10 NEW INSIGHTS IN CLIMATE SCIENCE

2026/2027

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For policymakers responding to the urgent challenge of the climate crisis, the *10 New Insights in Climate Science 2026/2027* offers credible guidance throughout 2027 and beyond.

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Title: 10 New Insights in Climate Science 2026/2027

Produced by: Future Earth, The Earth League, and the World Climate Research Programme

Layout and graphics: Azote

Printed on recycled, FSC-certified paper.

Cite this report as: Future Earth, The Earth League, WCRP (2026). *10 New Insights in Climate Science 2026/2027*. Stockholm. doi: 10.5281/zenodo.23008521



INSIGHTS AT A GLANCE

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1. **Ocean heat content keeps climbing as Earth's energy imbalance grows.** The ocean continues to absorb massive amounts of excess heat, in step with Earth's energy imbalance, locking in warming for decades to come. Given this lag, deep cuts in greenhouse gas emissions are urgently needed to prevent further long-term heat accumulation.

2. **Sea level rise in a warming world: acceleration, ice mass loss, and long-term commitment.** Ice mass loss and thermal expansion are driving sea level rise. Even without further warming, irreversible change is already locked in, making adaptation essential. The prospect of these committed changes underlines the urgency of near-term mitigation.

3. **Water gaps widen as continental drying accelerates.** Climate change and growing water use are causing the rapid loss of freshwater across continents, threatening water security, ecosystems, and food production. The consequences of inaction extend from threats to local livelihoods to cascading impacts across the Earth system.

4. **A larger overshoot of 1.5°C increases the risk of irreversible impacts, forces greater reliance on carbon dioxide (CO_2) removal, and narrows adaptation options.** Reversing surface warming cannot undo century-scale changes in slow-responding systems like oceans, glaciers, ice sheets, and permafrost. As we approach overshoot, mitigation must expand beyond net zero towards net-negative targets and adaptation planning must prepare for peak warming conditions.

5. **Bundled interventions for food system transformation can deliver major gains for human health and planetary stability.** A shift towards plant-rich diets is the primary demand-side lever for creating critical* "option space" to meet climate and environmental goals, while improving human health. Realising these co-benefits and managing potential impacts on labour demand, requires cross-sectoral policies that minimise trade-offs and support a just transition.

6. **The social cost of carbon has been severely underestimated.** The economic damages caused by carbon emissions are substantially higher than previously estimated, and every extra tonne of CO_2 carries additional risk. Using more realistic, up-to-date climate models reveal a social cost of carbon (SCC) up to four times higher.

7. **Advances in attribution science demonstrate individual emitters' climate impact.** Scientific advances now enable tracing the full causal chain from emissions to impact, enough to link a specific harm to a specific actor's emissions. This strengthens the evidence available for accountability, litigation, and for loss and damage discussions.

8. **Climate clubs can limit carbon leakage, but fairness shapes their feasibility and effectiveness.** Linking climate action to trade measures can help accelerate industrial decarbonisation and limit carbon leakage. However, careful design is essential to avoid imposing disproportionate adjustment costs on developing economies in order to secure political legitimacy and environmental effectiveness.

9. **Organised obstruction prevents effective climate policy through denial, delay, dilution and distraction.** Coordinated efforts driven by carbon-intensive industries have expanded beyond outright science denial to subtler tactics, including greenwashing, promoting misleading solutions, and spreading digital disinformation at scale.

10. **Just energy transition threatened by geopolitical risks and fragmentation.** Geopolitical instability can accelerate the clean-energy transition in some countries, while deepening fossil fuel reliance in others, increasing the risk of an unequal global transition

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INTRODUCTION

INTRODUCTION

Despite weak La Niña conditions last year, the global mean near-surface temperature in 2025 was approximately 1.43°C ± 0.13°C above preindustrial levels, extending the unbroken streak of 2015–2025 as the eleven warmest years ever recorded, as confirmed by the World Meteorological Organization (WMO).[1] This atmospheric warming was reflected across the Earth system: upper-ocean heat content (OHC) reached a new record in 2025; global mean sea level remained close to the record set in 2024; the annual maximum Arctic sea-ice extent was the lowest in the satellite record; and glaciers experienced another year of substantial net mass loss.[2] Human-caused climate change also increased the likelihood or intensity of many damaging heatwaves, droughts, fire-weather conditions and extreme-rainfall events during the year, although its influence varied among events and regions.[3] Underlying all these, global fossil carbon dioxide (CO_2) emissions, including cement production, reached a record 10.4 GtC, or 38.1 $GtCO_2$, while the annual mean atmospheric CO_2 concentration rose to approximately 425.6 ppm, 53% above its pre-industrial level.[4]

Amid these worrying trends, a central question is whether the Paris Agreement's ambition cycle is working as intended. The first Global Stocktake (GST1) concluded at COP28 in Dubai, and the third cycle of nationally determined contributions (NDCs), due in 2025 ahead of COP30 in Belém, was expected to respond to its findings with ambition commensurate with the scale of the gaps identified. But, the picture is mixed: The conclusions of the GST1 have influenced the structure and sectoral coverage of many new NDCs and reinforced international priorities such as renewable-energy expansion, energy efficiency and adaptation, but they have not generated the level of ambition or implementation commensurate with the Paris Agreement temperature goals. The latest NDCs imply an estimated 12% reduction in global emissions by 2035 relative to 2019, compared with approximately 55% required for a 1.5°C-consistent pathway, while current policies remain insufficient to deliver even existing commitments.[5] The Paris Agreement's ambition cycle is therefore functioning at the procedural level, but it is not yet producing the effective "ratchet" towards alignment with its temperature goal, owing to weak national follow-through, inadequate finance and the absence of a mechanism for translating collective gaps into differentiated national responsibilities.

With the launch of the information-collection phase of the second Global Stocktake (GST2) this year, and increasing awareness about the impending reality of the 1.5°C overshoot trajectory, COP31 represents an important point for climate diplomacy to continue the transition from negotiated pledges toward implementation. Parties must resolve the lingering issues to operationalise the 59 Belém Adaptation Indicators for the implementation of the Global Goal on Adaptation (GGA) framework, following the gridlock at the June 2026 meeting in Bonn(SB64). Progress is also needed in defining the governance and financial architecture of the Belém–Antalya Just Transition Mechanism to drive global energy transition pathways. On the ever crucial issue of finance, Parties are expected to advance the Baku-to-Belém roadmap toward USD 1.3 trillion annually by 2035, and fully capitalise the Loss and Damage Fund, both of which remain fundamental to enabling collective action. Meeting these priorities will require finalising Article 6 carbon market infrastructure to safeguard environmental integrity and furthering the institutionalisation of climate–trade dialogues within the UNFCCC to help navigate this increasingly central issue.

These discussions are taking place amid growing threats to the integrity of the information underpinning climate decision-making, involving misinformation, disinformation and deliberate attacks on environmental scientists, journalists and defenders, as was formally recognised at COP30.[6] The GST must be conducted "in the light

1 WMO (2026). *State of the Global Climate 2025.* Geneva: World Meteorological Organization.

2 Blunden, J., and Reagan, J. (eds) (2026). State of the Climate in 2025 *Bulletin of the American Meteorological Society*, 107(8); and C3S (2026) *Global Climate Highlights.* Copernicus Climate Change Service - EU Observation Programme

3 Otto, F.E.L., et al. (2025). *Unequal Evidence and Impacts, Limits to Adaptation: Extreme Weather in 2025.* World Weather Attribution. London: World Weather Attribution and Grantham Institute for Climate Change, Imperial College London

4 Forster, P.M., et al. (2026). Indicators of Global Climate Change 2025: annual update of key indicators of the state of the climate system and human influence. *Earth System Science Data*, 18(6), 3889–3933; and Friedlingstein, P., et al. (2026). Global carbon budget 2025. *Earth System Science Data*, 18(5), 3211–3288.

