

H HEURISTICS

RESEARCH REPORT · OCTOBER 2026

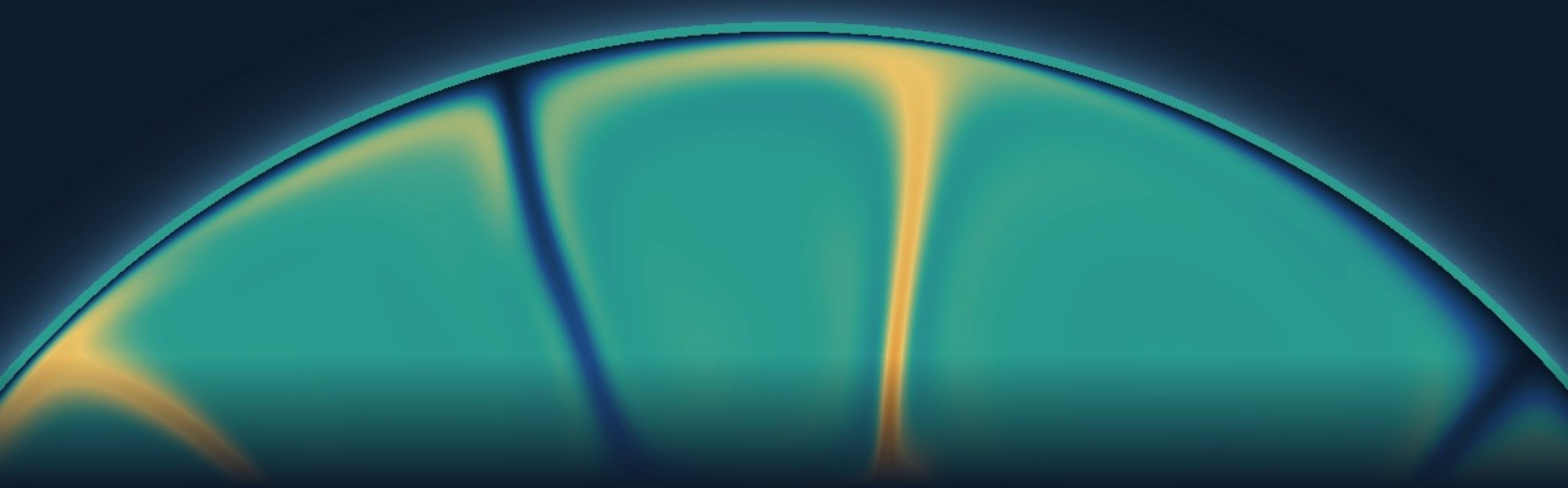
The Architecture of Earth

Energy, Feedback and the Creation Architecture of a
Habitable Planet

Interior · Atmosphere · Water · Biosphere · Deep time · Feedback · Humanity

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H Heuristics · Architecture of Creation series



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About This Report

This report asks how a dynamic planet builds interconnected systems, keeps itself habitable and responds to disturbance. It is the third major application of the framework set out in [The Architecture of Creation](#), the foundational report in the H Heuristics series of that name. That report asked why the same forms recur across unrelated systems and answered with a layered model in which physical constraints define a small space of viable forms, generative processes explore that space, and filters decide what persists. [The Architecture of Creation in the Universe](#) took the model to cosmology and ended with the formation of rocky planets. [The Architecture of Life](#) took it to biology and ended with life as a planetary force. This report sits between the two. It treats Earth as the intermediate scale between the formation of the universe and the emergence of life and civilisation.

The three reports are designed as a progression. The universe report explains how physical processes generate stars, galaxies and planets. This report asks how one of those planets organised itself into an interior, an atmosphere, oceans, ice and a biosphere, and how those subsystems became coupled tightly enough to keep liquid water on the surface for four billion years. The life report then asks how chemistry on that planet crossed into self-copying systems. The companion report [The Architecture of Entropy](#) supplies the thermodynamic background on which all three rely: every structure described here is maintained by a flow of energy and pays for its order by exporting entropy.

The report is written for readers who want a rigorous but readable account of Earth system science, and for those interested in whether planetary organisation can be understood as a coherent architecture of interacting processes rather than a list of separate topics. It integrates established science with the H Heuristics framework but keeps the two apart. Every major claim is graded for strength of evidence, analogies are labelled as analogies, and the framework's own propositions are flagged as such.

How to read this report

Each section starts on a new page and can be read on its own. Sections 1 and 2 state the thesis and translate the framework into planetary terms, including the systems model that organises the rest of the report. Sections 3 to 10 form the core and follow the eight-part structure shown in Figure 1: the interior, the atmosphere, water and ice, the biosphere, geological time, planetary feedback, human–Earth interaction and the future. Section 11 tests whether a common architecture runs through all eight and asks what makes Earth habitable when its neighbours are not. Sections 12 and 13 set out testable propositions and an overall verdict.

	I. The Architecture of the Planetary Interior Layers, heat, convection and the geodynamo	Section 3
	II. The Architecture of the Atmosphere Composition, radiation, the greenhouse effect and circulation	Section 4
	III. The Architecture of Water The hydrological cycle, oceans and the cryosphere	Section 5
	IV. The Architecture of the Biosphere Production, nutrient cycles and life as a geological force	Section 6
	V. The Architecture of Geological Time Plate tectonics, the rock cycle and deep-time climate	Section 7
	VI. The Architecture of Planetary Feedback Stabilising and amplifying loops, thresholds and tipping	Section 8
	VII. The Architecture of Human–Earth Interaction Energy, land, pollution, inequality and dependence	Section 9
	VIII. The Future Architecture of Earth Alternative trajectories to 2100 and beyond	Section 10

Figure 1. The structure of the report. The eight core parts move from the deep interior to the planet's possible futures. Parts I to V describe the subsystems and their history; Parts VI to VIII describe how they interact, how humans now act on them, and where the interactions could lead.

Source: H Heuristics. Illustrative.

Blue underlined text is a hyperlink. Links to the primary literature go to a DOI record where a specific result is cited, and to a reference article where a concept is introduced. Every link was checked for resolution before publication, and every DOI was checked against its registered title. A full reference list follows Section 13.

Evidence grades

Claims are graded using the same four-level scale as the rest of the series.

Table 1. Evidence grades used in this report

Grade	Meaning	Planetary example
A: Established	Derived from physical law, or confirmed repeatedly by independent observation or experiment.	Earth has a liquid outer core; rising CO ₂ strengthens the greenhouse effect
B: Well supported	Strong evidence from several lines of work, with unresolved detail or some dissent.	Silicate weathering stabilises climate over hundreds of thousands of years
C: Plausible or contested	A credible mechanism and partial evidence; the field is actively debating it.	Plate tectonics began more than 3 billion years ago; the Atlantic overturning circulation will collapse this century
D: Speculative	A hypothesis offered for testing, labelled as such wherever it appears.	Habitability is a generic outcome of a particular class of coupled feedbacks

The grade describes our knowledge of a claim, not its importance. Some of the most consequential questions in this report, including the exact thresholds of tipping elements, are graded C.

A note on the figures and calculations

The report contains 40 figures of three kinds. The first kind are original calculations and simulations made for this report: integration of a seismic density profile to recover Earth's mass, gravity and central pressure; the decline of radiogenic heating over 4.5 billion years; a numerical model of mantle convection, checked against a standard benchmark; the standoff distance of the magnetosphere; the vertical structure of the standard atmosphere; a one-layer greenhouse model; a latitude-resolved energy-balance model and the snowball-Earth hysteresis it produces; the Clausius–Clapeyron scaling of water vapour; the faint-young-Sun problem; a box model of the silicate-weathering thermostat; a Monte Carlo estimate of climate sensitivity from the published feedbacks; a simulation of critical slowing down before a tipping point; a cumulative-emissions projection of warming under four pathways; and the greenhouse effect on Venus, Earth and Mars. Each caption says what was computed. The second kind are charts of published measurements, credited in their source lines. The third kind are explanatory diagrams drawn for this report, which are schematic and not to scale unless stated.

How to cite

Hughes, H. (2026). *The Architecture of Earth: Energy, Feedback and the Creation Architecture of a Habitable Planet*. H Heuristics Research Report, Architecture of Creation series. The report synthesises published research and presents original calculations and propositions, which are labelled as such.

Executive Summary

The question

Earth formed about 4.54 billion years ago from the same disc of gas and dust as Venus and Mars. All three began with rock, metal, water and carbon. Today Venus has a surface hot enough to melt lead under an atmosphere 92 times as massive as ours; Mars is a cold desert with an atmosphere less than one per cent as dense. Earth alone has kept liquid water at its surface for at least four billion years, through a Sun that has brightened by about a third, through impacts, supervolcanic eruptions and global glaciations, and through the oxygenation of its atmosphere by life. This report asks why.

The defining question. What underlying physical processes and feedback mechanisms govern the organisation, persistence and transformation of Earth's planetary system?

The thesis

Earth is an interconnected planetary system whose structure and evolution emerge from the interaction of geological processes, atmospheric circulation, water, solar energy, ecosystems and the planet's interior. These systems generate the conditions that sustain life, while feedback loops and environmental thresholds shape the planet's stability and long-term transformation. In the language of the series, **physical law and planetary parameters act as constraints**: gravity, conservation of energy, radiative balance and the thermodynamics of water define what states are possible. **Energy flows act as generators**: about 122,000 terawatts of absorbed sunlight and 46 terawatts of internal heat drive convection, circulation, the water cycle, weathering and photosynthesis, and these processes continually produce new configurations. **Feedbacks act as filters**: stabilising loops hold some configurations in place for millions of years, while amplifying loops and thresholds remove others abruptly.

The report's central argument is that **Earth's habitability is an emergent property of interacting systems, not simply a consequence of its distance from the Sun**. The atmosphere, the oceans, the geological carbon cycle, the magnetic field and the biosphere each contribute, in different ways and with different degrees of certainty. Distance from the Sun sets the starting conditions; coupling between subsystems decides whether those conditions persist.

Principal findings

- 1. Two energy sources at very different scales run the planet.** Absorbed sunlight delivers about 2,600 times more power than the heat flowing out of the interior. Sunlight drives the fluid envelope: weather, ocean currents, the water cycle and photosynthesis. Internal heat drives the solid planet: mantle convection, plate tectonics, volcanism and the magnetic field. The two meet in the carbon cycle, where volcanic outgassing supplies CO₂ and weathering of rock removes it (Grade A).
- 2. The interior is a layered heat engine that is slowly running down.** Integrating a seismic density profile for this report recovers Earth's mass to within 1 per cent and a central pressure of about 355 billion pascals. Radioactive decay now supplies roughly 20 of the 46 terawatts that escape; 4.5 billion years ago it supplied about 94. The mantle's Rayleigh number, a measure of how vigorously it convects, is around ten million, far above the threshold of about a thousand, so convection is inevitable (Grade A to B).

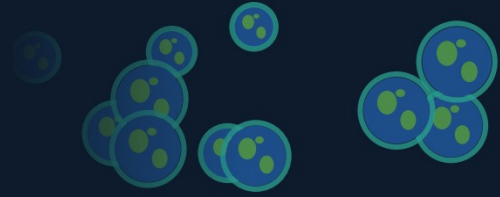
3. **The atmosphere regulates heat through a greenhouse effect built from trace gases.** Without it the mean surface temperature would be about -19°C ; with it, about 15°C . CO_2 is only 0.04 per cent of the air, yet its concentration has risen from 278 to 425 parts per million since the industrial revolution, adding about 2.3 watts per square metre of radiative forcing. Atmospheric and oceanic circulation carry up to 5.8 petawatts of heat poleward (Grade A).
4. **Water connects every subsystem.** It stores 91 per cent of the excess heat accumulated since 1971, carries heat and nutrients through the ocean overturning circulation, supplies the latent heat that powers storms, and lubricates plate tectonics. Saturation vapour pressure rises by about 6 to 7 per cent per degree of warming, which amplifies warming and intensifies heavy rainfall (Grade A).
5. **Life is a geological force.** Photosynthesis created the oxygen-rich atmosphere in two great steps, about 2.4 and 0.6 billion years ago. The biosphere cycles about 120 billion tonnes of carbon a year between air and land, roughly ten times the flux from fossil fuels, and controls the composition of the atmosphere on timescales of thousands of years (Grade A).
6. **Earth has a slow thermostat and fast amplifiers.** On timescales of hundreds of thousands of years, the dependence of silicate weathering on temperature removes excess CO_2 and stabilises climate; a box model built for this report gives an e-folding time of about 430,000 years. On human timescales the strongest feedbacks amplify change. A Monte Carlo combination of the published feedbacks gives a median climate sensitivity of 3.4°C per doubling of CO_2 , with an 18 per cent chance that it exceeds 5°C (Grade A to B).
7. **The climate system has alternative stable states.** A latitude-resolved energy-balance model built for this report has two stable climates for today's Sun: the present one and a snowball Earth. Once frozen, the planet would need about 26 per cent more sunlight to thaw. Geological evidence confirms that Earth entered snowball states at least twice, about 717 and 650 million years ago. Several components of today's climate system, including the Greenland and West Antarctic ice sheets, warm-water coral reefs and permafrost, may have thresholds between 1 and 3°C of warming (Grade A for the physics; Grade C for specific thresholds).
8. **Human civilisation is now a planetary subsystem.** Since 1950 population has risen 3.3-fold, energy use and fossil CO_2 emissions about 6-fold and synthetic nitrogen fixation about 30-fold. Human-made mass now outweighs all living biomass. Warming reached about 1.36°C of human-induced warming in 2024, and assessments now judge seven of nine proposed planetary boundaries to be transgressed. The richest tenth of humanity causes about half of emissions while the poorest half causes about an eighth and is most exposed to the consequences (Grade A to B).
9. **The coming centuries are a choice between trajectories, not a single forecast.** A cumulative-emissions model built for this report gives warming in 2100 of about 1.5°C under a rapid transformation, 1.8°C under a Paris-aligned pathway, 2.5°C under current policies and 4.0°C under fossil-intensive growth. Because CO_2 persists for millennia, the warming reached is largely permanent on human timescales, while sea level keeps rising for centuries after temperatures stabilise (Grade A for the physics; Grade B for the pathways).
10. **A coherent architecture of Earth exists, and it is a family of coupled mechanisms, not one law.** Energy gradients, gravitational layering, convection, reservoirs and cycles, and feedback recur as shared physical mechanisms across all subsystems. Selection and heredity are specific to the biosphere and to human institutions. What makes Earth distinctive is not any single component but the coupling between them: plate tectonics connects the interior to the climate through the carbon cycle, and life connects the climate to the chemistry of air and ocean (Section 11).

What follows from it

The practical implication is that habitability is maintained, not given. The same coupling that has kept Earth habitable can transmit disturbance from one subsystem to another, and the same feedbacks that stabilise the planet over geological time amplify change over human time. Maintaining a planet on which complex civilisation can flourish therefore depends on staying within the range of conditions in which the stabilising loops dominate. Section 13 sets out ten working heuristics for reading any planetary system in those terms.

01

CENTRAL THESIS



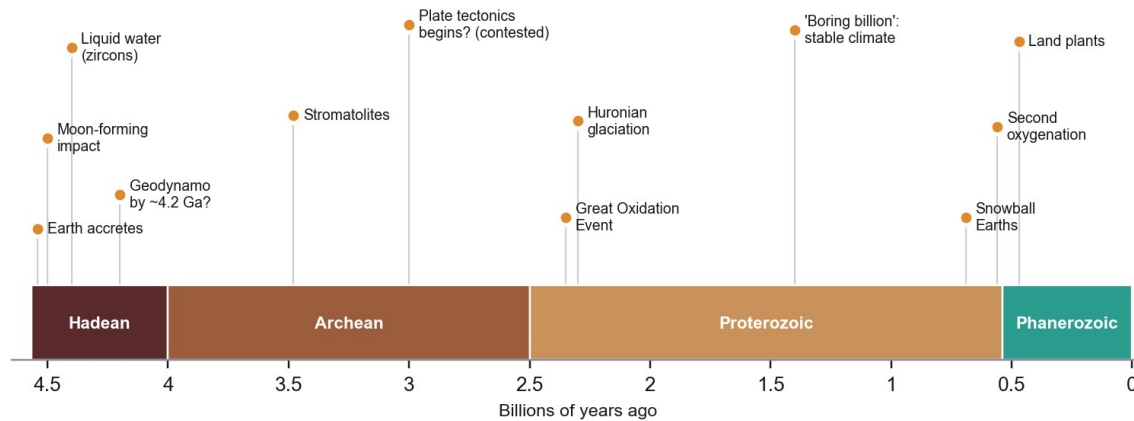
1. Central Thesis and Scope

1.1 What is being explained

Earth is a rocky planet 6,371 kilometres in radius with a mass of 5.97×10^{24} kilograms and a mean density of 5.5 grams per cubic centimetre, the highest of any planet in the Solar System. It formed about 4.54 billion years ago by the collision and accretion of smaller bodies, was struck within its first hundred million years by a Mars-sized object whose debris formed the [Moon](#), and separated into a metal core and a rock mantle almost immediately. Zircon crystals from Western Australia show that it had liquid water and continental-type crust by about [4.4 billion years ago](#). Since then its surface has never been permanently sterilised, boiled dry or frozen solid, although it has come close to the last of these at least twice.

Over the same 4.5 billion years almost everything else about the planet changed (Figure 2). The Sun brightened by about 30 per cent. The atmosphere went from a mixture of nitrogen, carbon dioxide and water vapour with essentially no free oxygen to one that is 21 per cent oxygen. Continents grew, assembled into supercontinents and broke apart several times. Ice sheets came and went. Life appeared, diversified and repeatedly lost most of its species to mass extinctions, then recovered. What needs explaining is therefore not a static structure but a pattern of persistence through change: a planet whose components have all been transformed, while the property that matters most to its inhabitants, a surface that holds liquid water, has been maintained.

A 4.6 billion years: a planet assembled, oxygenated and repeatedly reorganised



B The last 66 million years: from greenhouse to icehouse

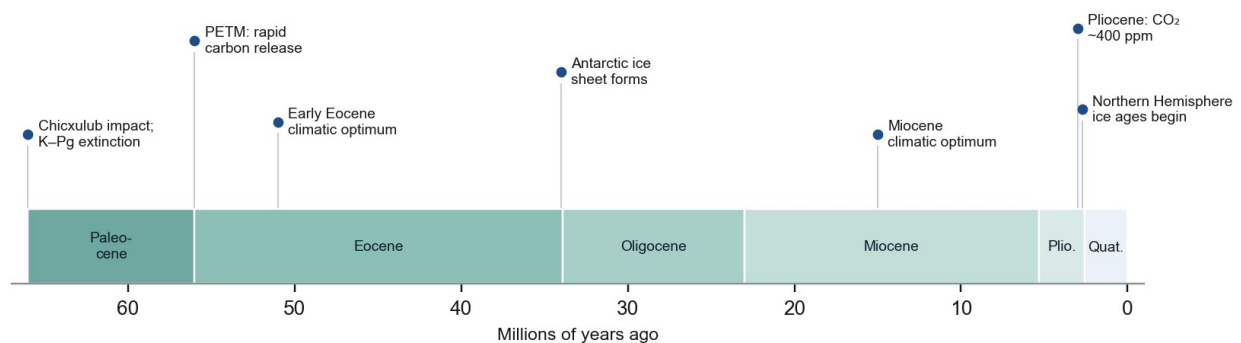


Figure 2. A timeline of Earth. Panel A covers 4.6 billion years from accretion to the present; Panel B covers the last 66 million years, during which the planet moved from a warm, ice-free greenhouse state to the glacial–interglacial cycles of the present icehouse.

Source: H Heuristics, from the studies cited in Sections 1, 3, 6 and 7. Dates are approximate; contested dates are marked with a question mark.

1.2 The thesis

Thesis. Earth is an interconnected planetary system whose structure and evolution emerge from the interaction of geological processes, atmospheric circulation, water, solar energy, ecosystems and the planet's interior. These systems generate the conditions that sustain life, while feedback loops and environmental thresholds shape the planet's stability and long-term transformation.

The thesis makes three claims of increasing ambition. The first is that Earth's subsystems are physically coupled, so that a change in one propagates to the others. This is the founding premise of [Earth system science](#) and is supported by every successful model of the climate, the carbon cycle and the history of the planet (Grade A). The second is that these couplings take the form of feedback loops, some stabilising and some amplifying, and that their balance determines whether the planet stays in a given state or moves to another. This is well supported for the main loops on human and geological timescales, though the strength of several remains uncertain (Grade A to B). The third is the distinctive claim of the H Heuristics framework: that the organisation of Earth can be read as a single architecture of interacting processes, in which the same small set of principles recurs in every subsystem. Section 11 grades this claim principle by principle.

1.3 The planetary scale

Within the Architecture of Creation series, Earth occupies the middle of the hierarchy. The universe report ended with planets forming in discs around young stars; the life report began with chemistry on the surface of one of them. Between the two lies a scale with its own physics. A planet is large enough for gravity to sort its materials by density and to hold an atmosphere, but small enough that its surface can be dominated by fluids in motion. It has two independent energy sources, its star and its own interior, and they act on different parts of it. It is the smallest scale at which an entire closed system of matter, cycling the same atoms for billions of years, can be studied. And it is the scale at which life, once present, becomes a component of the system rather than a passenger on it.

This intermediate position is why the report treats Earth as a system of systems. The interior, atmosphere, oceans, ice and biosphere each have their own dynamics and timescales, from the days over which weather systems form to the hundreds of millions of years over which oceans open and close. The interesting questions are about their coupling. How does heat from the core reach the climate? How does the composition of the air depend on the weathering of rock? How did microbes change the colour of the sky? How do ice sheets three kilometres thick respond to a few watts per square metre of extra energy? Answering these requires following matter and energy across the boundaries between disciplines.

1.4 What the thesis does and does not claim

Three clarifications prevent the thesis from being read as more or less than it is.

- **It does not claim that Earth is designed for life, or that it regulates itself for life's benefit.** The [Gaia hypothesis](#) proposed that the biosphere actively maintains conditions favourable to itself. The report treats life as a powerful component of the system whose effects can be stabilising or destabilising, and grades strong forms of planetary self-regulation as contested (Section 6).
- **It does not claim that Earth's stability is guaranteed.** Feedbacks that stabilise the planet over hundreds of thousands of years can coexist with feedbacks that amplify change over decades. The geological record contains mass extinctions, snowball glaciations and abrupt warming events. Stability is a property of particular regimes, not of the planet as such.
- **It does not claim that habitability is unique to Earth.** Whether habitable planets are common is an open question that one example cannot settle. The claim is narrower: on Earth, habitability depends on the coupling of subsystems, so a planet in the right orbit without that coupling would not necessarily be habitable, and a planet with it might be habitable over a wider range of orbits.

1.5 Method and place in the series

The report follows the series method. It assembles established findings from geophysics, atmospheric science, oceanography, glaciology, biogeochemistry, palaeoclimatology and the study of human–environment interaction; it reproduces key results with simple calculations so that readers can see where the numbers come from; and it asks at each step which elements of the creation framework apply. Wherever possible the calculations use published parameters, and where a simple model diverges from observation the text says so. The aim is not to replace detailed Earth system models but to expose the architecture that those models implement.

The report also differs from its predecessors in one respect. The universe and life reports describe processes that humans observe but do not alter. This report reaches a point, in Sections 9 and 10, at

which one species has become a planetary process in its own right. That shift brings questions of value and choice into a scientific account, and the report handles them by separating what the physics implies from what societies might decide.

02

THE FRAMEWORK



2. The Framework: Creation Structures in a Planetary System

2.1 Constraints, generators and filters

The foundational report describes recurring forms as the output of a three-part creation structure. Constraints define a space of viable configurations. Generators explore that space, producing variants. Filters determine which variants persist. Applied to a planet, each part has a clear physical counterpart (Figure 3).

Constraints are set by physical law and by the planet's parameters. Conservation of energy requires that, averaged over time, Earth radiates to space as much energy as it absorbs from the Sun plus what leaks from its interior. Gravity sorts materials by density, so that iron sinks, rock floats on iron, water lies on rock and gas lies on water. The thermodynamics of water fixes how much vapour air can hold at a given temperature. The planet's size, composition, distance from the Sun and rate of rotation fix the parameters within which all this happens.

Generators are the processes that turn energy flows into structure. Mantle convection, driven by internal heat, moves plates, builds mountains and opens oceans. Atmospheric and oceanic circulation, driven by the uneven heating of a spherical planet, organise the fluid envelope into cells, jets and gyres. Evaporation and precipitation move water and latent heat. Weathering and erosion break down mountains and deliver their chemistry to the sea. Photosynthesis builds organic matter and releases oxygen; evolution generates new organisms and new metabolisms; human industry now generates new materials and new fluxes.

Filters decide which configurations persist. The most fundamental is radiative damping: a warmer planet radiates more energy, so temperature perturbations decay. Others act on longer timescales: the temperature dependence of weathering removes excess CO₂; isostasy restores mountains and ocean basins towards buoyant equilibrium; natural selection removes poorly adapted organisms. The negative image of a filter is a threshold: a configuration that cannot persist under new conditions does not fade gradually but tips into another.

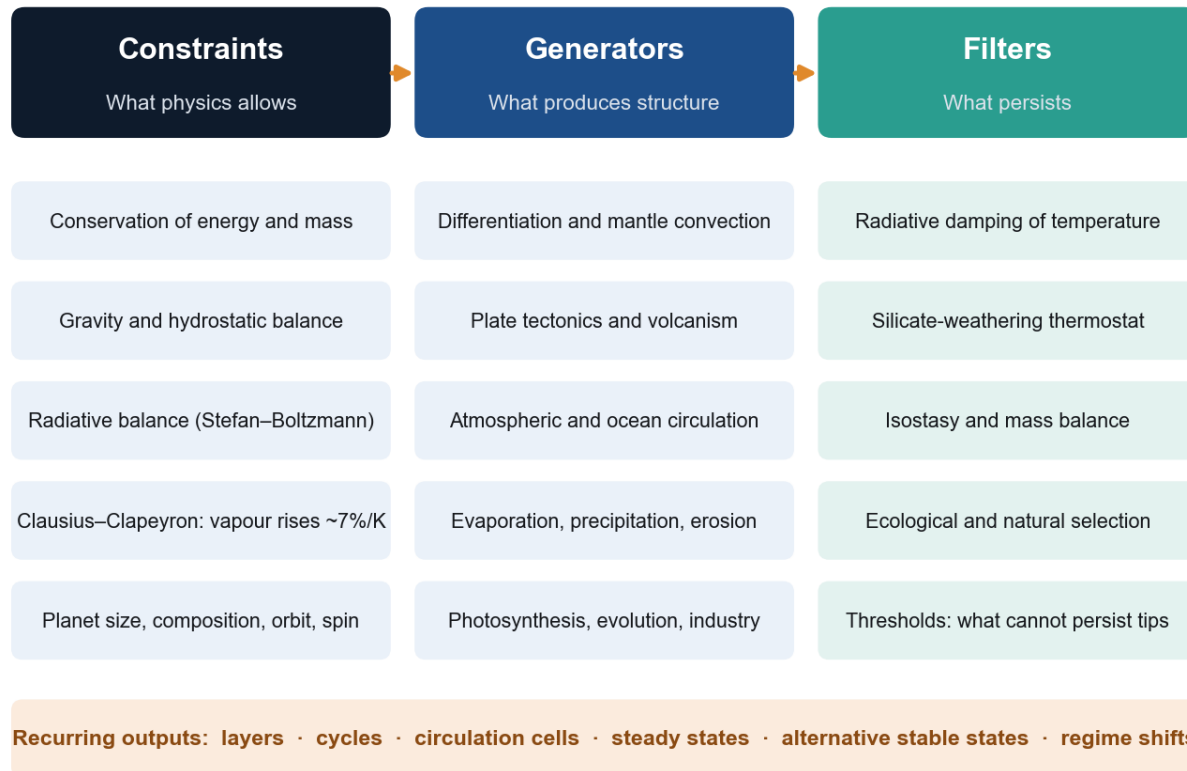


Figure 3. The creation structure applied to Earth. Physical law and planetary parameters constrain what states are possible; energy-driven processes generate structure; feedbacks and thresholds filter what persists. The bottom row lists the recurring forms the structure produces.

Source: H Heuristics, adapting the framework of *The Architecture of Creation* (2026).

2.2 The unifying architecture

The report's distinctive contribution is a systems model showing how Earth's major subsystems interact rather than treating geology, climate, water and life as separate topics (Figure 4). At the top are the energy inputs: sunlight, internal heat, gravity and rotation. In the middle are four subsystems that share the same atoms: the atmosphere and climate; the oceans, water and ice; the geosphere; and the biosphere. Between each pair runs an exchange of matter and energy: heat, water vapour and CO₂ between air and sea; volcanic gases, weathering and dust between rock and air; nutrients and the biological pump between ocean and life; soils and biominerals between life and rock. Human civilisation appears as a fifth subsystem, now large enough to alter every exchange. At the bottom are the planetary outcomes that the interactions produce: habitability, stability, environmental change and resilience.

