REVISION GUIDE

A planet running a *fever*

Climate change

Carbon dioxide on Mauna Loa has climbed every year since 1958. Here is why the extra greenhouse gas warms the planet, how the warming feeds itself, and what it is already doing to penguins, reefs, forests and the timing of spring.

12 chapters · a dry lab

The interactive guide, with every animation:

biologybybradford.com/guides/ib-biology-d4-3-climate-change

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By the end you can

- [ ] Explain how human emissions of carbon dioxide and methane cause climate change, and tell correlation from causation in the ice core record D4.3.1
- [ ] Describe five positive feedback cycles that speed up global warming D4.3.2
- [ ] Explain how a boreal forest can flip from storing carbon to losing it, as an example of a tipping point D4.3.3
- [ ] Explain how melting landfast ice and sea ice threaten emperor penguins and walruses D4.3.4
- [ ] Explain how warmer surface water reduces nutrient upwelling and primary production in the sea D4.3.5
- [ ] Describe poleward and upslope range shifts, using birds in New Guinea and North American trees D4.3.6
- [ ] Distinguish ocean acidification from coral bleaching, and explain how they threaten coral reefs D4.3.7
- [ ] Evaluate afforestation, forest regeneration and peat restoration as ways to sequester carbon D4.3.8
- [ ] Explain how photoperiod and temperature cue the timing of biological events D4.3.9
- [ ] Explain how climate change breaks the synchrony between linked species, with reindeer and great tits D4.3.10
- [ ] Explain why warmer years give spruce bark beetles more generations in a year D4.3.11
- [ ] Explain how changing snow cover has changed the colour of tawny owls in Finland by natural selection D4.3.12

Tick each one when you can do it without the book.

01

D4.3.1 ANTHROPOGENIC CAUSES OF CLIMATE CHANGE

The blanket we keep *thickening*

Sunlight passes through the atmosphere and warms the ground and the sea. The warm surface gives the energy off again as infrared, and some of that infrared is absorbed by **greenhouse gases**, which re-emit it in every direction, some of it back down. That is the **greenhouse effect**, and without it the Earth would average about −18 °C instead of about 15 °C.

Climate change is the trouble we have made by adding to it. **Anthropogenic** carbon dioxide comes mostly from burning coal, oil and gas, with more from clearing and burning forests and from making cement. Anthropogenic methane comes from cattle and sheep (microbes in their guts make it), flooded rice fields, landfill sites, and leaks from gas wells and coal mines. Methane is a far more powerful greenhouse gas than carbon dioxide molecule for molecule, but there is much less of it and it lasts only about a decade in the air.

Charles Keeling began measuring carbon dioxide on Mauna Loa, Hawaii, in 1958. It was about 315 parts per million then and passed 420 ppm in 2023. The Keeling curve rises every year and wiggles every year as the forests of the northern hemisphere take carbon dioxide up in summer and give it back in winter.

KEY TERMS

greenhouse gases
Gases in the atmosphere that absorb and re-emit infrared radiation given off by the Earth's surface, such as carbon dioxide, methane and water vapour.

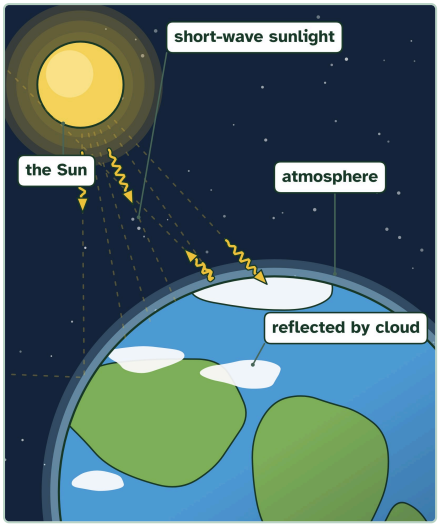
greenhouse effect
The warming of the Earth's surface and lower atmosphere because greenhouse gases absorb and re-emit infrared radiation from the surface.

anthropogenic
Caused by human activity.

ANIMATION · TRAPPING THE HEAT

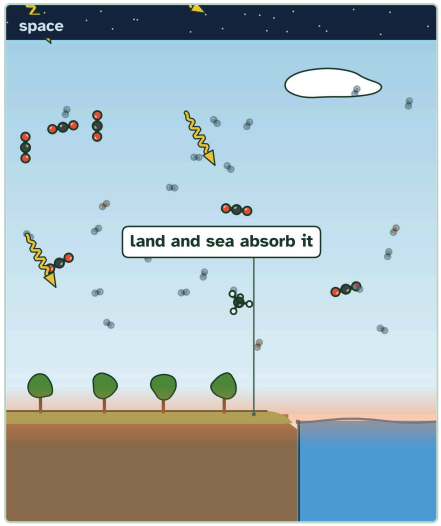
8 MOMENTS

1 SUNLIGHT IN



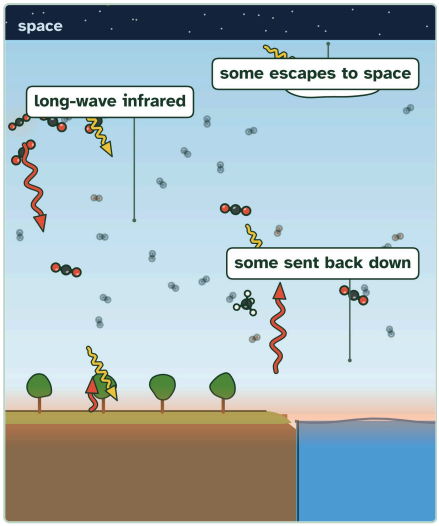
Sunlight streams in from the Sun as **short-wave radiation**. Clouds, snow and ice reflect some of it straight back to space.

2 ABSORBED



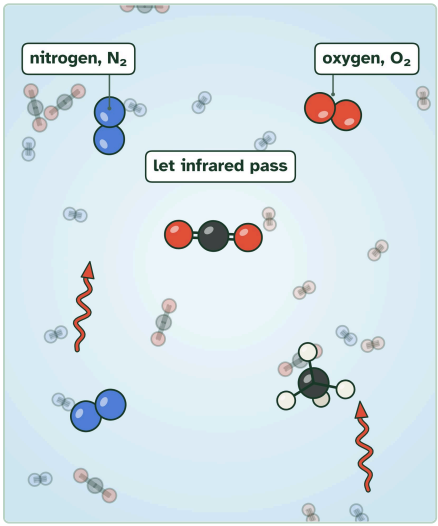
The rest passes through the air and is **absorbed** by the land and the sea, which warm up.

3 INFRARED OUT



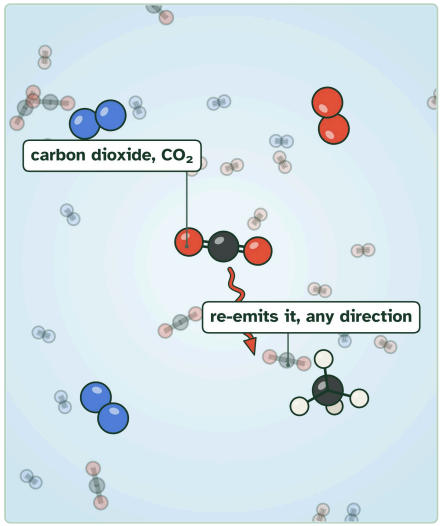
The warm surface gives off **long-wave infrared**. Some escapes to space; some is sent back down by gases in the air.

4 INTO THE AIR



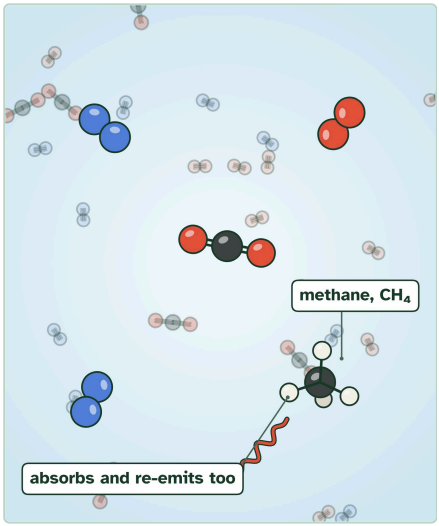
Zoom into the air. **Nitrogen** and **oxygen**, almost all of it, let infrared pass straight through.

5 CARBON DIOXIDE



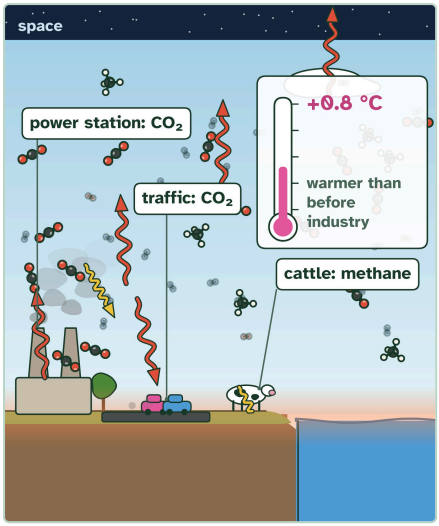
A **carbon dioxide** molecule absorbs the infrared and vibrates, then gives it out again in any direction: some back down.

6 METHANE



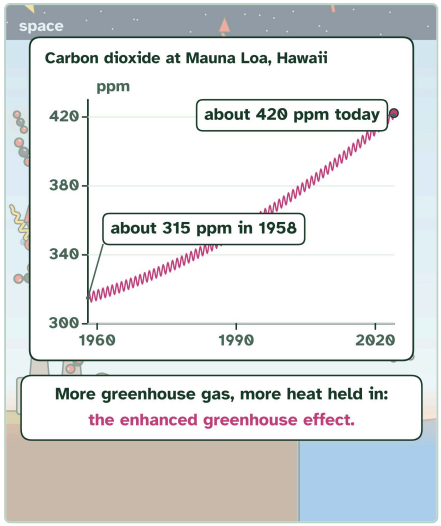
Methane does the same. Gases that absorb and re-emit infrared hold heat near the ground: the **greenhouse effect**.

7 MORE GAS



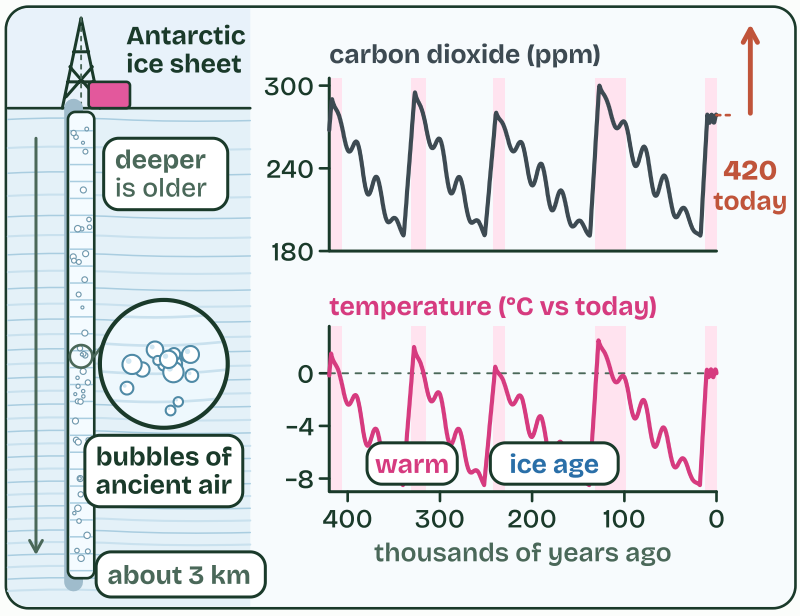
Burning coal, oil and gas adds **carbon dioxide**; cattle, rice paddies and landfill add **methane**. More infrared comes back down.

8 MAUNA LOA



At Mauna Loa, carbon dioxide has risen from about 315 ppm in 1958 to about 420 ppm today. More greenhouse gas, more heat held in: the **enhanced greenhouse effect**.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-d4-3-climate-change#causes



PREDICT

Ice cores from Antarctica show that over 800 000 years, temperature and carbon dioxide rose and fell together. What does this correlation show on its own?

(A) That carbon dioxide in the air is the cause of every rise in the temperature

(B) That the two are linked, but not which one causes the other, or whether a third factor drives both

(C) That the temperature changes are the cause of all the changes in carbon dioxide

Decide before you look. Answer on page 39.