5 UNEP (2025). *Emissions Gap Report 2025: Off Target – Continued Collective Inaction Puts Global Temperature Goal at Risk.* Nairobi: United Nations Environment Programme; and UNFCCC (2025). *Nationally Determined Contributions Synthesis Report.* Bonn: United Nations Framework Convention on Climate Change.

6 Global Initiative for Information Integrity on Climate Change: *Declaration on Information Integrity on Climate Change.* Presented at COP30, Belém, Brazil, 12 November 2025.

of equity and the best available science," with Intergovernmental Panel on Climate Change (IPCC) assessments serving as key authoritative scientific inputs. Yet repeated failures by IPCC member governments to agree on a timetable for the Seventh Assessment Report (AR7) Working Group reports have cast doubt on whether they will be available in time for the GST2, before it concludes in 2028. The dispute reflects a genuine tension between ensuring timely policy relevance and safeguarding assessment quality, adequate review and equitable participation, but it also risks leaving GST2 without a comprehensive and up-to-date assessment precisely when contested information environments make trusted scientific synthesis most important. This reinforces the need for timely, credible and policy-relevant knowledge synthesis to support the science–policy interface throughout the GST2 cycle.

The *10 New Insights in Climate Science* initiative provides an annual synthesis of key advances across diverse fields of climate change research, drawing on the latest relevant peer-reviewed literature. A joint initiative of Future Earth, The Earth League and the World Climate Research Programme, this year's report reflects the collective work of more than 70 researchers, informed by contributions from over 200 experts worldwide. Its purpose is to facilitate the timely uptake of credible scientific evidence in policymaking and international governance. Together, the ten insights trace a connected arc from accelerating and long-lasting changes in the Earth system to key transformations, governance arrangements and accountability mechanisms required for effective climate action, as well as economic and political barriers to overcome.

The first insights in this year's report highlight accelerating physical changes and the long-term 'commitments' across the Earth system. Global ocean heat content reached a record high for the ninth consecutive year, while the Earth's energy imbalance (EEI) continues to grow, with consequences for climate and ocean conditions over decades and longer (Insight 1). Relatedly, thermal expansion and rising ice sheet loss have led to a doubling in the rate of global sea level rise, creating multi-century coastal commitments that cannot be reversed for many generations to come (Insight 2). On land, intensifying drought and groundwater depletion are producing persistent hydrological deficits, and a phenomenon known as 'continental drying' (Insight 3). As these interconnected Earth system changes are already affecting societies, the impending trajectory of overshoot of the 1.5°C warming target entails escalating risks of further severe and potentially irreversible impacts. Climate governance in this context underscores the urgent imperative for immediate, deep and sustained reductions in gross GHG emissions, alongside responsibly governed carbon dioxide removal (CDR) to minimise the magnitude and duration of overshoot, while also investing in adaptation to expected peak warming levels (Insight 4).

The next set of insights addresses governance challenges in highly contested political arenas. Transforming food systems is an essential lever for climate action, but requires navigating sensitive cultural and economic choices by combining demand-side shifts towards healthy, plant-rich diets with just transition measures that protect agricultural workers and rural livelihoods (Insight 5). The case for food systems transformations, as well as for the all-important transition away from fossil fuels, is reinforced by a significant recalibration of a key benchmark used in climate-policy appraisal: updated methods for estimating the social cost of carbon (SCC) indicate substantially greater economic damages than previously recognised (Insight 6), materially strengthening the economic case for rapid and deep mitigation. Going beyond the macroeconomic and sector-level, advances in attribution science can now quantitatively connect specific climate impacts to emissions from major carbon emitters, as well as to the consumption and investment decisions of high-income groups (Insight 7). This provides an increasingly robust empirical basis that could inform climate litigation, corporate accountability and debates over loss and damage finance. But unlocking progress across these arenas also requires the dismantling of networks driven by carbon-intensive industries to deliberately obstruct effective climate policy (Insight 9). Advancing climate action depends not only on identifying effective solutions, but also on confronting vested interests, updating economic decision-making tools and strengthening accountability across contested policy domains.

The two remaining insights are particularly relevant in a challenging geopolitical context marked by growing strain on multilateral governance, including within the United Nations Framework Convention on Climate Change (UNFCCC). Climate clubs and associated trade-related measures (such as carbon border adjustment mechanisms, or CBAMs), could help coordinate climate action, limit carbon leakage and incentivise cleaner industrial production. However, their design and implementation raise significant political, legal, and distributional questions concerning compatibility with inter-

national trade rules, transparency and fairness towards developing-country exporters with limited capacity to decarbonise (Insight 8). These tensions are compounded by heightened geopolitical instability and fragmentation, which is reshaping energy security, investment, supply chains and international cooperation. This creates a severe risk of diverging decarbonisation pathways, where less developed countries lack the capital and access to secure green technologies and risk being left behind (Insight 10).

We hope that the 10 New Insights in Climate Science 2026/2027 will reach Party and Observer delegations to the UNFCCC, help inform their positions and arguments, and ultimately be reflected in the outcomes of COP31 in Antalya, Türkye, and beyond. In particular:

- **Grounding GST2 in robust understanding of overshoot pathways.** GST2 should reaffirm the relevance of pursuing the Paris Agreement's 1.5°C limit, set to assess collective progress against pathways that minimise the magnitude and duration of the overshoot trajectory. It should examine both ambition and implementation, distinguishing gross emissions reductions from CDR.

- **Operationalising the Belém–Addis Vision on Adaptation.** Equip a properly resourced technical task force to provide practical guidance and support countries testing the Belém Adaptation Indicators, including methodologies that capture persistent and slow-onset risks. Alongside a credible baseline, delivery trajectory and reporting framework for tripling adaptation finance by 2035, this can make progress towards the GGA meaningfully accountable.

- **Operationalising the Just Transition Mechanism.** Agree on its functions, governance, participation arrangements and means of support, so Parties can develop just transition pathways across energy, industry, critical-mineral supply chains and agrifood systems. The mechanism should help translate GST1 outcomes into implementation, including accelerated electrification and a just, equitable and orderly transition away from fossil fuels.

- **Converting climate-finance commitments into accessible support.** Set milestones from the USD 300 billion annual goal towards mobilising at least USD 1.3 trillion by 2035, prioritising predictable public, grant-based and concessional finance under Article 9.1. Substantial new contributions to the Fund for Responding to Loss and Damage (FRLD) are especially urgent as climate impacts and losses mount.

- **Managing tensions at the climate–trade nexus.** Use the dialogues to build shared understanding of how trade-related climate measures, including carbon border adjustments, can be designed and implemented to curb carbon leakage and preserve domestic climate ambition, and what additional measures would be required to minimise or balance the potential burden imposed on developing-country exporters.

- **Safeguarding information and institutional integrity.** Build on COP30's Declaration by advancing UNFCCC-wide safeguards against misinformation, disinformation, obstruction and undue influence. In particular, by requiring complete, verifiable disclosure of delegates' affiliations, funding and conflicts of interest, alongside clear rules for managing those conflicts.