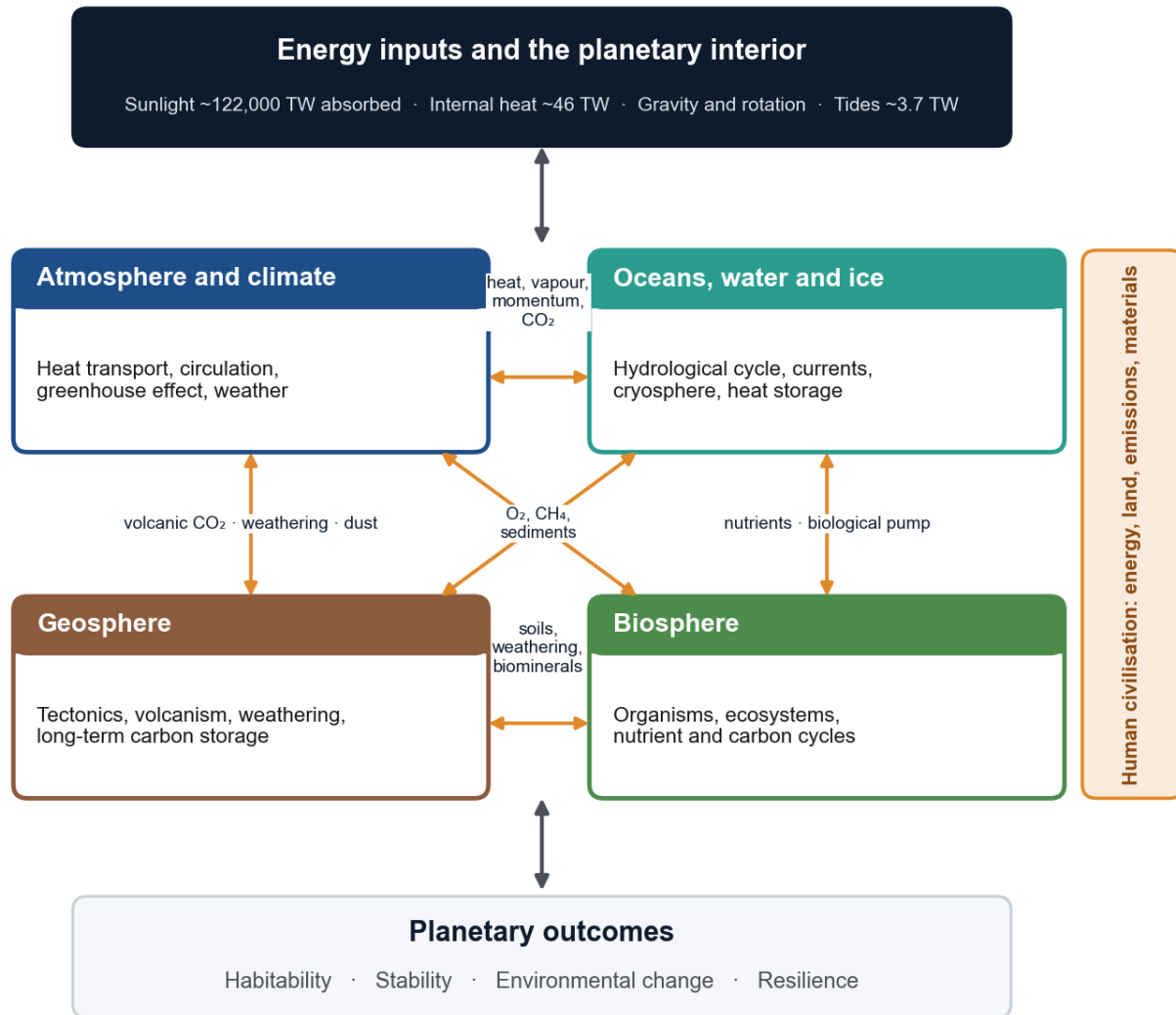


Figure 4. The unifying architecture of Earth. Energy inputs drive four coupled subsystems that exchange matter and energy across every boundary; human civilisation now modifies all of the exchanges. Planetary outcomes such as habitability are properties of the whole system, not of any one part.

Source: H Heuristics. Conceptual model: arrows represent interacting exchanges and feedbacks, not a single linear causal sequence. Energy values from the studies cited in Section 2.3.

Central argument. Earth's habitability is an emergent property of interacting systems, not simply a characteristic of its distance from the Sun. The atmosphere, oceans, geological carbon cycle, magnetic field and biosphere all contribute in different ways, with some mechanisms better understood than others.

The argument has a precise meaning. A property is emergent in the sense used here if it belongs to the coupled system and cannot be predicted from any one component in isolation. Earth's mean surface temperature is an example: it depends on solar input and orbital distance, but also on the albedo of clouds and ice, the infrared opacity of the atmosphere, the CO₂ supplied by volcanoes and removed by weathering, and the gases produced and consumed by life. The [habitable zone](#) of a star, the range of orbits in which liquid water could exist, is itself calculated by assuming that a carbonate–silicate feedback adjusts atmospheric CO₂; the zone is therefore a statement about planetary feedback as much as about distance. Modern estimates place Earth near its [inner edge](#).

2.3 Energy: what runs the planet

Every structure in this report is maintained by a flow of energy, and the flows span seven orders of magnitude (Figure 5). The largest by far is sunlight. At Earth's distance the Sun delivers 1,361 watts per square metre to a surface facing it; averaged over the rotating sphere this is 340 watts per square metre, of which about 30 per cent is reflected. The absorbed remainder, about 122,000 terawatts, is roughly 2,600 times the heat escaping from the interior and about 6,000 times humanity's primary energy use. The planet's effective radiating temperature follows directly from the balance between absorbed sunlight and emitted infrared radiation:

$$T_e = [S(1 - \alpha) / 4\sigma]^{1/4} \approx 255 \text{ K} \quad (1)$$

where S is the solar constant, α the planetary albedo and σ the Stefan–Boltzmann constant. Equation 1 gives about -19°C . The observed mean surface temperature of about 15°C is higher because the atmosphere absorbs and re-emits infrared radiation (Section 4). The global energy budget of [Trenberth, Fasullo and Kiehl](#) and its successors quantify every major flow, and satellite measurements show that since the early 2000s Earth has been absorbing more energy than it emits, with the imbalance [roughly doubling](#) between 2005 and 2019.

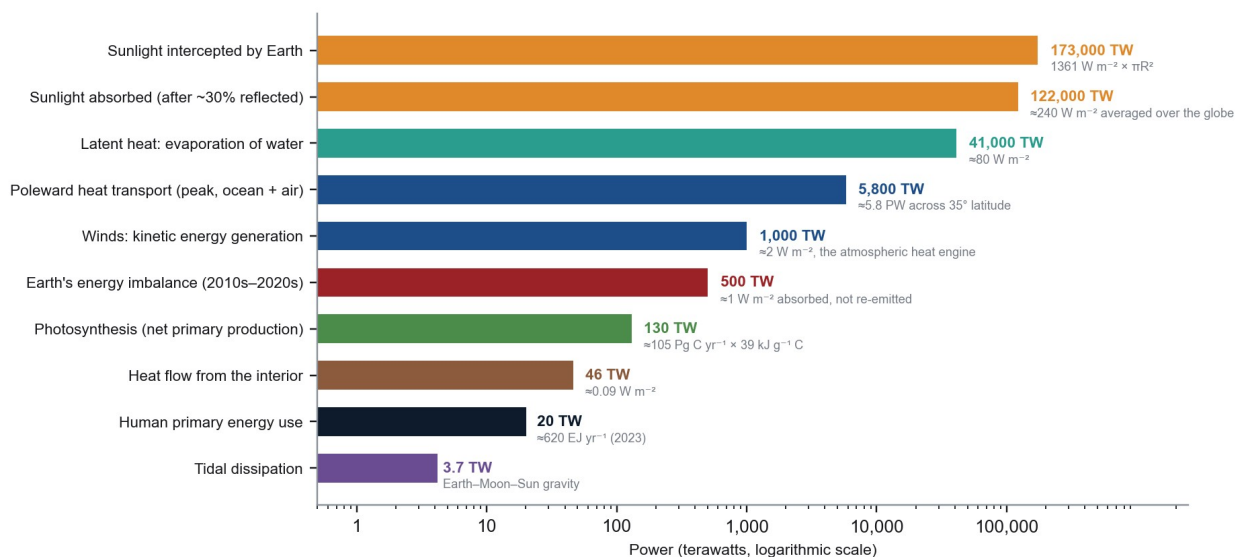


Figure 5. The power flows that run the planet. Absorbed sunlight dominates; the interior supplies a small but geologically decisive flow; humanity's energy use is now comparable to natural flows such as interior heat and is dwarfed by the energy the planet is accumulating because of the enhanced greenhouse effect.

Source: H Heuristics calculation from the solar constant and global energy-budget estimates (Trenberth et al., 2009; Loeb et al., 2021), poleward transport (Trenberth and Caron, 2001), interior heat flow (Davies and Davies, 2010), primary energy (Energy Institute, 2024) and tidal dissipation. Values are rounded.

The interior's flow is small but acts on a different part of the planet. The [46 terawatts of heat](#) escaping through the surface drive the motion of the solid Earth: plate tectonics, volcanism, earthquakes and the magnetic field. Sunlight drives the fluids: weather, currents, the water cycle and photosynthesis. The two meet chiefly in the carbon cycle. Volcanoes, powered by internal heat, supply CO_2 to the atmosphere; weathering of rock, powered by the water cycle and therefore by sunlight, removes it. This coupling between the deep interior and the surface climate is one of the most important in the report.

2.4 Reservoirs, fluxes and timescales

Each subsystem can be described as a set of reservoirs connected by fluxes. The mean time a molecule spends in a reservoir, its residence time, is the size of the reservoir divided by the flux through it:

$$\tau = M / F \quad (2)$$

Residence times range from about nine days for water vapour in the atmosphere to hundreds of millions of years for carbon in limestone. These differences matter because they set the speed of each feedback. A disturbance to a fast reservoir propagates quickly but is also corrected quickly; a disturbance to a slow reservoir, such as the deep ocean, an ice sheet or the carbon locked in rocks, persists for centuries to millions of years. Earth's dynamics are therefore organised as a hierarchy of nested timescales (Figure 6), and the question of whether the planet is stable has a different answer at each level.

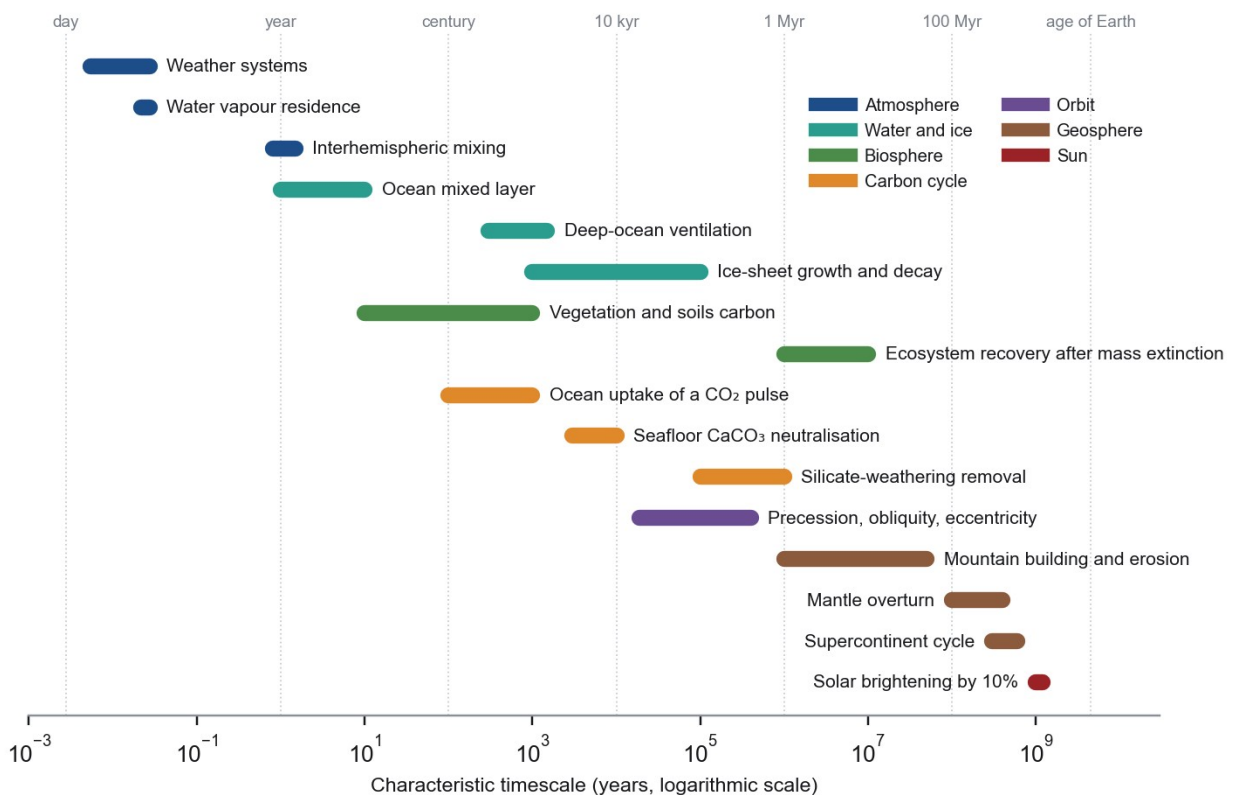


Figure 6. Characteristic timescales of Earth's subsystems. Processes span more than twelve orders of magnitude, from weather systems that last days to the supercontinent cycle and the slow brightening of the Sun. The stabilising silicate-weathering feedback operates on timescales of 10⁵ to 10⁸ years, far slower than the human perturbation.

Source: H Heuristics compilation from the studies cited in Sections 3 to 8. Ranges are indicative.

2.5 Feedback: the mathematics of stability

A feedback is a loop in which a change in one quantity causes changes elsewhere that return to affect the first. In climate, the standard formulation relates a change in the planet's energy balance, the radiative forcing F , to the resulting equilibrium change in temperature:

$$\Delta T = -F / \lambda, \quad \lambda = \lambda_{\text{Planck}} + \lambda_{\text{water vapour}} + \lambda_{\text{albedo}} + \lambda_{\text{clouds}} + \dots \quad (3)$$

Each λ measures how much a feedback process changes the outgoing energy per degree of warming. The Planck term is strongly negative, because a warmer body radiates more; it is the planet's basic stabiliser. The others are mostly positive and partly cancel it. As long as their sum stays negative the system is stable and perturbations decay. If the sum approached zero, sensitivity would grow without bound; if it became positive in some range of states, the system would run away until another process intervened. Section 8 applies this formula to the published feedbacks.

Two further relations recur. The first is the Clausius–Clapeyron equation, which governs how much water vapour the air can hold and therefore the strength of the water-vapour feedback and the intensity of rainfall:

$$d \ln e_s / dT = L / (R_v T^2) \approx 0.06\text{--}0.07 \text{ per K} \quad (4)$$

The second is the Rayleigh number, which measures how strongly a fluid heated from below will convect, and applies equally to the mantle, the outer core, the atmosphere and the ocean:

$$Ra = \rho g \alpha \Delta T d^3 / (\kappa \eta) \quad (5)$$

where ρ is density, g gravity, α thermal expansivity, ΔT the temperature contrast across a layer of depth d , κ thermal diffusivity and η viscosity. Convection begins when Ra exceeds about a thousand; in Earth's mantle it is around ten million (Section 3).

2.6 Recurring principles

The foundational report identified principles that recur wherever creation structures operate. Table 2 translates eight of them into planetary terms. Section 11 tests how far each applies across the subsystems.

Table 2. Eight recurring principles of planetary organisation

Principle	Planetary signature	Examples
Energy gradients drive structure	Order is maintained only while energy flows from hot to cold	Convection cells, hurricanes, photosynthesis
Layering by density	Gravity sorts matter into concentric shells	Core, mantle and crust; ocean thermocline; atmospheric layers
Circulation cells	Heated fluids organise into rolls and cells of characteristic size	Mantle plumes, Hadley cells, ocean gyres
Reservoirs and cycles	The same atoms cycle among stores at rates set by fluxes	Water, carbon, nitrogen and rock cycles
Stabilising feedback	Responses that oppose a change hold states in place	Planck response, weathering thermostat, isostasy
Amplifying feedback and thresholds	Responses that reinforce a change create alternative states and tipping points	Ice–albedo feedback, snowball Earth, monsoon shifts
Nested timescales	Fast subsystems sit inside slow ones and see them as boundary conditions	Weather within climate within the carbon cycle
Network coupling	Subsystems connect through shared fluxes, so disturbance propagates	Volcanism $\rightarrow$ CO ₂ $\rightarrow$ climate $\rightarrow$ weathering $\rightarrow$ ocean chemistry

Source: *H Heuristics*, adapting the principles of *The Architecture of Creation* (2026).

03

PART I · THE PLANETARY INTERIOR



3. The Architecture of the Planetary Interior

Key question: how does the planet's internal energy shape its surface and long-term evolution? This section follows Earth from a hot, partly molten body to a layered heat engine whose slow cooling drives plate tectonics, volcanism and the magnetic field.

3.1 Differentiation: how a planet becomes layered

Earth assembled from planetesimals and planetary embryos over a few tens of millions of years. Each collision converted kinetic energy into heat, and the decay of short-lived radioactive isotopes such as aluminium-26 added more. Much of the young planet was molten, and in a molten planet gravity acts quickly: dense iron–nickel metal sank through the silicate magma to form the core. Hafnium–tungsten dating shows that this separation was [essentially complete within about 30 million years](#) of the Solar System's formation. The sinking of the core itself released gravitational energy equivalent to heating the whole planet by roughly 2,000 kelvin, and that primordial heat is still escaping.

Differentiation is the first creation structure of the planetary scale. The constraint is gravity acting on materials of different density; the generator is melting, which allows them to move; the filter is buoyancy, which leaves each material at the depth where it floats. The result is a set of concentric shells (Figure 7): a solid inner core, a liquid outer core, a rocky mantle making up 84 per cent of the planet's volume, and a thin crust. The same principle later sorted the fluid envelope: water lies on rock and air on water. Table 3 summarises the layers.

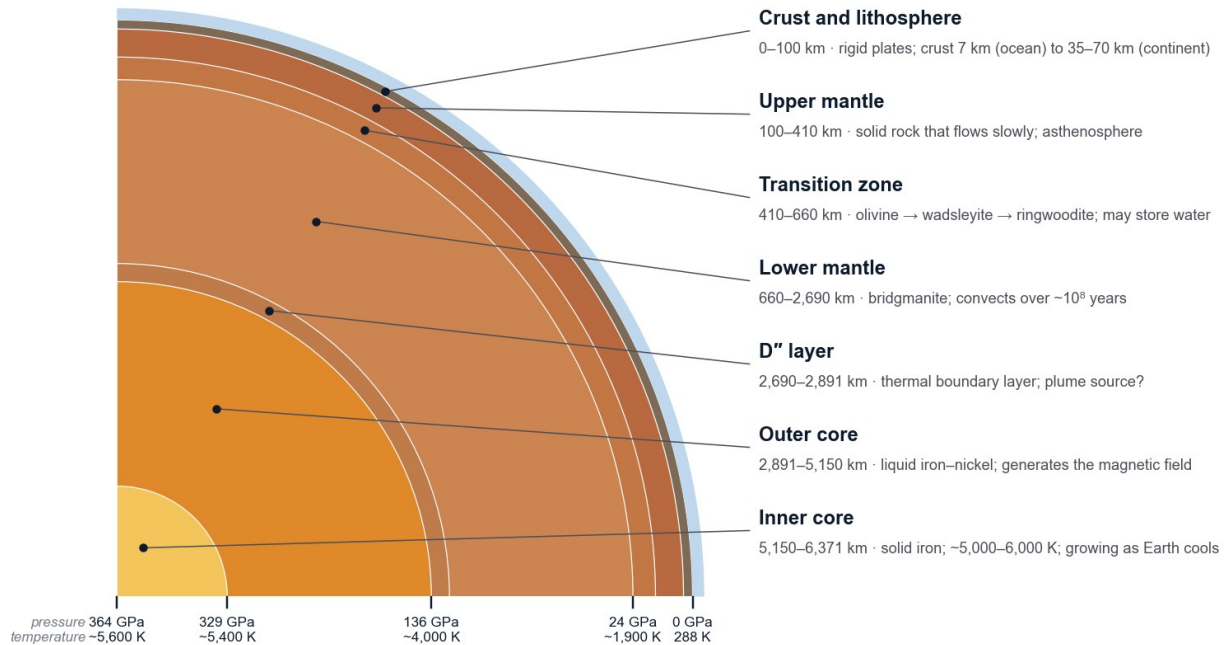


Figure 7. Earth's layered interior. Gravity sorted the planet by density into a solid inner core, liquid outer core, rocky mantle and thin crust. Pressure and temperature rise with depth to about 364 billion pascals and 5,600 K at the centre; the biosphere and the oceans occupy a film too thin to show at this scale.

Source: H Heuristics illustration. Boundaries after the Preliminary Reference Earth Model (Dziewonski and Anderson, 1981); temperatures are approximate and those of the deep interior are uncertain by several hundred kelvin.

Table 3. Earth's internal layers

Layer	Depth (km)	State and composition	Share of mass	Role in the system
Crust	0 to 7 (ocean), 35–70 (continent)	Solid; basalt under oceans, granite-like rock in continents	0.4%	Stores carbon, water and the chemical record; buoyant continents resist subduction
Upper mantle and transition zone	to 660	Solid peridotite that creeps; olivine changes structure at 410 and 660 km	$\sim 18\%$	Source of mid-ocean ridge magma; asthenosphere lets plates move; may store water
Lower mantle	660 to 2,891	Solid bridgmanite and ferropericlasite	$\sim 49\%$	Bulk of convection; holds radiogenic heat and slab graveyards
Outer core	2,891 to 5,150	Liquid iron–nickel with light elements	$\sim 31\%$	Convects to generate the magnetic field
Inner core	5,150 to 6,371	Solid iron–nickel	$\sim 1.7\%$	Grows as Earth cools, releasing latent heat and light elements that power the dynamo

Source: H Heuristics compilation from the Preliminary Reference Earth Model and the studies cited in this section. Mass shares are approximate.

3.2 What seismology reveals

Nobody has drilled deeper than about 12 kilometres. Knowledge of the deep interior comes mostly from earthquakes, whose waves travel through the planet at speeds that depend on the density and stiffness

of the rock. Compressional (P) waves pass through solids and liquids; shear (S) waves pass only through solids. In 1906 Richard Oldham found that seismic waves crossing the centre of the Earth arrived late, and in 1914 Beno Gutenberg located the core boundary at about 2,900 kilometres. The absence of S waves through the core showed that its outer part is liquid. In 1936 [Inge Lehmann](#) inferred from faint reflections that it contains a solid inner core. These results were combined in the [Preliminary Reference Earth Model](#), which is still the standard one-dimensional description of the interior.

A density profile is a strong test because it must satisfy independent constraints. For this report the profile was integrated from the centre outwards to calculate the enclosed mass, gravity and pressure at every depth (Figure 8). The calculation recovers Earth's total mass to within 1 per cent (5.93 against 5.97×10^{24} kg) and its moment of inertia factor to within half a per cent (0.332 against the measured 0.3307), which confirms that the dense core holds about a third of the planet's mass. It also shows a counterintuitive feature: gravity does not decrease below the surface but stays close to 10 metres per second squared through the mantle and peaks at about 10.5 at the core–mantle boundary, because the dense core dominates the enclosed mass. Pressure reaches about 134 billion pascals at the core–mantle boundary and 355 billion at the centre in this calculation, close to the reference model's 136 and 364.

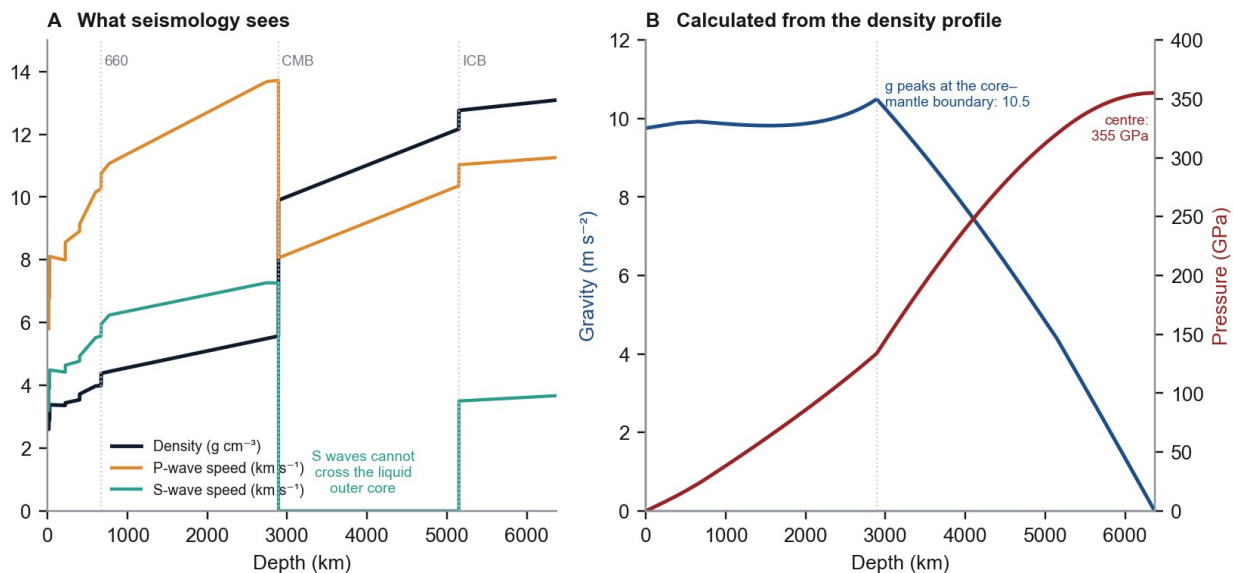


Figure 8. The interior seen by seismology and calculated from it. Panel A shows density and seismic wave speeds against depth; S waves vanish in the liquid outer core. Panel B shows gravity and pressure calculated for this report by integrating the density profile; the calculation reproduces Earth's mass and moment of inertia to within 1 per cent.

Source: H Heuristics calculation using piecewise-linear values from the Preliminary Reference Earth Model (Dziewonski and Anderson, 1981).

3.3 The heat engine and its fuel

Heat escapes from Earth's surface at about 46 ± 3 terawatts, an average of 0.09 watts per square metre. About 70 per cent leaves through the ocean floor, mostly near young crust at mid-ocean ridges, and 30 per cent through the continents. The heat has two sources: the decay of long-lived radioactive isotopes of uranium, thorium and potassium, and the slow cooling of a planet that started hot. Since 2005, detectors in Japan and Italy have measured the antineutrinos emitted by uranium and thorium decay inside the Earth. The KamLAND collaboration's [geoneutrino measurement](#) showed that radioactivity supplies roughly half of the heat flow and that the planet is still cooling from its formation.

For this report the radiogenic heat production of the bulk silicate Earth was calculated from standard abundances of the heat-producing elements and their half-lives (Figure 9). Today uranium supplies about 8.0 terawatts, thorium 8.4 and potassium 3.3, a total of about 20 terawatts, consistent with the geoneutrino results. Running the decay backwards shows that 4.5 billion years ago radioactivity produced about 94 terawatts, nearly five times as much, mostly from the short-lived uranium-235 and potassium-40. The early planet was therefore hotter and its mantle convected more vigorously. Lavas called komatiites, which erupted at temperatures that require a mantle a few hundred degrees hotter than today, are common in rocks older than 2.5 billion years and almost absent since.

