a planet, an *effective* emissivity can be defined the same way: the ratio of the infrared power actually escaping to space to the power a black body at the surface temperature would emit. Earth's surface radiates about 390 W m^{-2} (black body at 288 K) but only about 240 W m^{-2} escapes, giving an effective emissivity of about 0.6 — the atmosphere retains the rest. This is one compact way to quantify the greenhouse effect.

Worked example 2 — grey-body radiator

A sphere of radius 15 cm has a surface temperature of 400 K and emissivity 0.80. Calculate the power it radiates.

Surface area $A = 4\pi r^2 = 4\pi(0.15)^2 = 0.283\ m^2$.

$P = \varepsilon\sigma A T^4 = 0.80 \times 5.67 \times 10^{-8} \times 0.283 \times 400^4$

$P = 0.80 \times 5.67 \times 10^{-8} \times 0.283 \times 2.56 \times 10^{10} = \mathbf{3.3 \times 10^2\ W}$.

(A net-power question would also subtract absorption from the surroundings: $P_{net} = \varepsilon\sigma A(T^4 - T_{surr}^4)$.)

5. The bare-rock model: 255 K vs 288 K

Model the Earth with **no atmosphere**: a sphere of albedo α that absorbs sunlight and radiates to space as a black body (ε = 1). At equilibrium:

$$\textbf{absorbed: } (1 - \alpha)\, S\, \pi R^2 = \textbf{emitted: } \sigma T^4 \times 4\pi R^2$$

The planet radius cancels — the answer is the same for any size of planet. Solving for T:

$$T = [\, S(1 - \alpha) / 4\sigma \,]^{1/4}$$

Worked example 3 — Earth's bare-rock temperature

Calculate the equilibrium temperature of the Earth with $S = 1360\ W\ m^{-2}$, $\alpha = 0.30$, treating it as a black-body emitter.

Absorbed mean intensity $= S(1 - \alpha)/4 = 1360 \times 0.70 / 4 = 238\ W\ m^{-2}$.

Set $\sigma T^4 = 238$: $T^4 = 238 / (5.67 \times 10^{-8}) = 4.20 \times 10^9\ K^4$.

$T = (4.20 \times 10^9)^{1/4} = \mathbf{255\ K \approx -18\ °C}$.

The observed global mean surface temperature is about **288 K (+15 °C)**. The model is 33 K too cold.

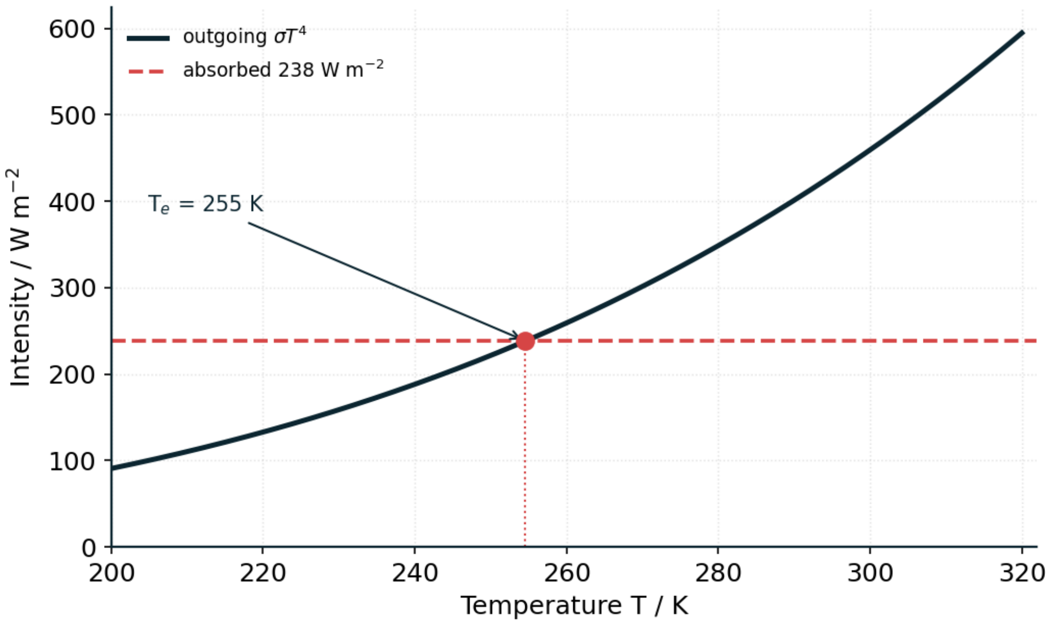

Figure 3. Radiative balance fixes Earth's effective temperature: the outgoing σT^4 curve meets the absorbed intensity $S(1 - \alpha)/4$ = 238 W m^{-2} (dashed) at $T_e \approx 255$ K.

