PHOTON ACADEMY

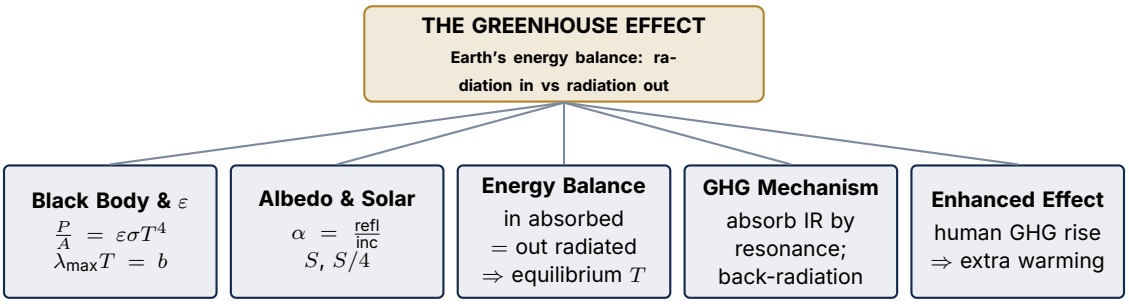
Topic B.2

# THE GREENHOUSE EFFECT

*Every Formula, Trick & Trap on a Page*
*& IB-Style Quick Reference*

| Topics Covered | Exam Relevance |
|---|---|
| Solar Constant & Radiation Balance | P1 & P2 (with & without GDC) |
| Albedo & Emissivity | Incident power & intensity |
| The Greenhouse Mechanism | Albedo / emissivity calcs |
| Greenhouse Gases | IR-active molecules |
| Energy Balance & Climate | Equilibrium temperature |

**The Big Picture — How B.2 Fits Together**




## §1 — Black Body Radiation & Emissivity

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**Stefan–Boltzmann Law (black body)**

$$\frac{P}{A} = \sigma T^4 \qquad \sigma = 5.67 \times 10^{-8}\,\text{W}/(\text{m}^2\,\text{K}^4)$$

Real surface: $\frac{P}{A} = \varepsilon\sigma T^4$, where $0 < \varepsilon \leq 1$

**Wien's Displacement Law**

$$\lambda_{max}T = b = 2.90 \times 10^{-3}\,\text{m K}$$

Sun ($T \approx 5800$ K): visible light. Earth ($T \approx 288$ K): infrared ($\sim$10 $\mu$m).

**Emissivity — Definition**

$$\varepsilon = \frac{\text{power radiated per unit area by surface}}{\sigma T^4}$$

$\varepsilon = 1$: perfect black body. Earth surface: $\varepsilon \approx 0.95$–$0.99$.

**TRICK** For total power from a sphere: $P = \varepsilon\sigma T^4 \times 4\pi R^2$.

**TRAP** Emissivity is not simply related to visible colour — it must be evaluated at the relevant wavelength (infrared for Earth).

## §2 — Albedo & Solar Constant

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**Albedo**

$$\alpha = \frac{\text{total scattered (reflected) power}}{\text{total incident power}} \qquad (0 \leq \alpha \leq 1)$$

Fraction absorbed $= 1 - \alpha$. Earth global average: $\alpha \approx 0.30$.

### Solar Constant & Mean Intensity

$S \approx 1361\,\text{W/m}^2$ (at Earth–Sun distance, outside atmosphere)

$$I_{\text{mean}} = \frac{S}{4} \approx 340\,\text{W/m}^2$$

Factor of 4: intercepting area $\pi R^2$ vs. sphere area $4\pi R^2$.

**NOTE** Earth's albedo varies daily — depends on cloud formations, latitude, season, and surface type.

**TRICK** $\alpha = \frac{\text{reflected}}{\text{incident}}$ only. Radiated IR from the surface is **not** part of albedo.

**TRAP** A very common error: forgetting to divide $S$ by 4 when finding mean incoming intensity.

**TRICK** **Two intensities:** solar constant $S$ (surface *facing* the Sun) vs mean $S/4$ (whole planet). Energy-balance / equilibrium-$T$ questions use $S/4$.

**TRICK** **Albedo vs emissivity:** $\alpha$ governs the *incoming* side (fraction of sunlight reflected); $\varepsilon$ governs the *outgoing* side (efficiency of IR emission, $\varepsilon\sigma T^4$).

**NOTE** **Fate of incoming radiation:** only $\approx 45\%$ of $S$ reaches the surface — the rest is reflected ($\approx 30\%$, the albedo) or absorbed in the atmosphere ($\approx 25\%$). At high latitudes rays hit at a shallow angle, spreading over a larger area and passing through more atmosphere $\Rightarrow$ lower intensity (this, with the $23.5°$ tilt, causes the seasons).

FROM THE PHOTON QUESTION BANK

Read incident/reflected intensities off an energy-budget diagram and apply $\alpha$ = reflected/incident; for light crossing several interfaces multiply the transmission fractions $(1-\alpha)$; choose $S$ (facing Sun) vs $S/4$ (whole planet) deliberately.