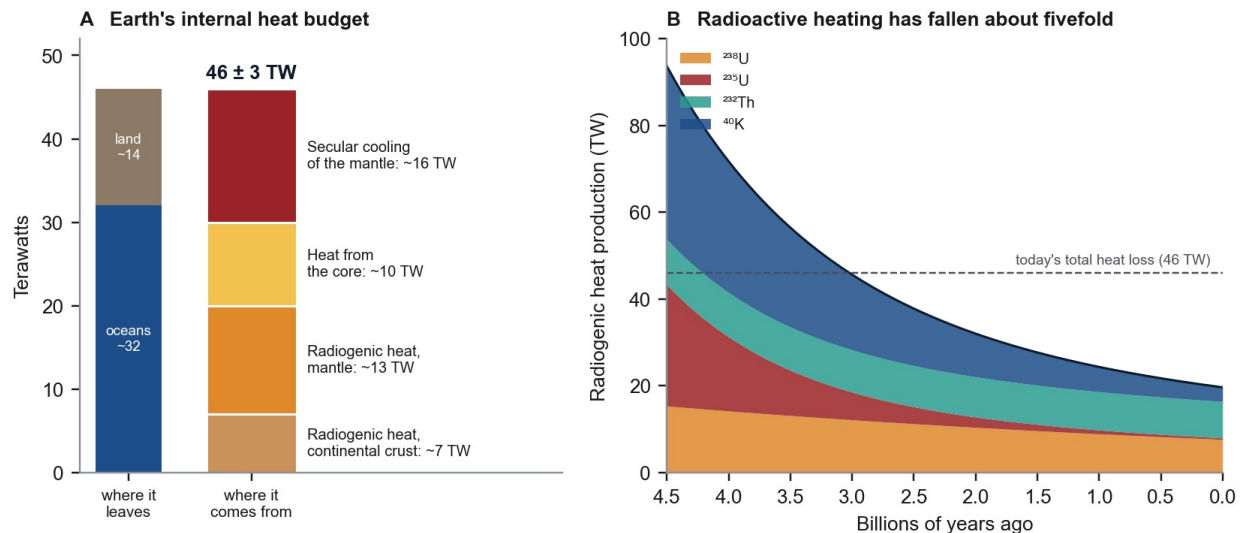


Figure 9. Earth's internal heat. Panel A shows the present budget: about 46 terawatts escape, roughly 20 from radioactive decay and the rest from the cooling of the mantle and core. Panel B, calculated for this report, shows that radiogenic heating has fallen about fivefold over Earth's history as uranium-235 and potassium-40 decayed.

Source: Panel A, *H Heuristics* compilation from Davies and Davies (2010), KamLAND Collaboration (2011) and Lay et al. (2008); component values are uncertain by several terawatts. Panel B, *H Heuristics* calculation using bulk silicate Earth abundances (McDonough and Sun, 1995) and standard decay constants.

The heat budget matters beyond geophysics because it sets the tempo of the surface. Faster convection in the past meant more volcanism, more outgassing of CO₂ and probably smaller, faster plates. As the planet cools, the supply of new crust and of volcanic gases declines. Earth's internal clock is slow, but it is running down, and one long-term limit on its habitability is the eventual weakening of the processes that recycle carbon.

3.4 Mantle convection

The mantle is solid rock, yet over millions of years it flows like an extremely viscous fluid, with a viscosity around 10²¹ to 10²² pascal-seconds, about 10²⁴ times that of water. Equation 5 shows why it must convect. With a mantle depth of 2,890 kilometres, a temperature contrast of a few thousand kelvin and standard values of density, expansivity and diffusivity, the Rayleigh number is about 6 million for a viscosity of 10²² and about 60 million for 10²¹. Either value is thousands of times above the threshold for convection.

To show what convection at such Rayleigh numbers looks like, this report solved the standard nondimensional equations for convection in a very viscous fluid heated from below (Figure 10). The model reproduces the published benchmark of [Blankenbach and colleagues](#) to within about 4 per cent. Its

behaviour illustrates three features of the real mantle. Heat is carried across thin thermal boundary layers at the top and bottom, while the interior is well mixed. Cold, dense material peels off the top boundary layer in narrow sheets, the analogue of subducting plates. Hot material rises from the bottom boundary layer in narrow plumes, the analogue of the plumes thought to feed Hawaii and Iceland. As the Rayleigh number rises from 10^4 to 10^6 the efficiency of heat transport, measured by the Nusselt number, increases as $Ra^{0.29}$, close to the theoretical exponent of one third.

A Simulated convection at Rayleigh number 2×10^6 (temperature; hot = orange, cold = navy)

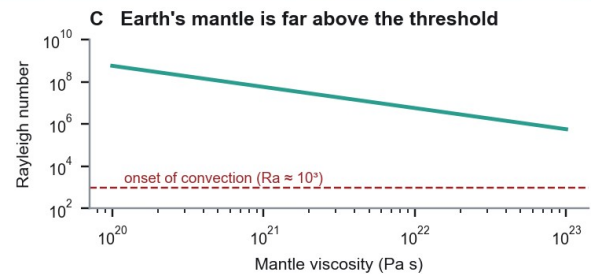
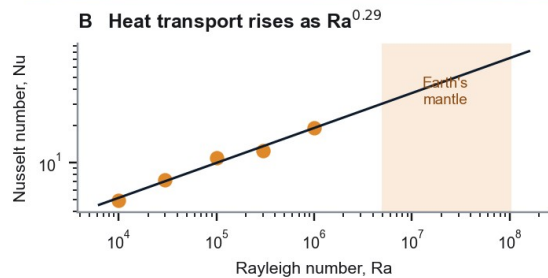
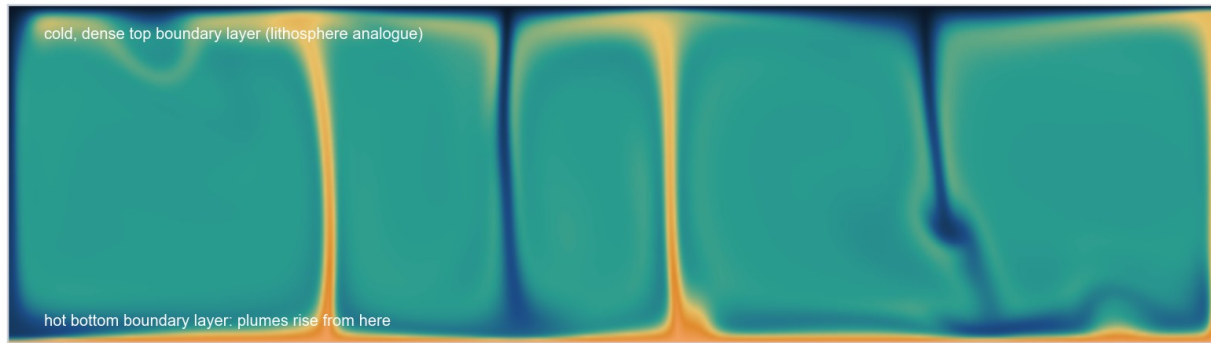


Figure 10. Convection in a model mantle. Panel A shows the temperature field of a simulation made for this report at Rayleigh number 2×10^6 : cold sheets sink from the top boundary layer and hot plumes rise from the bottom. Panel B shows that heat transport rises as about $Ra^{0.29}$ across five simulations. Panel C shows the Rayleigh number of Earth's mantle across plausible viscosities.

Source: H Heuristics simulation of infinite-Prandtl-number Boussinesq convection in a two-dimensional box, benchmarked against Blankenbach et al. (1989). Panel C assumes density $4,000 \text{ kg m}^{-3}$, expansivity $3 \times 10^{-5} \text{ K}^{-1}$, temperature contrast $2,000 \text{ K}$ and diffusivity $10^{-6} \text{ m}^2 \text{ s}^{-1}$.

The real mantle differs from the model in important ways: its viscosity varies by orders of magnitude with temperature and depth, it is heated partly from within by radioactivity, and its cold upper boundary layer is broken into rigid plates. The plates are not carried passively on top of convection; they are its upper boundary layer. Force-balance studies show that the pull of [sinking slabs](#) is the dominant force driving plate motion, as [Forsyth and Uyeda](#) first argued, and that plates attached to subducting slabs move fastest. Seismic imaging shows slabs sinking through the transition zone into the lower mantle, and two continent-sized regions of slow seismic speed at the base of the mantle beneath Africa and the Pacific, the [large low-shear-velocity provinces](#), whose origin is debated.

3.5 The geodynamo and the magnetic field

The liquid outer core is a second convecting layer, with a viscosity close to that of water. It is stirred by heat flowing out into the mantle and by light elements released as the inner core freezes. Because it is an electrical conductor rotating with the planet, its motion sustains a magnetic field by dynamo action. Palaeomagnetic measurements show that Earth had a field at least [3.4 to 3.45 billion years ago](#), and single zircon crystals suggest one [as early as 4.2 billion years ago](#), a result that remains contested. The

inner core is younger. Estimates of its age range from about half a billion to one and a half billion years, and one palaeointensity study argued for [nucleation in the Mesoproterozoic](#). Before then the dynamo must have run on thermal convection alone, a puzzle that depends on the uncertain thermal conductivity of iron at core pressures.

The field deflects the solar wind, a stream of charged particles flowing from the Sun at a few hundred kilometres per second. The boundary where the pressure of the field balances that of the wind, the magnetopause, lies at a distance proportional to the sixth root of the ratio of magnetic to wind pressure. The calculation made for this report (Figure 11) gives about 10 Earth radii for typical conditions, 6.5 for a strong storm and about 4 for an extreme event like the [Carrington event](#) of 1859. Because of the sixth-root dependence the magnetosphere is robust: even a field at one tenth of today's strength would hold the wind off at about 5 Earth radii under typical conditions.

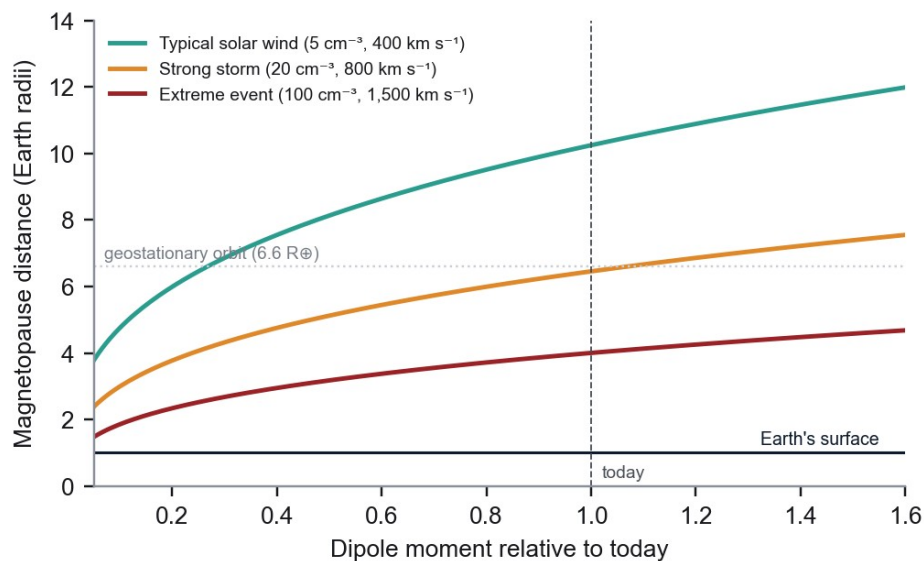


Figure 11. How far the magnetic field holds off the solar wind. The magnetopause distance, calculated for this report from the balance of magnetic and solar-wind pressure, depends only on the sixth root of the dipole strength, so even a much weaker field would keep the solar wind far above the atmosphere.

Source: H Heuristics calculation using the Chapman–Ferraro pressure balance with a compression factor of 2, an equatorial surface field of 31 microtesla and the solar-wind densities and speeds shown.

Whether the field is essential to habitability is less clear than is often assumed. It shields the surface from some energetic particles and channels them to the poles. But Venus, which has no internal field, retains a massive atmosphere, and modelling suggests that magnetic fields can sometimes [increase rather than reduce](#) the total escape of atmospheric ions by enlarging the area that intercepts solar-wind energy. The report therefore grades the claim that the geodynamo is necessary for Earth's habitability as contested (Grade C), while treating its role in shielding the surface and preserving a record of plate motions as established.

3.6 The deep water and carbon cycles

The interior is not only a source of heat but a reservoir of volatiles. Water is carried down into the mantle in hydrated minerals of subducting slabs, and some of it is returned by volcanoes. A diamond from Brazil containing the high-pressure mineral ringwoodite showed that the transition zone can hold [about 1 per cent water by weight](#); if that concentration is widespread, the mantle could contain as much water as the

oceans. Carbon follows a similar path. [Subducting slabs](#) carry carbonate and organic carbon into the mantle, and volcanoes, ridges and diffuse degassing return [a few hundred million tonnes of carbon a year](#), about one per cent of today's fossil-fuel emissions.

These deep cycles are slow but decisive. Water in the mantle lowers the melting point and the viscosity of rock and may be one reason Earth has plate tectonics while Venus does not. The balance between carbon going down and carbon coming up sets the long-term CO₂ content of the atmosphere, and therefore the climate, over tens of millions of years. The interior is thus connected to the surface not only by heat but by the chemistry of the air.

3.7 What the evidence shows and where it stops

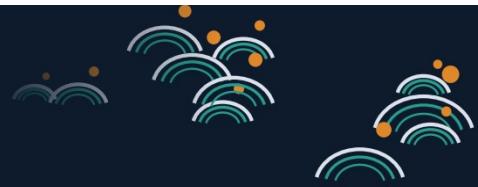
Table 4. The planetary interior: evidence grades

Claim	Grade	Note
Earth has a solid inner core, liquid outer core and solid but convecting mantle	A	Seismology, gravity, moment of inertia and the calculation in Figure 8 agree
Radioactivity supplies roughly half of the 46 TW heat flow	A–B	Geoneutrino measurements; the split among mantle, crust and core is uncertain
Slab pull is the main force driving plates	A–B	Force balance and plate kinematics
A geodynamo operated by 3.4 billion years ago	B	Palaeointensity; the 4.2 billion-year claim is contested
The inner core nucleated between 0.5 and 1.5 billion years ago	C	Depends on core thermal conductivity
The magnetic field is necessary for habitability	C	Shielding is real; its effect on net atmospheric loss is debated
The mantle holds as much water as the oceans	C	One diamond inclusion and indirect evidence

Source: H Heuristics assessment of the studies cited in this section.

04

PART II · THE ATMOSPHERE



4. The Architecture of the Atmosphere

Key question: how does the atmosphere regulate heat and shape planetary habitability? This section follows energy from the Sun through the air and back to space, and shows how a layer containing one millionth of Earth's mass controls its surface temperature.

4.1 A thin envelope with a long history

The atmosphere has a mass of about 5.1×10^{18} kilograms, roughly one millionth of the planet's. Half of it lies below 5.5 kilometres and 90 per cent below about 16 kilometres (Figure 12), so that if Earth were the size of an apple the air would be thinner than its skin. It is a secondary atmosphere: whatever gas the planet captured from the solar nebula was lost early, and the present envelope was built from gases released by the interior and delivered by impacts, then reshaped by life. Its argon, almost one per cent of the air, is argon-40 produced by the radioactive decay of potassium-40 in rocks, a direct chemical trace of the interior heat source described in Section 3. Its oxygen is a product of photosynthesis (Section 6). Its nitrogen has accumulated over billions of years and is cycled through the biosphere and the mantle.

Most of the gases that matter for climate are present only in traces (Figure 12, Panel B). Nitrogen and oxygen, which make up 99 per cent of dry air, are transparent to infrared radiation because their symmetric two-atom molecules do not absorb it. The gases that do absorb infrared, water vapour, carbon dioxide, methane, nitrous oxide and ozone, together amount to less than half a per cent. Small changes in these trace constituents can therefore produce large changes in the energy balance.

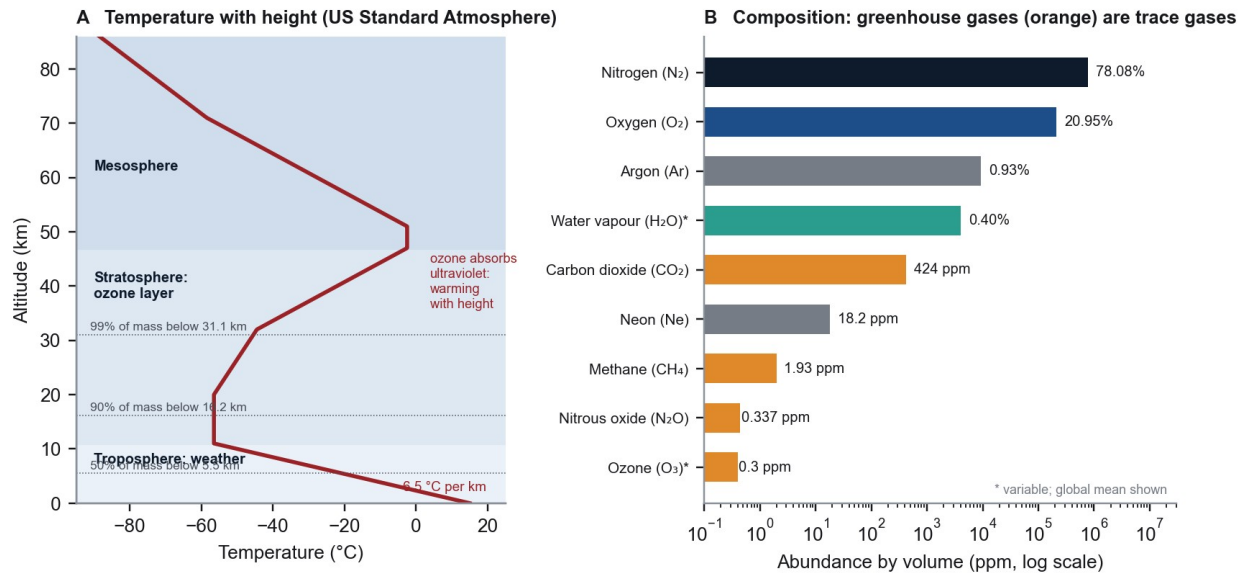


Figure 12. The structure and composition of the atmosphere. Panel A shows temperature against altitude in the US Standard Atmosphere, calculated for this report from its defining lapse rates, with the altitudes below which 50, 90 and 99 per cent of the air's mass lies. Panel B shows the abundance of the main gases on a logarithmic scale; the gases that absorb infrared radiation (orange and teal) are trace constituents.

Source: H Heuristics calculation from the US Standard Atmosphere (1976). Composition: NOAA Global Monitoring Laboratory (CO₂, CH₄, N₂O, 2024 means) and standard values; water vapour and ozone vary widely.

4.2 Vertical structure

Temperature does not fall steadily with height. In the lowest layer, the [troposphere](#), air is heated from below by the sunlit surface and cools as it rises and expands, at about 6.5 °C per kilometre on average. The troposphere is where weather happens and where almost all the water vapour is. It extends to about 16 kilometres over the tropics and 8 over the poles. Above it, in the stratosphere, temperature rises with height because ozone absorbs ultraviolet sunlight. The warm lid makes the stratosphere stable and stratified, which is why it has no weather and why volcanic aerosols injected into it can stay for a year or two. Above 50 kilometres temperature falls again through the mesosphere.

This structure is a filtered outcome of competing processes. Radiation alone would make the lower atmosphere hotter near the ground and cooler aloft than observed; convection redistributes heat upward until the lapse rate is close to the value at which rising air is neutrally buoyant. The pioneering radiative–convective model of [Manabe and Wetherald](#) showed in 1967 that combining these two processes reproduces the observed temperature profile and predicts that doubling CO₂ warms the surface by about 2 °C while cooling the stratosphere, a fingerprint that observations have since confirmed.

4.3 Sunlight in, infrared out

The Sun's surface radiates at about 5,800 K, so its energy peaks in visible light. Earth radiates at about 255 to 288 K, so its emission peaks near 10 to 15 micrometres in the infrared (Figure 13). The two spectra barely overlap. This separation is the physical basis of the greenhouse effect: the atmosphere is largely transparent to incoming sunlight but partly opaque to outgoing infrared, because water vapour, CO₂, methane and ozone absorb strongly in particular bands. Between 8 and 13 micrometres lies an atmospheric window through which surface radiation escapes directly to space, partly closed by ozone at

9.6 micrometres. The strong CO_2 band near 15 micrometres sits close to the peak of Earth's emission, which is why CO_2 is such an effective greenhouse gas despite its low concentration.

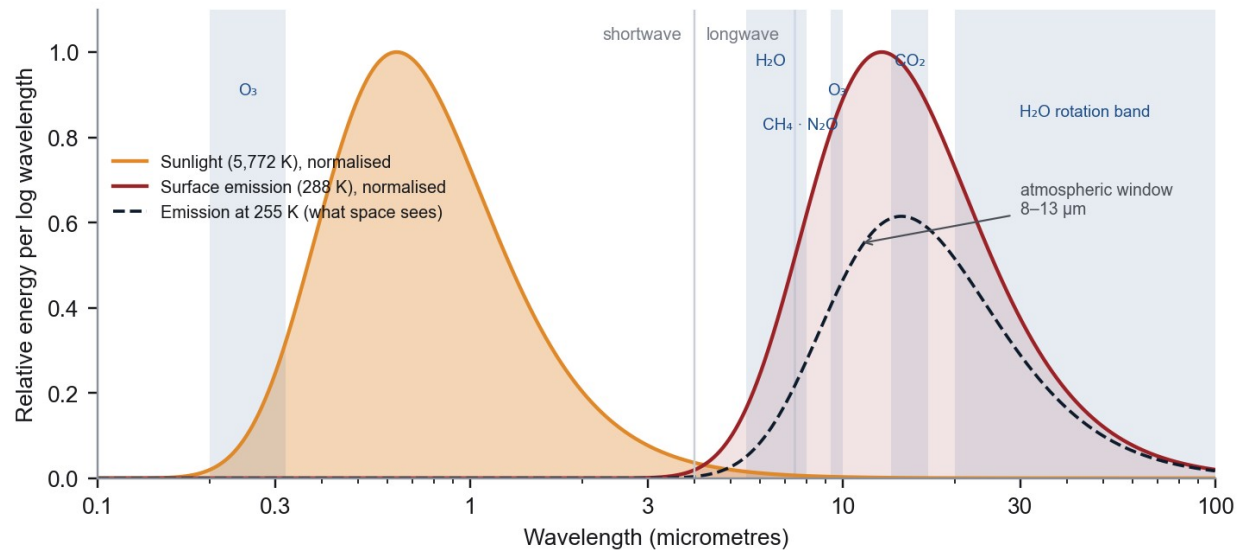


Figure 13. Sunlight in, infrared out. The normalised spectra of sunlight and of Earth's thermal emission barely overlap. Shaded bands mark the main absorbers of outgoing infrared radiation. The dashed curve shows emission at 255 K, the temperature at which Earth radiates to space; the surface is warmer because the atmosphere absorbs much of the surface emission and re-radiates part of it downward.

Source: H Heuristics calculation of Planck spectra; absorption bands indicative.

4.4 The greenhouse effect

The greenhouse effect was identified by Joseph Fourier in the 1820s, measured in the laboratory by John Tyndall in 1859 and first quantified by [Svante Arrhenius](#) in 1896, who estimated that halving CO_2 would bring an ice age and doubling it would warm the planet by several degrees. The global energy budget (Figure 14) shows how it works. Of the 341 watts per square metre of incoming sunlight, about 102 are reflected and 239 absorbed, 161 of them at the surface. The surface emits about 396 watts per square metre of infrared, far more than the 239 that eventually leave to space. The difference is made up by 333 watts per square metre of back radiation from the greenhouse gases and clouds above.

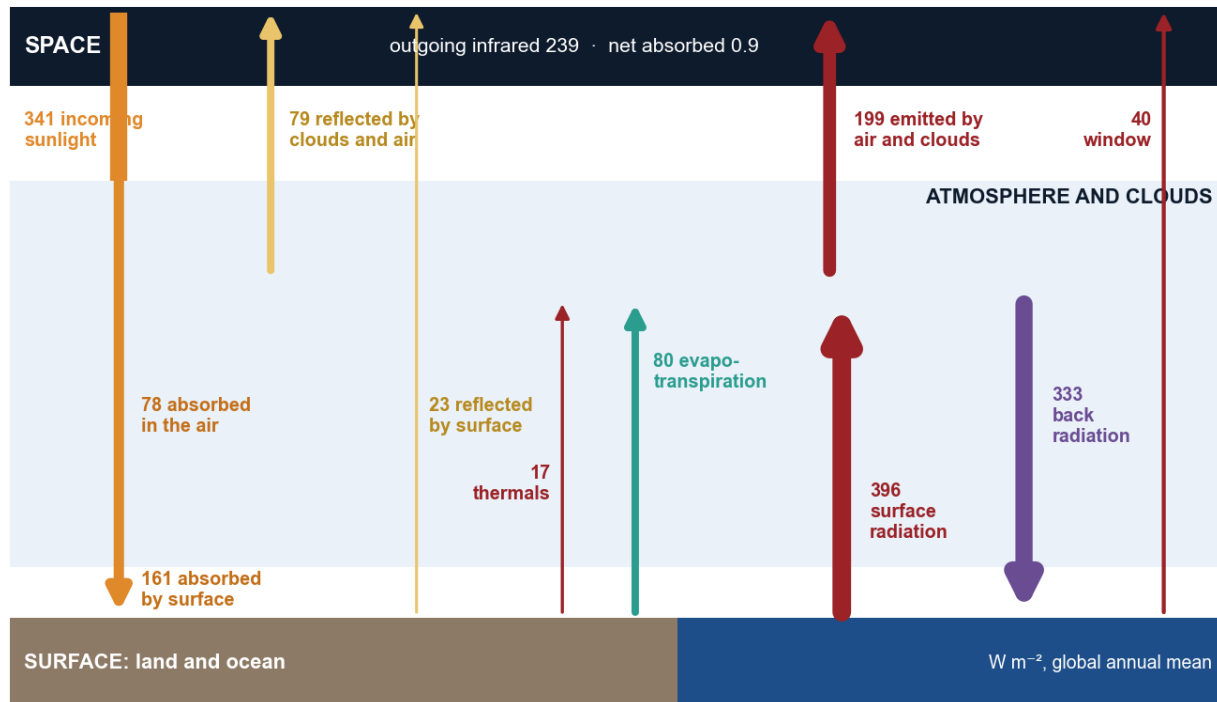


Figure 14. Earth's global energy budget. Flows are in watts per square metre averaged over the globe and over the year. The surface receives more energy from the atmosphere's back radiation than directly from the Sun. The small net imbalance at the top is the energy being accumulated by the planet as greenhouse gases increase.

Source: Trenberth, Fasullo and Kiehl (2009), with the net imbalance updated from satellite and ocean observations (Loeb et al., 2021; von Schuckmann et al., 2023). Arrow widths indicative.

A one-layer model captures the essence (Figure 15, Panel A). If a single atmospheric layer absorbs a fraction ϵ of the surface's infrared emission and re-emits it equally up and down, the surface temperature rises above the 255 K of Equation 1 by a factor of $(2/(2 - \epsilon))^{1/4}$. Matching the observed 288 K requires $\epsilon \approx 0.78$. Of the total greenhouse effect, [water vapour contributes about half, clouds a quarter and CO₂ about a fifth](#). But water vapour cannot set the temperature on its own: its concentration is controlled by temperature through Equation 4, so it amplifies rather than initiates change. The non-condensing gases, above all CO₂, are what [Lacis and colleagues](#) called the control knob of the greenhouse effect.

The forcing from CO₂ rises with the logarithm of its concentration, because the centre of its absorption band is already saturated and additional CO₂ acts mainly at the band's edges. The widely used expression of [Myhre and colleagues](#), $F = 5.35 \ln(C/C_0)$ watts per square metre, gives 3.7 watts per square metre for a doubling and about 2.3 for the rise from 278 to 425 ppm (Figure 15, Panel B). The logarithm means that each additional tonne of CO₂ has slightly less effect than the last, but the effect never stops, and the rate of emissions has grown faster than the logarithm has flattened.

