IB DP BIOLOGY

Theme D: Continuity and Change

D4.3 Climate Change

Revision Notes · Standard and Higher Level

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Original notes prepared for the IB Diploma Programme Biology course (2025 syllabus)

What the syllabus requires

By the end of D4.3 you should be able to explain the biological causes and consequences of climate change and evaluate the evidence for it. Use this list as a final checklist before the exam.

Understanding	You should be able to...
The greenhouse effect	Describe how greenhouse gases absorb and re-radiate long-wave infrared, and distinguish the natural effect from the enhanced effect.
Greenhouse gases	Identify the main gases (carbon dioxide, methane, water vapour, nitrous oxide), their relative contributions and their sources.
The carbon cycle	Outline the fluxes between reservoirs and explain how human activity has disturbed the balance.
Evidence	Interpret rising atmospheric carbon dioxide, temperature records, ice-core data and retreating ice as evidence for anthropogenic warming.
Consequences	Predict effects on species distribution, phenology, coral reefs and polar habitats.
Positive feedback	Explain feedback loops that amplify warming (ice-albedo, permafrost, reduced ocean solubility).
Mitigation	Describe strategies to reduce emissions and enhance carbon sinks, and the role of monitoring.

> **Exam note:** The core of D4.3 is common to SL and HL. Sections flagged **(HL)** add quantitative detail on feedback mechanisms and climate modelling and are examined only at Higher Level.

1. The natural greenhouse effect

The greenhouse effect is a natural and essential process. Without it the mean surface temperature of the Earth would be about −18 °C rather than the life-supporting ≈ +15 °C we observe. The effect arises from a difference in the wavelength of the radiation entering and leaving the atmosphere.

The mechanism, step by step

- Incoming solar radiation is mostly short-wave (visible and near-infrared). It passes largely unabsorbed through the atmosphere and warms the Earth's surface.
- The warmed surface re-emits energy, but as longer-wavelength (long-wave) infrared radiation, because the Earth is far cooler than the Sun.
- Greenhouse gas molecules in the atmosphere absorb this outgoing long-wave infrared. Their bonds vibrate, and they re-radiate the energy in all directions, including back towards the surface.
- This trapping and re-radiation slows the escape of heat to space and raises the equilibrium temperature of the surface and lower atmosphere.

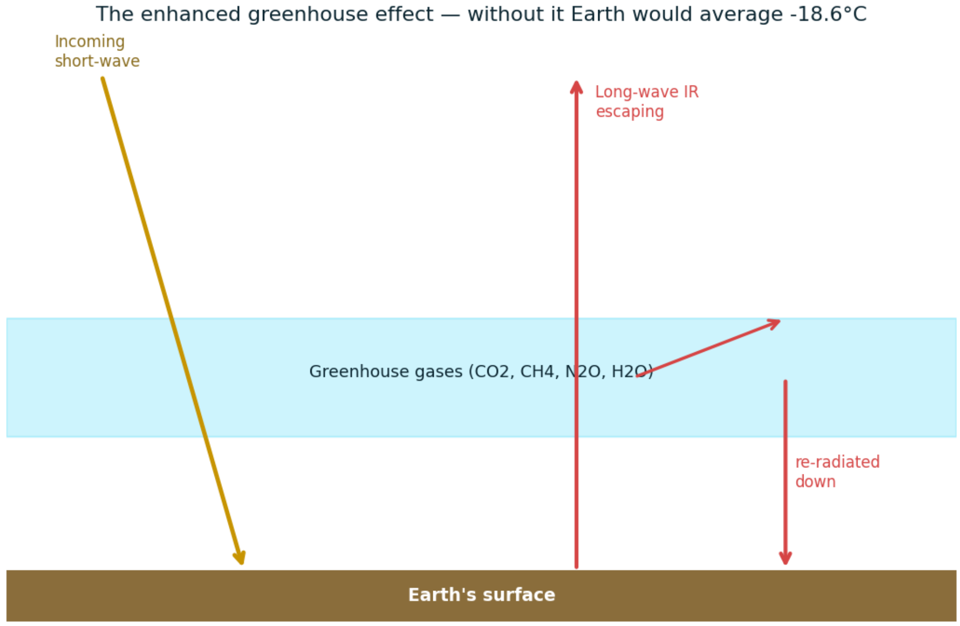

Figure 1. Short-wave solar radiation (solar constant 1361 W m^{-2}, albedo 0.30) warms the surface; the surface re-emits long-wave infrared, some of which greenhouse gases absorb and re-radiate back down. A simple radiative-balance calculation gives Earth's effective temperature without this trapping as ≈ -18.6°C, matching the value quoted in this section.