The science underpinning each of the insights presented in this report is described in more detail and with all the supporting references in:

Ospina, D.; Mirazo, P.; Alejo, C.; Andrei, R.; Bastien-Olvera, B. A.; Bastos, A.; Bodirsky, B. L.; Broadgate, W.; Callahan, C. W.; Chen, L.; Chen, D.; Chen, L.; de Nadal, L.; Dickau, M.; Downie, C.; Dussaillant, I.; Ebi, K. L.; Famiglietti, J. S.; Fanzo, J.; Franta, B.; Friedl, A.; Friedlingstein, P.; Fuss, S.; Gruber, N.; Hirota, M.; Hoffart, F. M.; Jacquet, J.; Kasuga, F.; Kimutai, J.; Kılkış, Ş.; Leal-Arcas, R.; Lee, S.-Y.; Maitland, D.; Martin, M. A.; Matthews, D.; Mauritsen, T.; Merner, L. D.; Milani, C. R. S.; Morin, J.-F.; Mrabet, R.; Muir, F.; Myhre, G.; Naish, T.; Nasiritousi, N.; Nauels, A.; Neal, T.; Pan, Y.; Patra, P. K.; Persson, Å.; Prakash, A.; Quilcaille, Y.; Redman, A.; Reisinger, A.; Rocchi, P.; Rockström, J.; Rosa, L.; Roy, J.; Samset, B. H.; Sanchez-Rodriguez, R.; Schlosser, P.; Schwarz Meyer, A.; Singh, V.; Sioen, G. B.; Sokona, Y.; Springmann, M.; Stuart-Smith, R. F.; Su, S. H. L.; Thawonmas, R.; Theokritoff, E.; Trenberth, K.; van den Akker, T.; Warszawski, L.; Wu, H. C.; Yoo, J. Ten New Insights in Climate Science 2026. under review in *Global Sustainability*. doi: 10.5281/zenodo.23059603

THE INSIGHTS

1 Ocean heat content keeps climbing as Earth's energy imbalance grows

KEY MESSAGES

- 2025 marked the ninth consecutive record year for ocean heat content. Warming has accelerated markedly over the past six decades and is now more widespread, with about a third of the global ocean reaching its top-three warmest levels last year.
- Since the ocean absorbs over 90% of excess heat from the Earth's growing energy imbalance, ocean heat content is one of the most reliable indicators of how much extra energy is accumulating in the climate system.
- Near-term warming is partly "locked in" by ocean heat already accumulated. Because heat takes decades to penetrate ocean depths, today's energy imbalance will keep shaping the climate for decades to come. Cutting emissions now can still prevent additional, potentially irreversible warming.
- Clouds, aerosols, and climate sensitivity add uncertainty to where and how warming plays out. Some models with lower climate sensitivity fail to reproduce observed energy imbalance trends, suggesting actual greenhouse-gas-driven warming could be stronger than most current simulations project.

The Earth is warming, but where exactly is that excess heat ending up? Several key indicators suggest that the world may already be on an accelerated warming pathway, highlighting the urgent need to decarbonise and prepare for impacts already set in motion. At the same time, geophysical components require further investigation to better understand how warming could manifest in the coming decades.

Earth's energy imbalance (EEI) is arguably the ultimate measuring stick of global warming. It is the difference between the radiation arriving from the Sun and the energy reflected or radiated back into space. By tracking EEI, scientists can quantify the effects of natural and human-caused warming and cooling, as well as feedback processes. Changes in EEI are estimated from radiometric measurements at the top of the atmosphere, while its absolute magnitude is quantified by summing the heat accumulated across the ocean, land, ice, and atmosphere.

More than 90% of the excess heat is absorbed by the oceans, but the specific geophysical connections between EEI and rising OHC are challenging to disentangle. Data spanning the past six decades reveal that OHC has risen with EEI, even though the signal has been complicated by natural variability since 2005, including El Niño. Figure 1 shows the marked rise in global OHC since the 1990s, reaching a record high in 2025. Heat takes about 25 years to penetrate the ocean column, from the surface down to 2,000 m, so additional warming at depth is already committed.

The latest figures are stark: 2025 saw the ninth consecutive record year for OHC, and about a third of the global ocean ranked among its three warmest states on record. From 2005 to 2025, the mean ocean warming rate increased markedly, reaching 0.32 ± 0.12 W/m^2 per decade, which is broadly consistent with the 0.47 ± 0.22 W/m^2 per decade rate measured by satellites over the same period. Warming extends from the surface into the deep ocean, though its magnitude varies by depth and region, with the strongest warming occurring in a band near 30–45° latitude in both hemispheres. This suggests that the distribution of heat is shaped by ocean and atmospheric flows, which in turn are influenced by natural variability, including events such as the El Niño–Southern Oscillation.

Across the Earth system, several feedbacks are at play. Radiative cooling is a strong negative feedback because, as the planet warms, it radiates more heat into space, thereby partly offsetting further warming. Water vapour works the other way: a warmer atmosphere can hold up to about 7% more per °C of warming, and since water vapour is itself a greenhouse gas, this amplifies the initial warming. Melting snow and ice add another positive feedback, since the darker ocean and land surfaces left behind absorb more sunlight than the bright, reflective ice they replace. Atmospheric aerosols cut both ways: soot particles absorb heat, while lighter-coloured sulphate particles reflect sunlight and cool the planet. Some studies suggest their cooling effect has weakened in the past two decades, meaning that measures to cut air pollution may have slightly accelerated warming, though the size of this effect remains debated.

The role clouds will play in a warming world remains unclear, and cloud feedbacks are among the largest sources of uncertainty in climate projections. Recent research suggests that cloud cover, particularly over the ocean, has been declining as temperatures rise, meaning less sunlight is reflected back to space, further contributing to the warming trend. The record heat of 2023–2024 coincided with a strong El Niño, consistent with a pattern of global warming jumping to new levels during such events. However, because climate models do not reproduce observed clouds and rainfall very well, the specific contribution of clouds to this warming remains an open question.

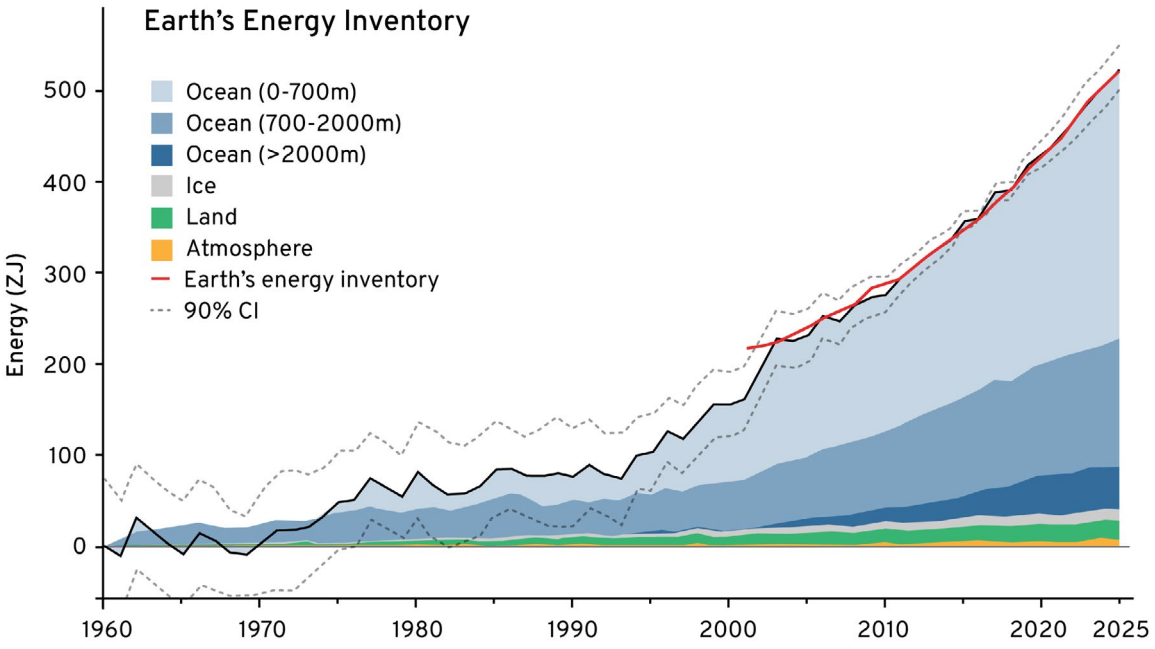


Figure 1. Global energy inventory. OHC annual mean time series from IAP relative to a 1958–1962 baseline, with different ocean layers shown in blue shadings and the grey dashed lines denoting the 90% confidence interval.[7] Also shown are estimates of the land, ice, and atmosphere heat uptake.[8] The Earth's energy inventory (red curve) is derived by first integrating monthly CERES EEI data in time to obtain cumulative heat uptake, then converting it to an annual series, and finally aligning the 2005–2025 baseline with that of the summed ocean, land, ice, and atmosphere heat content series. Updated from Cheng et al. 2024.[9]