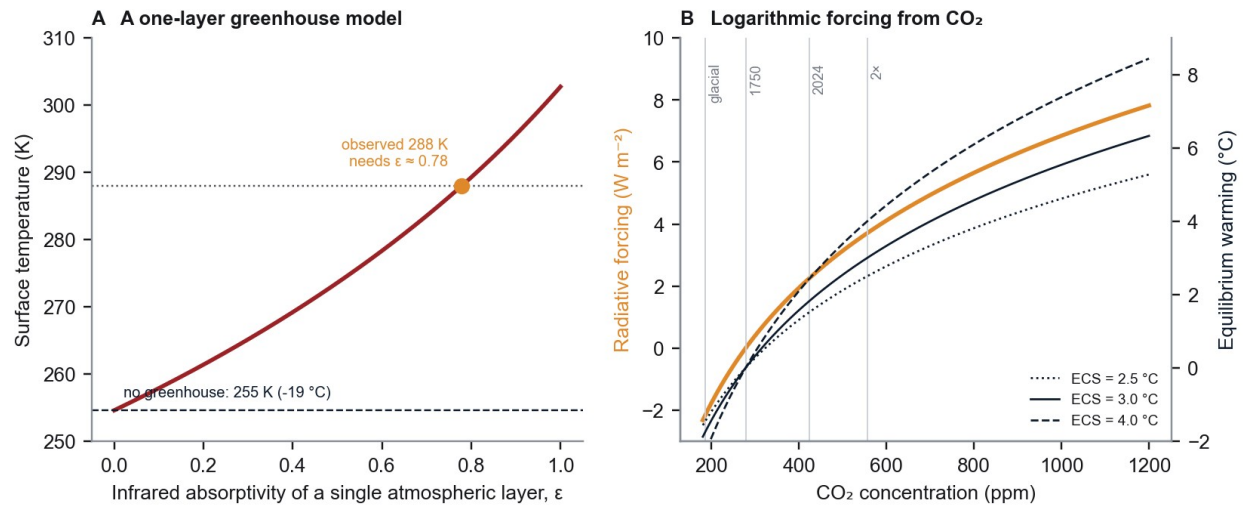


Figure 15. Greenhouse physics. Panel A, a one-layer model calculated for this report, shows that the observed surface temperature requires an atmosphere absorbing about 78 per cent of surface infrared. Panel B shows the radiative forcing from CO₂ against its concentration and the equilibrium warming it implies for three values of climate sensitivity.

Source: H Heuristics calculation. Forcing after Myhre et al. (1998); sensitivity values span the IPCC AR6 likely range.

4.5 The changing composition

Systematic measurement of atmospheric CO₂ began in 1958, when [Charles David Keeling](#) started recording it on Mauna Loa in Hawaii. The record, continued by the [NOAA Global Monitoring Laboratory](#), shows a rise from 316 ppm in 1959 to 425 ppm in 2024 (Figure 16), with growth accelerating from under 1 ppm a year in the 1960s to about 2.6 ppm a year over the last decade. Air bubbles trapped in Antarctic ice show that during the previous [800,000 years](#) CO₂ varied between about 180 ppm in ice ages and 300 ppm in warm interglacials. The present concentration is 53 per cent above the pre-industrial level and higher than at any time in at least two million years.

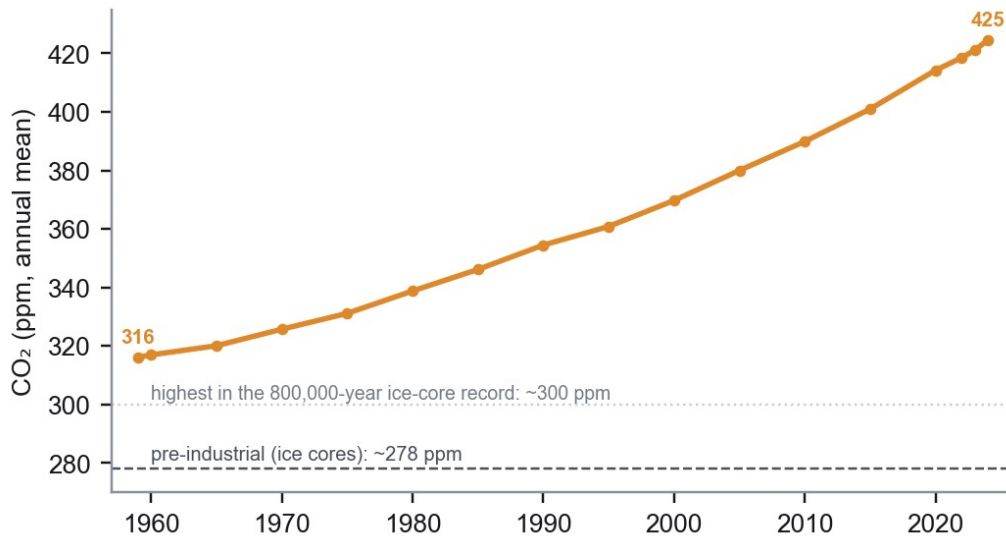


Figure 16. The Keeling curve. Annual mean CO₂ at Mauna Loa has risen every year since measurements began, from 316 ppm in 1959 to 425 ppm in 2024, far beyond the range of the ice-core record.

Source: NOAA Global Monitoring Laboratory and Scripps Institution of Oceanography, annual means; ice-core values from Lüthi et al. (2008).

Table 5. The main drivers of present-day radiative forcing

Driver	Pre-industrial → recent	Atmospheric lifetime	Effective forcing, 1750–2019 (W m ⁻²)
Carbon dioxide (CO ₂)	278 → 425 ppm (2024)	No single lifetime; 15–40% of a pulse remains after 1,000 years	+2.16
Methane (CH ₄)	~730 → ~1,930 ppb	About 12 years	+0.54
Nitrous oxide (N ₂ O)	~270 → ~337 ppb	About 110 years	+0.21
Halocarbons	0 → present	Years to millennia	+0.41
Tropospheric ozone	Rising with pollution	Weeks	+0.47
Aerosols (net, incl. clouds)	Rising, now falling in some regions	Days to weeks	-1.1 (-1.7 to -0.4)
Total human-caused			+2.72 (1.96 to 3.48)

Source: IPCC AR6 Working Group I, Chapter 7 (Forster et al., 2021) for forcing; NOAA Global Monitoring Laboratory for recent concentrations; Archer et al. (2009) for the CO₂ lifetime.

4.6 Circulation: the atmosphere as a heat engine

A spherical planet receives more sunlight per square metre at the equator than at the poles, but radiates heat more evenly. The tropics therefore run an energy surplus and the high latitudes a deficit, and the atmosphere and ocean must carry heat poleward to balance the books. To show this, the report built a latitude-resolved energy-balance model of the type introduced by [Mikhail Budyko](#) in 1969, with outgoing radiation that increases linearly with temperature, an ice albedo where the annual mean temperature is below -10 °C and a simple representation of heat transport (Figure 17). Tuned to give a global mean temperature of 14 °C and an ice edge near 77°, the model reproduces the surplus equatorward of about 35° and the deficit poleward of it. Its implied poleward transport peaks near 36° latitude at about 3

petawatts, around half the observed peak of 5.8, because a single diffusive term underrepresents the efficiency of real eddies and currents; the location of the peak, however, matches observations.

How the atmosphere carries the heat is shaped by rotation. Air rising in the tropics flows poleward aloft, but the Coriolis effect deflects it eastward, and at about 30° latitude it sinks, forming the Hadley cell. The sinking air is dry, which is why the great deserts lie near 30° north and south, and the returning surface flow forms the trade winds. Poleward of the Hadley cell, heat is carried mainly by the eddies of mid-latitude weather systems, which are organised by the polar-front jet stream; the Ferrel cell is a statistical average of their effect rather than a closed loop. The three-cell pattern is a classic creation structure: the constraint is the energy imbalance and the planet's rotation, the generator is convection, and the filter is the conservation of angular momentum, which limits how far a direct overturning cell can extend.

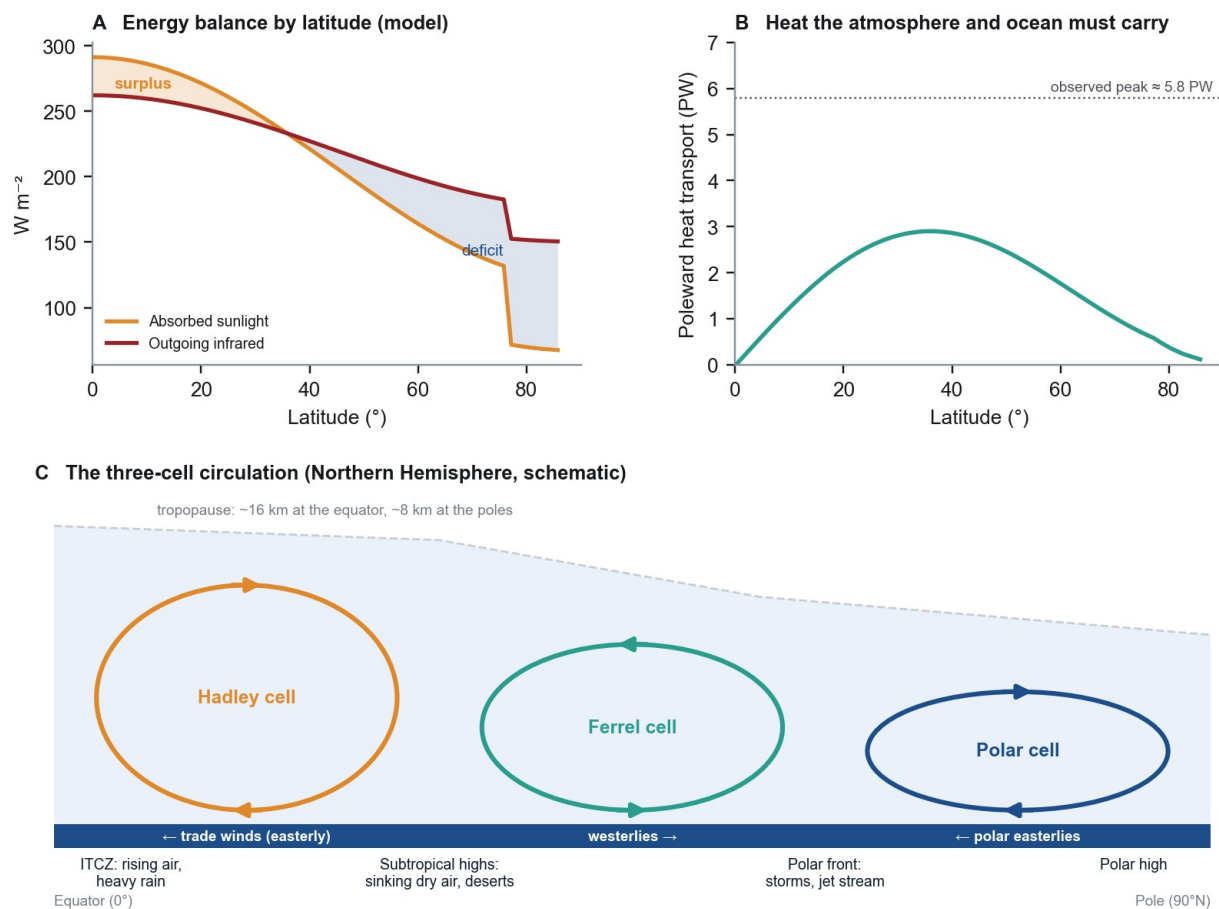


Figure 17. The atmosphere as a heat engine. Panels A and B come from a latitude-resolved energy-balance model built for this report: absorbed sunlight exceeds outgoing infrared in the tropics, so heat must be carried poleward. Panel C shows the three-cell circulation that carries it in each hemisphere.

Source: Panels A and B, H Heuristics energy-balance model after Budyko (1969) and North (1975); observed transport from Trenberth and Caron (2001). Panel C, H Heuristics schematic.

4.7 Weather, chaos and climate

In 1963 Edward Lorenz showed with a three-variable model of convection that a deterministic system can have [sensitive dependence on initial conditions](#): tiny errors grow exponentially until forecasts lose all skill. Modern estimates put the [limit of predictability](#) for mid-latitude weather at about two weeks. Climate is nevertheless predictable, because it is the statistics of weather constrained by the energy budget. A

single storm cannot be forecast a month ahead, but the response of the mean temperature to a change in forcing can be calculated decades in advance. This distinction between an initial-value problem and a boundary-value problem recurs throughout the report: individual trajectories are chaotic, while the space they explore is constrained.

4.8 The ozone layer: a case study in planetary repair

The stratospheric ozone layer absorbs ultraviolet radiation that would otherwise damage DNA at the surface. It is itself a product of the biosphere, since ozone forms from oxygen. In 1985 [Farman, Gardiner and Shanklin](#) reported large springtime losses of ozone over Antarctica, caused by chlorine from industrial chlorofluorocarbons acting on polar stratospheric clouds. The 1987 [Montreal Protocol](#) phased these chemicals out. Stratospheric chlorine has been falling since the late 1990s and the ozone layer is on track to recover to 1980 levels around mid-century over most of the world and in the 2060s over Antarctica. The episode is the clearest example so far of humans altering a planetary subsystem, recognising it and reversing course, and it shows that atmospheric feedbacks, once identified, can be managed.

4.9 What the evidence shows and where it stops

Table 6. The atmosphere: evidence grades

Claim	Grade	Note
The greenhouse effect raises Earth's surface temperature by about 33 °C	A	Radiative physics and observations
Rising CO ₂ is the dominant cause of the increase in radiative forcing since 1750	A	Isotopic, spectroscopic and budget evidence
CO ₂ forcing rises logarithmically with concentration	A	Line-by-line radiative calculations
Aerosols have offset part of greenhouse warming	A–B	Sign certain; magnitude uncertain by a factor of two
Mid-latitude weather is unpredictable beyond about two weeks	B	Chaos theory and ensemble forecasting
The Hadley circulation is widening as the planet warms	B–C	Observed in several data sets; magnitude debated

Source: H Heuristics assessment of the studies cited in this section.

05

PART III · WATER



5. The Architecture of Water

Key question: how does the water cycle connect Earth's surface, atmosphere and interior? This section treats water as the planet's great connector: a store of heat, a carrier of energy and chemistry, a sculptor of rock and, frozen, a switch that can change the planet's reflectivity.

5.1 A water planet

Oceans cover 71 per cent of Earth's surface to an average depth of 3.7 kilometres and hold about 1.34 billion cubic kilometres of water, 97 per cent of the water at or near the surface. Yet water makes up only about 0.02 per cent of the planet's mass. Its origin is still debated. Earth formed inside the zone where water ice could condense in the solar nebula, so its building blocks were probably fairly dry; the ratio of deuterium to hydrogen in the oceans resembles that of [carbonaceous chondrite meteorites](#), which suggests that much of the water was delivered by bodies from the outer asteroid belt during accretion rather than by comets.

Water's physical properties make it unusually effective as a planetary connector. It has the highest heat capacity of any common substance, so the oceans store vast amounts of energy: the top three metres of ocean hold as much heat per degree as the entire atmosphere. Its latent heat of evaporation is large, so evaporation moves energy from the surface to the air invisibly, releasing it where vapour condenses. It exists in all three phases at Earth's surface temperatures. It is an excellent solvent, which makes it the medium of weathering and of life. And ice is less dense than liquid water, so lakes and seas freeze from the top down.

5.2 The hydrological cycle

Each year about 486,000 cubic kilometres of water evaporate from the oceans and land, travel through the atmosphere and fall as rain or snow (Figure 18). Over the oceans evaporation exceeds precipitation by about 40,000 cubic kilometres; that surplus is carried by winds over land, where it falls and returns to the sea in rivers and groundwater. These figures, from the global budget of [Trenberth and colleagues](#), imply very different residence times. Dividing each store by the flow through it (Equation 2) gives about 9.5 days for water in the atmosphere, about 4.5 years for lakes and rivers, a few centuries for groundwater on average, and about 3,200 years for the ocean.

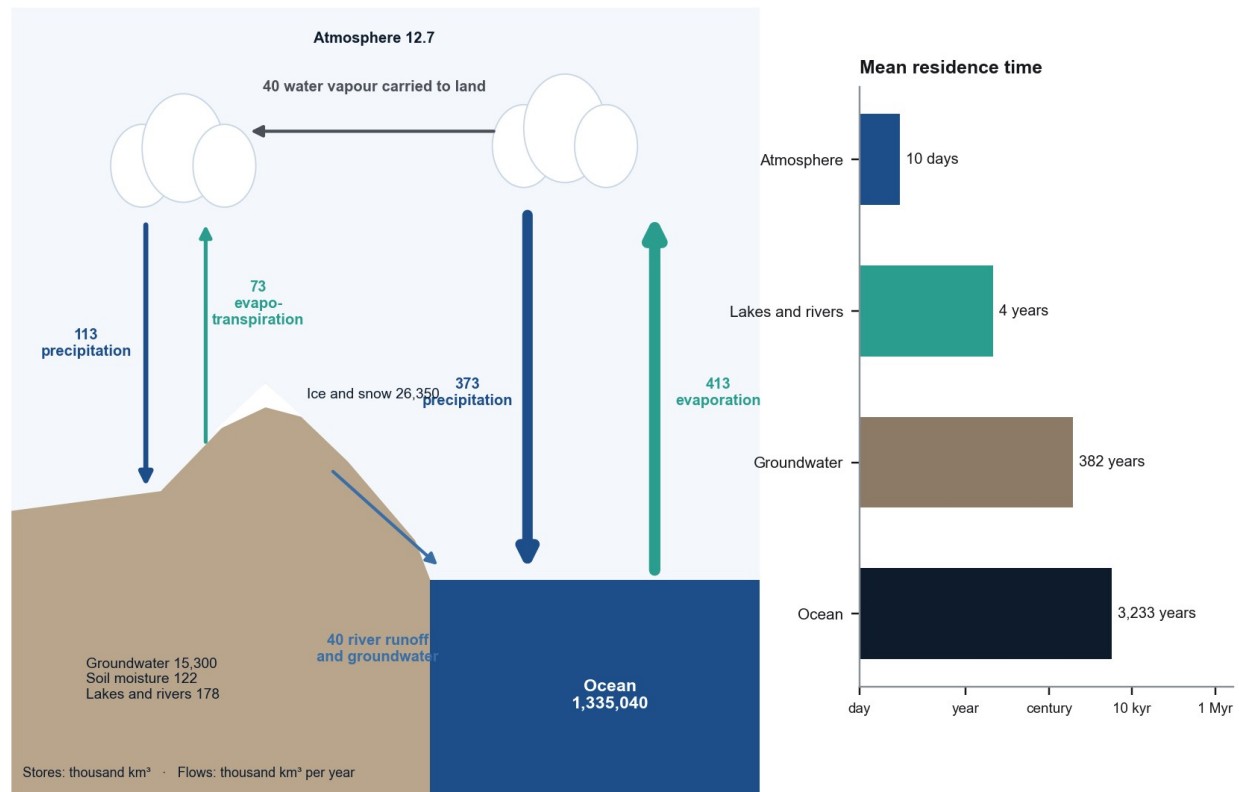


Figure 18. The global water cycle. Stores are in thousands of cubic kilometres and flows in thousands of cubic kilometres per year. The right panel, calculated for this report, shows mean residence times obtained by dividing each store by the flow through it; they span more than five orders of magnitude.

Source: Stores and flows from Trenberth et al. (2007). Residence times: H Heuristics calculation; the groundwater value is a crude average over stores whose ages range from days to millions of years.

The cycle is powered by sunlight. Evaporating 486,000 cubic kilometres of water a year takes about 80 watts per square metre averaged over the globe, roughly a third of all the solar energy absorbed by the planet (Figure 5). That energy is released as latent heat when vapour condenses into clouds, often thousands of kilometres from where it evaporated. The water cycle is therefore also an energy cycle: it cools the surface, warms the troposphere, powers thunderstorms and tropical cyclones, and carries heat poleward alongside the winds and currents.

5.3 Warmer air, wetter extremes

The maximum amount of water vapour that air can hold rises steeply with temperature (Figure 19). The Clausius–Clapeyron relation (Equation 4) gives an increase of about 6 to 7 per cent per degree near today's mean surface temperature. Observations confirm that humidity has risen roughly at this rate as the planet has warmed. Because water vapour is a greenhouse gas, the rise is a feedback that roughly doubles the warming that would occur without it.

Global-mean rainfall, however, increases much more slowly, by about 1 to 3 per cent per degree, because it is limited by the atmosphere's ability to radiate away the latent heat released by condensation. [Held and Soden](#) showed that the combination of rapidly rising humidity and slowly rising precipitation has robust consequences: wet regions tend to get wetter and dry regions drier, and the heaviest downpours, which draw on the moisture available in the air, intensify at roughly the Clausius–Clapeyron rate or faster. Observed increases in [short-duration rainfall extremes](#) are consistent with this.

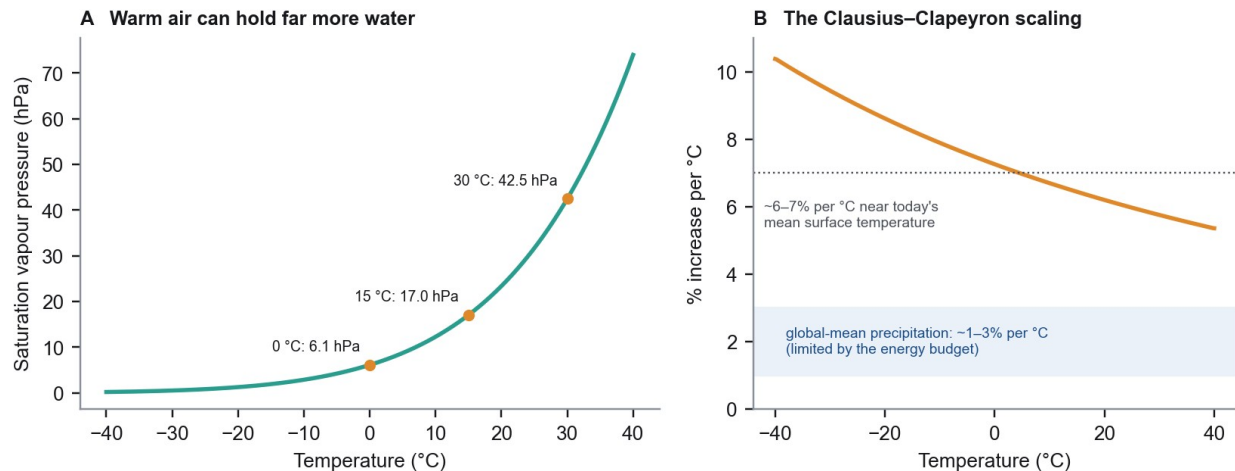


Figure 19. The Clausius–Clapeyron relation. Panel A shows saturation vapour pressure against temperature: at 30 °C air can hold about seven times as much water as at 0 °C. Panel B shows the fractional increase per degree, about 6 to 7 per cent near today's mean temperature, compared with the slower rise of global-mean precipitation.

Source: H Heuristics calculation using the Bolton (1980) approximation; precipitation range from Held and Soden (2006) and IPCC AR6.

5.4 The ocean as the planet's heat store

Because of its heat capacity and depth, the ocean is where the extra energy trapped by greenhouse gases goes. Between 1971 and 2018 about [91 per cent](#) of the heat accumulated by the climate system was stored in the ocean, about 5 per cent warmed the land, 3 per cent melted ice and only 1 per cent warmed the atmosphere (Figure 21, Panel B). Ocean heat content is therefore the most reliable single measure of global warming, and it has risen in almost every year of the modern record.

The ocean's thermal inertia has two consequences. It slows surface warming, because heat mixed into the deep ocean is temporarily out of contact with the atmosphere. And it creates a commitment: even if the forcing stopped rising, the surface would continue to warm slowly as the upper ocean equilibrated, while thermal expansion of the deep ocean would raise sea level for centuries. Warming water also holds less oxygen and less CO₂, and the upper ocean has become more stratified, which reduces the mixing of nutrients from below.

5.5 Ocean circulation

The ocean moves in two linked ways. Winds drive the surface currents, organising them into great gyres in each ocean basin, with fast western boundary currents such as the Gulf Stream and Kuroshio. Differences in density, set by temperature and salinity, drive a slower overturning circulation that reaches the abyss (Figure 20). In the North Atlantic, warm salty water carried north by the Gulf Stream cools, becomes dense and sinks in the Nordic and Labrador Seas, forming North Atlantic Deep Water that flows south at depth. Around Antarctica, the formation of sea ice rejects salt into the water beneath, producing the coldest and densest water in the ocean. The return path is largely through wind-driven upwelling in the Southern Ocean, as [Talley](#) and others have shown.

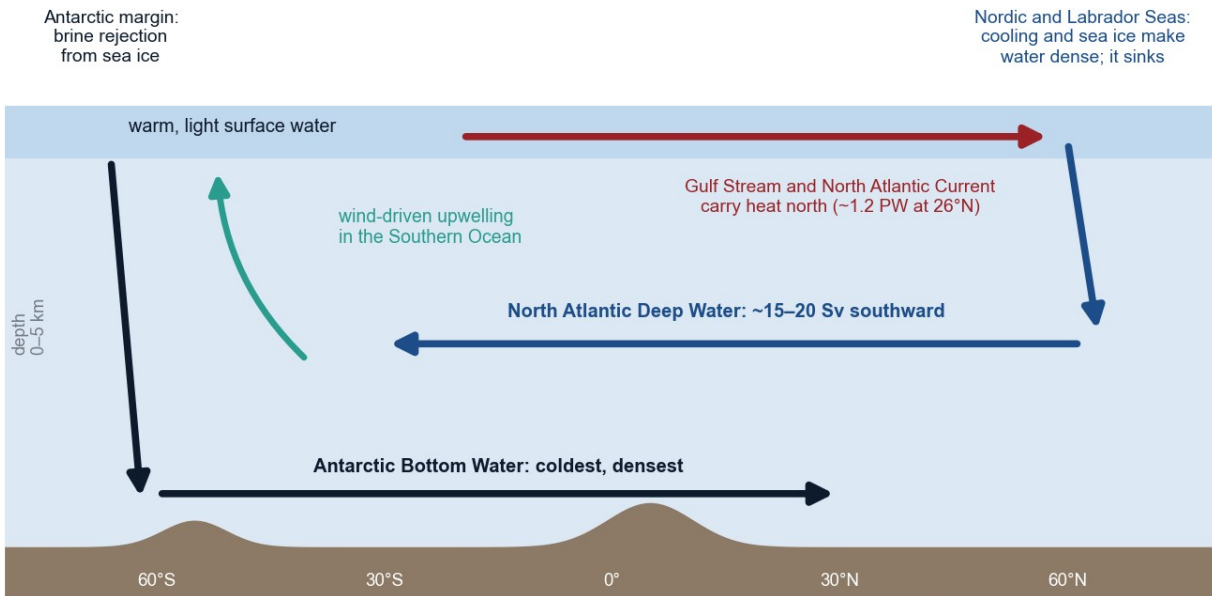


Figure 20. The ocean's overturning circulation, schematic north–south section. Warm surface water flows north in the Atlantic, sinks in the Nordic and Labrador Seas and returns south as deep water; the densest water forms around Antarctica; Southern Ocean winds bring deep water back to the surface. A full circuit takes on the order of a thousand years.

Source: H Heuristics schematic after Rahmstorf (2002) and Talley (2013). Transport and heat-flux values from the RAPID array at 26°N.

The overturning matters to the planetary system for three reasons. It carries heat: the Atlantic Meridional Overturning Circulation (AMOC) transports about 1.2 petawatts northward at 26° N, which is part of why north-western Europe is mild for its latitude. It ventilates the deep ocean, carrying oxygen and anthropogenic CO₂ downward; the ocean has absorbed [about a quarter](#) of all CO₂ emitted by humans, at the cost of [ocean acidification](#), a fall of about 0.1 pH units since pre-industrial times. And it is a candidate tipping element, because the sinking that drives it depends on salinity, and freshening by meltwater and rainfall can weaken it. [Rahmstorf](#) reviewed the palaeoclimatic evidence that the AMOC has switched between states in the past; Section 8 returns to the risk that it could do so again.

The overturning also needs energy to keep going, because deep water must be mixed upward through the stratified interior. [Munk and Wunsch](#) estimated that this requires about 2 terawatts, supplied by the winds and the tides. The tides, raised by the Moon and Sun (Figure 5), are thus part of the machinery of ocean circulation and climate: an example of a small energy flow that is structurally essential.

5.6 The cryosphere

About 10 per cent of the land surface is covered by glaciers and ice sheets. The Antarctic ice sheet holds enough water to raise global sea level by about [58 metres](#), the Greenland ice sheet about 7.4 metres and the world's mountain glaciers about [0.3 metres](#) (Figure 21). Floating sea ice covers a further 15 to 25 million square kilometres at its seasonal maximum in each hemisphere. Because snow and ice reflect most sunlight while open water and land absorb most of it, the cryosphere controls a large part of Earth's albedo, and its extent couples directly to temperature through the ice–albedo feedback.