Why the wavelength matters

Greenhouse gases are transparent to short-wave radiation but absorb strongly in the infrared. This one-way filtering — letting energy in as short-wave but hindering its exit as long-wave — is the essence of the effect. Nitrogen and oxygen, which make up most of the atmosphere, do not absorb infrared and are not greenhouse gases.

> **Key distinction:** The **natural** greenhouse effect keeps the planet habitable. The **enhanced** greenhouse effect is the additional warming caused by human emissions raising greenhouse gas concentrations above their natural levels — this is the driver of climate change. Do not describe the greenhouse effect itself as harmful.

Weather is not climate

Weather is the state of the atmosphere at a place over hours or days; **climate** is the long-term average of weather, typically over thirty years or more. A single cold winter no more disproves warming than one hot day proves it. Climate change is detected in shifting averages and trends, not in individual events, though it does raise the frequency and intensity of many extremes.

2. Greenhouse gases and their sources

Several gases contribute to warming. Their overall impact depends both on how strongly each molecule absorbs infrared (its warming potential) and on how much of it is present. Carbon dioxide is the single most important driver of the enhanced effect because human activity releases it in enormous quantities.

Gas	Main human sources	Notes on contribution
Carbon dioxide (CO_2)	Combustion of fossil fuels (coal, oil, gas); deforestation and land clearance; cement production	Largest overall contributor to the enhanced effect; long atmospheric lifetime
Methane (CH_4)	Enteric fermentation in livestock; rice paddies; landfill; leaks from fossil-fuel extraction	Far stronger per molecule than CO_2 but shorter-lived and less abundant
Nitrous oxide (N_2O)	Nitrogen fertilisers and intensive agriculture; some industrial processes	Very strong per molecule; long-lived; a smaller total share
Water vapour (H_2O)	Not directly controlled by emissions; rises as the atmosphere warms	Powerful absorber; acts mainly as a feedback that amplifies other warming

Warming potential versus abundance

Methane and nitrous oxide trap much more heat per molecule than carbon dioxide, yet carbon dioxide dominates the total effect because it is emitted in vastly greater amounts and persists in the atmosphere for centuries. Water vapour is best treated as a feedback: warming increases evaporation, and the extra vapour adds further warming rather than acting as an independent cause.

> **Exam tip:** If asked to ‘name a greenhouse gas and give a source’, always pair them correctly, for example methane from livestock or carbon dioxide from burning fossil fuels. A gas named without a matching human source rarely gains full marks.

3. The carbon cycle and how humans disturb it

Carbon moves continuously between reservoirs (the atmosphere, oceans, living organisms, soils and rock). In an undisturbed system the fluxes between these reservoirs are roughly balanced, so atmospheric carbon dioxide stays fairly steady. Human activity has broken this balance.

Fluxes and sinks

- **Photosynthesis** removes carbon dioxide from the atmosphere and fixes it into organic compounds; **respiration**, **decomposition** and **combustion** return it.
- A **carbon sink** absorbs more carbon than it releases. The main sinks are the **oceans** (dissolved carbon dioxide and marine organisms), **forests** and other vegetation, and **peatlands** and soils where partly decomposed matter accumulates.
- **Fossil fuels** (coal, oil, gas) are carbon locked away from the atmosphere over hundreds of millions of years — an ancient store, not an active part of the fast cycle.

How humans have shifted the balance

- **Combustion of fossil carbon** transfers carbon from a long-term geological store into the atmosphere far faster than natural sinks can absorb it, so atmospheric concentration rises.
- **Deforestation** removes a sink and, when trees are burned or decay, releases their stored carbon as an additional source.
- **Draining peatlands** exposes stored organic carbon to oxygen, so it decomposes and releases carbon dioxide.

The result is a net flux of carbon into the atmosphere: emissions exceed the capacity of the sinks, and concentrations climb year on year.

> **Common confusion:** Burning wood and burning coal both release carbon, but wood carbon was fixed recently and can be re-absorbed by regrowth, whereas fossil carbon has been out of the active cycle for millions of years — which is why fossil-fuel use adds ‘new’ carbon to the fast cycle.