7 Bao, S., et al. (2026). Ocean heat content in 2025. *Nature Reviews. Earth & Environment*, 7, 206–208.
8 von Schuckmann, K., et al. (2023). Heat stored in the Earth system 1960--2020: where does the energy go? *Earth System Science Data*, 15(4), 1675–1709.
9 Cheng, L., et al. (2024). IAPv4 ocean temperature and ocean heat content gridded dataset. *Earth System Science Data*, 16(8), 3517–3546.

Human-induced warming also strengthens atmospheric convection, making it narrower and taller while widening the regions of sinking air in the subtropics. When first described around the turn of the millennium, this "iris" effect was proposed as a negative feedback effect, since it allows more heat to escape into space from the warmer surface below. But subsequent research highlights that this view overlooks the fact that fewer clouds outside these narrower convection zones let in more sunlight, more than offsetting this effect. This is a non-local positive feedback.

EEI observations have been collected since March 2000 by CERES, a set of NASA satellite instruments that measure the sunlight reflected and heat radiated by Earth. EEI is too small to measure accurately in absolute terms, but because the instruments are far more stable than they are accurate, changes over time can be tracked reliably. Although short-term noise in the data is considerable, averaging it out over time reveals a clear, steady heating signal that has been compared directly with OHC.

Another tool that can help improve the accuracy of EEI measurement is "reanalysis", which combines models with observations to reconstruct past weather and climate. ERA5, a widely used dataset, improves on previous versions, though errors in how models represent clouds and rainfall still affect EEI estimates. Recent work suggests models with lower climate sensitivity fail to reproduce observed EEI trends, hinting that greenhouse gases may be driving more warming than most current models predict. These findings underscore the importance of sustained monitoring efforts such as the Global Ocean Observing System, an international network that tracks ocean temperature, currents, and other properties worldwide.

POLICY IMPLICATIONS

- **Accelerate nationally determined contributions (NDCs) implementation while preparing for long-term ocean change.** Accelerating EEI and ocean heat uptake reinforce the need for immediate, deep and sustained greenhouse-gas reductions. Parties should fully implement and, where possible, strengthen their 2035 NDCs and align long-term low-emission development strategies with pathways with limited overshoot of 1.5°C warming (see Insight 4). At the same time, the recognition of committed and potentially intensifying ocean changes, should be reflected in National Adaptation Plans (NAPs), long-term investment decisions and risk assessments, prioritising vulnerable coastal and marine-dependent communities. Because ocean heat penetrates progressively into deeper layers and some associated changes persist for centuries, choices made this decade will influence ocean and climate risks far into the future.

- **Integrate ocean action across the UNFCCC.** Building on COP30 ocean initiatives, including the Blue NDC Challenge, and the 2026 Ocean and Climate Change Dialogue, the ocean–climate nexus should become a cross-cutting component of UNFCCC governance. Key organising activities include:

    - Establish systematic reporting and a multi-year ocean–climate roadmap, identifying entry points across NDCs, the GST2, and other Paris Agreement processes, to facilitate continuity across COP presidencies and enable assessment of collective progress.

    - Mapping emerging ocean initiatives to identify gaps, implementation and finance bottlenecks, and potential duplication, clarifying responsibilities and opportunities for collaboration.

- **Sustain observing systems as critical infrastructure for climate action.** Governments and relevant international institutions should provide predictable, long-term support for the satellite and in-situ systems underpinning measurements of EEI and OHC—including radiation-budget instruments such as CERES, Argo floats, and national and regional ocean-observing networks.

    - Through the UNFCCC Research and Systematic Observation agenda, Parties should strengthen collaboration with WMO, GCOS, GOOS, UNESCO-IOC and relevant space agencies to identify coverage and capacity gaps and mobilise targeted support for vulnerable and under-observed regions.

    - The resulting open, standardised and sustained observations should inform the scientific inputs to the GST2, helping assess the climate system's response to emissions and evaluate climate models. They should also be translated into regional climate services, forecasts and early-warning information that support NAPs and other risk-management decisions.

    - Given the importance of this data for coastal states' adaptation planning, sustained funding and scientific cooperation for these programmes and systems is crucial and should be raised explicitly within adaptation discussions.

2 Sea level rise in a warming world: Acceleration, ice mass loss, and long-term commitment

KEY MESSAGES

- Global mean sea level rise (GMSLR) is accelerating, with the rate of increase doubling over the past thirty years. Thermal expansion and freshwater input from the cryosphere are the primary drivers.
- Glacier melt was the largest single contributor to sea level rise over the 20th century, but over recent decades thermal expansion has been the largest single contributor. Looking ahead, the Greenland and Antarctic ice sheets combined are expected to become the largest individual contributor to sea level rise by the end of the 21st century.
- Cumulative greenhouse gas emissions in the coming decades will lock in irreversible sea level rise for centuries to come. Stringent emission mitigation could still avoid a substantial fraction of the additional sea level rise projected by 2300 under current policies.
- A major source of uncertainty in sea level rise projections stems from tipping points and irreversible ice retreat. Evidence suggests that marine-based sectors of both major ice sheets may have already undergone irreversible change at current warming levels, potentially committing certain outlet glaciers to large-scale, self-sustained retreat.

An estimated one billion people live in coastal areas less than 10 m above sea level, and recent research suggests they face greater exposure to sea level rise than previously thought. Predicting the extent of this rise has never mattered more. Decisions made in the coming decades will shape coastal risks for generations.

GMSLR has accelerated during the 21st century, with the rate doubling in the past thirty years. This change has not been slow and steady. Research shows a step-like increase in the rate of sea level rise in the early 2010s, linked to natural fluctuations in the climate system, which exacerbated the human-induced baseline trend. Sea levels have been rising over the long term due to thermal expansion and freshwater from melting glaciers and the Greenland and Antarctic ice sheets. In recent decades, the contribution from glaciers has become increasingly prominent: they account for around 25 mm to global mean sea level since the mid-1970s, out of a total rise of 73–146 mm between 1971 and 2018. For perspective, global glaciers have recorded an ice mass loss almost 20% larger than that of the Greenland ice sheet and double that of the Antarctic ice sheet since 2000.

Irreversible change is already locked in. Recent estimates suggest global glaciers could lose up to 39% of their mass, adding roughly 113 mm to global sea level in the long term, even without further warming. Should warming continue, that figure could climb to 230 mm. Although glacier melt is likely to remain significant in the near term, future rise is expected to be increasingly influenced by the melting of the large polar ice sheets in Greenland and Antarctica (Figure 2). By 2100, Greenland's ice sheet could add between 320 mm and 900 mm to sea level, while the Antarctic ice sheet melt could contribute anywhere between -78 mm and +300 mm.