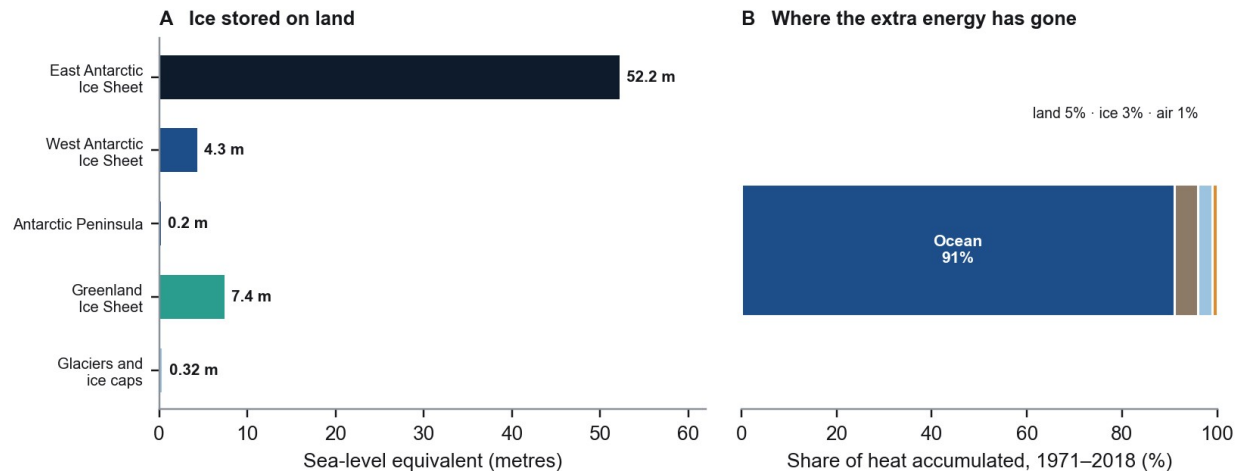


Figure 21. Ice and energy. Panel A shows how much sea-level rise is stored in the world's land ice. Panel B shows where the energy accumulated by the climate system between 1971 and 2018 has gone: overwhelmingly into the ocean.

Source: Panel A, Morlighem et al. (2017, 2020) and Farinotti et al. (2019). Panel B, von Schuckmann et al. (2023) and IPCC AR6.

The cryosphere is now losing mass across almost every component. The two ice sheets together lost about [7,500 billion tonnes of ice between 1992 and 2020](#), raising sea level by about 21 millimetres, and the rate of loss has increased. Mountain glaciers lost [about 267 billion tonnes a year](#) between 2000 and 2019. Arctic sea ice in September has declined by about 13 per cent per decade since 1979, and its loss is close to linear in cumulative emissions: [Notz and Stroeve](#) estimated about three square metres of September sea ice lost for every tonne of CO₂ emitted. Global mean sea level has risen by about 20 centimetres since 1901, and the rate has more than doubled, reaching about 4.7 millimetres a year over 2014–2023.

5.7 Water and rock

Water also connects the surface to the interior. Rain and rivers erode mountains and carry dissolved minerals to the sea, where they become sediment and, eventually, rock. Chemical weathering of silicate rocks consumes CO₂, which is the basis of the long-term thermostat discussed in Section 7. At subduction zones, water carried down in the oceanic crust lowers the melting point of the mantle above and generates the magmas of volcanic arcs such as the Andes and Japan. Water is also thought to weaken the lithosphere enough for plates to break and subduct at all. In this sense the hydrological cycle is not only a surface process: it is one of the reasons Earth has plate tectonics.

5.8 What the evidence shows and where it stops

Table 7. Water and ice: evidence grades

Claim	Grade	Note
The ocean has absorbed about 90 per cent of the excess heat since 1971	A	Ocean heat-content observations
Atmospheric humidity rises about 7 per cent per degree of warming	A	Physics and observation
Heavy rainfall is intensifying with warming	A–B	Robust globally; regional signals vary
Both ice sheets are losing mass at an accelerating rate	A	Gravimetry, altimetry and mass-budget methods agree
The AMOC has weakened since the mid-twentieth century	C	Proxy reconstructions suggest it; direct records are short
Much of Earth's water was delivered by asteroidal material	B–C	Isotopic similarity; other sources possible

Source: H Heuristics assessment of the studies cited in this section.

06

PART IV · THE BIOSPHERE

6. The Architecture of the Biosphere

Key question: how does life become an active force in planetary evolution? The companion report [The Architecture of Life](#) explains how living systems arose and organised themselves. This section looks at the same biosphere from the outside, as a subsystem of the planet that captures energy, moves elements and has repeatedly changed the chemistry of air, water and rock.

6.1 Life as a planetary layer

All the living matter on Earth contains about [550 billion tonnes of carbon](#) (Figure 22). Plants account for about 80 per cent of it, bacteria for about 15 per cent, and fungi, archaea, protists and animals for the rest. Most of this mass is on land, but much of the activity is not: ocean phytoplankton make up less than one per cent of biomass yet carry out about half of global photosynthesis, because they grow and are eaten within days. Life extends from the upper troposphere, where microbes ride in clouds, to the deepest ocean trenches and several kilometres into the crust. Seen against the planet, though, the biosphere is a film tens of kilometres thick on a body 6,371 kilometres in radius.

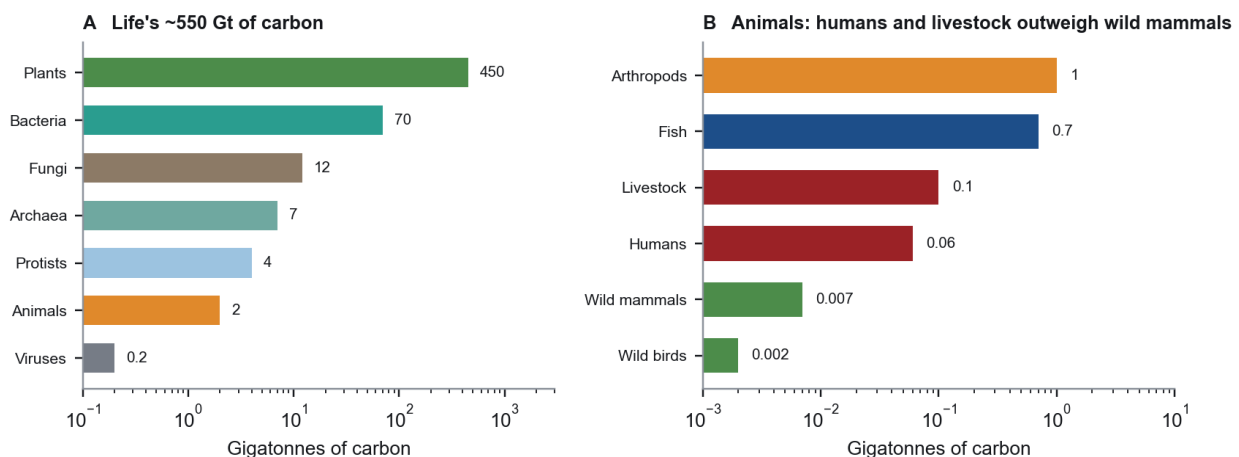


Figure 22. Where the biosphere's mass is. Panel A shows the carbon in each kingdom of life. Panel B shows animals in more detail: by mass, livestock and humans together outweigh all wild mammals more than twentyfold. Source: Bar-On, Phillips and Milo (2018). Values in gigatonnes of carbon; uncertainties are large for bacteria, archaea and protists.

The thinness is deceptive. Measured by its fluxes rather than its mass, the biosphere is one of the planet's most powerful subsystems. Net primary production, the carbon fixed by photosynthesis minus what plants respire, is about [105 billion tonnes a year](#), roughly evenly split between land and ocean. In energy terms that is about 130 terawatts, only one thousandth of the sunlight Earth absorbs, but almost three times the planet's internal heat flow (Figure 5). Because photosynthesis works on chemistry rather than temperature, its leverage is far greater than its share of the energy budget suggests.

6.2 The carbon cycle

Carbon moves among the atmosphere, oceans, land, biosphere and rocks on timescales from seconds to hundreds of millions of years (Figure 23). The fast cycle is dominated by life: each year photosynthesis on land draws about 120 billion tonnes of carbon from the air and respiration, decay and fire return almost the same amount, while the ocean exchanges about 80 billion tonnes in each direction with the atmosphere. These gross fluxes are ten times larger than human emissions. But they are nearly balanced, and a small imbalance in a large flux can matter: the seasonal sawtooth on the Keeling curve (Figure 16) is the Northern Hemisphere's forests breathing in during summer and out in winter.

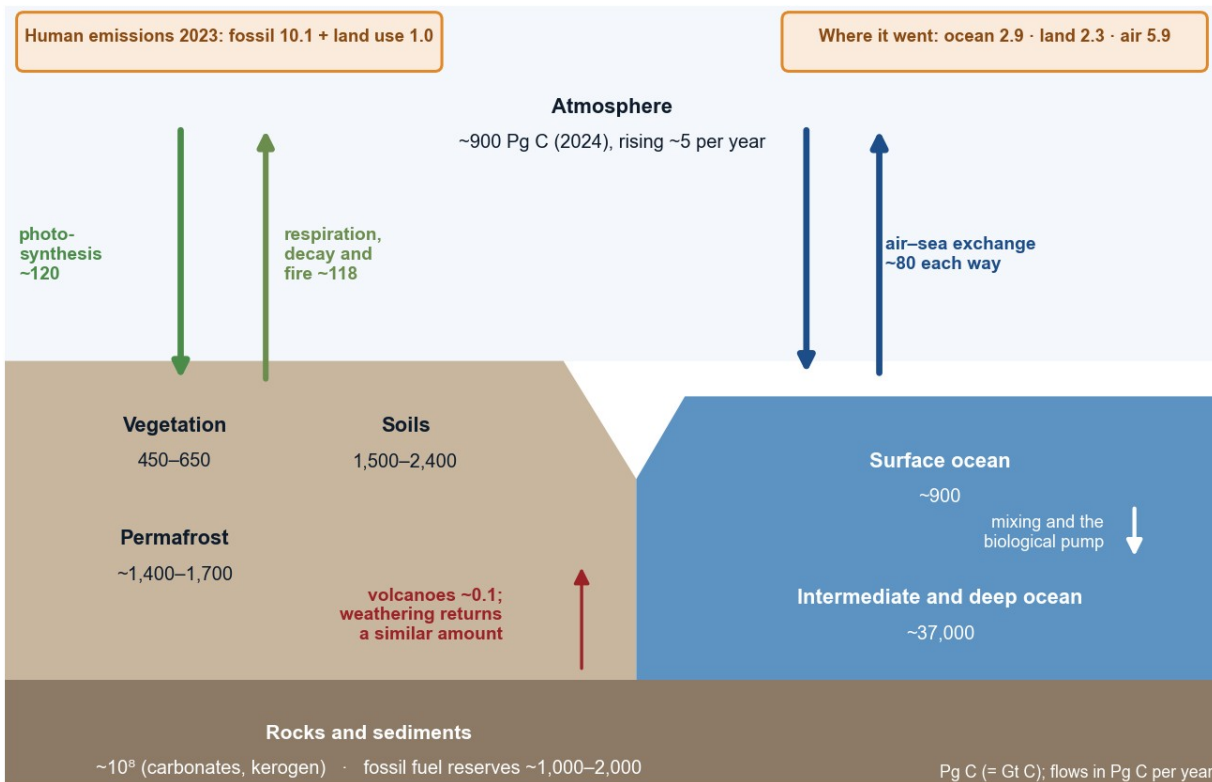


Figure 23. The global carbon cycle. Stores are in billions of tonnes (petagrams) of carbon and flows in billions of tonnes per year. The large natural fluxes between air, land and ocean are almost balanced; human emissions of about 11 billion tonnes a year have unbalanced them, and about half of each year's emissions remains in the air.

Source: H Heuristics, compiled from IPCC AR6 Working Group I, Chapter 5, and the Global Carbon Budget 2024 (Friedlingstein et al., 2025). Stores rounded; ranges reflect uncertainty.

Human activity has added a new flux. In 2023, fossil fuels and cement released about 10.1 billion tonnes of carbon and land-use change about 1.0 billion, according to the [Global Carbon Budget](#). Of that, the ocean absorbed about 2.9 billion tonnes and the land about 2.3, and 5.9 accumulated in the atmosphere. The natural sinks have grown in proportion to emissions, absorbing roughly half of each year's addition for six decades, but this is not guaranteed: the land sink fell sharply in the hot El Niño year of 2023. Whether these sinks weaken as warming continues is one of the main uncertainties in projections of the coming century (Section 8).

The slow carbon cycle runs through rocks. Most of Earth's surface carbon, roughly 10⁸ billion tonnes, is locked in limestone and in organic matter dispersed through sedimentary rocks. Volcanoes return carbon from the interior; weathering and burial remove it. Over millions of years these fluxes, each about 0.1

billion tonnes a year, set the level around which the fast cycle fluctuates (Section 7). Burning fossil fuels transfers carbon from the slow cycle to the fast one about a hundred times faster than volcanoes do.

6.3 Oxygen: a planet remade by life

The most dramatic example of life acting as a geological force is the oxygen in the air. For roughly the first half of Earth's history the atmosphere contained almost no free oxygen; the clearest evidence is an anomaly in the isotopes of [sulphur in ancient rocks](#) that could only be preserved in an atmosphere with less than about 0.001 per cent of today's oxygen. Cyanobacteria, which split water and release oxygen as a by-product of photosynthesis, probably evolved before 3 billion years ago, but for hundreds of millions of years the oxygen they produced was consumed by reduced iron, sulphur and volcanic gases.

Between about 2.43 and 2.06 billion years ago oxygen rose for the first time to a significant level, the Great Oxidation Event (Figure 24). A second rise, between about 800 and 540 million years ago, brought it close to present levels and preceded the appearance of large animals. [Lyons, Reinhard and Planavsky](#) and [Holland](#) review the evidence. The consequences reached every subsystem. Oxygen formed the ozone layer, which made the land surface habitable. It changed weathering, turning iron into insoluble rust and mobilising other elements, and it [more than doubled the number of mineral species](#) on Earth. It removed atmospheric methane, which may have triggered the Huronian glaciations. And it made possible the high-energy metabolism of animals.

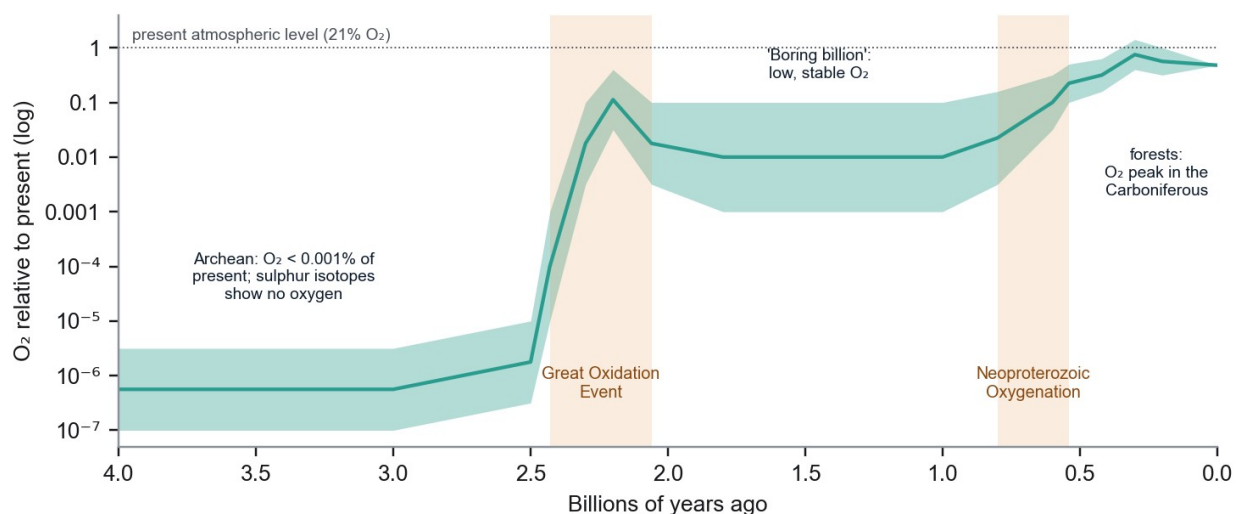


Figure 24. Oxygen in Earth's atmosphere, relative to the present level. Oxygen rose in two main steps, the Great Oxidation Event and the Neoproterozoic Oxygenation Event, separated by a long period of low and stable levels. The envelope shows the range of published estimates, which remain uncertain by an order of magnitude or more for most of Earth's history.

Source: H Heuristics schematic after Lyons et al. (2014) and Holland (2006).

Oxygen is held in balance by the carbon cycle. Every molecule of O_2 in the air corresponds to a molecule of organic carbon that was buried in sediments rather than respired. The oxygen level is thus a record of the long-term burial of organic matter, and it is regulated by feedbacks involving phosphorus, fire and the oxidation of exposed rock. Atmospheric oxygen has stayed between roughly 15 and 30 per cent for the last 400 million years; below the lower bound forests could not burn, above the upper bound they would burn too readily to persist.

6.4 Nutrient cycles

Life needs more than carbon. Nitrogen and phosphorus are the main limiting nutrients, and their cycles are shaped by biology. Nitrogen gas is abundant but inert; only a few microbes, using the enzyme nitrogenase, can break its triple bond and fix it into ammonia. Other microbes return it to the atmosphere through denitrification. As [Canfield, Glazer and Falkowski](#) describe, the planetary nitrogen cycle is essentially a network of microbial metabolisms. Phosphorus has no significant gas phase; it enters ecosystems through the weathering of rock and leaves through burial in sediments, which makes it the ultimate limit on biological productivity over geological time.

Human activity has altered both cycles more than it has altered the carbon cycle in relative terms (Table 8). The [Haber–Bosch process](#), which fixes nitrogen industrially for fertiliser, now supplies about as much reactive nitrogen as all natural terrestrial fixation, and about half the world's population is fed by food grown with it. Excess nitrogen and phosphorus wash into rivers and coasts, where they fuel algal blooms and oxygen-depleted dead zones, and nitrous oxide from fertilised soils is a long-lived greenhouse gas. [Gruber and Galloway](#) and [Fowler and colleagues](#) document the scale of the change.

Table 8. Human alteration of the major element cycles

Element	Natural flux	Human-driven flux	Main effects
Carbon	Volcanic outgassing ~0.1 Gt C yr ⁻¹	Fossil fuels and land use ~11 Gt C yr ⁻¹	Warming, ocean acidification
Nitrogen	Biological fixation on land ~60–100 Tg N yr ⁻¹	Fertiliser, crops and combustion ~190 Tg N yr ⁻¹	Eutrophication, N ₂ O, air pollution
Phosphorus	Weathering ~15–20 Tg P yr ⁻¹ (estimates vary)	Mining for fertiliser ~22 Tg P yr ⁻¹	Eutrophication, dead zones
Sulphur	Volcanoes and ocean emissions	Fossil fuels (falling since the 1980s)	Acid rain, aerosol cooling

Source: H Heuristics compilation from Fowler et al. (2013), Richardson et al. (2023) and the Global Carbon Budget 2024. Values rounded; natural fluxes are uncertain.

6.5 Life and rock

Life also shapes the solid Earth. Shell-building plankton and corals have turned dissolved carbon into vast deposits of limestone and chalk; the White Cliffs of Dover are the skeletons of single-celled algae. Roots and fungi break rock and create soil, which accelerates weathering. When land plants spread in the Devonian, about 400 million years ago, their enhancement of weathering is thought to have [drawn down atmospheric CO₂](#) substantially and contributed to the late Palaeozoic ice age. According to [Hazen and colleagues](#), about two-thirds of Earth's roughly 5,000 known mineral species would probably not exist without life. Even the continents may bear its imprint, through the effect of biologically mediated weathering on the sediments that are subducted and remelted into continental crust.

6.6 Does life regulate the planet?

In the 1970s James Lovelock and Lynn Margulis proposed that the biosphere regulates the planet's temperature and chemistry in a way that keeps it habitable, the [Gaia hypothesis](#). The idea stimulated the founding of Earth system science and drew attention to real biological feedbacks: plankton produce sulphur compounds that seed clouds, forests recycle rainfall, and plants enhance weathering. The life

report's Daisyworld simulation shows how such feedbacks could in principle stabilise temperature without any foresight.

The evidence for strong planetary self-regulation is, however, mixed. Life has sometimes destabilised the planet: the rise of oxygen probably triggered the Huronian glaciations, and the spread of land plants may have contributed to the late Palaeozoic ice age. Several mass extinctions, including the end-Permian, involved biological feedbacks such as the spread of ocean anoxia. The report's view is that life is an indispensable component of the planetary system, that it participates in both stabilising and amplifying loops, and that whether the net effect is regulation is contested (Grade C). The biosphere is a powerful lever, not a guarantor.

6.7 Biodiversity and ecosystem function

There are probably about [8.7 million species](#) of eukaryotes, most of them undescribed, and an unknown but much larger diversity of microbes. Biodiversity matters to the planetary system because the functions that ecosystems perform, from carbon storage to pollination to water purification, depend on the variety of organisms that perform them and on their redundancy. The global assessment of the [Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services](#) concluded that about one million species are threatened with extinction and that nature's contributions to people are declining. Estimated rates of vertebrate extinction over the last century are [tens to hundreds of times the background rate](#). Section 9 returns to biodiversity loss as one of the pressures by which humanity is reshaping the planet.

6.8 What the evidence shows and where it stops

Table 9. The biosphere: evidence grades

Claim	Grade	Note
Atmospheric oxygen is a product of photosynthesis	A	Isotopic, geochemical and biological evidence
Oxygen rose in two main steps, about 2.4 and 0.6 billion years ago	A–B	Timing of the second step is debated
Natural sinks absorb about half of human CO₂ emissions	A	Atmospheric, ocean and land budgets
Human nitrogen fixation exceeds natural terrestrial fixation	A–B	Natural fixation estimates vary widely
Land plants drew down CO₂ in the Devonian and Carboniferous	B	Models and proxies agree in direction
The biosphere regulates planetary conditions for its own benefit	C–D	Real feedbacks exist; net regulation contested

Source: H Heuristics assessment of the studies cited in this section.

07

PART V · GEOLOGICAL TIME

7. The Architecture of Geological Time

Key question: how do slow geological processes generate large-scale planetary change? This section turns from the subsystems to their history. Processes that move at the speed of a growing fingernail have rebuilt the planet's surface many times, and a feedback too slow to notice in a human lifetime has kept its climate within habitable bounds for billions of years.

7.1 Plate tectonics

Earth's outer shell is broken into about a dozen large plates and many smaller ones, which move relative to each other at a few centimetres a year. New ocean floor forms at mid-ocean ridges, where the mantle rises and partly melts; old ocean floor sinks back into the mantle at subduction zones, where one plate descends beneath another (Figure 25). The theory was assembled in the 1960s from several lines of evidence: the symmetric [magnetic stripes](#) on either side of mid-ocean ridges, recording reversals of the magnetic field as new crust cooled; [Tuzo Wilson's insight](#) that oceans open and close in cycles; and the demonstration by [McKenzie and Parker](#) that the motion of rigid plates on a sphere explains the pattern of earthquakes and faults.

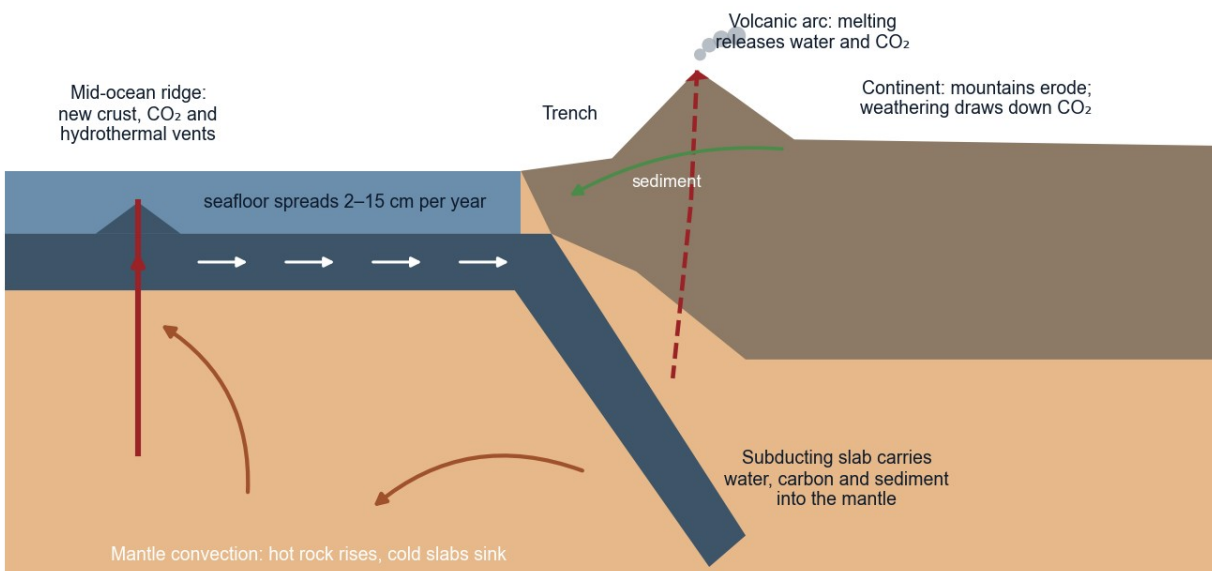


Figure 25. Plate tectonics as a planetary cycle. New crust forms at mid-ocean ridges and is consumed at subduction zones. The cycle carries water, carbon and sediment into the mantle and returns them through volcanic arcs, while mountains built at plate boundaries are eroded and weathered, drawing down CO₂.

Source: H Heuristics schematic, not to scale.

Plate tectonics is the surface expression of mantle convection (Section 3) and the main way Earth loses its internal heat. It is also the process that connects the interior to the climate. Ridges and arcs release CO_2 from the mantle; mountains raised at collision zones expose fresh rock to weathering, which removes CO_2 ; subduction carries carbon and water back down. No other known planet has plate tectonics today. Venus and Mars have a single rigid lid, through which heat escapes by volcanism and conduction, and their carbon is either locked in the atmosphere (Venus) or frozen and lost (Mars).

The pace of these processes spans many orders of magnitude (Figure 26). Plates move at roughly the speed fingernails grow. Active mountain ranges rise by millimetres a year and erode at similar rates. Sediments accumulate on the deep-sea floor at a few millimetres per thousand years. Global sea level is currently rising at about 4.7 millimetres a year, faster than most geological processes and comparable to the uplift of the Himalaya.

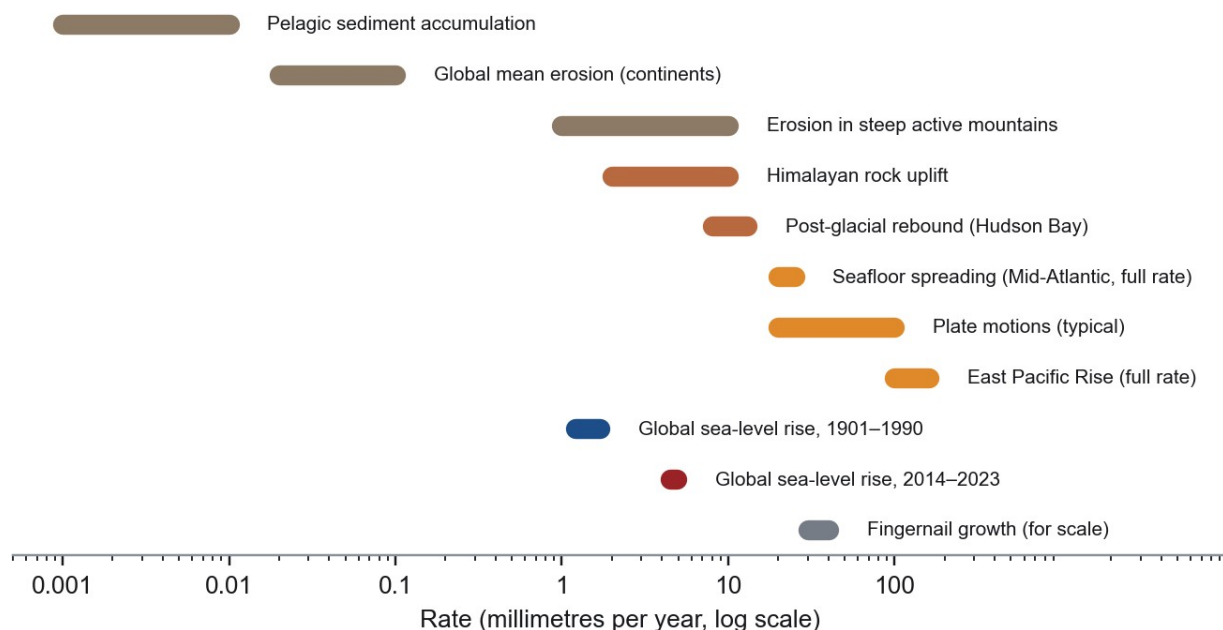


Figure 26. The speed of Earth processes. Geological rates span five orders of magnitude, from the slow accumulation of deep-sea sediment to the spreading of the fastest mid-ocean ridges. Modern sea-level rise, driven by human-caused warming, is now faster than most of them.

Source: H Heuristics compilation from standard geophysical references, the IPCC AR6 and the World Meteorological Organization. Ranges are indicative.