4. Evidence for anthropogenic climate change

The case that recent warming is human-driven rests on several independent lines of evidence that agree with one another.

Line of evidence	What it shows
Rising atmospheric CO_2	Continuous measurement (the idea behind the Keeling curve) shows CO_2 climbing from about 315 ppm in the late 1950s to over 420 ppm today, with a yearly saw-tooth from seasonal photosynthesis superimposed on a steep upward trend.
Temperature correlation	Global mean surface temperature has risen in step with CO_2, and the timing matches the acceleration of fossil-fuel use since industrialisation.
Ice-core data	Air bubbles trapped in polar ice record CO_2 and temperature over hundreds of thousands of years. They show the two have long moved together, and that present CO_2 is higher than at any point in that record.
Retreating ice	Shrinking glaciers, thinning Arctic sea ice and receding ice sheets provide direct physical evidence of warming.
Isotope signature	The proportion of carbon isotopes in atmospheric CO_2 is shifting in the way expected if the added carbon comes from fossil fuels, linking the rise specifically to human sources.

Reading the Keeling curve

The annual zig-zag comes from the seasonal rhythm of the large Northern Hemisphere land mass: carbon dioxide falls in the northern summer as plants photosynthesise and rises in winter as respiration and decomposition dominate. The important feature for climate is not the wiggle but the relentless upward slope beneath it.

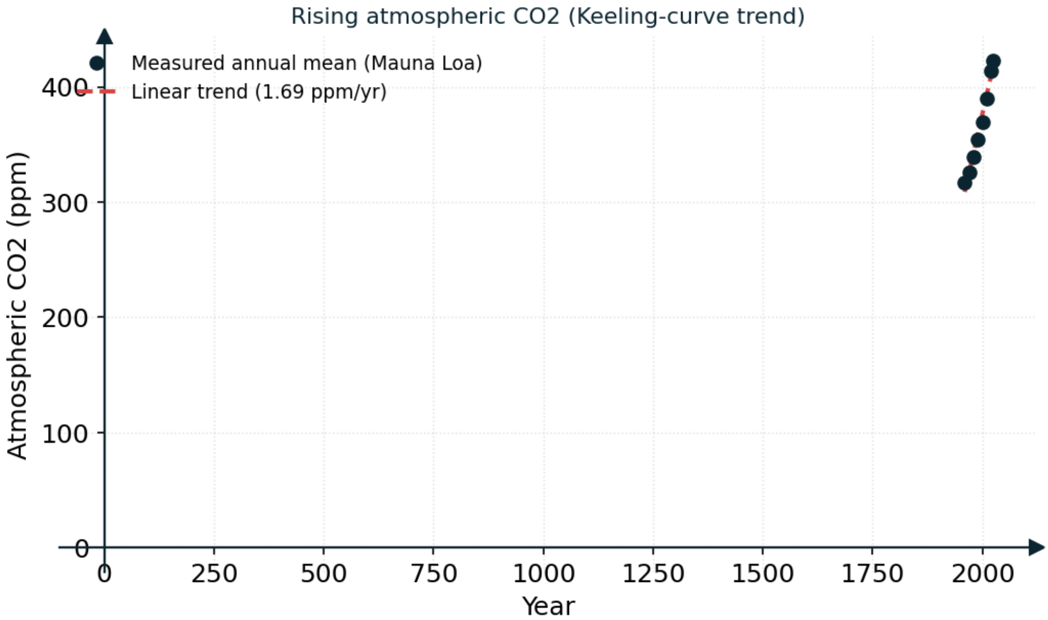

Figure 2. Atmospheric CO_2 (Mauna Loa annual means) from 1960 (317 ppm) to 2024 (423 ppm). Linear regression gives a mean rise of 1.69 ppm per year (R^2 = 0.980), a total increase of 106 ppm.