REMEMBER IT

Where the extra methane comes from

C Cows	R Rarely	L Leave	G Gas
Cattle and sheep microbes in the gut, out by belching	**Rice paddies** waterlogged soil, no oxygen	**Landfill** rotting rubbish, buried	**Gas and coal** leaks from wells, pipes and mines

IN THE EXAM

Correlation and causation:

1. A **positive correlation**: both variables increase together. A **negative correlation**: one increases as the other decreases.
2. A correlation does not prove that one variable causes the other.
3. For carbon dioxide and temperature, **other evidence** confirms the cause: carbon dioxide absorbs infrared, shown in the lab and seen from satellites.

02

D4.3.2 POSITIVE FEEDBACK CYCLES IN GLOBAL WARMING

Warming that makes *more* warming

A **positive feedback** cycle is one where a change sets off effects that make the same change bigger. Global warming has several, and each one turns a warming into a faster warming.

Loss of snow and ice. Snow and ice reflect most of the sunlight that hits them (a high **albedo**). When the Arctic sea ice melts, the dark ocean beneath absorbs that light instead and warms, which melts more ice.

Carbon dioxide from the deep ocean. Cold water holds more dissolved gas than warm water. As the ocean warms it holds less carbon dioxide, and some that was stored in deep water returns to the air.

Peat and permafrost. Peat is plant matter that never decomposed because it was waterlogged; **permafrost** holds the remains of plants frozen for thousands of years. Warmer and drier, both start to decompose and release carbon dioxide, and thawing, waterlogged permafrost releases **methane**.

Droughts and forest fires. Hotter summers dry out forests, and more and bigger fires burn, releasing the carbon in the trees and soil.

KEY TERMS

positive feedback
A cycle in which a change causes effects that increase the original change, so it speeds up.

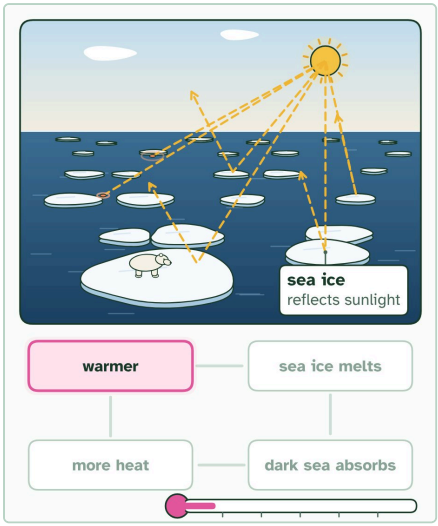
albedo
The fraction of the sunlight falling on a surface that is reflected. Fresh snow reflects about 80 to 90%, open ocean under 10%.

permafrost
Ground that stays frozen all year, for at least two years in a row. It covers about a quarter of the land in the northern hemisphere.

ANIMATION · WARMING THAT FEEDS ITSELF

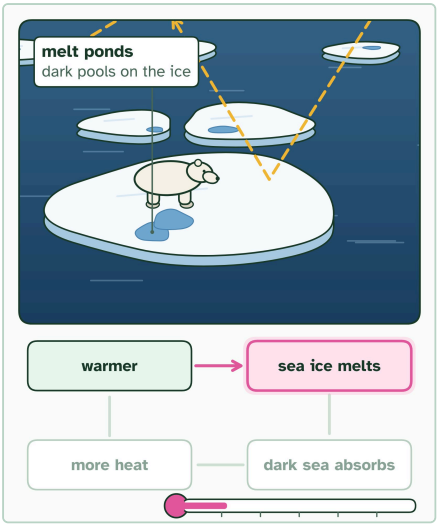
16 MOMENTS

1 SEA ICE



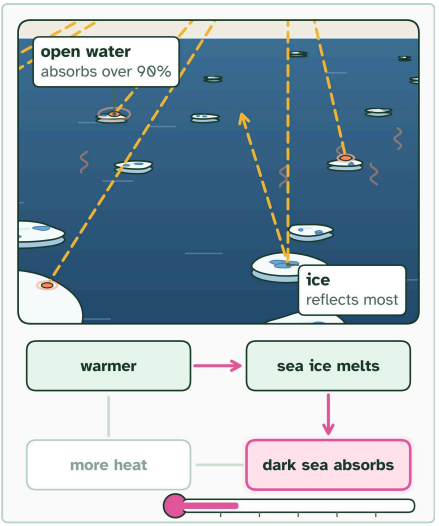
The Arctic Ocean in summer. Bright **sea ice** reflects most of the sunlight that reaches it straight back out to space.

2 SEA ICE



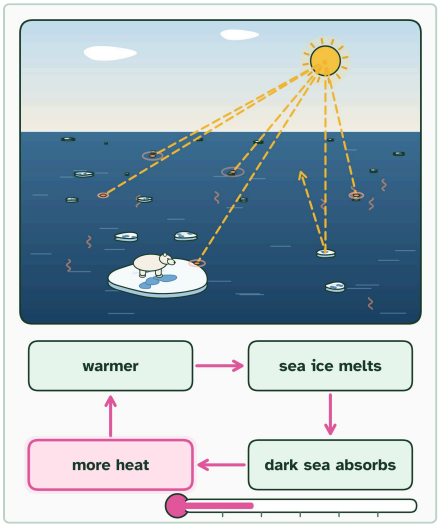
As the Arctic warms, the ice **melts**: pools of meltwater spread over the floes, and they shrink and break apart.

3 SEA ICE



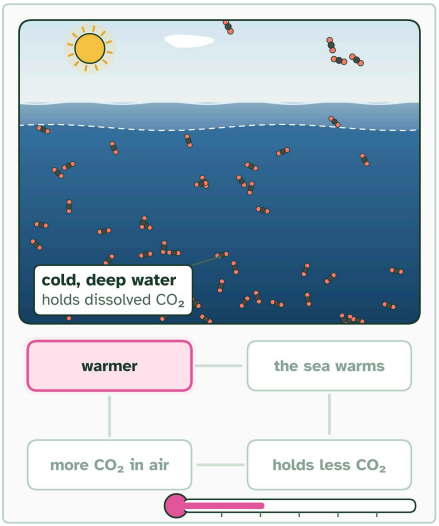
Dark open water reflects only a few percent of the sunlight. It **absorbs** the rest, and the sea warms.

4 SEA ICE



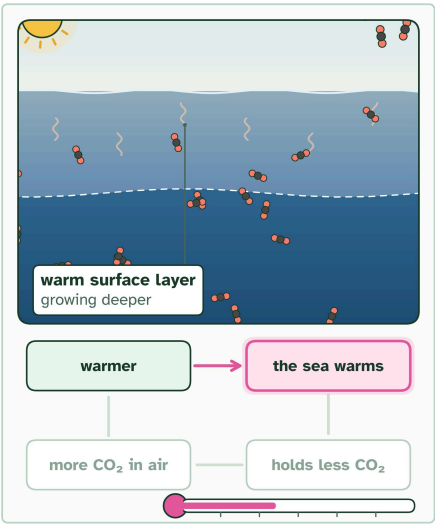
A warmer sea melts more ice, which lets in more heat: a **positive feedback**. The change speeds itself up.

5 OCEAN



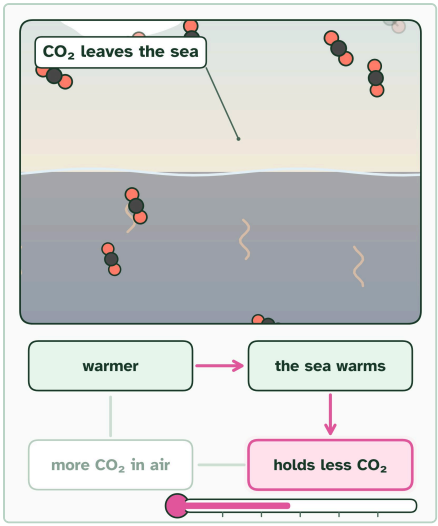
The ocean holds a vast store of dissolved **carbon dioxide**, much of it in cold, deep water.

6 OCEAN



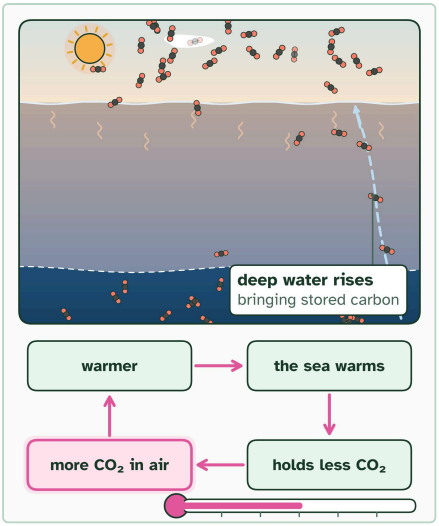
As the air warms, so does the sea, from the surface down.

7 OCEAN



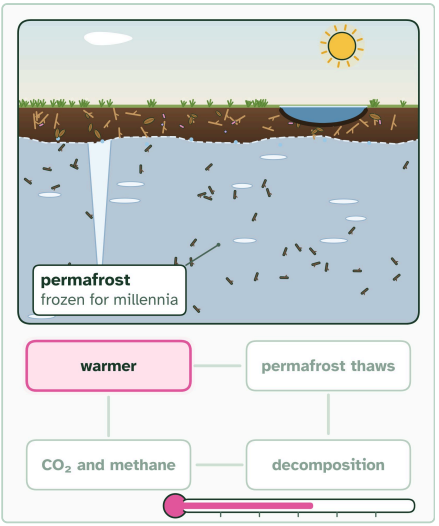
Warm water holds **less dissolved gas** than cold, so carbon dioxide leaves the warming sea, and deep water brings stored carbon back up.

8 OCEAN



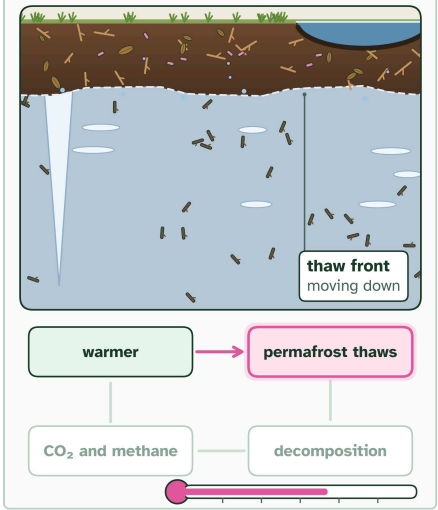
More carbon dioxide in the air traps more heat and warms the sea further: a **positive feedback**.

9 PERMAFROST



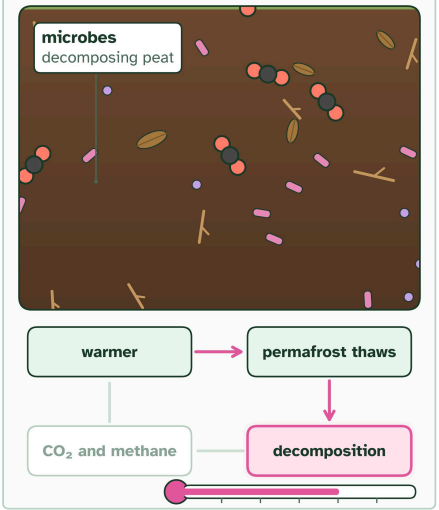
Under the tundra lies **permafrost**: ground frozen for thousands of years, full of the remains of plants that never decomposed.

10 PERMAFROST



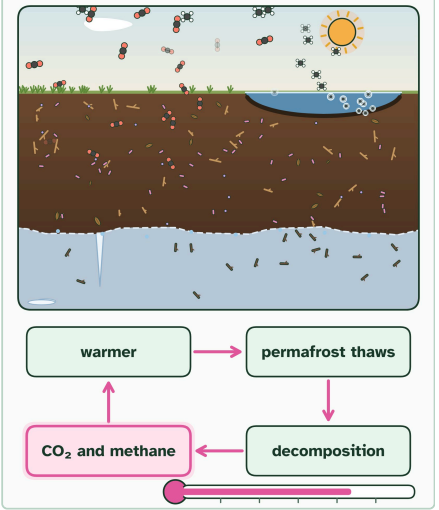
Warmer summers thaw it deeper each year. The ice in the ground melts, and **peat** that was frozen or waterlogged starts to rot.