- Fresh snow: $\alpha \approx 0.80$–$0.90$
- Clouds: $\alpha \approx 0.40$–$0.90$
- Ocean: $\alpha \approx 0.06$–$0.10$
- Forest: $\alpha \approx 0.08$–$0.15$
- Desert: $\alpha \approx 0.25$–$0.40$
- Ice: $\alpha \approx 0.50$–$0.70$
- Earth (global avg): $\alpha \approx 0.30$
- Moon: $\alpha \approx 0.10$

## §3 — Earth's Energy Balance

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### Equilibrium Temperature Formula

At equilibrium (power in = power out):

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

With $\alpha = 0.30$, $\varepsilon = 1$, $S = 1361\,\text{W/m}^2$: $T_e \approx 254\,\text{K} \approx -19\,^\circ\text{C}$.
Actual mean: $+15\,^\circ$C. The $\sim$34 °C difference is the natural greenhouse effect.

### Reading Energy Balance Diagrams

1. Absorbed solar = $(1-\alpha) \times S/4$
2. At equilibrium: power in = power out (each layer)
3. Surface radiation = solar absorbed at surface + atmospheric back-radiation
4. Apply energy conservation at **each** layer separately

**TRICK** $T \propto I_s^{1/4}$: graph of $T$ vs $I_s$ is a concave-down curve (not linear).

**TRAP** Do not confuse absorbed solar with total incoming. Absorbed = $(1-\alpha) \times$ incoming.

FROM THE PHOTON QUESTION BANK

Set absorbed $(1-\alpha)S/4 = \varepsilon\sigma T_e^4$ and solve for equilibrium $T$; recognise $T \propto I_s^{1/4}$ (concave-down graph); at the surface add solar absorbed *plus* back-radiation.

## §4 — Greenhouse Gases & Mechanism

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### The Four Greenhouse Gases (IB syllabus)

| Gas | Formula | Natural source | Human source |
|---|---|---|---|
| Carbon dioxide | $CO_2$ | Respiration, volcanism | Fossil fuels, deforestation |
| Water vapour | $H_2O$ | Evaporation | Cooling towers, irrigation |
| Methane | $CH_4$ | Wetlands | Livestock, landfills |
| Nitrous oxide | $N_2O$ | Soil bacteria | Fertilisers |

**Not** greenhouse gases: $O_2$, $N_2$ (symmetric, no IR absorption).

### Mechanism — Molecular Energy Levels

1. GHG molecules have vibrational modes at IR frequencies
2. Earth surface emits IR ($\sim$10 $\mu$m); GHG absorbs by **resonance** ($h\nu = \Delta E$)
3. Molecule transitions to higher vibrational energy level
4. Re-emits IR photon in **all directions** — $\approx$half returns to surface (back-radiation)
5. Surface temperature rises above the no-atmosphere equilibrium

**NOTE** Visible/UV from the Sun passes through the atmosphere. Earth's IR matches GHG vibrational frequencies — this asymmetry drives the greenhouse effect.

**TRAP** GHG molecules absorb and **re-emit** IR — they do NOT reflect it. Use the word "re-emit" in exam answers.

**TRICK** **Two ways to explain it:** *molecular* — GHGs resonantly absorb & re-emit IR (dipole change; $O_2$/$N_2$ can't); *energy balance* — less IR escapes to space, so equilibrium $T$ rises. Full-mark answers give both.

**NOTE** **Also contribute:** ozone $O_3$ and CFCs. GHGs absorb IR only in **selective bands**; the $8$–$12\,\mu$m **atmospheric window** lets IR escape. **Carbon fixation:** plants remove $CO_2$ by photosynthesis (deforestation both releases $CO_2$ and reduces this).

FROM THE PHOTON QUESTION BANK

Name the greenhouse gases ($O_2$/$N_2$ excluded — symmetric, no dipole change); explain as **absorb-and-re-emit** by resonance ($h\nu = \Delta E$), never "reflect"; read selective IR-absorption dips off a top-of-atmosphere-vs-surface spectral graph.

## §5 — Enhanced Greenhouse Effect

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### Enhanced Greenhouse Effect — Key Points

- **Primary cause:** Burning fossil fuels (releases $CO_2$)
- More GHG ⇒ more IR absorbed ⇒ more back-radiation ⇒ higher $T_{\text{surface}}$
- **Positive feedback:** Warming ⇒ more evaporation ⇒ more $H_2O$ (GHG) ⇒ more warming
- **Ice-albedo feedback:** Warming ⇒ ice melts ⇒ lower albedo ⇒ more absorbed ⇒ more warming

### Increases warming

- Burning fossil fuels
- Deforestation
- Increased volcanic activity
- Livestock & agriculture

### Reduces warming

- Carbon capture & storage
- Nuclear / renewable energy
- Afforestation
- Increased $CO_2$ ocean solubility

**TRICK** Switching from gas to **nuclear** reduces GHG. Switching from gas to **oil** does **not** (both fossil fuels).

**TRAP** Increased solubility of $CO_2$ in the ocean **decreases** warming (removes $CO_2$ from atmosphere). Often tested in the "wrong" direction.

## Causes & Evidence

**Possible causes** — *natural:* solar-intensity/flare changes, orbital cycles, volcanic activity; *human:* extra $CO_2$ from fossil fuels (IPCC: accepted cause).

**Positive feedback** (amplifies warming): ice–albedo, water vapour, lower $CO_2$ ocean solubility, tundra/permafrost $CO_2$ release.

**Evidence** — Antarctic ice cores (e.g. Vostok): isotopes give past temperature, trapped air bubbles give past $CO_2$; $>$400 000 yr record shows temperature and $CO_2$ closely correlated.

FROM THE PHOTON QUESTION BANK

Rank electricity sources by $CO_2$ (nuclear/renewables cut it; gas$\rightarrow$oil does not); trace positive-feedback chains; link the ice-core temperature–$CO_2$ correlation to the enhanced greenhouse effect.