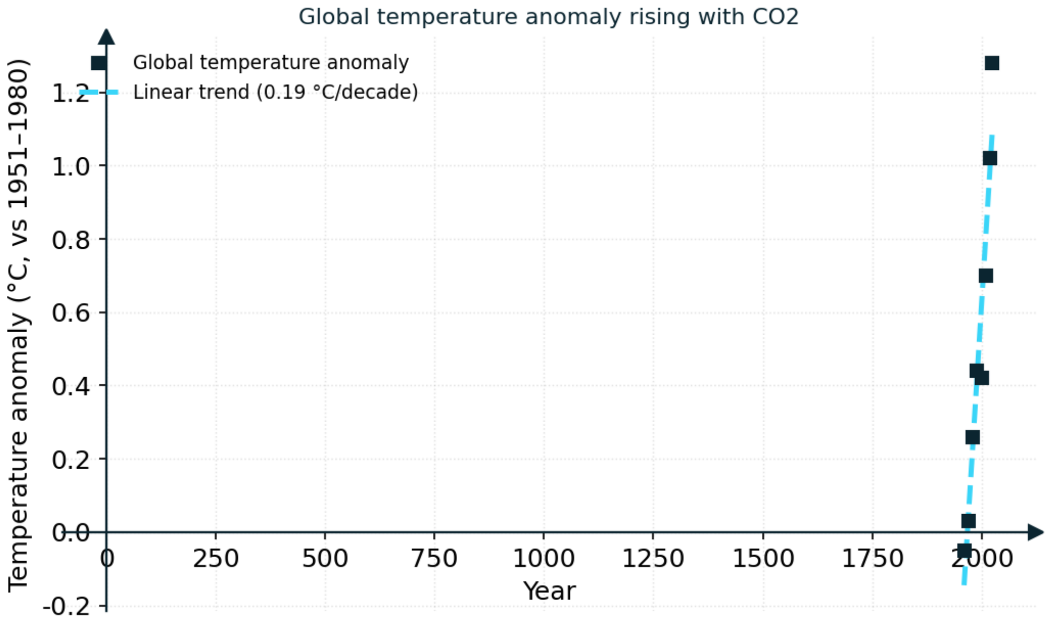

Figure 3. Global mean temperature anomaly rises at 0.19 °C per decade (linear regression, R^2 = 0.932), correlated with rising CO_2 (r = 0.984), consistent with the greenhouse mechanism in Section 1.

> **Correlation and causation:** A correlation between CO_2 and temperature is not by itself proof of cause. The link becomes convincing because there is a known physical **mechanism** (infrared absorption), the isotope evidence identifies the source, and multiple independent records agree. State the mechanism when arguing causation.

How ice cores record the past

As snow falls and compresses into glacial ice it traps tiny bubbles of the atmosphere of the time. Drilling deep cores and analysing these bubbles gives a direct sample of past CO_2 and CH_4 levels, while the ratio of oxygen isotopes in the ice itself acts as a thermometer for past temperature. Counting annual layers dates each sample. Cores from Antarctica extend this record back hundreds of thousands of years, allowing today's values to be judged against a long natural baseline rather than a few decades of instruments.

The records reveal natural glacial and interglacial cycles in which CO_2 and temperature rose and fell together. What marks the present as unusual is the speed and height of the recent CO_2 rise, which exceeds anything in the ice-core record and coincides with the industrial era.

5. Consequences for ecosystems and organisms

Warming and the associated changes in rainfall and ocean chemistry alter where and when organisms can live. Effects are already observable across many taxa.

Shifts in distribution

As isotherms move, many species track suitable conditions by shifting their ranges **polewards** (towards higher latitudes) and **upwards** (to higher altitudes on mountains). Species that cannot disperse fast enough, or that are already at a pole or mountain-top, have nowhere to go and face local extinction.

Changes in phenology

Phenology is the timing of seasonal biological events. Warmer springs bring earlier **flowering**, earlier insect emergence, earlier **breeding** in birds and amphibians, and shifted **migration**. When two interacting species respond at different rates, their timing can fall out of step — a **phenological mismatch**. A classic example is a bird whose chicks hatch after the peak abundance of the caterpillars they feed on, reducing breeding success.

Oceans: bleaching and acidification

- **Coral bleaching:** heat-stressed corals expel their symbiotic photosynthetic algae (zooxanthellae), lose their colour and their main food source, and die if stress is prolonged — devastating for reef biodiversity.
- **Ocean acidification:** dissolved CO_2 forms carbonic acid, lowering seawater pH and reducing the carbonate ions that corals, molluscs and many plankton need to build shells and skeletons.

Loss of polar and ice habitats

Species dependent on sea ice, such as polar bears and ice-breeding seals, lose the platform they hunt and rest on as ice retreats. Cold-adapted communities shrink as warmer-climate competitors move in.