11 PERMAFROST



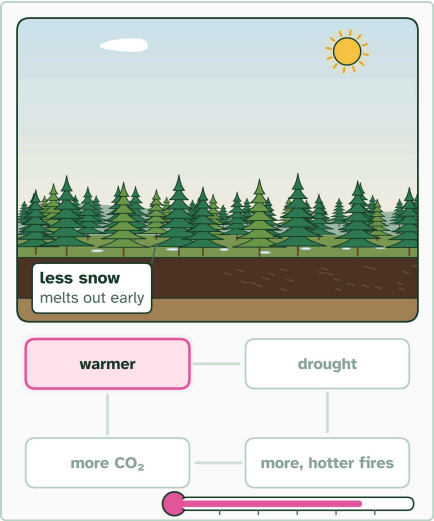
Microbes decompose the thawed matter and give off **carbon dioxide**; in waterlogged mud with no oxygen, they make **methane**.

12 PERMAFROST



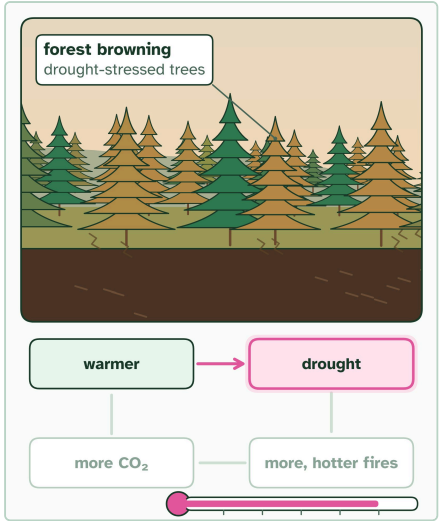
More greenhouse gas means more warming and a deeper thaw: a **positive feedback**.

13 FOREST FIRE



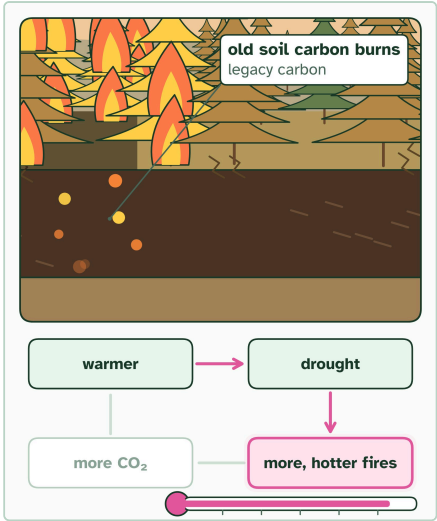
The boreal forest: spruce and larch on cold soil packed with carbon. Warmer winters bring **less snow**.

14 FOREST FIRE



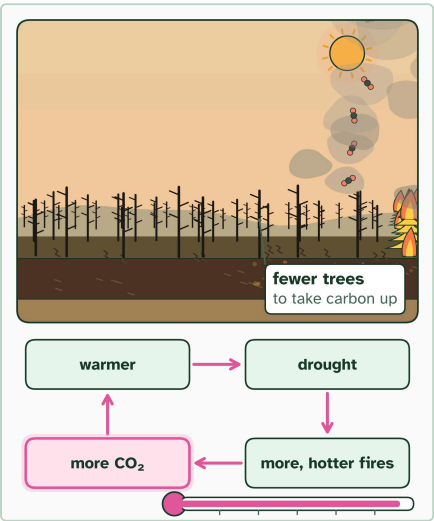
With less snowmelt and hotter summers, the soil dries out. **Drought** cuts photosynthesis, and the trees turn brown.

15 FOREST FIRE



Dry, dying trees burn: fires come **more often and burn hotter**, down into old carbon stored in the soil.

16 FOREST FIRE



The fires release **carbon dioxide**, and fewer trees are left to take it up: more warming, more drought, more fire.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-d4-3-climate-change#feedback

REMEMBER IT

The five feedback loops

I	O	P	P	F
Icy	Oceans	Push	Polar	Fires
Ice and snow	**Ocean**	**Peat**	**Permafrost**	**Fires and drought**
less reflected, more absorbed	warm water holds less CO_2	dries out and decomposes	thaws, releases CO_2 and methane	burn stored carbon

PREDICT

Why is the thawing of permafrost a positive feedback, not a negative one?

(A) The water from the melted ice cools the ground and slows down any further thawing

(B) Decomposers break down the thawed organic matter, releasing greenhouse gases that cause more warming and more thawing

(C) The plants that grow on thawed ground take up carbon dioxide faster than it is ever released

Decide before you look. Answer on page 39.

D4.3.3 CHANGE FROM NET CARBON ACCUMULATION TO NET LOSS IN BOREAL FORESTS AS AN EXAMPLE OF A TIPPING POINT

03 When a forest stops *storing* carbon

The **taiga**, or boreal forest, runs in a belt across Canada, Alaska, Scandinavia and Siberia. For thousands of years it has taken in more carbon than it gives out: the trees grow, and the cold, waterlogged soil and peat keep dead matter from decomposing. It holds more carbon than any other land biome, most of it in the soil.

Warming changes that. Summers are hotter and winters bring less snow, so there is less meltwater in spring and the soil dries. Drought stress cuts photosynthesis, so **primary production falls**, and stands of trees turn brown and die back, called **forest browning**. Dry, dead trees burn, and fires become more frequent and more intense.

An intense fire burns more than the trees. It burns down into the soil and peat, through organic matter that had survived earlier, lighter fires for centuries. Burning that old store is called **legacy carbon combustion**. Once a forest loses more carbon in fires and decomposition than it gains by growth, it has flipped from a net **sink** to a net **source** of carbon. That is a **tipping point**: the forest now speeds up the warming that tipped it.

KEY POINTS

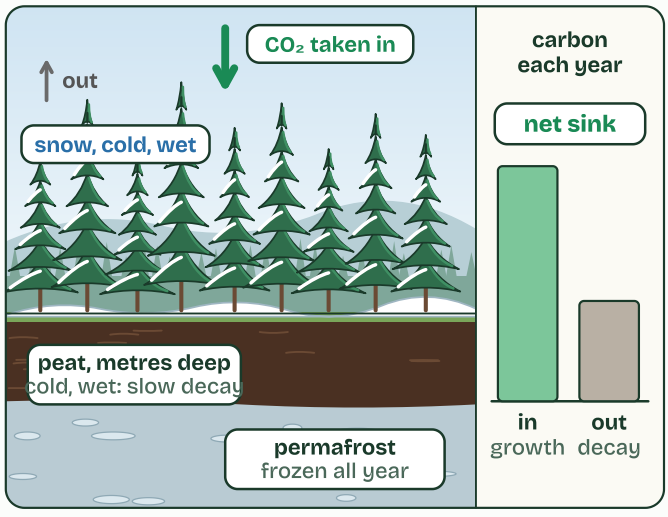
- Warmer temperatures and less winter snow: more **drought**.
- Drought: less **primary production**, forest **browning**.
- More frequent, more intense **fires**: **legacy carbon combustion**.
- Net carbon **accumulation** flips to net carbon **loss**: a tipping point.

KEY TERMS

taiga
The boreal forest of conifers (spruce, pine, larch, fir) across the far north of North America, Europe and Asia, with long cold winters.

legacy carbon combustion
The burning of soil carbon that had escaped earlier fires, often for centuries, when a fire is hot or deep enough to reach it.

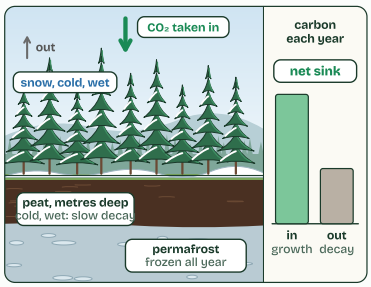
tipping point
A threshold beyond which a system changes to a different state, often suddenly and hard to reverse.



SWITCH IT

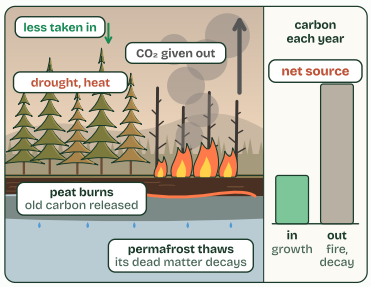
2 SETTINGS

1



Storing carbon

2



After the tipping point

PREDICT

Fires have always burned in the taiga. Why does legacy carbon combustion matter so much?

(A) It produces far more smoke, which blocks sunlight and makes the climate much colder

(B) It releases carbon that had been stored for centuries, so the forest loses carbon that regrowth cannot quickly replace

(C) It kills the seeds of conifers, so no trees can ever grow back on the burnt ground again

Decide before you look. Answer on page 39.

04 Standing on ice that *leaves early*

D4.3.4 MELTING OF LANDFAST ICE AND SEA ICE AS EXAMPLES OF POLAR HABITAT CHANGE

Emperor penguins (*Aptenodytes forsteri*) breed in the depth of the Antarctic winter, on **landfast ice**: sea ice frozen fast to the coast. The female lays one egg in May or June, the male holds it on his feet through the winter, and the chick must grow its waterproof feathers before the ice breaks up in December or January. If the ice breaks out early, the chicks fall into the sea before they can swim, and drown or freeze.

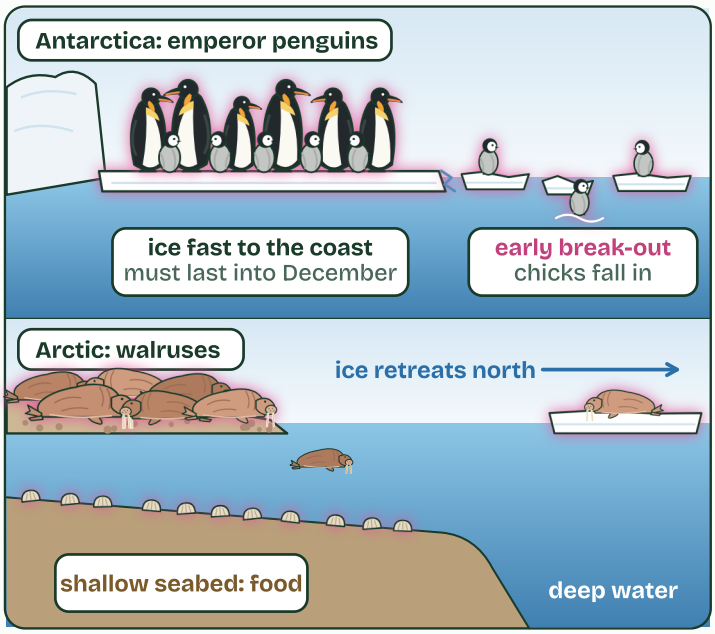
That is what happened at Halley Bay, then the second-largest colony, which failed almost completely from 2016 onwards. In 2022, four of the five colonies in the central Bellingshausen Sea lost nearly every chick when the ice melted early. Emperors can move to a new site, but if the landfast ice goes from much of the coast, there is nowhere left to go.

In the Arctic, walruses (*Odobenus rosmarus*) feed on clams and worms on the shallow seabed and rest on floating **sea ice** between dives. As summer sea ice retreats north, beyond the shallow feeding grounds of the Chukchi Sea, walruses haul out on land instead, tens of thousands together on beaches such as Point Lay in Alaska. They have to swim much farther to feed, and in a crowd that panics, calves are crushed.

KEY TERMS

landfast ice
Sea ice that is attached to the coast, to the sea floor in shallow water, or to grounded icebergs, so it does not drift.

sea ice
Ice formed when sea water freezes, floating on the ocean. Arctic summer sea ice has shrunk by about 13% a decade since 1979.



Landfast ice Sea ice frozen fast to the coast, so it does not drift. The colony needs it to last from about April until the chicks fledge in December or January.

Emperor penguins Emperor penguins (*Aptenodytes forsteri*) breed through the Antarctic winter on landfast ice. The male holds the egg on his feet for about two months while the female feeds at sea.

Early break-out If storms or warm water break the ice up before the chicks have their waterproof feathers, they fall into the sea and drown or freeze. Halley Bay failed from 2016, and four of five colonies in the Bellingshausen Sea in 2022.

Sea ice Walruses rest on floating sea ice between dives, close to their food. Arctic summer sea ice has shrunk by about 13% a decade since 1979, and now retreats beyond the shallow shelf.

Walruses on land With the summer sea ice far to the north, walruses (*Odobenus rosmarus*) haul out on beaches, tens of thousands together, as at Point Lay in Alaska. In a stampede, calves are crushed.