7.2 When did plate tectonics begin?

Whether plate tectonics has operated for most of Earth's history is one of the most debated questions in geology. Some geochemical and isotopic signals, including the chemistry of Hadean zircons, have been read as evidence for subduction before 4 billion years ago; others argue that the hotter early mantle produced a different regime, with a weaker, thicker lid broken by plumes. Modern-style subduction with cold, deep slabs leaves distinctive rocks such as blueschists and ultra-high-pressure metamorphic rocks, which are largely absent before about 1 billion years ago. Most estimates place the onset of some form of plate tectonics between about 3.2 and 2.5 billion years ago, but [Korenaga](#) and others emphasise how weakly the evidence constrains it. The report grades the claim that plate tectonics operated by 3 billion years ago as contested (Grade C).

7.3 The rock cycle and the supercontinent cycle

Rocks are recycled continuously. Igneous rocks crystallise from magma; weathering and erosion break them into sediment; sediment is buried, compacted and sometimes metamorphosed by heat and pressure; and some of it is carried down at subduction zones or melted to form new magma. On a larger scale, the continents assemble and disperse in a cycle of roughly 400 to 600 million years. The most recent supercontinent, [Pangaea](#), assembled about 335 million years ago and began breaking up about 175 million years ago; earlier supercontinents, Rodinia and Nuna, formed about 1.1 and 1.8 billion years ago.

The supercontinent cycle illustrates the creation structure on the longest timescale. Its constraint is the buoyancy of continental crust, which cannot be subducted and therefore accumulates; its generator is mantle convection, which moves continents until they collide; its filter is the stability of large continental assemblies, which insulate the mantle beneath them until rising heat breaks them apart. Each phase reshapes climate, sea level and life: supercontinents have dry interiors and fewer shallow seas, while dispersing continents create long coastlines and new ocean gateways that reroute currents.

7.4 The faint young Sun

Stars like the Sun brighten as they age, because the fusion of hydrogen into helium increases the density and temperature of their cores. Standard solar models give a luminosity [about 30 per cent lower](#) at the Sun's birth. For this report the luminosity history was combined with a fixed planetary albedo and today's greenhouse effect (Figure 27). The result is a paradox first noted by [Sagan and Mullen](#): with today's atmosphere, the early Earth would have been below freezing until about 2.9 billion years ago, yet the geological record shows liquid water throughout, including sediments deposited in water before 3.8 billion years ago.

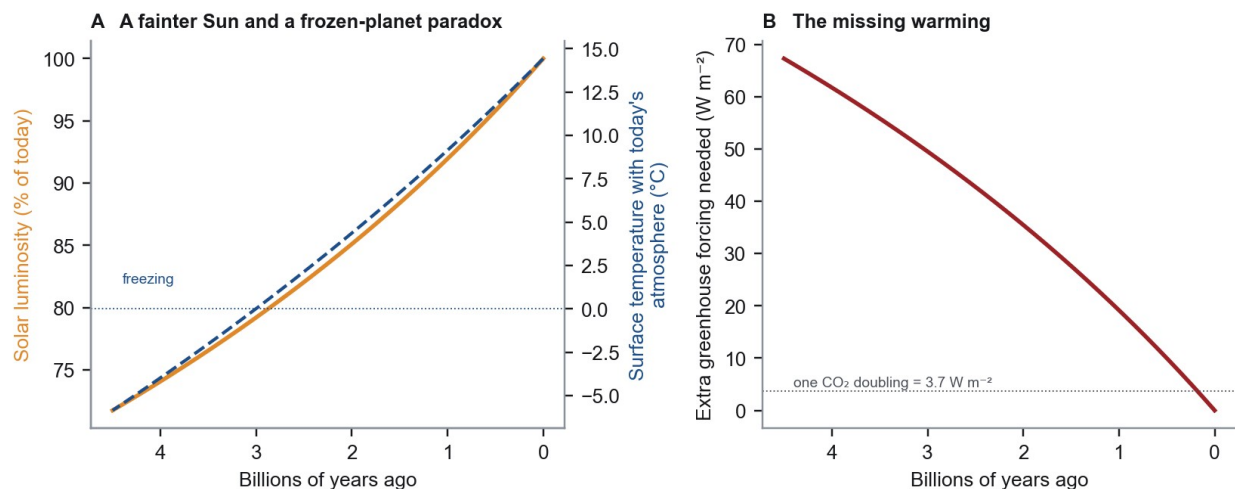


Figure 27. The faint-young-Sun problem. Panel A shows the Sun's luminosity over Earth's history and the surface temperature the planet would have had with today's atmosphere and albedo. Panel B shows the extra greenhouse forcing needed to keep the surface at today's temperature, about 62 watts per square metre 4 billion years ago, equivalent to many doublings of CO₂.

Source: H Heuristics calculation using the solar luminosity approximation of Gough (1981), a constant albedo of 0.30 and today's 33 K greenhouse effect.

Closing the gap required about 60 watts per square metre of extra warming 4 billion years ago, far more than the 3.7 watts per square metre of a CO₂ doubling. [Feulner](#) reviews the proposed solutions. The most

widely accepted is that the early atmosphere contained much more CO₂ than today, supplemented after the origin of methane-producing microbes by substantial [methane](#), with a possible contribution from a lower albedo because there were fewer continents and perhaps fewer clouds. The deeper point is that the atmosphere's composition must have changed in step with the Sun's output to keep the surface temperate. A process is needed that adjusts CO₂ automatically.

7.5 The silicate-weathering thermostat

That process was identified by [Walker, Hays and Kasting](#) in 1981. CO₂ dissolved in rainwater forms a weak acid that slowly dissolves silicate rocks. The products are carried by rivers to the ocean, where organisms and chemistry precipitate them as carbonate rock, locking the carbon away. Volcanoes and subduction eventually return it. Crucially, the rate of weathering increases with temperature and rainfall, both of which increase with CO₂. If CO₂ rises, the planet warms, weathering speeds up and CO₂ is drawn down; if CO₂ falls, the planet cools, weathering slows and volcanic outgassing builds CO₂ back up. This negative feedback, formalised in the model of [Berner, Lasaga and Garrels](#) and reviewed by [Kump, Brantley and Arthur](#), is Earth's long-term thermostat.

A box model built for this report shows how the thermostat behaves (Figure 28). Weathering is assumed to rise by about 10 per cent per degree of warming and with the square root of CO₂, and climate sensitivity is set at 3 °C per doubling. After a sudden release of carbon, the excess decays with an e-folding time of about 430,000 years. If volcanic outgassing rises by half and stays high for two million years, the feedback holds warming to about 2 °C, whereas without it the planet would still be warming after two million years and would already be more than 5 °C warmer. The thermostat is powerful but slow: it acts on timescales of 10⁵ to 10⁶ years, which is why the CO₂ released by humans will take [hundreds of thousands of years](#) to be fully removed.

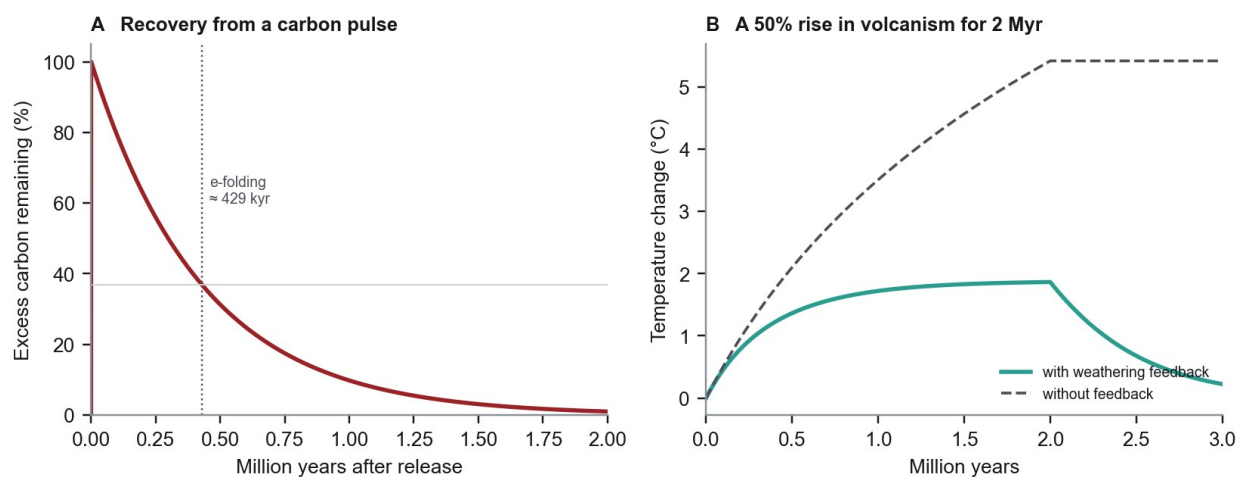


Figure 28. The silicate-weathering thermostat in a box model built for this report. Panel A shows the decay of an excess of carbon, with an e-folding time of about 430,000 years. Panel B shows that a sustained 50 per cent rise in volcanic outgassing produces a bounded warming when weathering responds to temperature, and continuing warming when it does not.

Source: H Heuristics calculation. Exchangeable carbon 40,000 Gt; baseline outgassing 0.1 Gt C yr⁻¹; weathering sensitivity 10% per °C and (CO₂)^{0.5}; climate sensitivity 3 °C per doubling. Illustrative; published estimates of the timescale range from about 100,000 to 1 million years.

The thermostat can also be pushed. [Raymo and Ruddiman](#) proposed that the uplift of the Himalaya and the Tibetan Plateau over the last 50 million years exposed so much fresh rock to monsoon rain that weathering drew down CO₂ and cooled the planet towards the present ice age. The hypothesis remains

debated, because the thermostat should eventually compensate, but it shows how tectonics, the water cycle and climate are coupled through the carbon cycle.

7.6 Deep-time climate

The thermostat keeps Earth's climate within broad bounds, but within them climate has varied enormously. At least twice in the Neoproterozoic, about 717 and 650 million years ago, ice reached the tropics in [snowball Earth](#) episodes that lasted millions of years and ended when volcanic CO₂, no longer removed by weathering under the ice, built up to very high levels. At the other extreme, the early Eocene, about 50 million years ago, was warm enough for forests near the poles and crocodile relatives in the Arctic.

The last 66 million years are recorded in detail by the oxygen and carbon isotopes of deep-sea fossils (Figure 29). The [CENOGRID](#) compilation and the earlier synthesis of [Zachos and colleagues](#) show a long cooling from the warm Eocene to the present ice age, punctuated by abrupt events. The Palaeocene–Eocene Thermal Maximum, 56 million years ago, saw a [rapid release of thousands of billions of tonnes of carbon](#), several degrees of warming and ocean acidification, from which the climate took about 150,000 years to recover. The Antarctic ice sheet formed abruptly at 34 million years ago as CO₂ fell below a threshold. The Pliocene, about 3 million years ago, had CO₂ near 400 ppm, temperatures 2 to 3 °C above pre-industrial and sea levels many metres higher, which makes it a [natural analogue](#) for the near future.

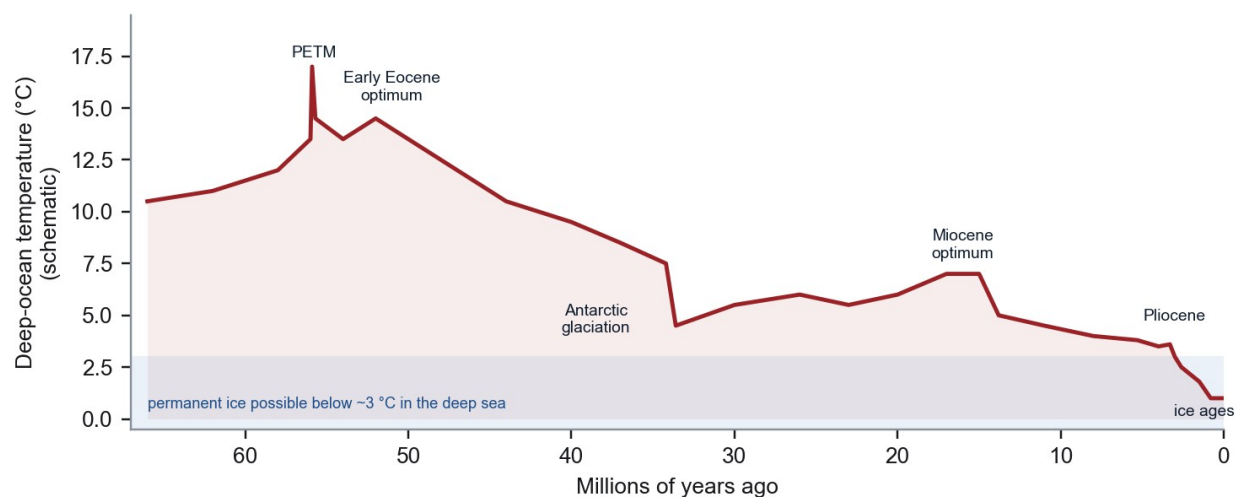


Figure 29. Climate of the last 66 million years, schematic of the deep-ocean temperature record. A warm greenhouse world in the Eocene gave way, in steps, to the glaciated icehouse of today. Abrupt events such as the PETM and the onset of Antarctic glaciation punctuate the long-term trend.

Source: H Heuristics schematic after Zachos et al. (2001, 2008) and Westerhold et al. (2020). Values approximate and smoothed.

Over the last 2.6 million years climate has oscillated between glacial and interglacial states, paced by small changes in Earth's orbit. [Hays, Imbrie and Shackleton](#) showed in 1976 that the cycles match the periods of the orbital variations described by Milutin Milanković: about 23,000, 41,000 and 100,000 years. The orbital changes alone are too small to explain the size of the glacial cycles; they are amplified by ice–albedo, CO₂ and ocean-circulation feedbacks. The cycles are also a reminder that the Moon matters: by damping variations in Earth's axial tilt, it [prevents the chaotic swings in obliquity](#) that would otherwise produce much larger climate swings.

7.7 Mass extinctions

Five times in the last 500 million years, more than three-quarters of species disappeared in geologically short intervals (Table 10). The [statistical pattern](#) was established by Raup and Sepkoski in 1982. Each extinction is a case study in how disturbance propagates through coupled subsystems. The end-Cretaceous extinction followed the [Chicxulub asteroid impact](#), first proposed by [Alvarez and colleagues](#) in 1980, which threw dust, soot and sulphate into the atmosphere and caused a short, severe global winter. Most of the others are linked to large igneous provinces, vast volcanic outpourings that released carbon and sulphur over tens of thousands of years. The worst, at the end of the Permian 252 million years ago, coincided with the Siberian Traps and unfolded over [about 60,000 years](#): rapid warming, ocean acidification and the spread of oxygen-free and sulphidic water killed most marine species. In each case, the trigger came from outside the climate system, but the damage was done by feedbacks within it.

Table 10. The five major mass extinctions

Event	Age (Ma)	Species lost (marine)	Main trigger	Main kill mechanisms
End-Ordovician	~445	~85%	Glaciation, possibly linked to weathering	Cooling, sea-level fall, anoxia
Late Devonian	~372	~75%	Uncertain; volcanism and land-plant expansion	Ocean anoxia, cooling pulses
End-Permian	~252	~80–90%	Siberian Traps volcanism	Warming, acidification, anoxia
End-Triassic	~201	~75%	Central Atlantic Magmatic Province	Warming, acidification
End-Cretaceous	66	~75%	Chicxulub impact (with Deccan Traps volcanism)	Impact winter, collapse of photosynthesis

Source: H Heuristics compilation from Raup and Sepkoski (1982), Schulte et al. (2010), Burgess et al. (2014) and standard references. Percentages are approximate estimates of species-level loss.

7.8 What the evidence shows and where it stops

Table 11. Geological time: evidence grades

Claim	Grade	Note
Plate tectonics explains the present configuration of the surface	A	Magnetic, seismic, geodetic and geological evidence
The early Sun was about 25–30 per cent fainter	A	Standard stellar physics
Silicate weathering stabilises climate over 10^5 – 10^6 years	B	Strong theory and support from the geological record; strength debated
Snowball Earth episodes occurred in the Neoproterozoic	B	Tropical glacial deposits and cap carbonates
Plate tectonics operated by 3 billion years ago	C	Evidence is indirect and disputed
Himalayan uplift drove Cenozoic cooling	C	Plausible; competing explanations exist

Source: H Heuristics assessment of the studies cited in this section.

08

PART VI · PLANETARY FEEDBACK



8. The Architecture of Planetary Feedback

Key question: under what conditions does Earth absorb disturbances, shift into a new state, or undergo persistent change? This section brings together the feedbacks introduced in Sections 3 to 7, quantifies their combined effect, and asks where the planet's stability ends.

8.1 The anatomy of planetary feedback

Every subsystem described so far contains loops that either oppose or reinforce a change (Figure 30). The most important stabilising loop is also the simplest: a warmer planet radiates more energy to space, in proportion to the fourth power of its temperature. This Planck response acts within years. On geological timescales the silicate-weathering thermostat adds a second stabiliser. Between them sit a set of amplifying loops. Warmer air holds more water vapour, which traps more heat. Melting snow and ice expose darker surfaces that absorb more sunlight. Thawing permafrost releases carbon, and warmer soils and oceans absorb less of it. Clouds can amplify or damp change depending on their type and altitude.

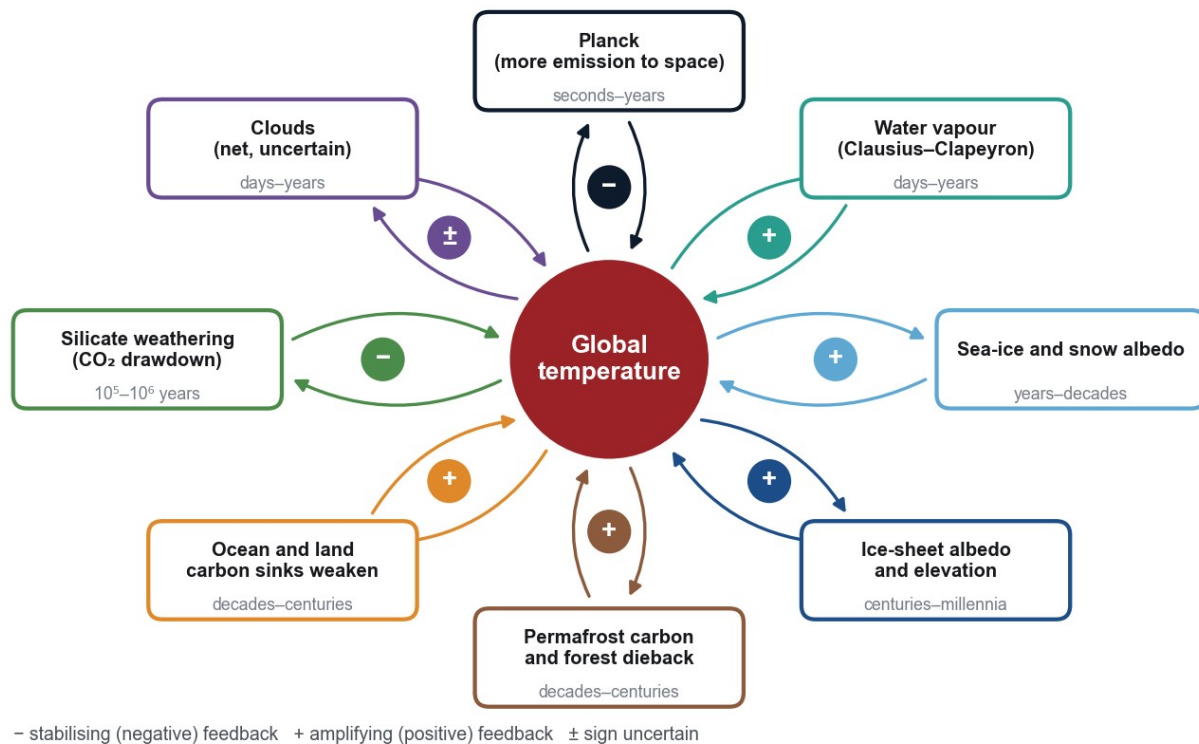


Figure 30. The main feedback loops acting on global temperature. Stabilising loops (–) oppose a change; amplifying loops (+) reinforce it. The loops act on timescales from days to hundreds of thousands of years, so the balance between them depends on the timescale considered.

Source: H Heuristics, from IPCC AR6 Working Group I, Chapters 5 and 7, and the studies cited in Sections 4 to 7.

Two features of this structure recur throughout the report. First, feedbacks are nested by timescale. Over decades, the fast amplifiers dominate and the slow stabiliser is effectively absent; over hundreds of thousands of years, the weathering thermostat wins. The planet is therefore sensitive on human timescales and stable on geological ones. Second, the loops are coupled: the ice–albedo feedback changes temperature, which changes water vapour, which changes the carbon sinks. The net response of the system is not the sum of separate effects but the outcome of their interaction.

8.2 How sensitive is the climate?

Equation 3 turns this structure into a number. The Intergovernmental Panel on Climate Change's [Sixth Assessment Report](#) gives best estimates for each feedback parameter, in watts per square metre per degree of warming (Figure 31, Panel A): –3.22 for the Planck response, +1.30 for water vapour and lapse rate combined, +0.35 for surface albedo, +0.42 for clouds and about zero for other processes. The net feedback is –1.16. With a forcing of 3.93 watts per square metre for a doubling of CO₂, Equation 3 gives an equilibrium climate sensitivity of about 3.4 °C.

Because the denominator is the sum of terms with large uncertainties, the result is skewed. To show this, the report drew 400,000 random combinations of the feedback parameters and the forcing, each from a normal distribution matching its published very likely range (Figure 31, Panel B). The median sensitivity is 3.4 °C and the 5–95 per cent range is 2.1 to 7.7 °C. There is an 18 per cent chance that sensitivity exceeds 5 °C on this evidence alone, but less than a 4 per cent chance that it is below 2 °C. The long

upper tail arises because a net feedback close to zero produces a very large response. The IPCC's assessed likely range of 2.5 to 4 °C is narrower because it combines the process evidence with independent constraints from the historical record and past climates, as in the review by [Sherwood and colleagues](#), which trim the upper tail.

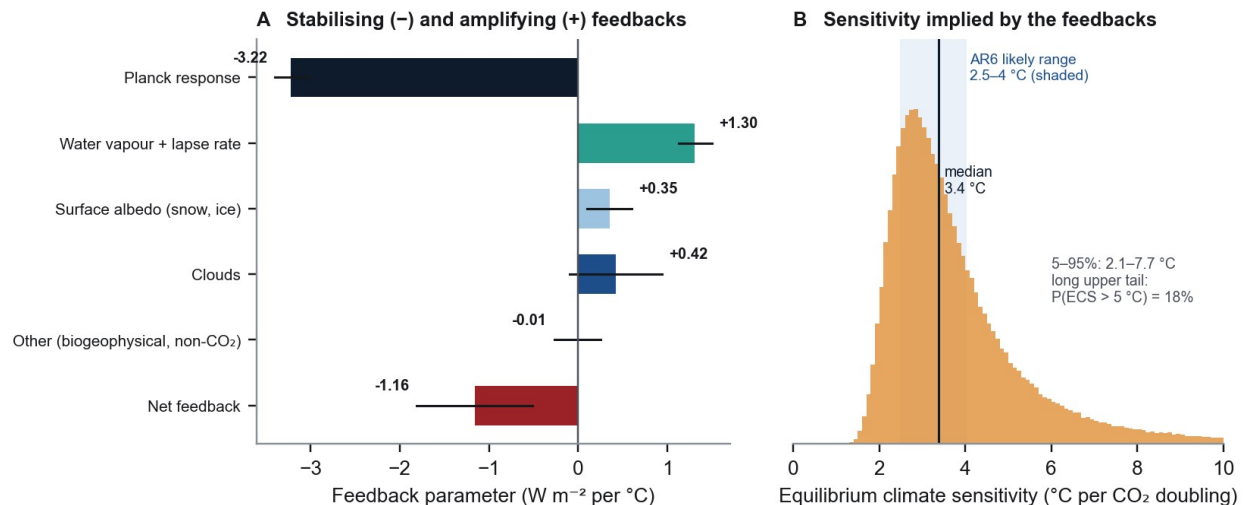


Figure 31. Climate feedbacks and the sensitivity they imply. Panel A shows the IPCC AR6 central estimates and very likely ranges. Panel B shows the distribution of equilibrium climate sensitivity from a Monte Carlo combination of these feedbacks made for this report: median 3.4 °C, with a long upper tail because the net feedback could be close to zero.

Source: Panel A, IPCC AR6 Working Group I, Table 7.10. Panel B, H Heuristics calculation with 400,000 samples; uncertainties assumed normal and independent.

Sensitivity measures the response to a doubling of CO₂ after the fast feedbacks have equilibrated. It omits the slow ones. Over centuries to millennia, the loss of ice sheets and changes in vegetation would add further warming, and Earth system sensitivity estimated from past climates, such as the Pliocene, is roughly 1.5 to 2 times larger. The carbon cycle adds another amplifier: warming weakens the ocean and land sinks and releases carbon from soils and [permafrost](#), which holds roughly twice as much carbon as the atmosphere. These carbon-cycle feedbacks are slower and less certain than the physical ones, but all point in the same direction.

8.3 Alternative stable states

A system with strong amplifying feedback can have more than one stable state for the same external conditions. The ice–albedo feedback is the classic planetary example, identified by [Budyko](#) in 1969. Using the energy-balance model introduced in Section 4, the report traced the planet's equilibrium as the Sun was slowly dimmed from a warm start and then slowly brightened from a frozen one (Figure 32). For today's Sun the model has two stable climates: the present one, with a mean temperature of about 14 °C and ice poleward of 77°, and a snowball with a mean temperature of about –35 °C. If sunlight fell by about 18 per cent, the ice edge would advance gradually and then, once it passed roughly 30° latitude, run away to the equator. Once frozen, the planet would not thaw until sunlight was about 26 per cent stronger than today.

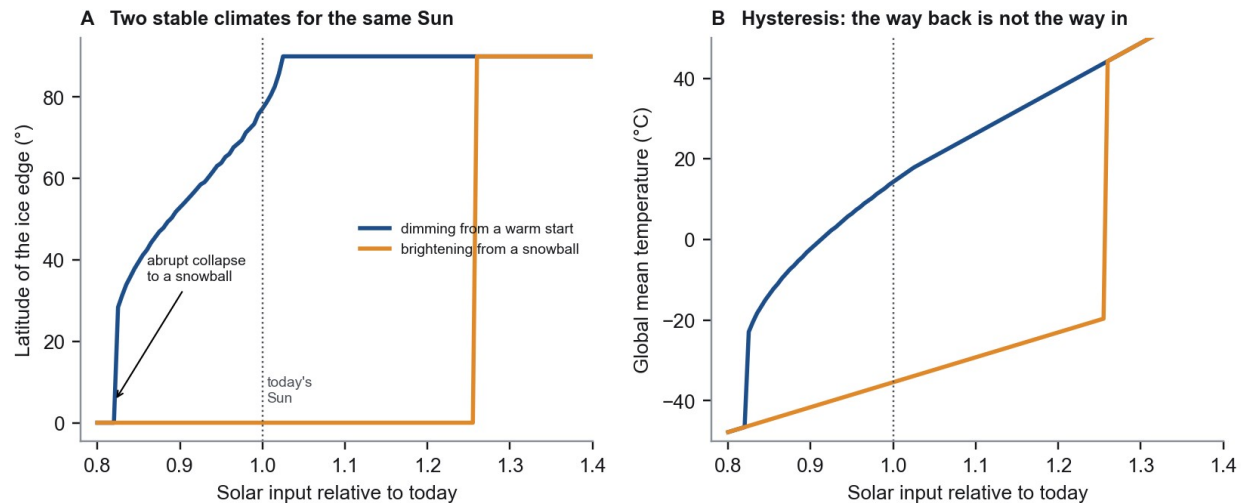


Figure 32. Two stable climates for the same Sun. In the latitude-resolved energy-balance model built for this report, dimming the Sun moves the ice edge gradually equatorward until it collapses into a snowball; brightening a snowball does not reverse the collapse until solar input is far above today's. Panel B shows the global mean temperature along the two paths.

Source: H Heuristics calculation. Model after Budyko (1969) and North (1975): outgoing radiation $203.3 + 2.09T \text{ W m}^{-2}$, transport coefficient $2.1 \text{ W m}^{-2} \text{ K}^{-1}$, albedo 0.31 ice-free and 0.62 where $T < -10^\circ \text{C}$.