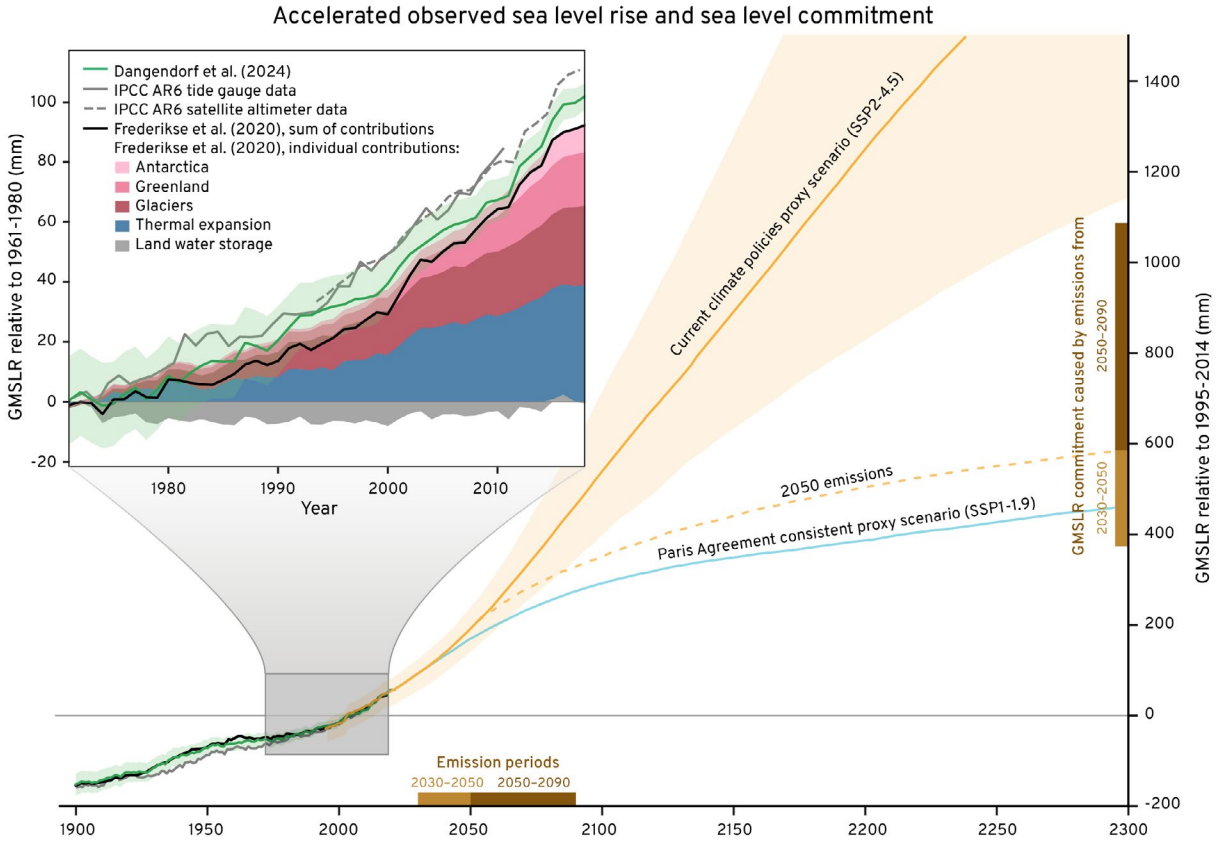


Figure 2. GMSLR and future sea level rise commitments. IPCC AR6 historical GMSLR data (dark grey, central estimate) and reconstructions[10]. GMSLR projections[11] under SSP2-4.5 as a current climate policy proxy scenario (solid orange, median and 66% model range) and the locked-in GMSLR commitments from corresponding SSP2-4.5 cumulative greenhouse gas emissions in 2050 (dashed orange, median); and median SSP1-1.9 projection as a proxy for a Paris Agreement-consistent scenario (solid light blue). All data are provided in mm relative to 1995–2014. Brown bars indicate illustrative 2030–2050 and 2050–2090 emission periods and the resulting GMSLR commitments by 2300.

Inset: Stacked sea level budget in mm relative to 1961–1980 based on Frederikse et al. (2020), showing individual contributions from thermal expansion (blue), glaciers (light red), Greenland (red), Antarctica (dark red), and land water storage (grey), as well as the sum of contributions (black line). Also shown are the Dangendorf et al. (2024) reconstruction (green, central estimate and 95% confidence range) and central estimates from IPCC AR6 tide gauge (solid dark grey line) and IPCC AR6 satellite altimeter records (dashed dark grey line).

Much of this uncertainty stems from how these dynamical processes unfold over centuries, as model choices and starting conditions can produce widely varying outcomes. Whether or not we hit tipping points in the unstable retreat of melting ice will have major implications, particularly for the Greenland and Antarctic ice sheets, which are both drained by ice streams prone to instability. But science is advancing. Recent modelling breakthroughs that better match today's observed mass changes have boosted confidence in ice-sheet projections and sharpened understanding of instability within parts of the land ice. Palaeoclimate evidence adds another layer: it suggests the marine sectors and margins of these ice sheets may already have crossed nonlinear or irreversible thresholds at warming levels close to today's, or may do so within this century. This has fuelled debate over whether some ice streams are already locked into, or fast approaching, large-scale, self-sustaining retreat.

It is clear that ice sheets and glaciers respond slowly to global warming. Therefore, crossing thresholds in cumulative greenhouse gas emissions locks in irreversible sea level rise for centuries to come. Greenhouse gas emissions in the coming decades can be linked to multi-century global and regional sea level rise through a recent modelling framework based on the Shared Socioeconomic Pathways (SSPs) assessed in the IPCC Sixth Assessment Report. Under a continuation of current climate policies (SSP2-4.5, Figure 2), emissions up to 2050 would lock in 300 mm of additional global mean sea level rise by 2300, on top of what historical emissions

10 Frederikse, T., et al. (2020). The causes of sea-level rise since 1900. *Nature*, 584(7821), 393–397. and Dangendorf, S., et al. (2024). Probabilistic reconstruction of sea-level changes and their causes since 1900. *Earth System Science Data*, 16(7), 3471–3494.

11 Nauels, A., et al. (2025). Multi-century global and regional sea-level rise commitments from cumulative greenhouse gas emissions in the coming decades. *Nature Climate Change*, 15(11), 1198–1204

to 2020 have already triggered. Extend that policy trajectory to 2090, and the commitment grows to 800 mm. Alternatively, switching to the stringent mitigation pathway consistent with the Paris Agreement (SSP1-1.9) could avoid around 600 mm of that 800 mm rise. Under a very high emissions scenario (SSP5-8.5), the model projects a likely Antarctic sea level rise contribution of 4,700 mm to 10,500 mm by 2300, including ice-shelf collapse.

The prospect of these locked-in changes underlines the urgency of near-term mitigation and the need to better understand future sea level response. It also highlights why limiting peak warming matters and why relying on uncertain future cooling of global temperatures is risky. Even if global temperature rise could be reversed, long-term sea level rise cannot be undone on human timescales, making effective adaptation essential for impacts that are now unavoidable. Assessing coastal vulnerability means going beyond the global average; it requires accounting for regional variation in sea level rise and using accurate estimates of coastal land elevation. Recent studies suggest coastal populations' exposure has been consistently underestimated. For highly vulnerable countries such as Small Island Developing States, effective adaptation planning grounded in precise physical risk data and local context is essential to reduce severe impacts on economic and social infrastructure, livelihoods, human health and security, affecting millions of people.

Above all, to slow sea level rise and avoid locked-in rises of several metres, sustained global reductions in greenhouse gas emissions must start immediately. A climate-resilient future requires a dual response: immediate mitigation paired with effective, equitable adaptation.