Food on the seabed Walruses feed on clams and worms on the shallow seabed. From a beach they must swim much farther to reach it, using energy they would have saved resting on ice nearby.

PREDICT

Why does an early break-up of landfast ice harm emperor penguins, even if the ice forms again the next winter?

(A) The adults can no longer reach their feeding grounds in the open sea once the ice is gone

(B) Chicks without waterproof feathers fall into the sea before they can swim, so that year's breeding fails

(C) The eggs are laid later in the year, so the chicks hatch in the coldest part of winter

Decide before you look. Answer on page 39.

IN THE EXAM

Polar habitat change:

1. **Landfast ice** (Antarctic): breeding ground of the emperor penguin; early break-out drowns chicks before they fledge.
2. **Sea ice** (Arctic): resting platform for walruses between feeding dives; its loss forces them onto land, far from food.

05

D4.3.5 CHANGES IN OCEAN CURRENTS ALTERING THE TIMING AND EXTENT OF NUTRIENT UPWELLING

When the deep water stops *rising*

Phytoplankton need light, which they find only near the surface, and nitrate, phosphate and iron, which sink to the deep ocean in dead organisms and droppings. Where winds blow surface water away from a coast, cold, nutrient-rich water rises from below to replace it. This **upwelling** feeds the phytoplankton, and with them some of the richest fisheries in the world: anchovies off Peru, sardines off California and South Africa.

Warming the surface makes it lighter than the cold water below. The layers stop mixing (the water becomes **stratified**), and winds have to work harder to bring deep water up. Upwelling can weaken, start later in the season or stop altogether. With fewer nutrients, **primary production falls**, and less energy flows up the food chain to fish, seabirds and mammals.

An El Niño shows what this looks like. Warm water spreads east across the Pacific, the upwelling off Peru shuts down, and the anchovy catch crashes, as it did in 1972 and 1983.

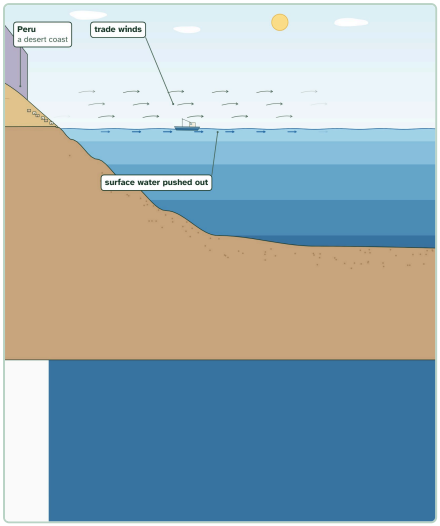
KEY TERMS

upwelling
The rise of cold, nutrient-rich water from the deep ocean to the sunlit surface, usually where wind pushes surface water away from a coast.

ANIMATION · WIND, UPWELLING AND ANCHOVIES

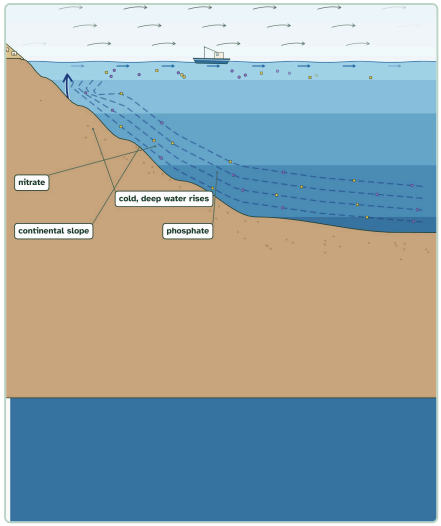
6 MOMENTS

1 THE COAST OF PERU



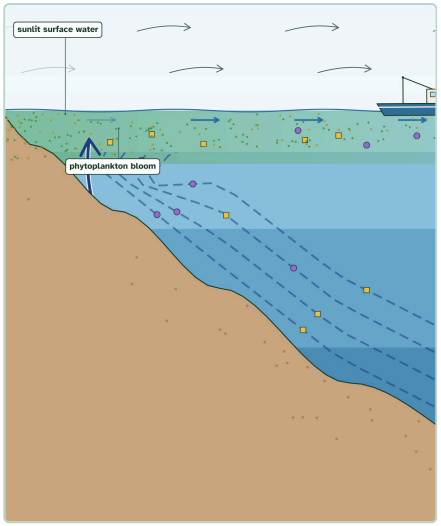
Off the desert coast of Peru, the **trade winds** blow along the shore and drive the surface water out to sea.

2 UPWELLING



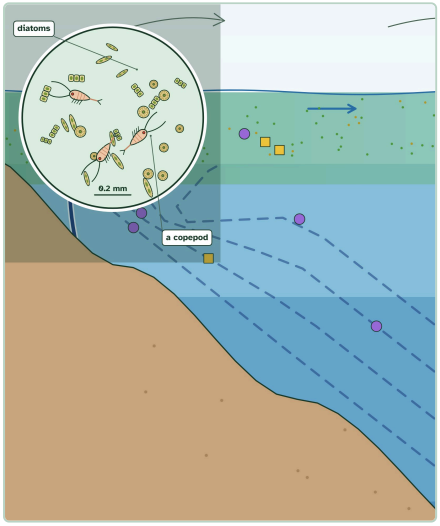
Cold water rises from the deep to replace it: **upwelling**. It brings up **nitrate and phosphate** released as dead matter sank and decayed.

3 THE BLOOM



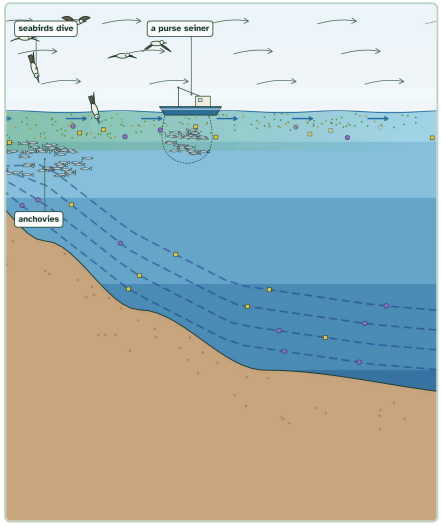
In the sunlit surface, **phytoplankton** use the nutrients and multiply until the sea turns green: some of the highest primary production in any ocean.

4 A DROP OF WATER



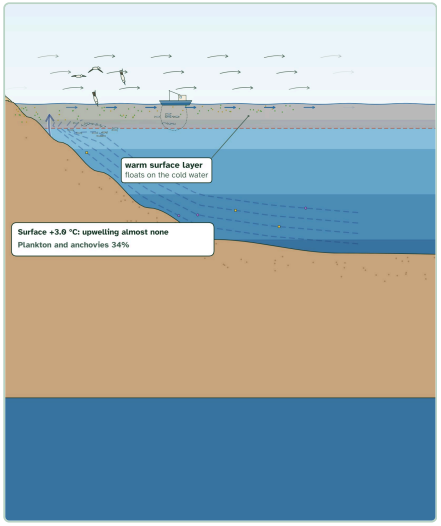
One drop of that water: **diatoms** and other phytoplankton, and **zooplankton** such as copepods grazing on them.

5 THE FISHERY



Vast shoals of **Peruvian anchovies** eat the plankton; seabirds dive for the anchovies, and the boats net them: one of the largest fisheries on Earth.

6 A WARM YEAR



Now warm the surface, as in a strong **El Niño** year: warm, light water floats on the cold, the layers stop mixing and the upwelling almost stops. Plankton and anchovies crash.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-d4-3-climate-change#upwelling

PREDICT

Why does warm surface water reduce primary production in the sea, when warmth usually speeds photosynthesis up?

(A) Warm water holds much less dissolved carbon dioxide, which phytoplankton need for photosynthesis

(B) A warm surface layer floats on the cold water and stops nutrients rising, so phytoplankton run short of nitrate and phosphate

(C) Warm water lets far less sunlight through it, so phytoplankton near the surface get too little light

Decide before you look. Answer on page 39.

06

D4.3.6 POLEWARD AND UPSLOPE RANGE SHIFTS OF TEMPERATE SPECIES

Moving *uphill* to stay cool

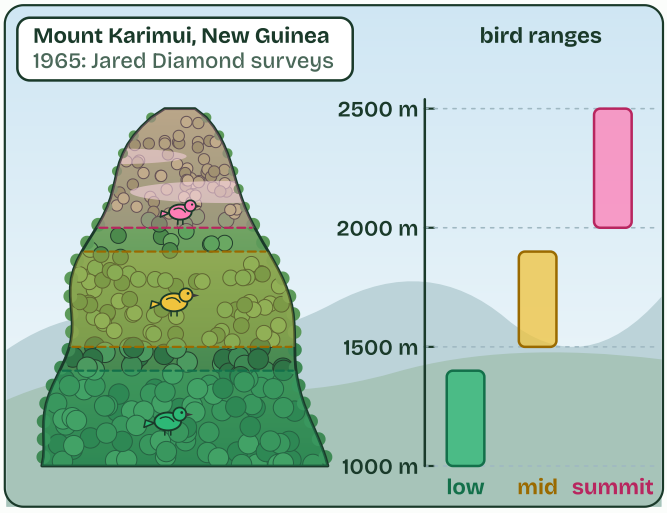
Every species lives within a range of temperatures it can tolerate. As the climate warms, the places within that range move: towards the poles, and up mountains, where it is cooler. Populations follow by dispersal. A species spreads where its new range opens and dies out where its old one closes. That is a **range shift**.

On Mount Karimui in Papua New Guinea, Jared Diamond recorded the elevations of the birds in 1965. Ben and Alexandra Freeman surveyed the same slope in 2012. Most of the species had moved uphill, on average by around 100 metres, about what the 0.4 °C of local warming would predict. Species already at the summit had nowhere to go, and some had shrunk to a strip at the very top.

In North America, tree species are not moving north as neat belts. Surveys comparing seedlings (where trees are establishing now) with adult trees (where they established decades ago) find many species spreading north at their cold edge, but more of them contracting at their warm edge, with few new seedlings there, so their ranges are shrinking overall. Trees spread slowly, by seed, one generation at a time, and the climate is moving faster.

KEY TERMS

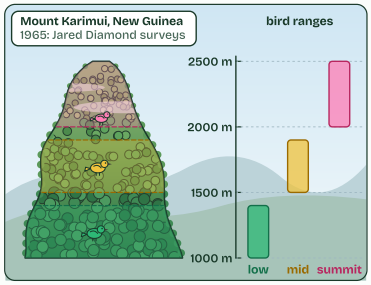
range shift
A change in where a species is found, as populations spread into newly suitable places and die out in places that have become unsuitable.



SWITCH IT

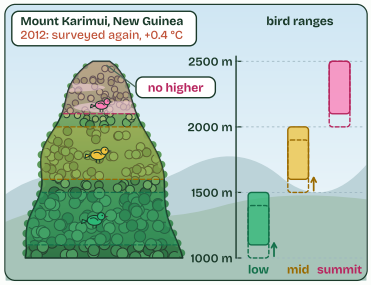
2 SETTINGS

1



1965

2



2012

PREDICT

A bird lives only near the top of a mountain in New Guinea. Why is it more at risk from warming than a bird that lives halfway up?

(A) Birds at higher altitude breed less often, so their populations take longer to recover

(B) As it moves upslope its range shrinks, because there is less land higher up, and at the summit it has nowhere left to go

(C) The air near the summit warms faster than the air further down the mountain slopes

Decide before you look. Answer on page 39.

07 Two threats to a *reef*

D4.3.7 THREATS TO CORAL REEFS AS AN EXAMPLE OF POTENTIAL ECOSYSTEM COLLAPSE

A coral reef is built by tiny animals, coral polyps, that lay down skeletons of calcium carbonate. Inside the cells of each polyp live photosynthetic algae, **zooxanthellae**, which give the coral most of its food in return for shelter and the coral's waste nutrients. A quarter of all marine species live on reefs, in less than 1% of the ocean.