The 33 K gap *is* the natural greenhouse effect

The bare-rock model gets the physics of absorption and emission right but omits the atmosphere. The 33 K discrepancy is not an error to be embarrassed about — it is a **measurement of the natural greenhouse effect**: the warming produced by atmospheric gases that let sunlight in but impede the escape of infrared. Without it, Earth's oceans would largely be frozen.

Worked example 4 — the Moon and Venus as controls

(a) The Moon (same distance from the Sun, albedo 0.11, no atmosphere): absorbed intensity = 1360 × 0.89 / 4 = 303 W m^{-2}; T = $(303 / 5.67 \times 10^{-8})^{1/4}$ = $(5.34 \times 10^{9})^{1/4}$ = **270 K** — close to the Moon's actual mean, because with no atmosphere the bare-rock model is the right model.

(b) Venus (0.72 AU, so S_V = 1360/0.72^2 = 2620 W m^{-2}; albedo 0.75): absorbed = 2620 × 0.25 / 4 = 164 W m^{-2}; T = $(164 / 5.67 \times 10^{-8})^{1/4}$ = **232 K**. Venus's actual surface is about **735 K** — a spectacular 500 K greenhouse warming from its dense CO_2 atmosphere.

Comparing the three worlds shows the greenhouse contribution cleanly: Moon ≈ 0 K, Earth ≈ 33 K, Venus ≈ 500 K.

6. The mechanism: how greenhouse gases work

The four greenhouse gases named in the syllabus are **water vapour (H_2O), carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O)**. Together they make up well under 1% of the atmosphere, yet they control its infrared behaviour.

Absorption by molecular resonance

A molecule can store energy in **vibrations** of its bonds (stretching, bending) and in rotation. These modes have natural frequencies, and quantum mechanics restricts them to discrete energy levels. The energy spacing of the vibrational levels of H_2O, CO_2, CH_4 and N_2O happens to match the photon energies of **infrared** radiation (wavelengths of a few μm to tens of μm). When an infrared photon of matching energy arrives, the molecule absorbs it and is set into resonant vibration — exactly the resonance idea used elsewhere in physics: energy transfer is efficient when the driving frequency matches a natural frequency.

Re-radiation in all directions

The excited molecule quickly loses the energy again, either by colliding with neighbouring molecules (sharing the energy as random thermal motion, warming the air) or by re-emitting an infrared photon. Crucially, re-emission occurs in a **random direction**: roughly half of the re-radiated infrared heads back *downwards*. The surface therefore receives energy from two sources — the Sun *and* the atmosphere — and must warm up until its (larger) emission again balances the books.

Why N_2 and O_2 are not greenhouse gases

Nitrogen and oxygen, 99% of the atmosphere, are symmetric diatomic molecules. Their vibration does not change the molecule's electric charge distribution (they have no dipole moment, and stretching a symmetric bond creates none), so they cannot interact with the oscillating electric field of an infrared photon. Greenhouse molecules, with three or more atoms, have bending and asymmetric stretching modes that *do* shift charge around — these are the modes infrared light can drive.

Gas	Main sources	Notes for exams
H_2O	Evaporation (natural)	The largest contributor to the natural effect; its concentration responds to temperature (feedback) rather than being emitted directly in significant amounts
CO_2	Respiration, volcanoes; combustion of fossil fuels, deforestation (anthropogenic)	The key anthropogenic gas; long atmospheric lifetime
CH_4	Wetlands; livestock, rice paddies, gas leaks, landfill	Far stronger absorber per molecule than CO_2, but less abundant
N_2O	Soil processes; fertilisers, some industry	Strong absorber; long-lived

> **3-mark answer skeleton (“explain the greenhouse effect”):** (1) Surface absorbs visible sunlight and emits infrared. (2) Greenhouse gas molecules absorb infrared because photon energies match their vibrational energy-level spacing (resonance). (3) They re-radiate in all directions, so some infrared returns to the surface, raising the equilibrium surface temperature.