POLICY IMPLICATIONS

- **Emphasise long-term sea level commitments to accelerate implementation and mobilise higher ambition.** Parties should strengthen and implement their 2035 NDCs using multi-century sea-level assessments to communicate the consequences of delayed emissions cuts, and increasing risks of irreversible changes (see Insight 4). The Ambition on Melting Ice coalition, a 25-nation ministerial-level group, could spearhead this message through a joint COP31 ministerial statement and coordinated engagement with the COP Presidencies.

- **Embed dynamic adaptation pathways in NDCs.** Implement near-term measures, preserve future options, and monitor agreed indicators that trigger action before existing measures become inadequate. Planners should combine local sea-level projections, elevation and land-motion data, and stress-test long-lived infrastructure against plausible high-end scenarios. Adaptation plans for areas vulnerable to sea level rise should use the best available regional projections to guide near-term preparedness, land-use planning and relocation planning.

- **Deliver loss-and-damage finance for slow-onset sea-level impacts.** Increasing resources for the FRLD and support for its first replenishment process, starting in 2027, are critical. The Board and Secretariat of the FRLD should work towards ensuring that application and assessment procedures accommodate slow-onset impacts, including permanent land loss, loss of livelihoods and non-economic losses. Governments of vulnerable Small Island Developing States and delta countries should develop country-led requests with affected communities, including support for safe, dignified mobility where needed.

- **Strengthen coastal observations and warnings where capacity is weakest.** Governments and space agencies should sustain tide-gauge, satellite, and vertical-land-motion monitoring, prioritising countries with limited observational capacity and supporting the Global Sea Level Observing System. Observing agencies should share quality-controlled records consistent with Global Climate Observing System requirements.

3 Water gaps widen as continental drying accelerates

KEY MESSAGES

- Climate change and human freshwater use are driving massive, accelerating water losses across all landmasses (excluding Greenland and Antarctica), a phenomenon known as continental drying.
- Groundwater loss is currently a critical contributor to global sea level rise. In the past decade, these continental water losses have contributed more freshwater to sea level rise than either the Antarctic or the Greenland ice sheets individually.
- The world is experiencing a fundamental shift in hydrological regimes, where entire regions are transitioning into persistent deficit states driven by intensified evapotranspiration, rising human water consumption, and water resource mismanagement.
- Multi-year droughts (MYDs) are increasing in both frequency and intensity. Unlike seasonal droughts, multi-year droughts create an ecological "debt": soil moisture and groundwater reserves go unreplenished across successive seasons, escalating threats to forest health, aquatic biodiversity, and food security.

Roughly three-quarters of the global population lives in the 101 countries that have been losing freshwater since 2002. Within continents, water is disappearing from snow, ice, surface water, soil moisture, and groundwater, with much of it ultimately ending up in the oceans. As a result, this reduction in total water storage (TWS) threatens water availability and ecosystem resilience while also contributing directly to sea level rise.

Climate change and direct human activity are driving these massive water losses. Rising temperatures, melting ice, permafrost thaw, and a growing reliance on non-renewable groundwater reserves are all contributing factors (see Insight 5, 2025/2026 edition). New research is shedding light on the mechanisms driving continental drying and pointing to solutions that could mitigate and reverse the trend.

Groundwater loss now contributes roughly as much to sea level rise as melting glaciers and ice caps, accounting for 68% of non-glacier TWS loss. Since 2012, these combined continental losses have contributed more freshwater to sea level rise than the Antarctic ice sheet, and since 2015, roughly as much as, and in most years more than, the Greenland ice sheet. This trend compounds the risk of sea level rise already posed by ice sheet loss alongside thermal expansion and salinity changes (see Insight 2).

Changes are being revealed by NASA's GRACE and GRACE-FO satellite missions, which track how much water is stored on land by detecting tiny changes in Earth's gravity caused by shifting water mass. Two decades of data (April 2002–April 2024) show that the continents (excluding Greenland and Antarctica) are drying at an unprecedented rate. A decade ago, the evidence suggested that high- and low-latitude wet areas were getting wetter, while mid-latitude dry areas were getting drier. New findings overturn part of that picture: only the tropics are still getting wetter. The rapidly warming high latitudes are now losing water, as snow and ice melt and permafrost thaws, resulting in "mega-drying" regions across boreal Canada and Russia (Figure 3).

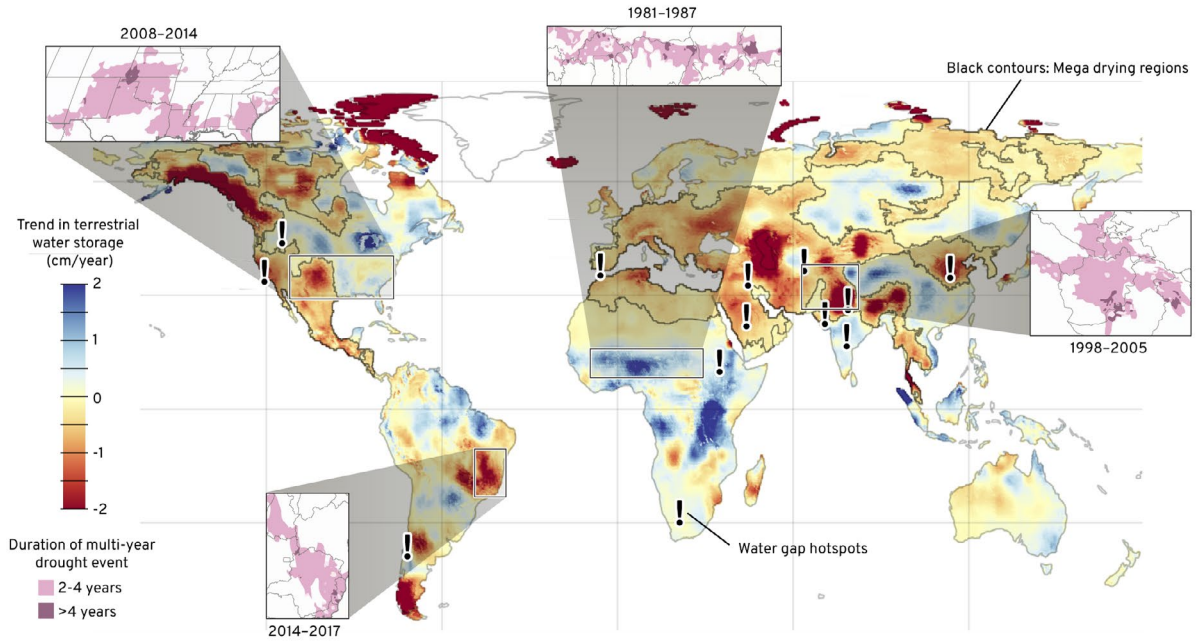


Figure 3. Regional patterns of water depletion from climate change. Red and blue shading shows long-term (2004–2024) TWS trends from GRACE and from human water consumption,[12] resulting in water gaps. Pink symbols indicate modelled water gaps for 2001–2010, where consumption exceeds renewable water availability. Water gaps can occur in regions of long-term drying, but in some instances also in wetting regions, driven by high consumption. Of the top MYD events from 1980–2018, some occurred in regions of long-term drying, and some in regions that are overall getting wetter. These selected examples highlight the complex nexus of climate change, human activity, and water security, with water depletion (and its opposite) resulting from both direct human influence and indirect climate effects, alongside natural variability.

Crucially, dry areas are now drying faster than wet areas are wetting, and the area of land shifting to a drying trend is expanding by roughly twice the size of California every year. As a result, two additional mega-drying regions are emerging, linking together previously distinct hotspots: southwestern North America and a vast Middle East–North Africa–Pan-Eurasia belt. Both are driven by aridification (rising potential evapotranspiration) and excessive groundwater pumping. Together, this drying and the rise in prolonged droughts amount to a hydrological regime change under global warming, one that is increasingly measurable through the concept of water gaps (Box 1).