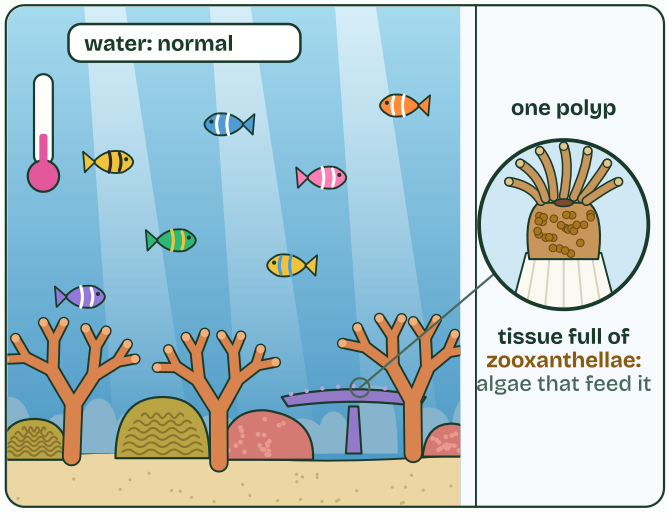
Ocean acidification. About a quarter of the carbon dioxide we release dissolves in the sea. There it forms carbonic acid, which lowers the pH and uses up carbonate ions. Corals need carbonate ions to build their skeletons, so with fewer of them, **calcification is suppressed**: skeletons grow more slowly and are weaker. The sea's surface pH has fallen from about 8.2 to 8.1 since 1750, a rise of about 30% in hydrogen ions.

Coral bleaching. When the water stays 1 °C or more above the usual summer maximum for weeks, the zooxanthellae are damaged and the coral expels them. Without them it turns white, and it starves. If the heat ends soon, the algae can return; if not, the coral dies. The Great Barrier Reef bleached on a mass scale in 1998, 2002, 2016, 2017, 2020, 2022 and 2024.

Dead coral is covered by seaweed and broken down by waves and burrowing animals. The fish and invertebrates that depended on its shelter go, and the reef ecosystem **collapses**.

KEY TERMS

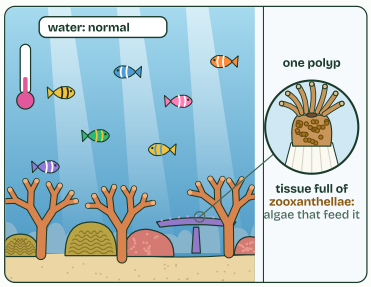
zooxanthellae
Single-celled algae (dinoflagellates) that live inside coral cells, give the coral sugars from photosynthesis and give it its colour.



SWITCH IT

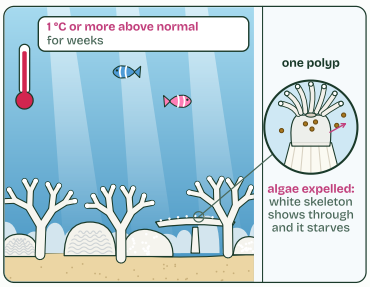
3 SETTINGS

1



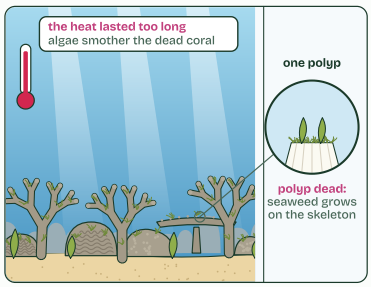
Healthy

2



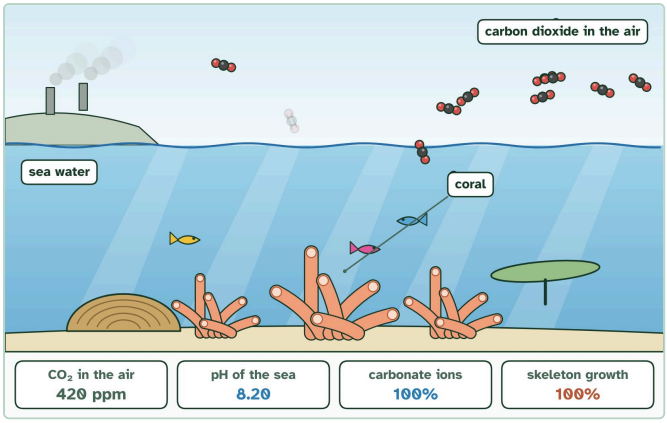
Bleached

3



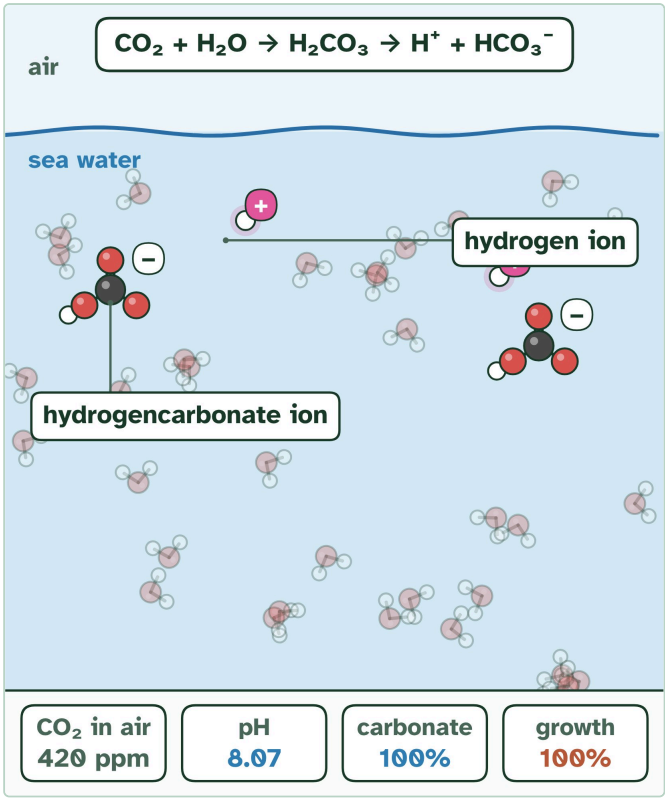
Dead

1 420 PPM: THE REEF



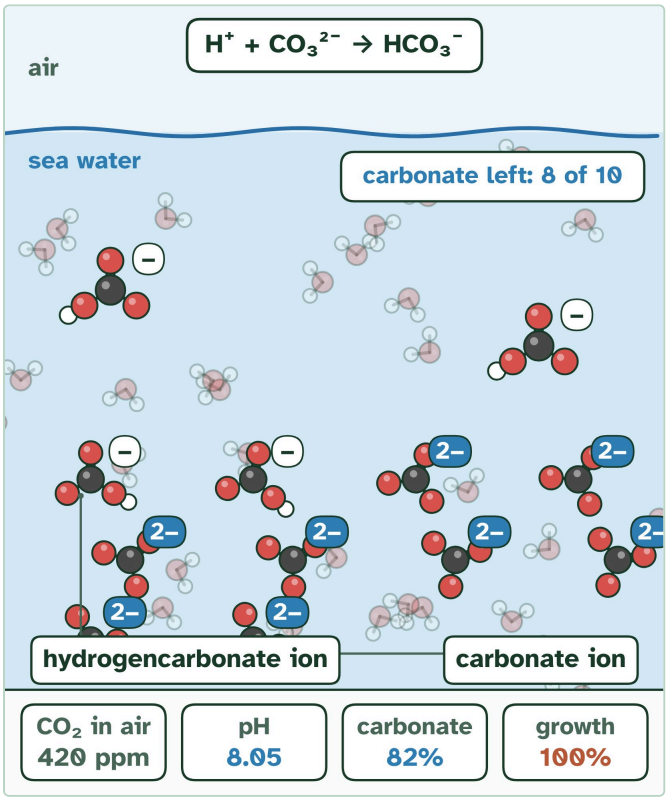
The air now holds 420 ppm of carbon dioxide, up from 280 in 1750. The oceans take up about a quarter of what we release, so more dissolves than comes back out.

2 420 PPM: SURFACE WATER



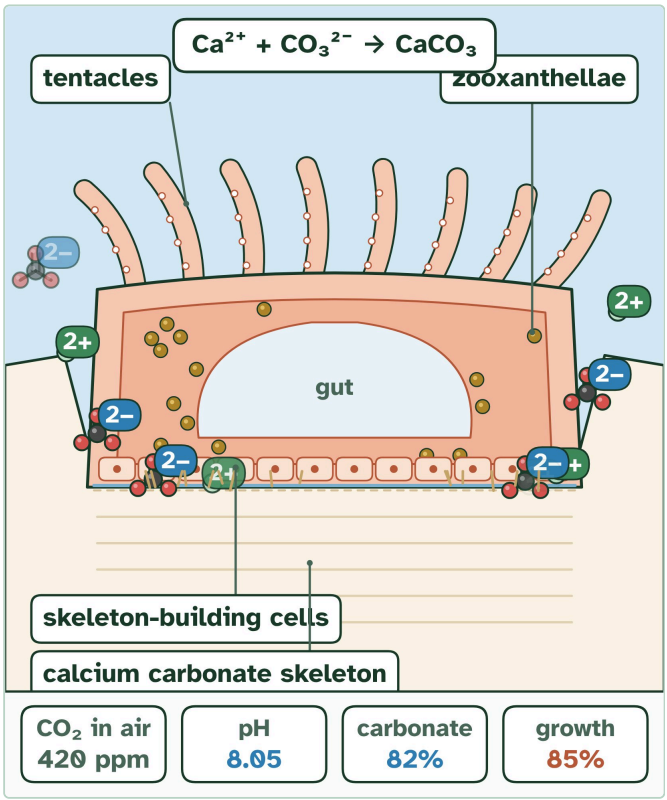
Zoom into the surface water. Dissolved carbon dioxide reacts with water to make **carbonic acid**, which releases **hydrogen ions**. More hydrogen ions means a lower pH: down from about 8.2 to 8.05. The sea is still alkaline, but less so: **ocean acidification**.

3 420 PPM: CARBONATE IONS



Hydrogen ions combine with **carbonate ions**, turning them into hydrogencarbonate ions. About 18% of the carbonate is gone.

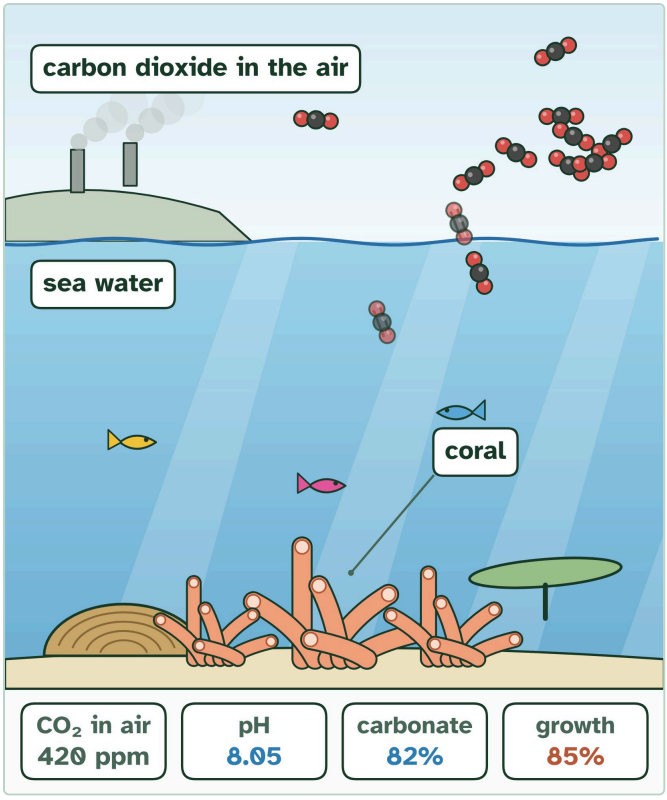
4 420 PPM: ONE POLYP



A coral polyp, cut open. The cells at its base take **calcium** and **carbonate ions** from the sea water and lay down **calcium carbonate** skeleton. With less carbonate it grows more slowly, about 85% of the old rate.

5

420 PPM: THE REEF



Acidification adds to warming, which bleaches corals. A reef that grows more slowly than waves and animals wear it down shrinks.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-d4-3-climate-change#coral

PREDICT

Which change causes coral bleaching?

(A) A lower pH in the sea water, which dissolves the calcium carbonate of the coral skeleton

(B) A rise in water temperature that lasts for weeks, which makes the coral expel its zooxanthellae

(C) More carbon dioxide in the water, which the zooxanthellae cannot use for their photosynthesis

Decide before you look. Answer on page 39.

IN THE EXAM

Keep the two causes apart:

1. Increased **carbon dioxide**: ocean **acidification**, fewer carbonate ions, **calcification suppressed**.
2. Increased **water temperature**: **bleaching**, the zooxanthellae are expelled and the coral starves.
3. Loss of corals: **collapse** of the reef ecosystem.