> **Exam skill:** When asked to predict a consequence, name the organism or ecosystem, state the environmental change (temperature, pH, ice cover, timing), and then give the biological outcome (range shift, mismatch, mortality). A three-step answer scores reliably.

Why the rate of change matters

Species have always experienced a changing climate, but past natural changes were usually far slower, giving populations time to migrate or adapt through natural selection over many generations. The current rate is exceptionally rapid, so species with long generation times, poor dispersal, or specialised requirements are least able to keep pace. The result is expected to be a reshuffling of communities and a net loss of biodiversity, with generalist species faring better than specialists.

> **Link to natural selection:** Adaptation by natural selection needs heritable variation and time. Fast environmental change can outrun a population's ability to evolve, which is why rate, not just amount, of warming determines biological impact.

6. Positive feedback loops that amplify warming

A positive feedback loop is a process in which an initial change triggers effects that reinforce that same change. Several such loops make the climate system amplify warming rather than damp it.

Feedback loop	How it amplifies warming
Ice-albedo	Bright ice and snow reflect sunlight (high albedo). Warming melts them, exposing darker ocean or land that absorbs more radiation, which warms the surface further and melts still more ice.
Permafrost thaw	Frozen soils store vast amounts of organic carbon. Warming thaws them; microbes decompose the carbon and release CO_2 and CH_4, adding greenhouse gases that drive more warming.
Reduced ocean solubility	Gases are less soluble in warmer water. As the ocean warms it holds less CO_2, so it absorbs less of our emissions (and may even release some), leaving more in the atmosphere.
Water vapour	Warming raises evaporation; water vapour is itself a greenhouse gas, so the extra vapour adds further warming.

Because these loops reinforce one another, a relatively small initial forcing can produce a larger overall temperature change than the forcing alone would suggest. Some negative (damping) feedbacks exist, such as increased plant growth absorbing carbon, but the balance of evidence is that the net feedback amplifies warming.

> **Define it precisely:** In a **positive** feedback the output pushes the system further from its starting point (amplifying); in a **negative** feedback the output opposes the change (stabilising). ‘Positive’ here means self-reinforcing, not ‘good’.

Positive versus negative feedback at a glance

Type	Effect on the initial change	Climate example
Positive (amplifying)	Reinforces and enlarges it	Ice-albedo; permafrost thaw releasing CO_2 and CH_4
Negative (stabilising)	Opposes and reduces it	Extra warmth and CO_2 boosting plant growth, absorbing some carbon

The concern for climate is that the dominant feedbacks in the current system are positive, so the planet responds to a given forcing with more warming than the forcing alone would produce, and some loops risk crossing thresholds beyond which they continue on their own.

7. Mitigation and response

Responses to climate change fall into two broad categories: reducing the emission of greenhouse gases, and increasing their removal by strengthening carbon sinks. Monitoring underpins both by tracking whether measures are working.

Reducing emissions

- Replacing fossil fuels with **renewable energy** (solar, wind, hydro, geothermal) and nuclear power, which release little or no CO_2.
- Improving **energy efficiency** and reducing consumption in transport, industry and buildings.
- Changing agricultural practice to cut methane and nitrous oxide, for example better livestock and fertiliser management.

Enhancing carbon sinks

- **Reforestation and afforestation** increase the biomass fixing CO_2 through photosynthesis (carbon sequestration).
- **Protecting and restoring peatlands, wetlands and coastal ‘blue carbon’ habitats** preserves large existing carbon stores.
- **Carbon capture and storage** aims to remove CO_2 and lock it away underground.

Monitoring

Long-term measurement of atmospheric CO_2, satellite tracking of ice and vegetation, and temperature records allow scientists to detect trends, test climate models and evaluate whether mitigation is having an effect. International agreements coordinate emission targets across countries.

> **Balanced evaluation:** Strong answers weigh benefits against limits: reforestation stores carbon but takes decades and competes for land; renewables cut emissions but need investment and storage. Recognising trade-offs shows genuine understanding.

Adaptation alongside mitigation

Mitigation tackles the cause by limiting warming; **adaptation** reduces the harm from warming that is already unavoidable. Biological and practical examples include establishing habitat corridors so species can shift range, protecting and connecting reserves along temperature gradients, breeding heat- and drought-tolerant crop varieties, and restoring wetlands as natural flood buffers. Adaptation and mitigation are complementary, not alternatives.