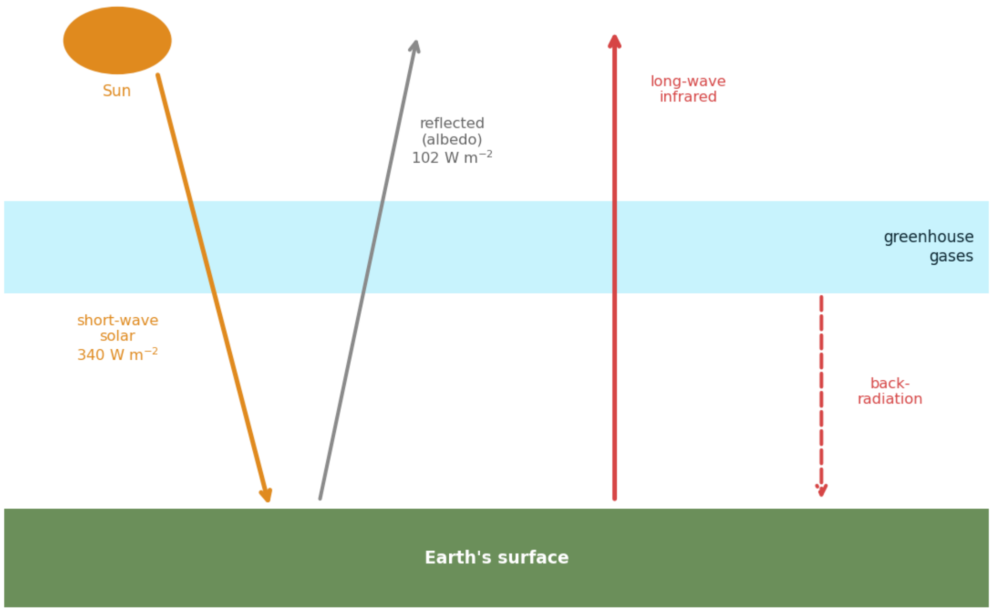

Figure 1. Earth's energy balance. Short-wave solar radiation ($S/4 \approx 340$ W m^{-2}) arrives; a fraction $\alpha \approx 0.3$ is reflected, leaving 238 W m^{-2} absorbed. The warm surface emits long-wave infrared, which greenhouse gases absorb and re-radiate in all directions, returning some to the surface.

7. Incoming sunlight vs outgoing infrared (Wien's law)

Why does the atmosphere let the Sun's energy in but hinder the Earth's energy on the way out? Because the two radiation streams occupy **different parts of the spectrum**, set by the temperatures of their sources through Wien's displacement law (from B.1):

$$\lambda_{max} = 2.9 \times 10^{-3} / T \text{ (m K)}$$

Worked example 5 — the two peak wavelengths

Find the peak emission wavelength of (a) the Sun (surface ≈ 5800 K), (b) the Earth (surface ≈ 288 K).

(a) $\lambda_{max} = 2.9 \times 10^{-3} / 5800 =$ **5.0×10^{-7} m = 500 nm** — green visible light; the solar spectrum spans the near-UV, visible and near-IR.

(b) $\lambda_{max} = 2.9 \times 10^{-3} / 288 =$ **1.0×10^{-5} m ≈ 10 μm** — far infrared, about 20 times longer than the solar peak.