D4.3.8 AFFORESTATION, FOREST REGENERATION AND RESTORATION OF PEAT-FORMING WETLANDS AS APPROACHES TO CARBON SEQUESTRATION

08 Putting carbon *back* in the ground

Carbon sequestration takes carbon dioxide out of the air and locks it away. Three ways use living things to do it.

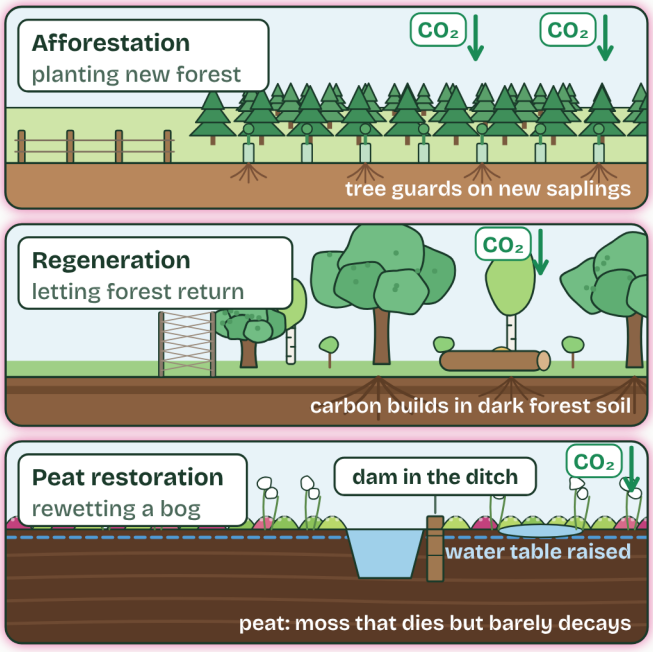
Afforestation is planting trees where there has been no forest for a long time. **Forest regeneration** is letting a forest grow back, or helping it to, where it was cleared or burnt. Growing trees take up carbon dioxide in photosynthesis and store the carbon in wood and roots, and in the soil as their leaves decay.

Restoring peat-forming wetlands means raising the water table again in a drained bog, often by blocking the drainage ditches. Peat forms when plants such as *Sphagnum* moss die in waterlogged, acidic, oxygen-poor water, where decomposers can barely work, so their carbon builds up. Peat forms naturally in the cool, wet temperate and boreal zones, and very fast in some tropical swamps, such as those of Borneo and the Congo basin. Peatlands cover 3% of the land but hold about twice as much carbon as all the world's forests.

Plantation of fast-growing non-native trees	Rewilding with native species
Takes up carbon fast while young (Sitka spruce in Scotland, eucalyptus in Brazil)	Grows more slowly at first, but builds a store that lasts
Often harvested every 30 to 50 years, which sends much of the carbon back	Left standing, so the carbon stays in old trees and soil
One species: little habitat, and at risk from one pest or disease	Many species: habitat for wildlife, and more resilient
Planting on peat or grassland can release more soil carbon than the trees take up	Fits the soils and the ecosystem already there

KEY TERMS

carbon sequestration
Taking carbon dioxide out of the atmosphere and storing it for a long time, for example in wood, soil or peat.



Afforestation Planting trees on land that has not been forest for a long time, such as old pasture. The trees take in carbon dioxide and store carbon in wood, roots and soil. Fast-growing non-native conifers take carbon in quickly, but are often felled within 50 years.

Peat restoration Blocking the drainage ditches of a drained bog raises the water table again. In waterlogged, acidic, oxygen-poor peat, *Sphagnum* moss dies but barely decays, so carbon builds up year after year. Peatlands cover 3% of the land but hold about twice as much carbon as all the world's forests.

Forest regeneration Letting a cleared or burnt forest grow back, from seeds and stumps in the soil, or helping it with planting and keeping grazers out. Native trees of mixed ages and species build a store that lasts and makes habitat for wildlife.

PREDICT

Scientists still argue whether plantations or native forests are better for carbon. Why can't a quick measurement settle it?

(A) Nobody has a reliable method to measure how much carbon a living tree is holding

(B) The answer depends on the time scale and on what happens later, such as harvesting, fires, pests and the soil carbon lost in planting

(C) Native forests and plantations always store exactly the same carbon over their lifetimes

Decide before you look. Answer on page 40.

09 Reading the *calendar* of nature

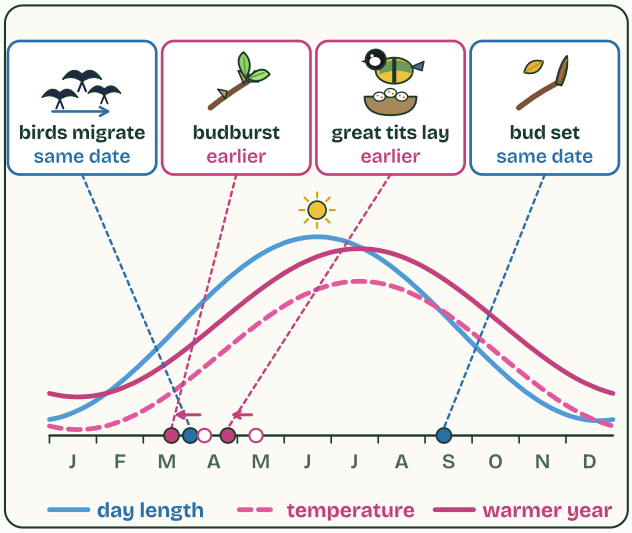
D4.3.9 HL PHENOLOGY AS RESEARCH INTO THE TIMING OF BIOLOGICAL EVENTS

Phenology is the study of when things happen in nature: when buds burst and leaves fall, when plants flower, when birds arrive, nest and leave. Some of the longest records in science are phenological. Robert Marsham noted the first signs of spring on his estate in Norfolk from 1736, and his family kept it up for nearly two centuries. The court in Kyoto recorded the day the cherry trees flowered for over a thousand years.

Organisms time these events by cues from the environment. **Photoperiod**, the length of the day, is the same on a given date every year, so it is a reliable calendar. **Temperature** varies from year to year, but it tracks the season as it actually arrives. Many deciduous trees need a run of warm days to set off **budburst** in spring, while **bud set** in autumn, when they stop growing and form winter buds, is often triggered by shortening days. Many birds start migrating as the days lengthen, and lay their eggs when spring warmth has arrived.

KEY TERMS

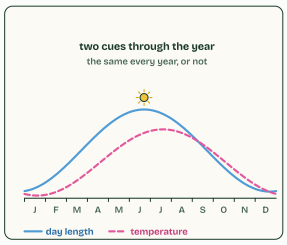
phenology
The study of the timing of recurring biological events, such as flowering, budburst, migration and nesting, and how climate affects them.



STEP BY STEP

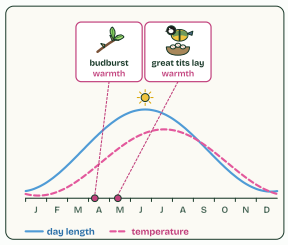
4 STEPS

1



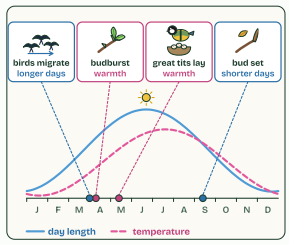
Two cues. Day length follows the same curve every year. Temperature follows the season as it actually comes, and differs from year to year.

2



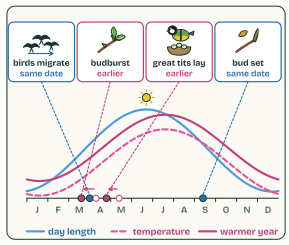
Cued by warmth. Budburst in many trees, and egg laying in many birds, follow a run of warm days.

3



Cued by day length. Birds start migrating as the days lengthen; trees set their winter buds as the days shorten.

4



A warmer year. The warmth-cued events move earlier. The day-length events stay put, so the two can fall out of step.

PREDICT

Which cue would let a tree burst its buds earlier in a warm spring, and later in a cold one?

(A) Photoperiod, because the length of the day changes as the spring arrives each year

(B) Temperature, because it differs between years, while day length on a given date is always the same

(C) Neither cue, because trees open their buds on a fixed date set by an internal clock

Decide before you look. Answer on page 40.

10 Arriving after the *feast*

D4.3.10 HL DISRUPTION TO THE SYNCHRONY OF PHENOLOGICAL EVENTS BY CLIMATE CHANGE

Within one ecosystem, one population may time its year by temperature and another by photoperiod. While the climate was steady, the two kept in step. As it warms, the temperature-cued events move earlier and the photoperiod-cued ones do not, and the two drift apart: a **phenological mismatch**.

In West Greenland, the Arctic mouse-ear chickweed (*Cerastium arcticum*) and other tundra plants grow in spring as the temperature rises, and grow earlier as the Arctic warms. Reindeer (*Rangifer tarandus*) migrate to their calving grounds timed by day length, so they arrive on the same date as before. By then the plants are past their best, the calves get less nutritious food, and fewer survive.

In the oak woods of northern Europe, winter moth caterpillars hatch as the oak leaves open, timed by temperature, and reach a peak of biomass in a burst of two or three weeks. Great tits (*Parus major*) need that peak to feed their chicks, and time their laying partly by day length. In warm springs the caterpillar peak has moved earlier than the birds' breeding, and chicks hatch after the feast. Wytham Woods near Oxford, where great tits have been studied since 1947, has shown the birds laying earlier, but not always by enough.

KEY POINTS

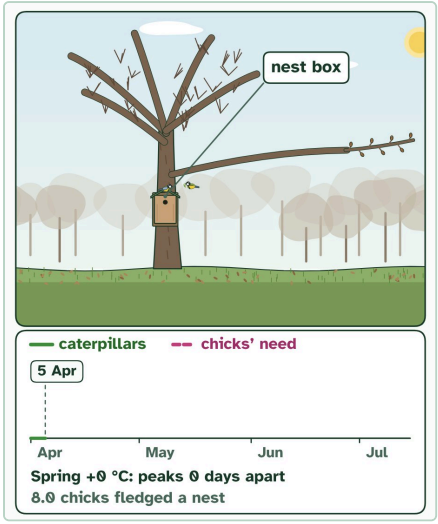
- Temperature cue: the event shifts earlier as the climate warms.
- Photoperiod cue: the event stays on the same date.
- Two linked populations on different cues fall out of **synchrony**.
- Examples: chickweed and **reindeer** in Greenland; caterpillars and **great tits** in European oak woods.

KEY TERMS

phenological mismatch
A loss of synchrony between the timing of linked events in two populations, such as a predator's breeding and the peak of its prey.

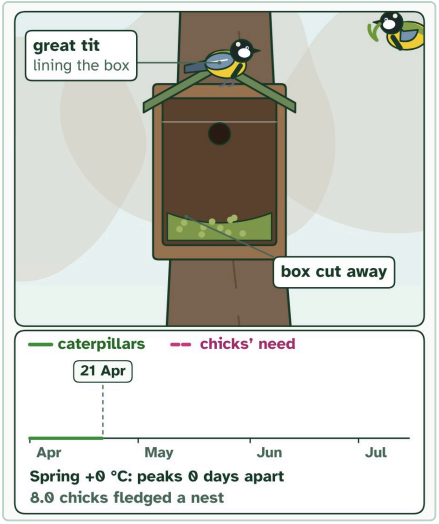
ANIMATION · GREAT TITS AND THE CATERPILLAR PEAK
6 MOMENTS

1 BARE OAKS, APRIL



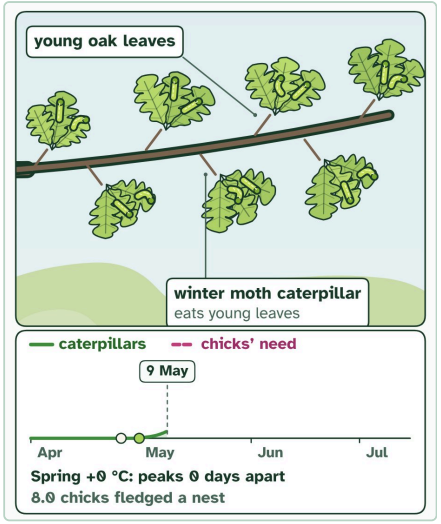
April in an oak wood near Oxford. The oaks are still bare, and a pair of **great tits** has chosen a nest box.