Beyond this background drying trend, imbalances between rainfall and evaporative demand are also becoming more frequent and intense, fuelling more MYDs. A global inventory identified over 10,000 such droughts between 1980 and 2018, and found that the land area they affect has grown by 49.3 ± 14.8 thousand km^2 per year, an area larger than Switzerland or the Dominican Republic.

Unlike flash or seasonal droughts, which unfold quickly and end within months, MYDs create a lasting ecological debt: soil moisture and groundwater reserves struggle to recover across successive seasons under persistent drying and rising demand. The threats can escalate, leading to tree mortality (with effects varying by biome) and drought-driven loss of aquatic biodiversity. The impacts of prolonged droughts grow disproportionately compared to short-term droughts, increasing the risk of pushing

BOX 1. GLOBALLY, WATER GAPS ARE GROWING

A water gap is the mismatch between how much water people consume and how much is renewably and sustainably available: water that comes from a renewable source and still leaves enough for ecosystems to function. A recent global assessment found that human water consumption already exceeds sustainable availability by 458 km^3 a year, roughly equivalent to the total annual water withdrawals of the USA or India. This gap will not remain fixed: it will grow disproportionately with warming, increasing by around 6% at 1.5°C and 15% at 3°C, with strong regional variation. That nonlinear growth suggests some regions might transition into persistent deficit states driven by altered precipitation patterns, intensified evapotranspiration, and rising water consumption.

12 Chandanpurkar, H. A., et al. (2025). Unprecedented continental drying, shrinking freshwater availability, and increasing land contributions to sea level rise. *Science Advances*, 11(30), eadx0298.

Earth past planetary boundaries for climate, biosphere integrity, and biogeochemical flows.

These water gaps are tracked across major irrigation regions at decadal resolution. Multi-model analyses show that unsustainable irrigation, meaning irrigation that depletes groundwater and environmental flows, is already concentrated in South Asian hotspots including the Ganges, Sabarmati, and Indus, with further intensification projected there and across the US High Plains; the Nile Delta stands out for its high pressure per unit of irrigated land. This has cascading effects for agriculture, energy, ecosystems, and socio-economic and political stability within and across countries. Unlike traditional water-scarcity indicators, the water gap framework quantifies the volume of unsustainable use, revealing where adaptation needs are greatest and where mitigation is most urgently required.

These findings can translate directly into actionable solutions. Estimating water gaps helps decision-makers gauge the scale of intervention required. A portfolio of measures is needed: on the supply side, this includes potable water reuse, desalination, managed aquifer recharge, and enhanced storage; on the demand side, more efficient industrial and agricultural water use, and siting water-intensive activities where resources are more abundant. Managed aquifer recharge alone, capturing surplus floodwater and channelling it back underground, could offset 4–6% of unsustainable irrigation globally.

Tackling the issue of continental drying represents a critical nexus of climate change, human activity, and water security. Consequences of inaction extend from threats to local livelihoods to cascading impacts for planetary systems.

POLICY IMPLICATIONS

- **Monitor terrestrial water-storage decline and water gaps**. Parties should integrate terrestrial water storage trends (TWS) and basin- or aquifer-level supply–demand gaps into NAP monitoring, evaluation, and learning systems. These measures would complement the Belém Adaptation Indicators on water stress, water-use efficiency, and access, supporting implementation of the UAE Framework and advancement of the GGA. COP31's Global Climate Change Agenda (GCAA) could further catalyse action on water-availability risks through its Food Security and Clean Energy tracks.

- **Recognise slow-onset freshwater depletion within loss-and-damage institutions and responses.** The FRLD should operationalise support for economic and non-economic losses arising from climate-related groundwater decline, prolonged drought, freshwater salinisation, and associated ecosystem degradation. Support could cover assessment, response planning, rehabilitation where feasible, and irreversible or residual losses. The Santiago Network could provide technical assistance for hydrological monitoring, attribution-informed assessment, loss accounting, identification of adaptation limits, and funding-proposal preparation.

- **Elevate awareness about climate-related transboundary water risks.** As the impacts of climate change on freshwater resources become more acute, historical allocation rules may become increasingly unreliable. Advancing on the SDG indicator 6.5.2 and in accordance with the UAE Framework's recognition of climate-informed transboundary management, neighbouring governments should collaborate through basin organisations, to strengthen joint monitoring, adaptable allocation and withdrawal rules, environmental-flow protections, and coordinated drought planning. The UN Water Convention provides a general framework, and the UNESCO Intergovernmental Hydrological Programme and the International Groundwater Resources Assessment Centre can provide technical support.

- **Build strategic drought reserves and prepare demand management plans for prolonged drought.** When conditions are suitable, water authorities should consider investing in managed aquifer recharge systems that capture suitable wet-period flows or treated wastewater for underground storage and recovery during prolonged drought. These can be coupled with staged drought-management plans that trigger restrictions, reallocation, and conservation measures as water availability declines, protecting essential human needs and environmental flows.

4 A larger overshoot of 1.5°C forces greater reliance on CO2 removals and narrows adaptation options

KEY MESSAGES

- Even if global warming were successfully returned to 1.5°C, some physical impacts are likely irreversible, particularly in slow-responding systems such as the ocean, glaciers, and permafrost.
- The feasibility and effectiveness of adaptation measures decline as the magnitude of exceedance and duration of an overshoot increase, with hard and soft adaptation limits increasingly being reached.
- Limiting the magnitude of overshoot requires a rapid acceleration of mitigation efforts, retaining the goal of reaching at least net-zero CO_2 emissions globally by mid-century. Limiting the duration of overshoot will require a combination of mitigation strategies, including greatly scaling up CDR which entails trade-offs with biodiversity, food security, energy, and water.

According to the latest science, limiting end-of-century warming to 1.5°C will require a temporary overshoot before temperatures are brought back down. But heating the Earth is not like changing the thermostat in a house, where conditions soon return to their previous state. It is closer to heat exhaustion tipping into heatstroke: once the body's core temperature crosses a critical threshold, cells and organs can be severely damaged – and cooling back down does not undo that harm. Beyond 1.5°C, components of the Earth system may enter fundamentally new states, and extra energy in the system could exacerbate climate risks even as temperatures dip. As we approach the impending transgression of 1.5°C, it is critical to understand the consequences of temperature overshoot and to keep it as small and short-lasting as possible (Figure 4A).

Human-induced global warming reached 1.37°C in 2025, and at the current rate, we will pass 1.5°C around 2030. Returning to 1.5°C will require more than achieving global net-zero CO_2. It will require an increasing number of countries to set quantitative net-negative greenhouse gas emission targets beyond 2050 (Figure 4B), alongside policies capable of delivering such outcomes. At the same time, beyond 1.5°C, adaptation needs will further increase and, in some cases, become impossible to meet. Adaptation limits will be reached and losses and damages will accumulate.

Irreversibility is particularly likely in slow-responding components of the climate system, such as the ocean, glaciers, permafrost, and ice sheets. Sea level rise is a clear example. Thermal expansion and glacial retreat drive a rise that persists for centuries, even after surface temperatures decrease and stabilise following overshoot. The magnitude and duration of the overshoot determine the severity of these lasting changes, which ripple out into coastal flood damage, agricultural losses from saltwater intrusion, and lost cultural heritage.