This dependence of the present state on the path taken to reach it is called hysteresis, and it means that some changes are effectively irreversible on the timescale of the forcing. The real Earth did enter snowball states in the Neoproterozoic, and escaped them only after volcanic CO_2 built up for millions of years to levels that overwhelmed the ice albedo. [Scheffer and colleagues](#) showed that similar alternative states and catastrophic shifts occur in lakes, coral reefs, forests and deserts. [Holling](#) had already distinguished between stability, the tendency to return to equilibrium after a small disturbance, and resilience, the size of the disturbance a system can absorb before shifting to another state. The distinction is central to this section.

8.4 Tipping elements

A tipping element is a component of the Earth system that can be switched into a qualitatively different state by a small perturbation once it passes a critical threshold. The concept was set out for the climate system by [Lenton and colleagues](#) in 2008. The most comprehensive recent assessment, by [Armstrong McKay and colleagues](#), identified nine global core elements and seven regional ones and estimated a threshold warming for each (Figure 33). Five of them, including the collapse of the Greenland and West Antarctic ice sheets, abrupt permafrost thaw, the die-off of low-latitude coral reefs and the collapse of convection in the Labrador Sea, have central threshold estimates around 1.5°C , and their uncertainty ranges begin below the present level of warming.

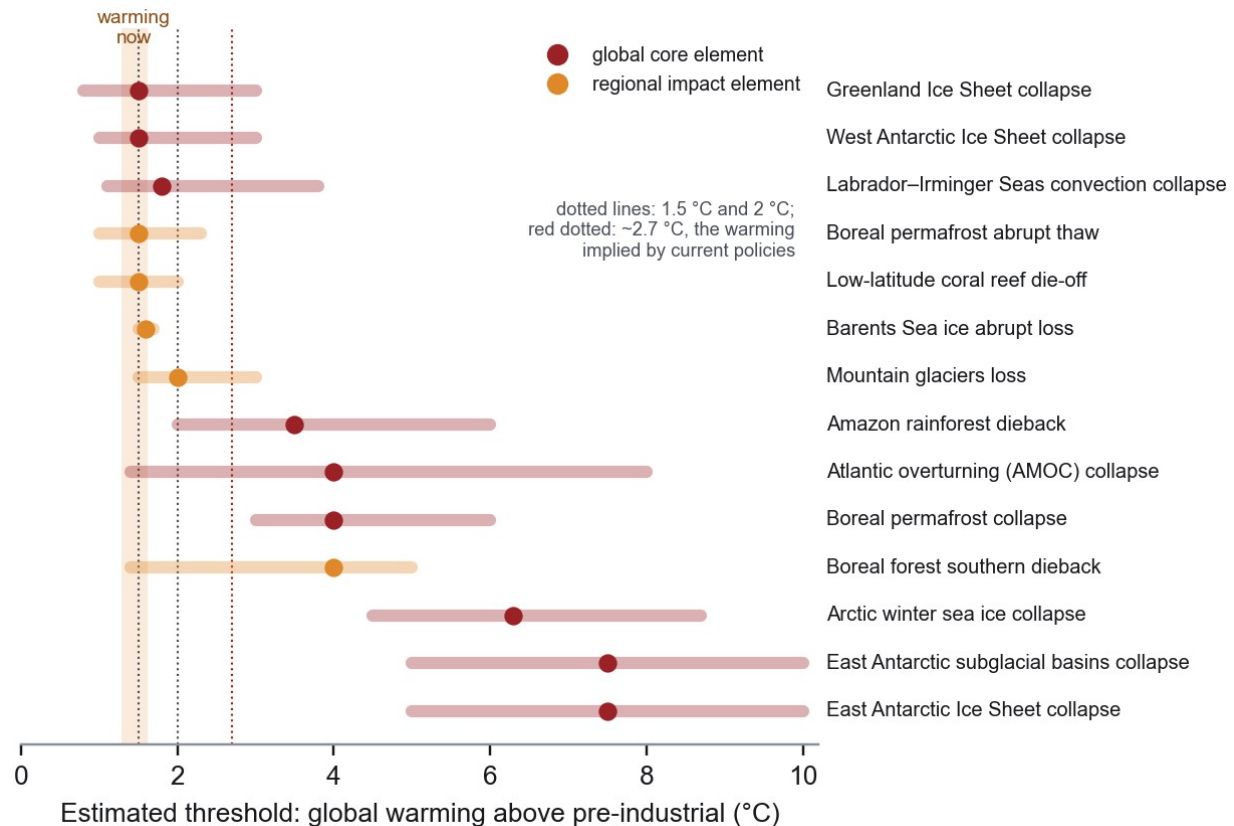


Figure 33. Estimated thresholds of tipping elements. Dots show central estimates and bars the range of the threshold warming, above pre-industrial, at which each element could be committed to change. Several elements have thresholds within or near the range of present warming; ice-sheet collapse would unfold over centuries to millennia once committed.

Source: Armstrong McKay et al. (2022). Present warming from Forster et al. (2025); current-policy warming from the UNEP Emissions Gap Report.

Three candidates illustrate the different mechanisms involved. The **Atlantic overturning circulation** has a salt-advection feedback: the northward flow carries salty water that keeps the sinking region dense, so a weaker flow carries less salt and weakens further. Proxy records suggest the AMOC is [at its weakest in over a millennium](#); statistical indicators show [loss of stability](#); one analysis estimated that collapse could occur [between 2025 and 2095](#); and a high-resolution model run found a [physics-based early-warning signal](#) for a tipping event. These results are contested and the timing is highly uncertain, but the existence of the threshold is well established in models and the palaeoclimate record. The **Amazon rainforest** recycles much of its own rainfall, so drought and deforestation reduce the moisture that sustains it; satellite data show [declining resilience across most of the forest](#), and it has been argued that deforestation of [20 to 25 per cent](#) could tip parts of it to savanna. **Ice sheets** have an elevation feedback: as they thin, their surface sinks into warmer air and melts faster, and the marine-based parts of West Antarctica rest on bedrock that deepens inland, which can make retreat self-sustaining.

Tipping elements are coupled. Melting Greenland freshens the North Atlantic and weakens the AMOC; a weaker AMOC shifts tropical rainfall and could dry the Amazon; Amazon dieback releases carbon that warms the planet. A network analysis by [Wunderling and colleagues](#) found that such interactions tend to lower the effective thresholds and can produce cascades. This is the mechanism behind the [Hothouse Earth](#) scenario of Steffen and colleagues, in which a cascade of feedbacks commits the planet to a much warmer state regardless of later emissions cuts. The report grades the existence of tipping interactions as

well supported but the possibility of a self-sustaining global cascade below about 2 °C as speculative (Grade C to D).

8.5 Early warning signals

Systems approaching a tipping point often share a generic signature. As the stabilising feedback weakens, the system recovers more slowly from small disturbances, a phenomenon called critical slowing down. Its statistical fingerprints are rising autocorrelation and variance in the system's fluctuations. To illustrate, the report simulated a simple system with two stable states, driven slowly towards the point at which the upper state disappears and subjected to random noise (Figure 34). As the forcing approaches the threshold, the lag-1 autocorrelation of the fluctuations rises from about 0.68 to 0.95 and their variance increases several-fold before the system jumps to the alternative state. [Dakos and colleagues](#) found the same signature in the palaeoclimate record before several abrupt climate transitions, and [Scheffer and colleagues](#) showed that it appears in ecosystems, financial markets and physiological systems.

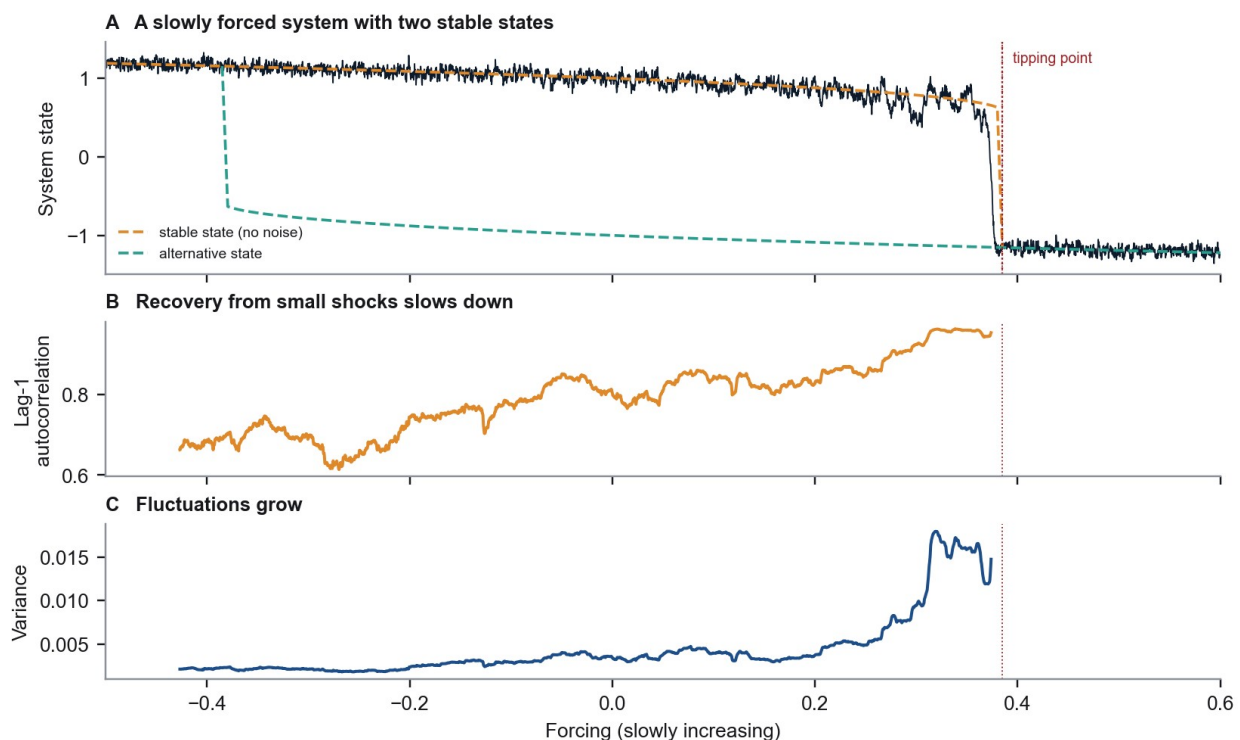


Figure 34. Critical slowing down before a tipping point. Panel A shows a simulated system with two stable states, slowly forced towards the threshold at which its current state vanishes. Panels B and C show that the autocorrelation and variance of its fluctuations rise as the threshold approaches, providing a potential early warning.

Source: H Heuristics simulation of $dx/dt = -x^3 + x - c(t) + \text{noise}$ with slowly increasing c ; rolling statistics over windows of 400 samples after quadratic detrending.

Early warning signals have limits. They require long, high-quality records; they can be masked by noise or by changes in the noise itself; and they do not warn of tipping caused by rapid forcing or by a large shock, which leaves no time for slowing down to appear. They are a reason to monitor, not a forecast.

8.6 How Earth responds to disturbance

The key question of this section can now be answered in general terms. Earth's response to a disturbance depends on its size and speed relative to the feedbacks that act on it (Table 12). Small disturbances within the basin of the present state are absorbed by the Planck response and, eventually, by the carbon cycle. Larger or faster disturbances can push components across thresholds into new states, and if the amplifying loops are strong enough and the hysteresis wide enough, the change persists long after the disturbance has ended.

Table 12. Four ways the Earth system responds to disturbance

Response	Mechanism	Earth example	Timescale of recovery
Absorption	Stabilising feedback restores the previous state	Cooling after the 1991 Pinatubo eruption reversed within about three years	Years
Slow recovery	A slow stabiliser eventually wins over fast amplifiers	Recovery from the PETM carbon release	~10 ⁵ years
Regime shift	A threshold is crossed and the system moves to another state	Onset of Antarctic glaciation 34 million years ago; Sahara greening and drying	Persistent while conditions last
Persistent change with hysteresis	Return requires a much larger reverse forcing	Snowball Earth; ice-sheet loss	Millions of years, or never

Source: H Heuristics, from the studies cited in Sections 7 and 8.

8.7 What the evidence shows and where it stops

Table 13. Planetary feedback: evidence grades

Claim	Grade	Note
The Planck response is the main stabilising feedback on human timescales	A	Basic radiative physics
Water-vapour and ice–albedo feedbacks amplify warming	A	Physics, observations and models
Equilibrium climate sensitivity is likely 2.5–4 °C	A–B	Multiple lines of evidence; process evidence alone is wider
The climate system has alternative stable states	A–B	Theory, models and the geological record
Several tipping elements may cross thresholds between 1.5 and 2 °C	B–C	Thresholds uncertain by a degree or more
The AMOC will collapse this century	C	Possible; estimates of likelihood vary widely
A self-sustaining global tipping cascade below 2 °C	C–D	Mechanism plausible; evidence limited

Source: H Heuristics assessment of the studies cited in this section.

09

PART VII · HUMANS AND EARTH



9. The Architecture of Human–Earth Interaction

Key question: how have energy production, industrialisation, urbanisation, agriculture, pollution and land-use change altered planetary systems, and how do human societies depend on their continued functioning? This section treats civilisation as the newest subsystem in the architecture of Figure 4: one that draws on every other subsystem and now modifies the exchanges between them.

9.1 A new planetary force

Humans have been reshaping their environment for tens of thousands of years, through fire, hunting and, from about 11,000 years ago, farming. [Ellis and colleagues](#) estimate that people had already shaped about three-quarters of terrestrial nature 12,000 years ago. What changed in the last two centuries, and especially after 1950, is scale. The use of fossil fuels released an energy store accumulated over hundreds of millions of years, and with it came industrial agriculture, mass urbanisation and global trade. In 2002 the atmospheric chemist Paul Crutzen proposed that Earth had entered a new geological epoch dominated by human activity, the [Anthropocene](#). Geologists have debated the proposal intensively; in 2024 the International Union of Geological Sciences declined to adopt it as a formal epoch, but the underlying observation, that humans now rival natural forces in shaping the planet, is not in dispute.

The indicators of what [Steffen and colleagues](#) called the Great Acceleration show the change (Figure 35, Panel A). Since 1950 the world's population has risen from 2.5 to 8.2 billion, primary energy use and fossil CO₂ emissions have each risen about six-fold, and synthetic nitrogen fertiliser use about thirtyfold. Human-made mass, mostly concrete, aggregates, bricks and asphalt, has grown from about 3 per cent of the planet's biomass in 1900 to [exceeding it around 2020](#) (Panel B). Humanity now uses about 20 terawatts of primary energy, comparable to half the planet's internal heat flow (Figure 5).

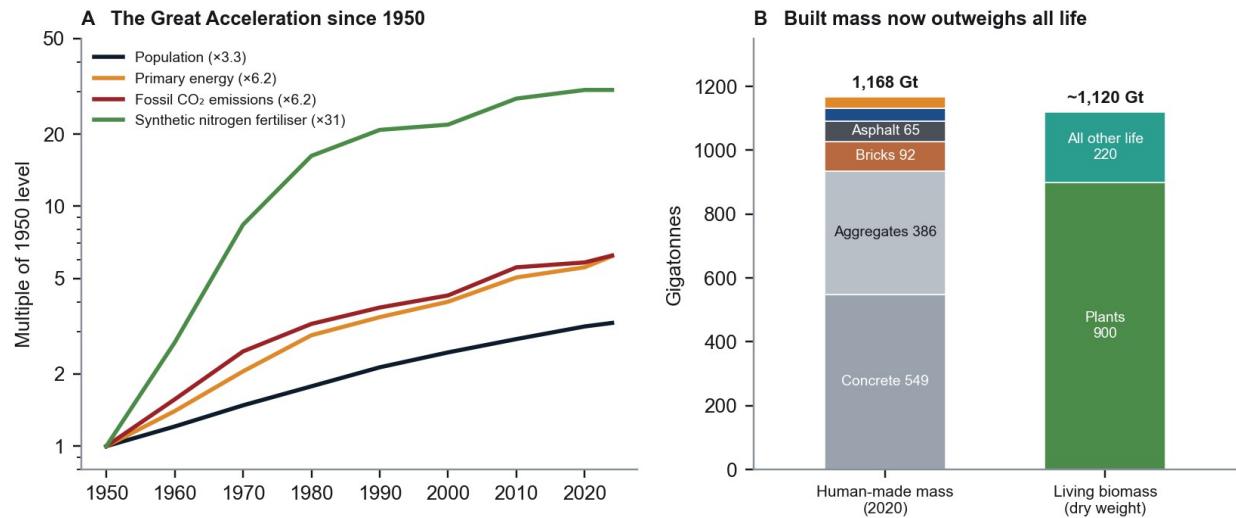


Figure 35. The human footprint. Panel A shows indicators of the Great Acceleration as multiples of their 1950 values. Panel B compares human-made mass in 2020 with the dry mass of all living things: built mass now outweighs the biosphere.

Source: Panel A, H Heuristics compilation from UN population estimates, the Energy Institute Statistical Review, the Global Carbon Project and FAO fertiliser statistics; approximate values. Panel B, Elhacham et al. (2020).

9.2 Five pressures on the planetary system

Human activity acts on Earth's subsystems through five main pressures, each of which links to the subsystems and feedbacks described in Sections 3 to 8 (Table 14).

Table 14. How human activity acts on Earth's subsystems

Pressure	Scale today	Subsystems affected	Feedbacks engaged
Greenhouse gas emissions	~41 Gt CO ₂ a year plus methane and N ₂ O; ~1.36 °C of human-induced warming (2024)	Atmosphere, ocean, ice, biosphere	Water vapour, ice–albedo, carbon sinks, tipping elements
Land-use change	~38% of ice-free land used for agriculture; forest cover ~60% of its natural extent	Biosphere, water, carbon cycle	Rainfall recycling, carbon release, albedo
Pollution	Air pollution linked to millions of deaths a year; plastics, nitrogen and phosphorus run-off	Atmosphere, ocean, biosphere, human health	Aerosol cooling, eutrophication, dead zones
Resource extraction	~100 Gt of materials a year	Geosphere, biosphere, water	Erosion, habitat loss, water stress
Biodiversity loss	~1 million species threatened; wild vertebrate populations sharply reduced	Biosphere	Loss of ecosystem functions and resilience

Source: H Heuristics compilation from the Global Carbon Budget 2024, Forster et al. (2025), Foley et al. (2005), Fuller et al. (2022), Richardson et al. (2023), IPBES (2019) and UNEP International Resource Panel. Values rounded.

Greenhouse gas emissions are the most consequential, because they act on the planet's energy balance and therefore on every subsystem at once. Human-induced warming reached about [1.36 °C in 2024](#) relative to 1850–1900, rising at about 0.27 °C per decade, and 2024 was the first calendar year in which observed global temperature exceeded 1.5 °C. The rise has engaged the feedbacks of Section 8:

Arctic sea ice is retreating, ice sheets are losing mass, ocean heat content is rising and the land carbon sink falters in hot years.

Land-use change has transformed the surface. Agriculture occupies about 38 per cent of the ice-free land, and [Foley and colleagues](#) showed that land use is among the largest drivers of global environmental change, altering carbon storage, rainfall recycling and albedo as well as habitat. Tropical deforestation has been the largest source of land-use emissions. **Pollution** includes greenhouse gases but also aerosols, reactive nitrogen, pesticides, plastics and thousands of synthetic chemicals. The [Lancet Commission on pollution and health](#) estimated that pollution caused about 9 million premature deaths in 2019, most from air pollution. **Resource extraction** now moves more sediment and rock than all the world's rivers. **Biodiversity loss**, discussed in Section 6, erodes the variety on which ecosystem functions depend.

9.3 Planetary boundaries

In 2009 [Rockström and colleagues](#) proposed a set of planetary boundaries: limits on human pressure on nine Earth-system processes, within which humanity can operate safely given the stability of the Holocene. The framework was updated in [2015](#) and fully quantified for the first time by [Richardson and colleagues](#) in 2023, who concluded that six of the nine boundaries had been transgressed (Figure 36). In 2025 the Planetary Health Check assessed ocean acidification as having crossed its boundary too, bringing the total to seven of nine. Only stratospheric ozone, which is recovering under the Montreal Protocol, and aerosol loading, which is within its boundary globally though not in parts of South Asia, remained in the safe zone.

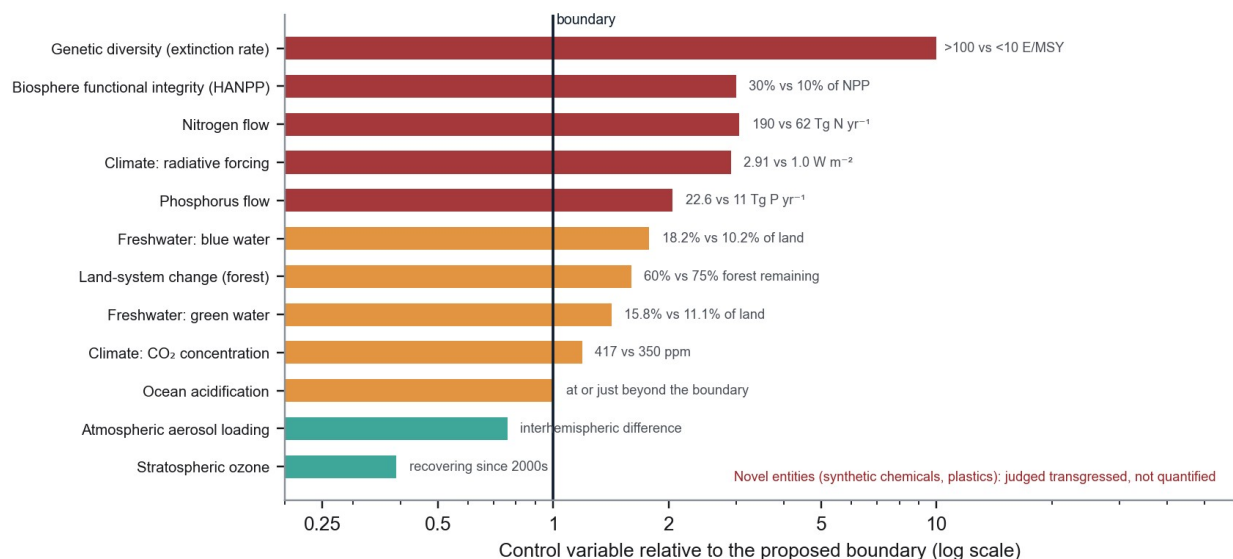


Figure 36. Planetary boundaries. Bars show the current value of each control variable relative to its proposed boundary (1 = boundary). Values above 1 indicate transgression; red bars mark processes more than twice beyond the boundary. Seven of nine boundaries are now assessed as transgressed.

Source: Richardson et al. (2023), with ocean acidification updated by the Planetary Health Check (2025). Ratios for land-system change and ocean acidification are expressed as fractional departure relative to the boundary's allowed departure.

The framework has limits that the report notes. The boundary positions involve judgement about acceptable risk, some processes are regional rather than global, and transgressing a boundary is a warning of increased risk rather than a prediction of collapse. A related effort, the [safe and just Earth](#)

[system boundaries](#) of Rockström and colleagues, adds a justice criterion: limits set to avoid significant harm to people, which are in several cases stricter than those set to protect the stability of the Earth system.

9.4 Development, health and dependence

Human societies depend on the functioning of planetary systems in ways that are easy to overlook because they have been so reliable. Food production depends on a stable climate, predictable monsoons, soil fertility, pollinators and freshwater. About [four billion people](#) already face severe water scarcity for at least one month a year. Cities depend on the stability of coastlines and on infrastructure designed for the climate of the twentieth century. Public health depends on clean air and water and on temperatures within the range the human body can tolerate.

That range is narrower than is often assumed. [Xu and colleagues](#) showed that for at least six thousand years humans have been concentrated within a narrow climatic niche, at mean annual temperatures around 11 to 15 °C. [Lenton and colleagues](#) estimated that under current policies, leading to about 2.7 °C of warming, around two billion people could be pushed outside that niche by the end of the century. [Mora and colleagues](#) found that about 30 per cent of the world's population already experiences, for at least 20 days a year, combinations of heat and humidity associated with excess mortality. The earlier H Heuristics reports [The Heat Trap](#) and [The Future of Global Habitability](#) examine these risks in detail.

9.5 Inequality and vulnerability

The pressures on the planet and the exposure to their consequences are both unevenly distributed. According to [Chancel](#), the richest 10 per cent of the world's population were responsible for about 48 per cent of greenhouse gas emissions in 2019 and the poorest 50 per cent for about 12 per cent (Figure 37). Per-person footprints range from about 1.6 tonnes of CO₂-equivalent a year for the poorest half to about 110 tonnes for the richest 1 per cent. Historical responsibility is more uneven still.

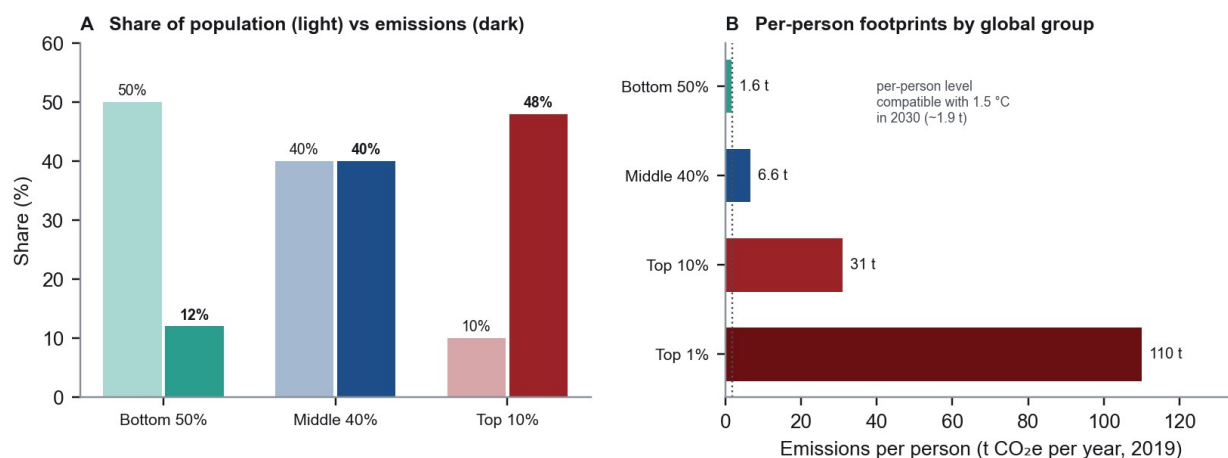


Figure 37. Unequal responsibility for emissions. Panel A compares each global income group's share of population with its share of greenhouse gas emissions in 2019. Panel B shows average per-person emissions by group, against the level compatible with limiting warming to 1.5 °C.

Source: Chancel (2022), World Inequality Lab; consumption-based emissions including investment. The 1.5 °C-compatible level is an approximate 2030 per-capita average.

Exposure runs the other way. The populations least responsible for emissions tend to live in hotter regions, depend more on rain-fed agriculture and have fewer resources to adapt. Heat, drought, flooding and sea-level rise act as multipliers on existing vulnerabilities, and the impacts on one region spread through food prices, migration and trade. Inequality is therefore not a separate issue from planetary stability: it determines who bears the costs of disturbance and shapes the political capacity to respond. Earlier H Heuristics reports, including the [Cascading Risk Atlas](#), trace these pathways.

9.6 Humans as a feedback

Humans differ from other components of the planetary system in one respect: they can observe the system, model it and change their behaviour in response. This makes human institutions a potential feedback in the architecture, either stabilising or amplifying. The phase-out of ozone-depleting substances (Section 4) is a stabilising example: a perturbation was detected, its mechanism understood and the source removed within two decades. The response to climate change has so far been slower; emissions have flattened but not yet fallen, while the deployment of solar power, wind and electric vehicles has grown exponentially and their costs have fallen faster than projected. Whether human decisions act as a stabilising loop on the planet's trajectory is the central question of Section 10.

9.7 What the evidence shows and where it stops

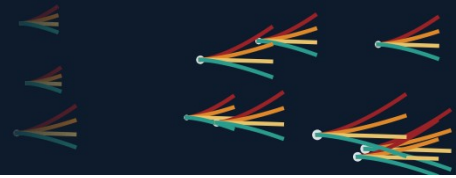
Table 15. Human–Earth interaction: evidence grades

Claim	Grade	Note
Human activity has caused essentially all warming since 1850–1900	A	IPCC AR6: unequivocal
Human-made mass now exceeds global living biomass	B	Single comprehensive estimate with ± 6 -year uncertainty on the crossover
Six or seven of nine planetary boundaries are transgressed	B	Depends on boundary positions, which involve judgement
The richest 10% cause about half of emissions	A–B	Robust across methods; exact shares vary
Two billion people could be outside the human climate niche by 2100 under current policies	C	Depends on niche definition and future population

Source: H Heuristics assessment of the studies cited in this section.