2 THE NEST BOX



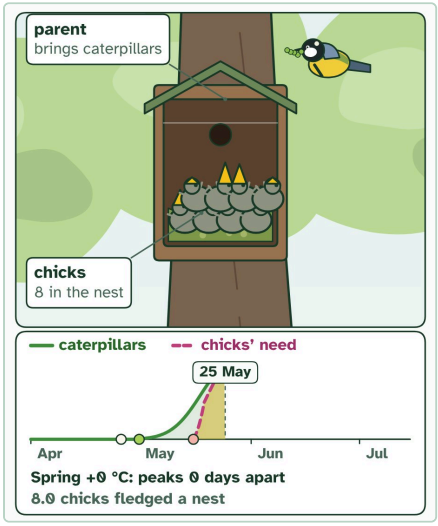
They line the box with moss. The female lays one egg a day, about eight, then sits on them for two weeks. Day length is a main cue for when she starts.

3 BUDBURST



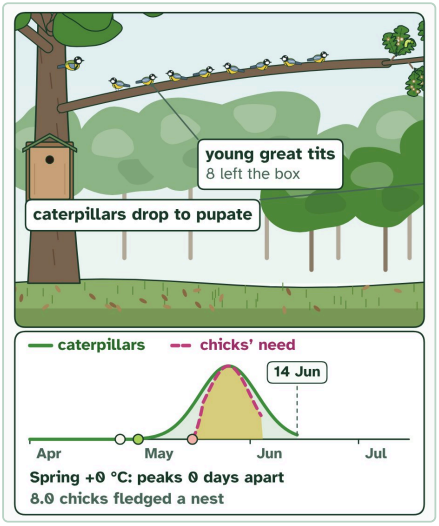
Warmth makes the oak buds burst. **Winter moth caterpillars** hatch with them and eat the soft young leaves, for only a few weeks.

4 CHICKS HATCH



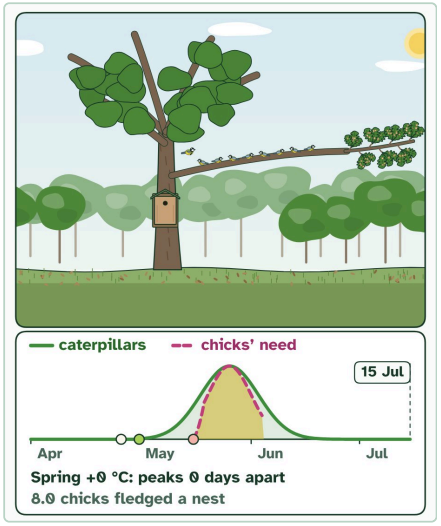
The chicks hatch. The parents carry caterpillars in all day: a brood needs most food about ten days after hatching.

5 THE YOUNG LEAVE



Fully grown, the caterpillars drop on silk threads to pupate in the soil. The oak leaves turn dark and tough, and the young birds leave the box.

6 TWO PEAKS



When the two peaks line up, most chicks fledge. Warm the spring: the caterpillars move earlier much more than the birds do.

Watch it move, and change it as it runs: biologybybradford.com/guides/ib-biology-d4-3-climate-change#mismatch

PREDICT

Great tits in Wytham Woods now lay about two weeks earlier than in the 1960s. What does this suggest?

(A) That great tits use day length alone as the cue that tells them when to lay their eggs

(B) That their laying responds partly to temperature too, so they can follow some of the shift in the caterpillar peak

(C) That the caterpillar peak has moved later in the year, so the birds now have more time to lay

Decide before you look. Answer on page 40.

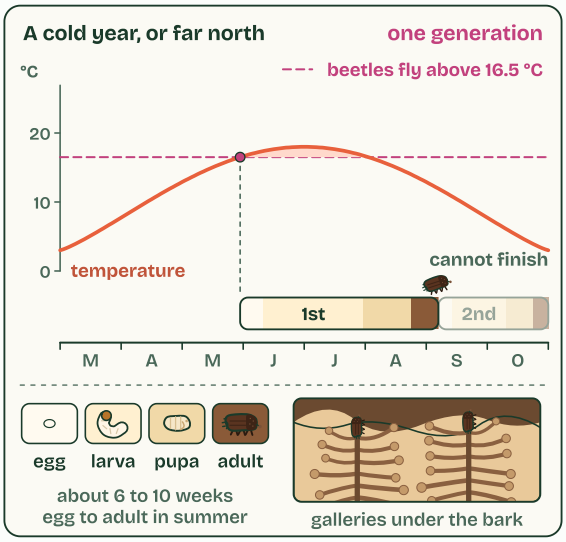
D4.3.11 HL INCREASES TO THE NUMBER OF INSECT LIFE CYCLES WITHIN A YEAR DUE TO CLIMATE CHANGE

11 A third *generation* of beetles

The European spruce bark beetle (*Ips typographus*) bores under the bark of Norway spruce. The females lay eggs in tunnels, the larvae eat the living tissue under the bark and the tree dies. A beetle needs a set amount of warmth to develop from egg to adult, and it only flies to a new tree once the air is warm enough in spring, at about 16.5 °C.

In a cold year, or in the far north and high in the mountains, a population fits in only one generation before autumn. In a warm year in central Europe there is time for two. With warmer springs starting the flight earlier and long hot summers speeding development, beetles in the lowlands now often complete two generations and a sister brood, and in the hottest years, such as 2018, a third. Each generation multiplies the population.

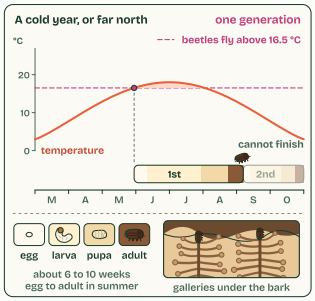
Drought weakens the spruce at the same time, so it makes less resin to drown the beetles. After the hot, dry summers from 2018, outbreaks killed spruce over hundreds of thousands of hectares across Germany and the Czech Republic. Those dead forests stopped taking up carbon and began to release it, another positive feedback.



SWITCH IT

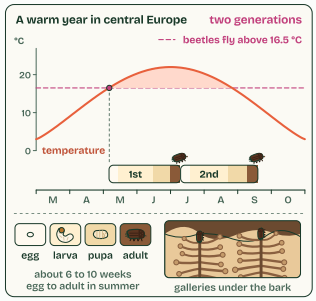
3 SETTINGS

1



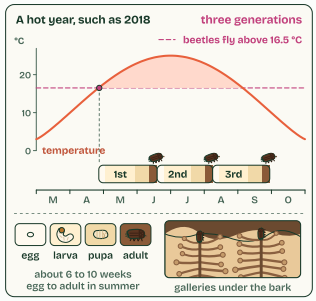
Cold year

2



Warm year

3



Hot year

PREDICT

Why does a warmer year allow more generations of bark beetles?

(A) Warmth makes each female beetle lay far more eggs in her tunnels under the bark

(B) Each generation needs a set amount of warmth to develop, so in a warmer, longer season it is reached more times

(C) Warm summers kill the birds and other predators that normally eat the bark beetles

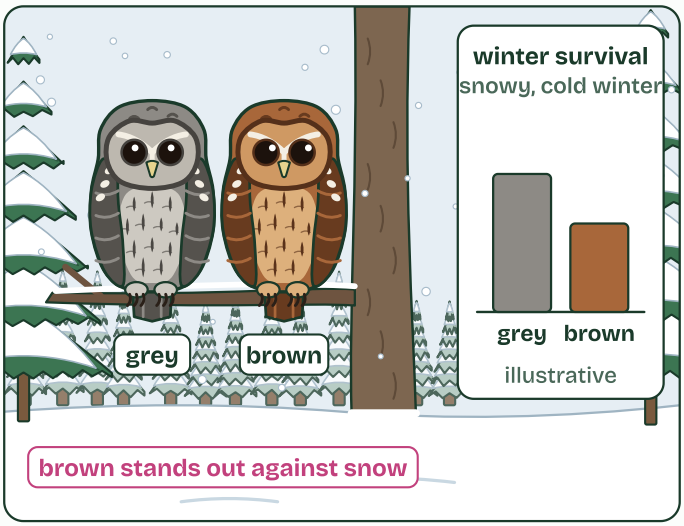
Decide before you look. Answer on page 40.

12 Grey owls, brown owls and *snow*

D4.3.12 HL EVOLUTION AS A CONSEQUENCE OF CLIMATE CHANGE

Tawny owls (*Strix aluco*) come in two colour variants, grey and brown, and the colour is inherited. In Finland, near the northern edge of the species' range, Patrik Karell and colleagues followed tawny owls for nearly thirty years. In winters with deep snow and hard cold, grey owls survived better than brown ones: the grey blends with snowy forest and may cope better with cold. In mild winters with little snow, the difference disappeared.

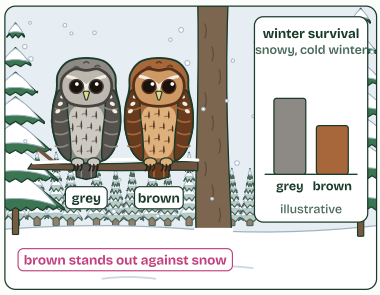
As Finnish winters warmed and snow cover shrank, the selection against brown owls weakened, and the brown variant became much more common, rising from about one owl in eight in the 1960s to around four in ten. A change in the frequency of an inherited variant in a population is **evolution**, and here climate change has driven it by changing the **fitness** of each colour.



SWITCH IT

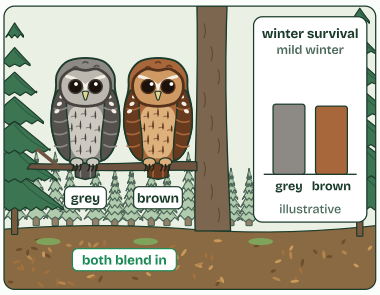
3 SETTINGS

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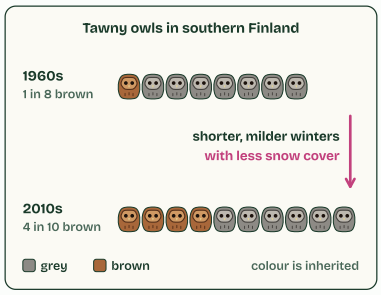
Snowy winter

2



Mild winter

3



Over 50 years

PREDICT

Why is the rise in brown tawny owls an example of evolution, and not just a change in the owls' plumage?

(A) Each owl gradually moults into brown feathers when it lives through a series of warm winters

(B) The colour is inherited, and its allele frequency in the population changed as the fitness of each colour changed

(C) Warm winters make the owls' feather pigment genes mutate to the brown version more often

Decide before you look. Answer on page 40.

IN THE EXAM

Evolution from climate change:

1. Colour (grey or brown) is a **heritable** variation.
2. Snowy winters: grey owls have **higher fitness** (better survival).
3. Less snow as winters warm: selection against brown weakens.
4. The **frequency** of brown owls rises: evolution.

Key terms

Every term this guide defines, A to Z, with the chapter it is in. Cover the right-hand side and test yourself.

albedo 02
The fraction of the sunlight falling on a surface that is reflected. Fresh snow reflects about 80 to 90%, open ocean under 10%.

anthropogenic 01
Caused by human activity.

carbon sequestration 08
Taking carbon dioxide out of the atmosphere and storing it for a long time, for example in wood, soil or peat.

greenhouse effect 01
The warming of the Earth's surface and lower atmosphere because greenhouse gases absorb and re-emit infrared radiation from the surface.

greenhouse gases 01
Gases in the atmosphere that absorb and re-emit infrared radiation given off by the Earth's surface, such as carbon dioxide, methane and water vapour.

landfast ice 04
Sea ice that is attached to the coast, to the sea floor in shallow water, or to grounded icebergs, so it does not drift.

legacy carbon combustion 03
The burning of soil carbon that had escaped earlier fires, often for centuries, when a fire is hot or deep enough to reach it.

permafrost 02
Ground that stays frozen all year, for at least two years in a row. It covers about a quarter of the land in the northern hemisphere.

phenological mismatch 10
A loss of synchrony between the timing of linked events in two populations, such as a predator's breeding and the peak of its prey.

phenology 09
The study of the timing of recurring biological events, such as flowering, budburst, migration and nesting, and how climate affects them.

positive feedback 02
A cycle in which a change causes effects that increase the original change, so it speeds up.

range shift 06
A change in where a species is found, as populations spread into newly suitable places and die out in places that have become unsuitable.

sea ice 04
Ice formed when sea water freezes, floating on the ocean. Arctic summer sea ice has shrunk by about 13% a decade since 1979.

taiga 03
The boreal forest of conifers (spruce, pine, larch, fir) across the far north of North America, Europe and Asia, with long cold winters.