8. (HL) Feedback mechanisms and climate modelling

At Higher Level you are expected to reason more quantitatively about feedbacks and about how climate models are built and used.

Feedback strength and tipping points

Each feedback can be described by a gain: the fraction by which it multiplies an initial temperature change. Positive feedbacks with combined gain below one produce a finite, amplified but stable response. A **tipping point** is a threshold beyond which a feedback becomes self-sustaining and the change continues even if the original forcing is removed — for example large-scale permafrost thaw or ice-sheet collapse. Such changes may be effectively irreversible on human timescales.

Climate sensitivity

Equilibrium climate sensitivity is the eventual global temperature rise expected from a doubling of atmospheric CO_2. Its value depends chiefly on the sum of the feedbacks: water vapour and ice-albedo push it up, while some cloud responses are uncertain. This uncertainty in feedbacks is the main reason different models give a range of projections.

How models work

- Models divide the atmosphere and oceans into a three-dimensional grid and apply physical laws (energy balance, fluid motion, gas exchange) to each cell over small time steps.
- They are **validated** by testing whether they reproduce past and present climate (for example ice-core records and the observed temperature rise) before being used to project future scenarios.
- Because the future depends on human choices, models are run under several **emission scenarios**, producing a range rather than a single prediction.

> **(HL) Watch for:** A feedback amplifies but need not run away; only past a tipping point does it become self-sustaining. Keep 'amplification' and 'tipping point' distinct in your answers.

9. Worked examples and exam skills

Worked example 1 — interpreting a CO■ versus temperature graph

A graph shows atmospheric CO_2 (ppm) and global mean temperature anomaly (°C) both rising from 1900 to the present. Describe the relationship and explain how it supports the idea of human-caused warming.

Describe: both variables rise over the period and the two curves are strongly positively correlated — as CO_2 increases, temperature increases.

Explain: CO_2 is a greenhouse gas that absorbs and re-radiates long-wave infrared, so a rise in its concentration is expected to raise surface temperature. The increase in CO_2 coincides with expanding fossil-fuel combustion, linking the warming to human activity.

Caution: correlation alone is not proof; the argument is convincing because a physical mechanism connects the two, not merely because the lines rise together.

Worked example 2 — explaining a named feedback loop

Explain how the ice-albedo feedback amplifies warming.

Step 1: rising temperature melts reflective sea ice and snow.

Step 2: the exposed ocean or land is darker and has lower albedo, so it absorbs more incoming solar radiation instead of reflecting it.

Step 3: this extra absorbed energy warms the surface further, which melts still more ice.

Because the outcome (more warming) reinforces the initial cause, the loop is a **positive feedback** that amplifies the original warming.

Worked example 3 — linking a greenhouse gas to its source

Livestock farming is said to contribute to climate change. Identify the gas involved and explain the link.

The gas is **methane (CH_4)**, produced by microbial fermentation in the digestive systems of ruminant animals such as cattle (enteric fermentation) and released when they belch.

Methane is a potent greenhouse gas: per molecule it absorbs far more infrared than CO_2, so increasing livestock numbers raises atmospheric methane and enhances the greenhouse effect.

Worked example 4 — predicting an ecosystem consequence

A mountain plant is restricted to cool conditions near a summit. Predict the effect of regional warming on this species.

As temperature rises, the band of suitable cool climate shifts to higher altitude. The plant can track it by moving **upslope**, but near the summit the available area shrinks.

If warming continues, suitable habitat disappears from the top of the mountain, the population has nowhere higher to go, and the species faces local extinction — an example of a range being squeezed off a mountain-top.

Worked example 5 — reasoning from ice-core data

An ice core shows that over the last 800,000 years CO_2 stayed between about 180 and 300 ppm, yet today it exceeds 420 ppm. What can be concluded, and what assumption must be checked?

Conclude: present CO_2 is well above the natural range of the last 800,000 years, so the current level is exceptional rather than part of a normal cycle. The rapid rise coincides with industrial fossil-fuel use.

Check: that the ice-core samples reliably represent the past atmosphere (trapped bubbles are not contaminated and layers are dated correctly). Because independent cores from different sites agree, this assumption is well supported.