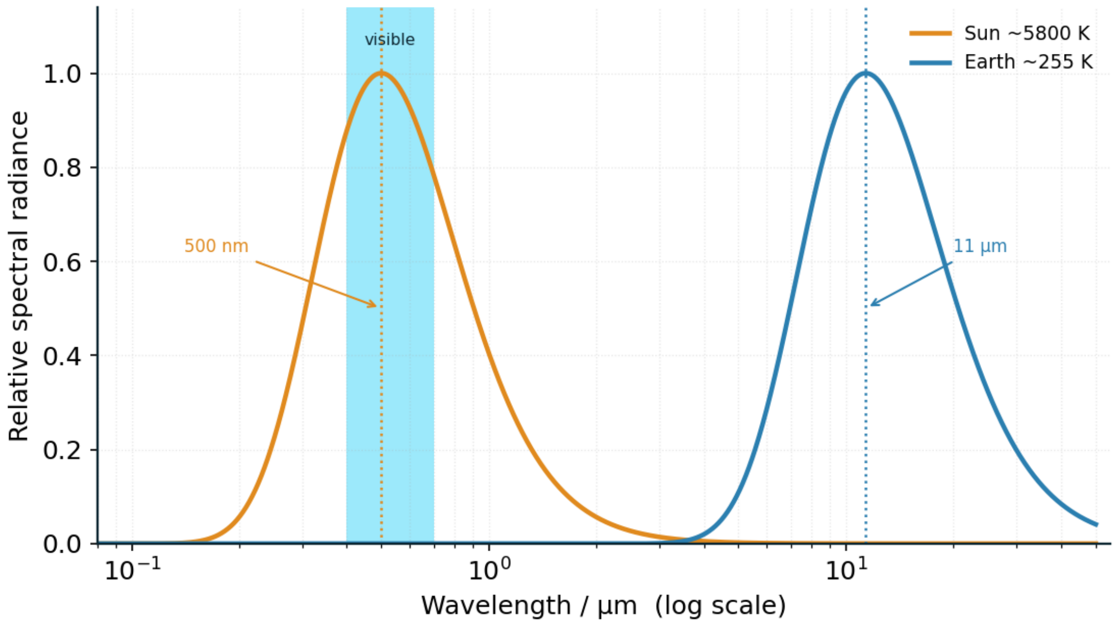

Figure 2. Black-body spectra (each normalised to its own peak). Wien's law λ_{max} = b/T shifts the peak with temperature: the Sun (~5800 K) peaks near 500 nm (visible), while the Earth (~255 K) peaks near 11 μm (infrared).

The atmosphere is largely **transparent at visible wavelengths** (no abundant gas has energy-level spacings matching visible photons, apart from some scattering), so sunlight reaches the surface. But the surface re-emits at ~4–50 μm, squarely in the absorption bands of H_2O, CO_2, CH_4 and N_2O. The atmosphere is therefore **opaque to much of the outgoing infrared**: it acts like a one-way filter, and that asymmetry is the greenhouse effect.

> **Exam technique:** Always describe the radiation streams as “short-wavelength (visible) solar radiation” and “long-wavelength (infrared) terrestrial radiation”. Writing “heat gets trapped” earns nothing; naming the wavelength contrast and the absorption mechanism earns the marks.

8. A one-layer atmosphere model

The simplest energy-balance model that reproduces greenhouse warming adds a single atmospheric layer above the surface with two properties: it is **transparent to solar radiation** but **absorbs all infrared** from the surface, re-emitting as a black body at its own temperature T_a — upwards to space *and* downwards to the ground.

Setting up the balances (per square metre, with I = S(1 – α)/4 = 238 W m^{-2}):

- **Top of atmosphere:** only the layer radiates to space, so $\sigma T_a^4 = I$. Hence T_a = 255 K: the bare-rock temperature now belongs to the *atmosphere*, not the ground.
- **Surface:** it receives sunlight I *plus* back-radiation $\sigma T_a^4 = I$, a total of 2I, and emits σT_s^4. So $\sigma T_s^4 = 2I$.

$$\mathbf{T_s = 2^{1/4}\,T_a = 1.19 \times 255\ K \approx 303\ K}$$

The model predicts a surface roughly 48 K warmer than bare rock — an overestimate (observed warming is 33 K) because the real atmosphere is not a perfect infrared absorber: some surface infrared escapes directly through the “atmospheric window” around 8–13 μm. A partial-absorption layer lands between 255 K and 303 K, which is exactly where 288 K sits. The lesson examiners want: **adding infrared absorption**

above the surface raises the surface equilibrium temperature, and better absorption means more warming.

Strengths and limitations of the model

- Captures energy conservation, the T^4 law and the role of back-radiation.
- Ignores convection, evaporation, clouds, latitude variation, and treats absorption as all-or-nothing.
- Uses a single albedo and a single layer; real atmospheres need many layers and wavelength-dependent absorption.