10

PART VIII · FUTURE ARCHITECTURE



10. The Future Architecture of Earth

Key question: what alternative trajectories are open for climate, ecosystems, freshwater, biodiversity and planetary habitability under different emissions, conservation, adaptation and development pathways? This section uses the physics of the previous sections to bound the possibilities, and is explicit about where choice, not physics, decides the outcome.

10.1 From forecast to trajectories

The future of the planet over the coming centuries cannot be forecast in the way an eclipse can, because its largest driver is human behaviour. What can be calculated is the consequence of each pathway. The most useful single relation for doing so is the near-proportionality between cumulative CO₂ emissions and warming, the transient climate response to cumulative emissions (TCRE), identified independently by [Matthews and colleagues](#) and [Allen and colleagues](#) in 2009. The IPCC's best estimate is 0.45 °C per 1,000 billion tonnes of CO₂, with a likely range of 0.27 to 0.63. The relation holds because two effects nearly cancel: the forcing per tonne declines as CO₂ accumulates (the logarithm of Section 4), while the ocean's ability to take up heat and carbon also declines. A corollary is that when net CO₂ emissions reach zero, warming from CO₂ roughly stops rising; multi-model studies put this [zero-emissions commitment](#) close to zero.

10.2 Four pathways to 2100

To make these relations concrete, the report calculated the warming implied by four illustrative emissions pathways (Figure 38). Each starts from the 41.6 billion tonnes of CO₂ emitted in 2024 and from 1.36 °C of human-induced warming. Warming is computed from cumulative emissions using the TCRE, with an additional 0.1 to 0.3 °C from non-CO₂ gases and the decline of cooling aerosols, depending on the pathway.

- **Rapid transformation:** emissions fall by about 40 per cent by 2030, reach net zero around 2050 and become net negative thereafter. Warming peaks at about 1.6 °C in the 2060s and declines to about 1.5 °C by 2100.
- **Paris-aligned:** emissions fall more gradually, reaching net zero around 2070. Warming peaks at about 1.9 °C and is about 1.8 °C in 2100.
- **Current policies:** emissions plateau near today's level until mid-century, then decline slowly to about a quarter of today's level by 2100. Warming reaches about 2.5 °C in 2100 (likely range 2.1 to 2.9 °C) and is still rising.
- **Fossil-intensive growth:** emissions roughly double by 2100. Warming reaches about 4.0 °C (3.1 to 4.9 °C) and is rising rapidly.

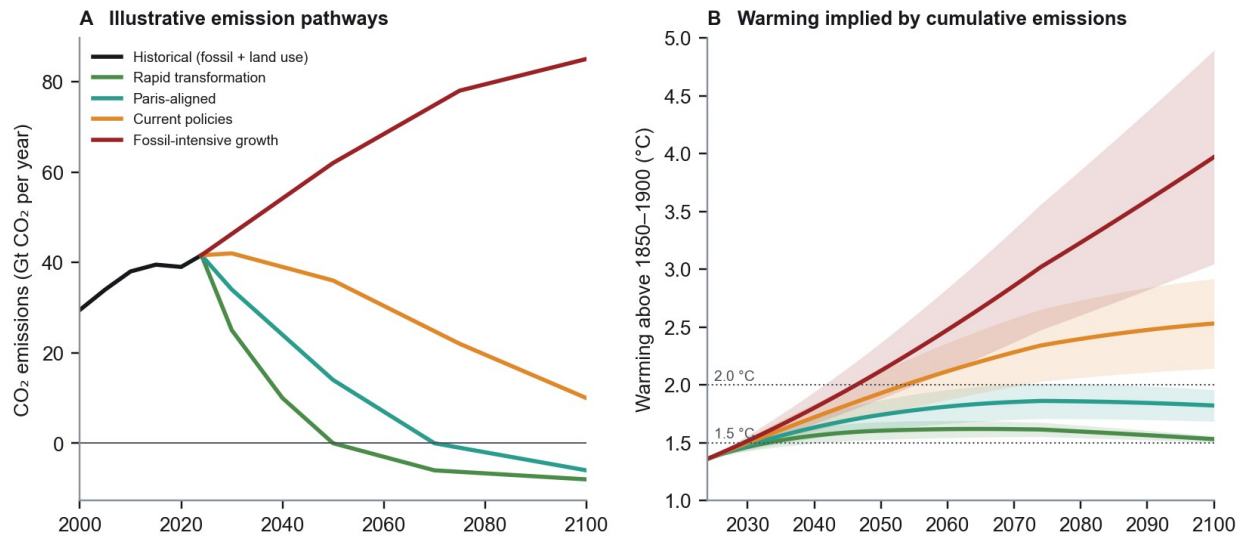


Figure 38. Four futures. Panel A shows illustrative CO₂ emission pathways after 2024. Panel B shows the warming each implies, calculated for this report from cumulative emissions; shading shows the IPCC likely range of the climate response to cumulative emissions.

Source: H Heuristics calculation using $TCRE = 0.45\text{ °C per }1,000\text{ Gt CO}_2$ (likely range 0.27–0.63; IPCC AR6), human-induced warming of 1.36 °C in 2024 (Forster et al., 2025) and a non-CO₂ contribution rising to 0.10–0.30 °C. Historical emissions from the Global Carbon Budget 2024. Illustrative; not a substitute for Earth system model projections.

These results are close to the IPCC's assessed projections for the corresponding shared socioeconomic pathways (Table 16), which provides a check on the simple model. They also make the arithmetic of the 1.5 °C goal stark. With non-CO₂ warming of about 0.1 °C, the model implies that only about 90 billion tonnes of CO₂ could be emitted from the start of 2025 for a 50 per cent chance of holding warming to 1.5 °C, about two years of current emissions. The most recent assessment by Forster and colleagues gives a similar figure of about 130 billion tonnes. On any of these estimates, holding warming to 1.5 °C without a temporary overshoot is no longer realistic; the question is how large the overshoot is and how quickly it is reversed. For 2 °C, the model's budget is about 1,200 billion tonnes, roughly 30 years of current emissions.

Table 16. IPCC AR6 projections for five illustrative scenarios

Scenario	Description	Warming 2081–2100 (°C, very likely range)	Sea-level rise by 2100 (m, likely range)
SSP1-1.9	Very low emissions; net zero CO ₂ around 2050	1.4 (1.0–1.8)	0.38 (0.28–0.55)
SSP1-2.6	Low emissions; net zero CO ₂ around 2075	1.8 (1.3–2.4)	0.44 (0.32–0.62)
SSP2-4.5	Intermediate; roughly current policies	2.7 (2.1–3.5)	0.56 (0.44–0.76)
SSP3-7.0	High emissions; regional rivalry	3.6 (2.8–4.6)	0.68 (0.55–0.90)
SSP5-8.5	Very high emissions; fossil-fuelled development	4.4 (3.3–5.7)	0.77 (0.63–1.01)

Source: IPCC AR6 Working Group I, Summary for Policymakers. Warming relative to 1850–1900; sea-level rise relative to 1995–2014. Sea-level rise of up to about 2 m by 2100 under very high emissions cannot be ruled out because of ice-sheet processes of deep uncertainty.

10.3 Beyond 2100: the long tail

The year 2100 is a convenient horizon for policy but not for the planet. Because a substantial fraction of emitted CO₂ stays in the atmosphere for millennia, the [warming reached is largely permanent](#) on human timescales unless CO₂ is actively removed. The slow components of the Earth system continue to respond long after temperatures stabilise. The deep ocean keeps warming and expanding for centuries. Ice sheets respond over centuries to millennia. The IPCC assesses that by 2300 sea level would rise by about 0.3 to 3.1 metres under low emissions and 1.7 to 6.8 metres under very high emissions, with larger rises possible. [Clark and colleagues](#) showed that the emissions of the twenty-first century will determine sea levels, ice cover and temperatures for the next ten thousand years: on the highest pathways, eventual sea-level rise would be measured in tens of metres.

This asymmetry of timescales is the defining feature of the future architecture. Human decisions are made over years to decades; the consequences unfold over centuries to millennia; and the natural process that would eventually remove the carbon, the weathering thermostat of Section 7, takes hundreds of thousands of years. Within the planning horizon of any human institution, the effects of CO₂ emissions are effectively irreversible.

10.4 Futures for ecosystems, freshwater and biodiversity

Climate is one dimension of the future. The state of ecosystems, freshwater and biodiversity depends also on land use, pollution, conservation and the pattern of development. The shared socioeconomic pathways developed by [O'Neill and colleagues](#) and quantified by [Riahi and colleagues](#) combine these dimensions into coherent narratives. Table 17 summarises four futures in the same spirit, using the H Heuristics framework to describe which feedbacks dominate in each.

Table 17. Four futures for the Earth system, around 2100

Dimension	Rapid transformation	Paris-aligned	Current policies	Fossil-intensive growth
Warming in 2100	~1.5 °C after a peak of ~1.6 °C	~1.8 °C	~2.5 °C and rising	~4 °C and rising
Tipping elements	Some regional elements lost (warm-water reefs); ice-sheet commitments limited	Higher risk to Greenland, West Antarctica and permafrost	Several elements likely committed; AMOC and Amazon risk rises	Multiple elements committed; cascade risk significant
Ecosystems and biodiversity	Protection of 30% of land and sea; restoration offsets losses	Losses slow; many range shifts	Continued decline; widespread coral loss	Large-scale loss; mass-extinction trajectory
Freshwater	Managed demand; stable monsoons	Growing drought and flood extremes	Water stress spreads in subtropics	Severe stress in many basins; glacier-fed rivers decline
Habitability	Most people within the human climate niche	Limited niche loss with adaptation	~2 billion outside the niche	Large regions near physiological heat limits
Dominant feedbacks	Stabilising human feedback outpaces physical amplifiers	Stabilising, with overshoot	Physical amplifiers gain ground	Physical amplifiers dominate

Source: H Heuristics synthesis of IPCC AR6, [Armstrong McKay et al. \(2022\)](#), [Lenton et al. \(2023\)](#) and the Kunming–Montreal Global Biodiversity Framework. Qualitative; values are central estimates.

Conservation and adaptation pathways shape these outcomes independently of emissions. The [Kunming–Montreal Global Biodiversity Framework](#) commits governments to protect 30 per cent of land and sea by 2030 and to restore 30 per cent of degraded ecosystems. Protecting tropical forests reduces both emissions and the risk of Amazon tipping. Adaptation, from heat-health warning systems to flood defences and drought-resistant crops, reduces the human cost of a given level of warming, but it has limits: beyond certain thresholds of heat, sea-level rise or water scarcity, adaptation in place becomes impossible.

10.5 What decides the trajectory

Physics constrains the futures but does not choose among them. Which trajectory unfolds depends on how quickly emissions fall, which depends on technology, economics and politics. Here too there are feedbacks. Clean technologies follow learning curves: the cost of solar photovoltaic modules has fallen by more than 99 per cent since 1976, and each doubling of deployment has cut costs by roughly a fifth, which drives further deployment. Policies, once established, create constituencies that defend them. Social norms can tip. On the other side, fossil-fuel infrastructure locks in emissions for decades, and the impacts of warming can erode the economic and political capacity to respond. Whether the stabilising human loop or the amplifying physical loops win the race is not determined by the architecture of the planet. It is the central uncertainty of the century.

10.6 What the evidence shows and where it stops

Table 18. Future trajectories: evidence grades

Claim	Grade	Note
Warming is approximately proportional to cumulative CO₂ emissions	A	Models and observations; IPCC AR6
Warming stops rising soon after net-zero CO₂	A–B	Zero-emissions commitment close to zero; non-CO ₂ gases matter
The remaining 1.5 °C budget is a few years of current emissions	A–B	Estimates range from about 90 to 200 Gt CO ₂
Sea level will keep rising for centuries after warming stops	A	Ocean and ice-sheet physics
Current policies lead to about 2.5–2.9 °C by 2100	B	Depends on policy implementation
Rapid technology diffusion can bend emissions faster than past trends	B–C	Evidence from solar, wind, batteries; adoption in heavy industry uncertain

Source: H Heuristics assessment of the studies cited in this section.

11

SYNTHESIS



11. The Unifying Architecture: Habitability as an Emergent Property

Sections 3 to 10 examined the planet one subsystem at a time. This section puts them back together. It asks why Earth stayed habitable when its neighbours did not, which components contribute to that outcome, and which principles of the creation framework genuinely run through all the subsystems.

11.1 Three planets, three outcomes

Venus, Earth and Mars formed from similar materials in the same part of the Solar System. A calculation of their effective temperatures from sunlight and albedo alone (Equation 1) gives similar values: about 229 K for Venus, which reflects most sunlight from its clouds, 255 K for Earth and 210 K for Mars (Figure 39). Their actual surface temperatures could hardly be more different. Venus's surface is 737 K, more than 500 degrees above its effective temperature, under a CO₂ atmosphere 92 times as massive as Earth's. Mars's surface is about 210 K, with almost no greenhouse effect, under an atmosphere less than one per cent as dense.

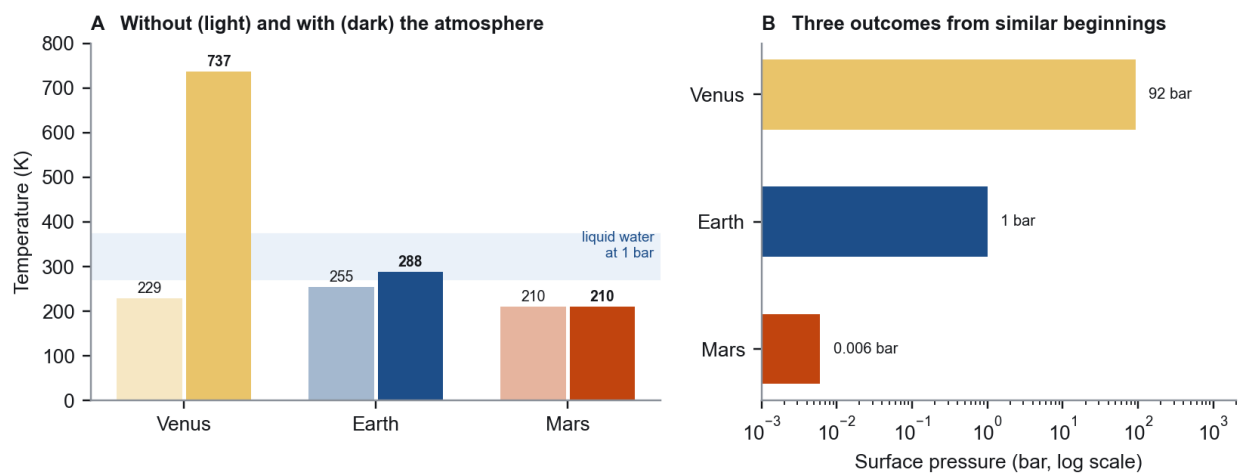


Figure 39. Three planets, three outcomes. Panel A compares the temperature each planet would have from absorbed sunlight alone (light bars, calculated for this report) with its observed mean surface temperature (dark bars). Panel B shows surface pressure. The difference is made by the atmosphere, and the atmosphere is shaped by each planet's history of feedbacks.

Source: H Heuristics calculation using solar flux at each planet's mean distance and Bond albedos of 0.76, 0.30 and 0.25; observed values from NASA planetary fact sheets.

The differences arose from feedbacks. Venus, receiving almost twice Earth's sunlight, probably lost any early ocean through a runaway or moist greenhouse: as the surface warmed, water evaporated, trapping

more heat, until water vapour reached the upper atmosphere and was split by ultraviolet light, its hydrogen escaping to space. The ratio of deuterium to hydrogen on Venus, about 150 times Earth's, is the [isotopic signature of that loss](#). Without water, weathering stopped, and volcanic CO₂ accumulated in the atmosphere instead of in rock. Mars, smaller and farther from the Sun, cooled quickly. Its dynamo died early, its volcanism waned, and its atmosphere was [stripped by the solar wind](#) and locked in its crust and polar caps. The weathering thermostat, which on Earth links climate to the interior, could not operate on either planet: on Venus because there was no liquid water, on Mars because there was too little heat to resupply CO₂.

11.2 What makes Earth habitable

Earth's habitability is therefore the joint product of several components (Table 19). Some are initial conditions; others are processes that maintain those conditions. No single component is sufficient, and the evidence for each varies.

Table 19. Contributions to Earth's long-term habitability

Component	Contribution	Mechanism	Grade
Distance from the Sun	Sets the starting energy budget	Places Earth near the inner edge of the habitable zone	A
Planetary size	Retains internal heat and an atmosphere	Large enough to sustain convection, volcanism and plate tectonics for billions of years	A–B
Oceans and the water cycle	Store and redistribute heat; enable weathering	High heat capacity; latent heat transport; dissolves rock	A
Plate tectonics and the carbon cycle	Long-term thermostat	Volcanic outgassing balanced by temperature-dependent weathering	B
Atmospheric greenhouse effect	Keeps the surface above freezing	Trace gases regulated by geochemistry and life	A
Biosphere	Controls composition of air and ocean	Oxygen, methane, enhanced weathering, carbon burial	A for effects; C for net regulation
Magnetic field	Shields the surface from energetic particles	Geodynamo deflects the solar wind	C for necessity
The Moon	Stabilises axial tilt; drives tides	Damps chaotic obliquity variations	B

Source: H Heuristics synthesis of Sections 3 to 8.

The table supports the report's central argument. Distance from the Sun sets the problem; it does not solve it. Over 4 billion years the Sun brightened by about a third, and Earth would have frozen early or boiled late without processes that adjusted its atmosphere. Those processes involve the interior (outgassing), the water cycle (weathering), the oceans (carbonate deposition) and life (oxygen, methane, enhanced weathering). Habitability is a property of their coupling. This is what it means to call it emergent.

Proposition (H Heuristics). Long-term planetary habitability requires at least one stabilising feedback that links the composition of the atmosphere to surface temperature on timescales shorter than those of stellar evolution. On Earth that feedback is the silicate-weathering thermostat, which in turn requires liquid water, exposed rock and a geologically active interior. Planets without such a link may be temporarily habitable but will not remain so (Grade C to D).

11.3 Principles across the subsystems

Figure 40 tests the eight principles of Table 2, together with two that were central to the life report, against the six domains of this report. Each cell records whether the principle operates in that domain as a shared physical mechanism, as an analogy, or not at all.

	Interior	Atmosphere	Water and ice	Biosphere	Geological time	Human systems
Energy gradients drive structure	shared	shared	shared	shared	shared	shared
Layering by density and gravity	shared	shared	shared	analogy	shared	—
Convection and circulation cells	shared	shared	shared	analogy	shared	analogy
Reservoirs, fluxes and cycles	analogy	shared	shared	shared	shared	shared
Stabilising (negative) feedback	shared	shared	shared	shared	shared	analogy
Amplifying feedback and thresholds	analogy	shared	shared	shared	shared	shared
Nested timescales	shared	shared	shared	shared	shared	shared
Network coupling between subsystems	analogy	shared	shared	shared	shared	shared
Selection and persistence filters	—	—	—	shared	analogy	analogy
Heredity and information	—	—	—	shared	analogy	shared

Figure 40. Which principles run through which subsystems. 'Shared' means the same physical mechanism operates; 'analogy' means a similar pattern arises from different mechanisms; '—' means the principle does not meaningfully apply. Energy gradients, nested timescales and feedback are universal; selection and heredity are confined to life and human systems.

Source: H Heuristics assessment.

Three groups emerge. **Universal mechanisms** operate in every subsystem through the same physics: energy gradients driving structure, stabilising and amplifying feedback, nested timescales and network coupling. These are the backbone of the planetary architecture. **Widespread but not universal mechanisms**, such as layering by density and convective circulation, operate wherever matter is fluid on the relevant timescale (the mantle, the core, the atmosphere and the ocean) and appear only as analogies in the biosphere and human systems. **Domain-specific mechanisms**, notably selection and heredity, are central to life and to human institutions but absent from the physical subsystems. Rocks, air and water do not inherit information; their configurations persist because they are physically stable, not because they are copied.

11.4 What carries over from the framework, and what is specific to planets

The series' foundational report proposed that recurring forms arise from constraints, biased generators and filters. Applied to Earth, that structure fits well, but the planetary case adds features that do not appear at other scales (Table 20).

Table 20. Framework principles at the planetary scale

Framework principle	Applies to Earth?	Planetary form
Constraint is stronger than expected	Yes	Radiative balance fixes the effective temperature to within a few kelvin; the Clausius–Clapeyron relation fixes how humidity responds to warming
Simple local rules generate global order	Yes	Buoyancy and rotation alone produce convection cells, Hadley cells, jets and gyres
Parameters set by history, geometry set by physics	Yes, by analogy	Planet size, composition and orbit are inherited; circulation patterns follow from physics
Development is contingent and channelled	Yes	Impacts and eruptions are contingent; the weathering thermostat channels climate back towards habitability
Two independent energy sources	Specific to planets	Stellar energy drives fluids; interior energy drives the solid planet; they meet in the carbon cycle
A closed material system	Specific to planets	The same atoms cycle for billions of years, so every flux must be balanced by a return path
Hysteresis between global states	Specific in scale	The planet as a whole can occupy alternative states, such as snowball and temperate
A conscious subsystem	Specific to Earth (so far)	One component can model the system and change its own behaviour

Source: H Heuristics, comparing *The Architecture of Creation* (2026) with Sections 2 to 10 of this report.

11.5 What the architecture does not explain

The architecture explains the persistence of habitable conditions and the general form of Earth's subsystems. It does not explain the particular events that shaped the planet: the Moon-forming impact, the asteroid that ended the Cretaceous, the timing of the great oxygenation. These are contingent, and a different sequence of contingencies would have produced a different Earth. Nor does the architecture fix the precise values of thresholds such as the point at which the West Antarctic ice sheet becomes committed to collapse; those depend on details that only observation and detailed modelling can establish. And it does not determine human choices, which now set the dominant forcing on the system. The architecture defines the space of possible planets and possible futures; history and decision select among them.

12

TESTS

12. Testable Propositions

A framework is useful only if it could be wrong. The propositions below are drawn from the report's arguments. Each states what would count against it. Propositions marked H Heuristics are original to this report; the others restate established hypotheses in the framework's terms.

Table 21. Testable propositions

#	Proposition	Test	Would be undermined if
1	Habitability requires a feedback linking atmospheric composition to temperature on sub-stellar timescales (H Heuristics)	Atmospheric surveys of rocky exoplanets in and near habitable zones	Temperate planets are found with compositions uncorrelated with stellar flux
2	Rocky planets in the habitable zone show lower CO ₂ at higher stellar flux, as the weathering thermostat predicts	Statistical CO ₂ survey with next-generation telescopes	No such trend appears across a large sample
3	Silicate weathering responds to temperature strongly enough to stabilise climate within 10 ⁶ years	Weathering records across past warm events such as the PETM	Weathering shows no acceleration during warm intervals
4	The water-vapour feedback scales with the Clausius–Clapeyron rate	Satellite humidity and radiation records	Upper-tropospheric humidity fails to rise with temperature
5	Equilibrium climate sensitivity lies between 2 and 5 °C	Continued observation of warming and energy imbalance	Observed energy-budget constraints fall outside this range
6	Components approaching tipping points show critical slowing down	Monitoring of AMOC indices, Amazon vegetation and ice-sheet dynamics	Elements tip without preceding rises in autocorrelation or variance, under slow forcing
7	Warming roughly stops within decades of net-zero CO ₂	Observation after emissions peak; model intercomparisons	Substantial continued warming after net zero from internal feedbacks
8	Coupled tipping elements lower each other's effective thresholds (H Heuristics restatement)	Palaeoclimate records of abrupt events; coupled modelling	Elements tip independently in the record and in models
9	Human decision-making can act as a net stabilising feedback on planetary change (H Heuristics)	Emissions trajectories relative to impacts over the next two decades	Emissions continue to rise as impacts intensify
10	Shared physical mechanisms, not analogies, account for most recurring structure across Earth's subsystems (H Heuristics)	Systematic classification of recurring forms across subsystems	Most recurring patterns prove to be analogies with different causes

Source: H Heuristics.

13

VERDICT



13. Conclusion: Is There a Coherent Architecture of Earth?

13.1 The verdict

The report asked what underlying physical processes and feedback mechanisms govern the organisation, persistence and transformation of Earth's planetary system. Its answer is that Earth's organisation can be understood as a coherent architecture of interacting processes, provided that architecture is understood as a family of coupled mechanisms rather than a single law. Two energy sources, sunlight and internal heat, drive the generators. Gravity, conservation laws, radiative balance and the thermodynamics of water constrain what they can produce. A hierarchy of feedbacks, nested by timescale, filters the outcome: fast amplifiers make the climate sensitive on human timescales, while slow stabilisers keep it habitable on geological ones. Table 22 summarises the answers to the key questions of each part.

Table 22. Answers to the report's key questions

Question	Answer	Grade
How does internal energy shape the surface?	Through convection, plate tectonics and volcanism, which build continents, recycle crust and supply the CO ₂ that weathering removes	A–B
How does the atmosphere regulate heat?	Through a greenhouse effect controlled by trace gases, and circulation that carries heat poleward	A
How does water connect the subsystems?	As a store and carrier of heat, a solvent for weathering, a lubricant of tectonics and, as ice, a switch on albedo	A
How does life act on the planet?	By controlling the composition of air and ocean and accelerating weathering; whether it regulates the planet is contested	A / C
How do slow processes produce large change?	By accumulation over vast times and through thresholds, such as the onset of glaciation	A–B
When does Earth absorb, shift or persist?	It absorbs small disturbances, shifts when thresholds are crossed, and persists in new states where hysteresis is wide	B
How have humans altered the system?	By becoming a dominant forcing on the energy balance and on the carbon, nitrogen and phosphorus cycles	A
Which futures are possible?	Warming between about 1.5 and 4 °C by 2100, decided mainly by cumulative emissions	A–B

Source: H Heuristics.

13.2 What this implies for habitability and civilisation

Three implications follow for the coming centuries. First, habitability is maintained, not given. The processes that keep Earth habitable are real but slow; the processes that amplify change are fast. A disturbance as rapid as the present one will play out under the influence of the amplifiers long before the stabilisers can respond. Second, the coupling that makes Earth habitable also transmits disturbance. Warming the atmosphere warms the ocean, melts ice, shifts rainfall, stresses forests and alters the carbon cycle, and those changes feed back on the atmosphere. Planetary risks are therefore systemic, not sectoral. Third, many of the changes now under way are effectively irreversible on human timescales. Sea level will rise for centuries, ice sheets once committed to loss will not regrow for millennia, and extinct species do not return. The choices of the next few decades will set conditions for the next several thousand years.

There is also reason for confidence. The physics that makes the problem severe also makes it tractable. Warming is approximately proportional to cumulative emissions and stops soon after they reach net zero, so the outcome is under human control to a degree that few planetary processes are. The ozone layer shows that a planetary perturbation can be recognised and reversed. And the same coupling that propagates harm can propagate repair: restored forests store carbon and recycle rain, protected oceans rebuild fisheries and carbon sinks, and clean energy reduces both emissions and the air pollution that kills millions each year.

13.3 Ten heuristics for reading a planetary system

The working heuristics below translate the architecture into questions that can be asked of any planetary process, from a glacier to the global carbon cycle.

1. **Find the energy source.** Ask whether a process is driven by sunlight, internal heat, gravity or tides, and how large the flow is.
2. **Find the reservoirs and the fluxes.** Divide each store by its flow to get a residence time, and ask which reservoir is slowest.
3. **Find the stabilising loop.** Identify what opposes a change, and on what timescale it acts.
4. **Find the amplifying loop.** Identify what reinforces a change, and whether it can create an alternative state.
5. **Compare the timescales.** Ask whether the disturbance is faster or slower than the feedbacks that would correct it.
6. **Look for thresholds and hysteresis.** Ask whether reversing the cause would reverse the effect, or whether the way back is longer than the way in.
7. **Follow the coupling.** Trace how a change in one subsystem propagates to the others, and back.
8. **Separate constraint from contingency.** Ask whether an outcome was required by physics or produced by a particular event.
9. **Watch for slowing down.** Rising autocorrelation and variance can signal a weakening stabiliser.
10. **Grade the claim.** Ask whether the evidence is direct, inferred, contested or speculative, and say so.

13.4 Closing

The first report in this series asked why the same forms recur across unrelated systems. The universe report showed how physical law builds stars and planets. The life report followed chemistry into structures

that copy themselves. This report has examined the scale in between: a planet on which rock, air, water and life are bound together by flows of energy and loops of feedback. That binding is what has kept Earth habitable through four billion years of change. It is also what makes the planet responsive to the forces now acting on it. Earth is not a fixed stage on which life and history unfold. It is a dynamic architecture, maintained by its own processes, and now shaped by one of its inhabitants. Understanding that architecture is the first condition for keeping it habitable.

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