10. Common pitfalls

- Describing the greenhouse effect as harmful — the natural effect is essential; it is the **enhanced** effect that causes climate change.
- Confusing short-wave incoming with long-wave outgoing radiation, or saying greenhouse gases block sunlight coming in.
- Treating correlation between CO_2 and temperature as proof without citing the infrared-absorption mechanism.
- Calling a feedback 'positive' as if it were beneficial — it means self-reinforcing, and here it worsens warming.
- Naming a greenhouse gas without a matching human source, or crediting carbon dioxide with the strongest per-molecule effect (methane and nitrous oxide are stronger per molecule).
- Confusing ocean warming with ocean acidification — bleaching is caused by heat stress, acidification by dissolved CO_2 lowering pH.
- Forgetting that fossil-fuel carbon is 'new' to the fast cycle, unlike carbon from recently living material.

11. Quick reference

Idea	Statement
Natural greenhouse effect	Greenhouse gases absorb outgoing long-wave infrared and re-radiate it; keeps Earth about 33 °C warmer than it would otherwise be.
Enhanced effect	Extra warming from human emissions raising greenhouse gas levels; the cause of climate change.
Main gases	CO_2 (fossil fuels, deforestation), CH_4 (livestock, rice, landfill), N_2O (fertilisers), water vapour (feedback).
Carbon sinks	Oceans, forests, peatlands; humans add carbon faster than sinks remove it.
Evidence	Rising CO_2 (Keeling curve), temperature correlation, ice cores, retreating ice, isotope signature.
Consequences	Poleward/upward range shifts, phenological mismatch, coral bleaching, acidification, loss of ice habitat.
Positive feedbacks	Ice-albedo, permafrost thaw, reduced ocean CO_2 solubility, water vapour.
Mitigation	Cut emissions (renewables, efficiency), enhance sinks (reforestation, peat protection, capture), monitor.

12. Test yourself

Attempt these without notes; full answers follow.

1. Explain why the greenhouse effect depends on the difference in wavelength between incoming and outgoing radiation.

2. Distinguish clearly between the natural and the enhanced greenhouse effect.

3. Name three greenhouse gases and give one human source of each.

4. Explain how burning fossil fuels disturbs the carbon cycle, referring to sinks and fluxes.
5. State two independent lines of evidence for anthropogenic climate change and say what each shows.
6. Explain what a phenological mismatch is, using a named example.
7. Describe the ice-albedo feedback and explain why it is described as positive.
8. (HL) Distinguish between amplification by a feedback and a tipping point.

Answers

1. Incoming solar radiation is mostly short-wave and passes through the atmosphere to warm the surface. The surface re-emits energy as long-wave infrared, which greenhouse gases absorb and re-radiate. The gases are transparent to short-wave but opaque to long-wave, so energy enters more easily than it leaves, warming the surface.

2. The natural effect is the warming from naturally present greenhouse gases that keeps Earth habitable ($\approx +15$ °C rather than -18 °C). The enhanced effect is the additional warming from human emissions raising gas concentrations above natural levels, and it is what drives climate change.

3. For example: carbon dioxide from burning fossil fuels; methane from livestock (or rice paddies or landfill); nitrous oxide from nitrogen fertilisers. (Each gas correctly paired with a human source.)

4. Fossil fuels are a long-term carbon store outside the fast cycle. Combustion is a flux that releases this carbon as CO_2 into the atmosphere faster than sinks (oceans, forests, peat) can absorb it. The balance between source and sink fluxes is broken, so atmospheric CO_2 rises.

5. Any two, for example: rising atmospheric CO_2 measured continuously (the Keeling curve) shows concentration climbing with a seasonal wobble; ice cores show CO_2 and temperature have moved together for hundreds of thousands of years and that present CO_2 is unusually high. (Retreating ice and isotope evidence are also acceptable.)

6. A phenological mismatch occurs when the timing of seasonal events in two interacting species shifts by different amounts, so they fall out of step. Example: if warmer springs make caterpillars peak earlier but insect-eating birds do not advance their breeding as much, chicks hatch after peak food, reducing survival.

7. Warming melts reflective ice and snow, exposing darker ocean or land with lower albedo that absorbs more solar radiation; this warms the surface further and melts more ice. It is positive because the outcome reinforces the original warming (self-reinforcing), not because it is beneficial.

8. (HL) Amplification means a feedback multiplies an initial temperature change but the system still settles to a new stable state and stops if the forcing is removed. A tipping point is a threshold beyond which a feedback becomes self-sustaining, so change continues even without the original forcing and may be effectively irreversible.