9. The enhanced greenhouse effect

The **natural** greenhouse effect (33 K) makes Earth habitable. The **enhanced** greenhouse effect is the additional warming caused by human activity increasing the concentration of greenhouse gases — chiefly CO_2 from burning fossil fuels and deforestation, plus CH_4 and N_2O from agriculture and industry.

The evidence

- **The Keeling curve:** continuous measurements of atmospheric CO_2 at Mauna Loa since 1958 show a steady rise from about 315 ppm to well above 420 ppm, with a small annual zig-zag superimposed (northern-hemisphere vegetation absorbs CO_2 in summer and releases it in winter). Ice cores extend the record: pre-industrial levels were about 280 ppm for thousands of years.
- **Temperature records:** global mean surface temperature has risen by more than 1 K since the late 19th century, and the rise correlates with the CO_2 record.
- **Mechanism + correlation:** correlation alone never proves causation, but here the correlation is backed by an independently verified physical mechanism (infrared absorption by CO_2, measurable in the laboratory) and by satellite observations of reduced outgoing infrared in CO_2 absorption bands. That combination makes the causal case.

Feedback loops (qualitative)

- **Ice–albedo feedback (positive):** warming melts snow and ice → exposed ocean/land is darker → albedo falls → more solar radiation absorbed → further warming.
- **Water-vapour feedback (positive):** warmer air holds more water vapour → H_2O is itself a greenhouse gas → more infrared absorbed → further warming. This roughly doubles the direct effect of CO_2.
- Clouds produce both signs: more low cloud raises albedo (cooling), more high cloud absorbs infrared (warming); the net effect is a major modelling uncertainty.

> **Language check:** Distinguish carefully between the *greenhouse effect* (natural, beneficial, explains the 33 K), the *enhanced greenhouse effect* (anthropogenic addition) and *global warming* (the resulting temperature rise). Muddling them costs marks.

10. Common pitfalls

- Forgetting the factor 4: using S instead of S/4 (or πR^2 on one side and $4\pi R^2$ on the other without cancelling correctly).
- Applying the albedo to the *emitted* infrared. Albedo reduces absorbed sunlight only; use emissivity for emission.

- Taking the fourth root incorrectly — evaluate T^4 first, then use the $x^{1/4}$ button (or square-root twice).
- Using °C in σT^4. Stefan–Boltzmann demands kelvin, always.
- Saying greenhouse gases "reflect" infrared. They **absorb and re-radiate** it, in all directions — reflection is the wrong physics.
- Claiming the atmosphere "traps heat like a blanket/greenhouse glass" with no mechanism. Name the resonance absorption and re-radiation.
- Listing N_2 or O_2 as greenhouse gases, or forgetting that water vapour is one.
- Treating the 255 K result as "wrong". It is the correct answer to the no-atmosphere question; the 33 K difference is the physics.

11. Quick reference

Result	Statement
Solar constant	$S \approx 1360$ W m^{-2} at Earth; $S \propto 1/d^2$
Intercepted power	$S\pi R^2$ (planet presents a disc to the Sun)
Mean incident intensity	$S/4 \approx 340$ W m^{-2} (sphere has 4× the disc area)
Albedo	α = scattered power / incident power; global mean ≈ 0.3
Mean absorbed intensity	$(1 - \alpha)S/4 \approx 238$ W m^{-2}
Emissivity	ε = emitted power / black-body power at same T; $P = \varepsilon\sigma A T^4$
Bare-rock temperature	$T = [S(1 - \alpha)/4\sigma]^{1/4} \approx 255$ K for Earth
Natural greenhouse effect	288 K – 255 K = 33 K of warming from H_2O, CO_2, CH_4, N_2O
Wavelength contrast	Solar peak ≈ 500 nm (visible); terrestrial peak ≈ 10 μm (infrared)
Mechanism	IR photon energy matches molecular vibrational levels (resonance); re-radiation in all directions
One-layer model	$\sigma T_a^4 = I$ and $\sigma T_s^4 = 2I$, so $T_s = 2^{1/4} T_a \approx 303$ K
Enhanced effect	Anthropogenic rise in greenhouse gases (Keeling curve: 315 → 420+ ppm since 1958)

12. Test yourself

Attempt these without notes; full answers below. Use $S = 1360$ W m^{-2}, $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}, Wien constant 2.9×10^{-3} m K.