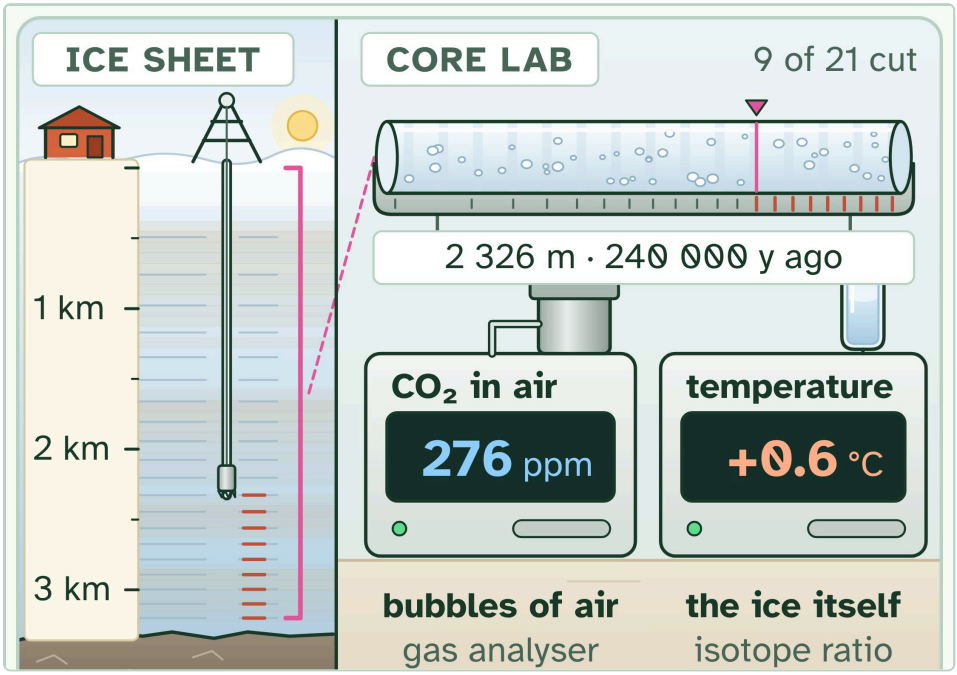
tipping point 03
A threshold beyond which a system changes to a different state, often suddenly and hard to reverse.

upwelling 05
The rise of cold, nutrient-rich water from the deep ocean to the sunlit surface, usually where wind pushes surface water away from a coast.

zooxanthellae 07
Single-celled algae (dinoflagellates) that live inside coral cells, give the coral sugars from photosynthesis and give it its colour.

Dry lab: *Reading an ice core*

Drill down through 400 000 years of Antarctic ice. Take samples, read the carbon dioxide trapped in each bubble and the temperature when the snow fell, plot them and test the correlation.



Run it online: change the variables, run the trials, and the table and graph fill in as you go. `biologybybradford.com/guides/ib-biology-d4-3-climate-change#lab`

Your question

Do carbon dioxide and temperature rise and fall together over the ice ages, and does that prove one causes the other? Snow that falls on Antarctica each year is buried and turned to ice, trapping bubbles of the air of the time.

What you can change

Which stretch of the core to sample, all 400 000 years or the last warming, and how closely to space the samples. Add the present-day reading from the air at the end.

What to record

The depth, the age, the carbon dioxide in parts per million and the temperature compared with today for each sample. The graph plots both against age, and a scatter graph tests the correlation. Download the CSV to plot your own.

Find out

- **The whole record.** Sample the core every 20 000 years from the top to 400 000 years. Describe the pattern of carbon dioxide and of temperature, and count the ice ages.
- **Test the correlation.** Look at the scatter graph of carbon dioxide against temperature. Is the correlation positive or negative, and how strong is it (the value of r)?
- **Zoom into a warming.** Sample the last deglaciation, from 20 000 to 10 000 years ago, every 1000 years. Which rises first, temperature or carbon dioxide?
- **Today.** Add the present-day carbon dioxide reading. How far is it outside the range of the last 400 000 years?
- **Back to the climate.** Why does your correlation not prove that carbon dioxide causes warming, and how could carbon dioxide released by a warming ocean still have added to it?

Record

- The depth, the age, the carbon dioxide (ppm) and the temperature difference from today (°C) for every sample.
- The highest and lowest carbon dioxide and temperature in the record, and the dates of each warm interglacial.
- The correlation coefficient shown under the scatter graph, and whether it is positive or negative.
- Download the CSV to plot your own graphs.

Your question Do carbon dioxide and temperature rise and fall together over the ice ages, and does that prove one causes the other? Snow that falls on Antarctica each year is buried and turned to ice, trapping bubbles of the air of the time.**What you can change**Which stretch of the core to sample, all 400 000 years or the last warming, and how closely to space the samples. Add the present-day reading from the air at the end.**What to record**The depth, the age, the carbon dioxide in parts per million and the temperature compared with today for each sample. The graph plots both against age, and a scatter graph tests the correlation. Download the CSV to plot your own.

Back to the climate

Your scatter graph shows a strong positive correlation. Why does that not prove that carbon dioxide causes warming, and how could carbon dioxide still have added to the warming at the end of an ice age?

QUESTIONS ON THE LAB

QUESTION 1

The scatter graph shows a strong positive correlation between carbon dioxide and temperature. Which conclusion is justified by this data alone?

(A) Carbon dioxide in the air caused each of the ice ages in the record to end

(B) Over the last 400 000 years, periods of higher carbon dioxide were also periods of higher temperature

(C) The temperature changes are what caused all of the changes in carbon dioxide

Answer on page 40.

QUESTION 2

In the zoomed record, Antarctic temperature starts to rise a few centuries before carbon dioxide does. How can carbon dioxide still have contributed to the warming?

(A) It cannot have contributed, because a cause always has to come before its effect

(B) A change in the Earth's orbit started the warming, the warming ocean released carbon dioxide, and that carbon dioxide then added more warming: a positive feedback

(C) The ice core records the carbon dioxide wrongly, so the two must really change together

Answer on page 40.

Check yourself

The check for this guide is online: a fresh paper of past-paper style questions from the exam bank on D4.3 each time, marked as you go, and saved to your Exam practice progress when you are signed in. Scan the code, or type the link.

biologybybradford.com/exam-maker/sit?topics=D4.3&level=HL&paper=quiz&marks=15&src=ep

Answers

PREDICTIONS IN THE CHAPTERS

01 Ice cores from Antarctica show that over 800 000 years, temperature and carbon dioxide rose and fell together. What does this correlation show on its own?

B **That the two are linked, but not which one causes the other, or whether a third factor drives both**

A **positive correlation**: as one rises, so does the other. Correlation is not causation. In the ice ages, small changes in the Earth's orbit started the warming, and warmer oceans then released carbon dioxide, which warmed the Earth further. The evidence that carbon dioxide causes warming comes from elsewhere: the physics of how it absorbs infrared, laboratory measurements, and satellites that see less infrared escaping at exactly the wavelengths carbon dioxide absorbs.

02 Why is the thawing of permafrost a positive feedback, not a negative one?

B **Decomposers break down the thawed organic matter, releasing greenhouse gases that cause more warming and more thawing**

The effect (greenhouse gases released) adds to the cause (warming), so the change speeds itself up. A negative feedback would push the other way and slow the change, as more plant growth on thawed ground does a little.

03 Fires have always burned in the taiga. Why does legacy carbon combustion matter so much?

B **It releases carbon that had been stored for centuries, so the forest loses carbon that regrowth cannot quickly replace**

A normal fire burns this year's fuel, and regrowth over the next decades takes it back. Burning soil carbon that built up over centuries cannot be replaced in that time, so the forest becomes a net source of carbon dioxide.

04 Why does an **early** break-up of landfast ice harm emperor penguins, even if the ice forms again the next winter?

B **Chicks without waterproof feathers fall into the sea before they can swim, so that year's breeding fails**

The timing matters. Chicks need the ice to last until they have fledged. Each early break-up wipes out that year's chicks, and a long-lived species with one chick a year cannot replace many lost years.

05 Why does warm surface water reduce primary production in the sea, when warmth usually speeds photosynthesis up?

B **A warm surface layer floats on the cold water and stops nutrients rising, so phytoplankton run short of nitrate and phosphate**

In most of the ocean, nutrients, not warmth or light, limit photosynthesis. A warm, light surface layer floats on the dense cold water below, the two stop mixing, and upwelling of nutrients weakens.

06 A bird lives only near the top of a mountain in New Guinea. Why is it more at risk from warming than a bird that lives halfway up?

B **As it moves upslope its range shrinks, because there is less land higher up, and at the summit it has nowhere left to go**

A mountain narrows towards the top, so each band of elevation holds less land. A species pushed up loses area until there is none left: sometimes called the escalator to extinction.

07 Which change causes coral **bleaching**?

B **A rise in water temperature that lasts for weeks, which makes the coral expel its zooxanthellae**

Heat causes bleaching. Carbon dioxide causes acidification, which slows calcification. Both come from the same emissions, and a reef facing both recovers more slowly from each.

08 Scientists still argue whether plantations or native forests are better for carbon. Why can't a quick measurement settle it?

B **The answer depends on the time scale and on what happens later, such as harvesting, fires, pests and the soil carbon lost in planting**

A plantation may win over 20 years and lose over 100. What counts is how long the carbon stays locked away, which depends on harvesting, disturbance and the soil, so the debate is about assumptions as much as data.

09 Which cue would let a tree burst its buds earlier in a warm spring, and later in a cold one?

B **Temperature, because it differs between years, while day length on a given date is always the same**

Temperature. Photoperiod is identical on the same date every year, so it can never shift an event earlier or later. That is also why species that time events by day length cannot follow a warming climate.

10 Great tits in Wytham Woods now lay about two weeks earlier than in the 1960s. What does this suggest?

B **That their laying responds partly to temperature too, so they can follow some of the shift in the caterpillar peak**

Day length alone would not let them shift at all. The Wytham birds respond to spring temperature as well, so they have tracked much of the change. Populations elsewhere, such as in the Netherlands, have shifted less and suffered more mismatch.

11 Why does a warmer year allow more generations of bark beetles?

B **Each generation needs a set amount of warmth to develop, so in a warmer, longer season it is reached more times**

Development rate rises with temperature. A beetle needs a fixed total of warmth (measured in degree-days above a threshold) to go from egg to adult, so a warmer year with an earlier spring fits that total in more times.

12 Why is the rise in brown tawny owls an example of evolution, and not just a change in the owls' plumage?

B **The colour is inherited, and its allele frequency in the population changed as the fitness of each colour changed**

Evolution is a change in heritable characteristics of a population. Each owl keeps its colour for life; what changed is how many brown and grey owls survived and bred, so the proportion of each colour in the population changed.

QUESTIONS ON THE DRY LAB

Q1 The scatter graph shows a strong positive correlation between carbon dioxide and temperature. Which conclusion is justified by this data alone?

B **Over the last 400 000 years, periods of higher carbon dioxide were also periods of higher temperature**

The data shows the two varied together, nothing more. To show cause, you need a mechanism and other evidence: carbon dioxide absorbs infrared (measured in the lab), and satellites see less infrared escaping at its wavelengths as its concentration rises.

Q2 In the zoomed record, Antarctic temperature starts to rise a few centuries before carbon dioxide does. How can carbon dioxide still have contributed to the warming?

B **A change in the Earth's orbit started the warming, the warming ocean released carbon dioxide, and that carbon dioxide then added more warming: a positive feedback**

In the ice ages, carbon dioxide acted as a feedback, not the trigger: small orbital changes started each warming, and the carbon dioxide released from the oceans amplified and spread it. Today, the carbon dioxide is coming first, from fossil fuels.

How this was made. The course structure, the activities and the teaching choices come from my own classroom, my presentations and my years of teaching IB and AP Biology. I use Claude, an AI, to help write and build the interactive guides, lesson plans, slides and practice questions, and to draw the diagrams and code the interactives. I direct the work and review it against the IB and AP specifications before it goes live.

Written and drawn for Biology by Bradford, biologybybradford.com. Free to print and share with a class.