1. Define (a) the solar constant, (b) albedo, (c) emissivity.

2. Show that the average intensity absorbed per square metre of the Earth's surface is about 240 W m^{-2}. Explain the origin of the factor of 4 in your working.

3. Mars orbits at 1.52 AU and has albedo 0.25. Calculate its expected bare-rock equilibrium temperature.

4. Explain why carbon dioxide absorbs infrared radiation but nitrogen does not.

5. The human body has a surface temperature of about 310 K. (a) Find its peak emission wavelength. (b) State why this radiation interacts strongly with the atmosphere's greenhouse gases.

6. A planet's measured surface temperature exceeds the value predicted by $T = [S(1 - \alpha)/4\sigma]^{1/4}$. Outline three assumptions of the bare-rock model and identify which one fails.

7. In the one-layer model, the atmosphere absorbs all surface infrared and radiates equally up and down. Show that the surface temperature is $2^{1/4}$ times the bare-rock temperature, and comment on why the real factor is smaller.

8. Describe the ice–albedo feedback and explain why it is classified as a positive feedback.

Answers

1. (a) The intensity of solar radiation incident on a surface placed perpendicular to the Sun's rays at the mean Earth–Sun distance, just outside the atmosphere (≈ 1360 W m^{-2}). (b) The ratio of total scattered/reflected power to total incident power for a surface or planet. (c) The ratio of the power emitted per unit area by a surface to that emitted by a black body at the same temperature.

2. The Earth intercepts $S\pi R^2$ (it presents a disc of area πR^2 to the Sun), but this power is shared over the full rotating sphere of area $4\pi R^2$; the ratio of the two areas gives the factor 4. Mean incident intensity = 1360/4 = 340 W m^{-2}; with $\alpha = 0.30$, absorbed intensity = 0.70 × 340 = 238 ≈ 240 W m^{-2}.

3. S_{Mars} = 1360 / 1.52^2 = 589 W m^{-2}. Absorbed intensity = 589 × 0.75 / 4 = 110 W m^{-2}. T^4 = 110 / (5.67 × 10^{-8}) = 1.95 × 10^9, so T ≈ **210 K**. (Mars's thin CO_2 atmosphere adds only a few kelvin.)

4. CO_2 has bending and asymmetric stretching vibrational modes whose quantised energy-level spacings match infrared photon energies; these vibrations shift the charge distribution, so the molecule couples to the photon's oscillating electric field and absorbs resonantly. N_2 is a symmetric diatomic molecule: its single vibration produces no change in charge distribution (no dipole), so it cannot absorb infrared photons.

5. (a) λ_{max} = 2.9 × 10^{-3} / 310 = **9.4 μm**. (b) This lies in the infrared, where the vibrational energy-level spacings of H_2O, CO_2, CH_4 and N_2O match the photon energies, so absorption is strong.

6. Assumptions: the planet (i) has no atmosphere (all emitted radiation escapes directly to space), (ii) emits as a black body ($\varepsilon = 1$), (iii) is in radiative equilibrium with a single uniform temperature and constant albedo. Assumption (i) fails for a planet with greenhouse gases: the atmosphere absorbs outgoing infrared and re-radiates part of it back to the surface, so the surface must sit hotter than the bare-rock value for the planet as a whole to stay in balance.

7. Top of atmosphere: $\sigma T_a^4 = I$ (only the layer radiates to space), where $I = S(1 - \alpha)/4$, so T_a equals the bare-rock temperature. Surface: receives I from the Sun plus $\sigma T_a^4 = I$ back-radiated from the layer, so $\sigma T_s^4 = 2I = 2\sigma T_a^4$, giving $T_s = 2^{1/4} T_a$ ≈ 1.19 × 255 = 303 K. The real factor is smaller because the atmosphere is only a partial infrared absorber — some surface radiation escapes directly through the atmospheric window — so the observed surface temperature (288 K) lies between 255 K and 303 K.

8. Warming melts highly reflective snow and sea ice, exposing darker ocean or land. The albedo falls, so a larger fraction of the incident solar radiation is absorbed, which raises the temperature further and melts more ice. Because the initial change (warming) produces an effect that reinforces itself rather than opposing it, the loop is a positive feedback: it amplifies the original disturbance.