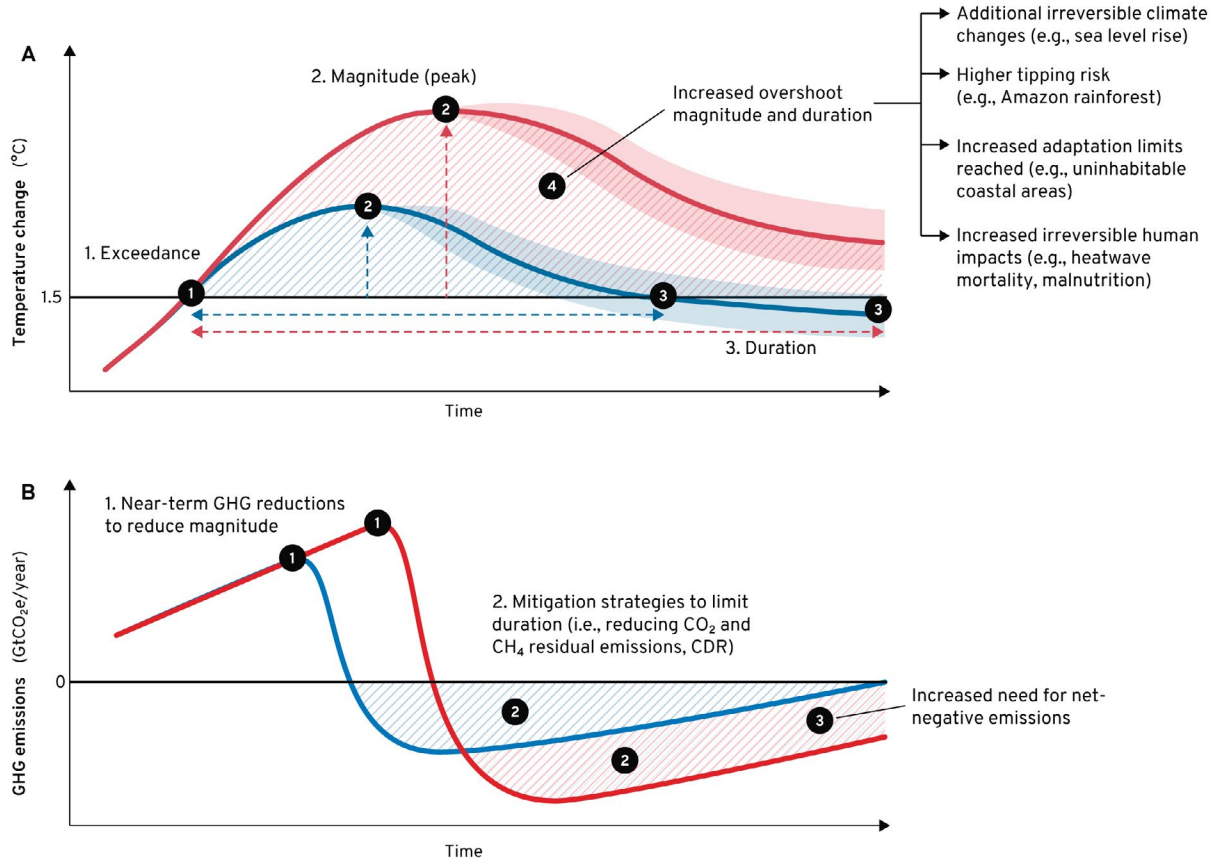


Figure 4. Conceptual pathways, risks, and mitigation implications of overshooting and returning to 1.5°C. Panel A. Point 1 marks the initial exceedance of 1.5°C, Point 2 indicates the peak warming magnitude above 1.5°C, and Point 3 marks the duration of time spent above the 1.5°C threshold. The red pathway shows a greater overshoot magnitude and a longer duration (Point 4) than the blue pathway, which results in additional environmental and human impacts. Panel B. The panel shows the corresponding global greenhouse gas emissions pathways for the two overshoot pathways. Point 1 highlights that stronger near-term greenhouse gas emissions reductions can reduce overshoot magnitude. Point 2 exhibits mitigation strategies that can shorten overshoot duration after the peak. Point 3 indicates that pathways with larger and longer overshoot imply a greater need for sustained net-negative emissions.

BOX 2. OVERSHOOT LEGACIES AND TIPPING POINTS

Temporarily exceeding critical thresholds can produce lasting impacts that persist beyond the overshoot period. Ecological systems are also vulnerable to overshoot legacies. In a warmer Arctic, ice loss and permafrost thaw can intensify even after global temperatures decline, causing irreversible consequences for ecosystem integrity. Ecological tipping point risks increase with overshoot magnitude and duration, with coral reefs and Amazon forests particularly vulnerable to interacting pressures.

A rise in heat-related mortality is the starkest irreversible human impact. Repeated droughts and other forms of extreme weather are likely to weaken food security, leading to malnutrition, which in turn results in multigenerational effects on health, human development, and income. Meanwhile, continuing sea level rise will force more permanent retreats from coastal areas. A world that returns to 1.5°C after decades spent above it will bear more human and environmental damage than one that never crossed the threshold.

Even when global averages appear to show recovery, they may still mask regional legacies that affect people and ecosystems (Box 2). For instance, exceeding and then reversing 1.5°C generally enhances high-latitude warming and suppresses low-latitude warming, and these regional patterns will reverse more slowly than the global average. In the Arctic, this dynamic could feed a vicious cycle, intensifying further ice loss and permafrost thaw, even after global temperatures start to decline. Globally, climate-related risks to biodiversity can outlast peak warming, potentially affecting livelihoods and economic activities for decades, e.g., through reductions in fish stocks.

The response should be science-backed adaptation that accounts for long-term climate risks, especially for long-lived infrastructure. In practice, this means planning for potential peak warming levels rather than the eventual 1.5°C stabilisation goal, since building for peak conditions proves more cost-efficient, particularly for nature-based solutions and early-warning measures. We need flexible designs that can adapt as risks evolve.

Take sea level rise as an example, since the already-committed rise is irreversible on human timescales. Costly measures such as seawalls, dikes, and levees can reduce risks over long timescales, but as sea levels keep rising, during overshoot and even after a return to 1.5°C, adaptation limits – points at which risks become intolerable – will increasingly be reached. Once limits are reached, protective measures cease to work, coastal areas become uninhabitable, and livelihoods are lost. These knock-on effects can compound across sectors, ecosystems, and communities, deepening vulnerability and disproportionately affecting those least prepared to cope. Exceeding 1.5°C will also make the relationship between warming and its impacts less predictable, bringing unforeseen additional challenges. The reality is that adaptation will become increasingly difficult and can only be effective up to a point.

So, how can we effectively reduce temperatures once the 1.5°C limit is exceeded? Doing so requires three mitigation strategies working together:

1. Further reducing residual CO_2 emissions;
2. Further upscaling CDR beyond what is required for net zero;
3. Cutting residual methane emissions.

Each measure carries substantial challenges. One widely modelled CDR method, bioenergy with carbon capture and storage (BECCS), illustrates why: it involves growing crops or trees, burning them for electricity, then capturing and burying the resulting CO_2 underground. Deploying BECCS at scale means converting vast areas to bioenergy crops, raising sustainability challenges linked with freshwater use, biodiversity, and competition for land used for food production. Assuming the easier-to-abate methane sources from fossil fuel extraction and use are addressed by mid-century, further methane cuts will require reducing emissions from livestock, which would entail dietary changes and may affect rural livelihoods.

Crucially, if peak warming exceeds 1.8°C, a return to 1.5°C by 2100 may no longer be achievable. This would force greater reliance on CDR and heighten the risks that come with it. Given these challenges, the further we edge past 1.5°C, the greater the risk of irreversible damage and sustained, long-term elevated temperatures. Policies and frameworks that can achieve and sustain net-negative emissions within a just transition will take time and sustained political will. Therefore, understanding overshoot legacies, reversal requirements, and adaptation needs is essential to shaping these long-term, science-based strategies. Because of these deep uncertainties and challenges, rapid and deep emissions reductions remain the most urgent priority.

POLICY IMPLICATIONS

- **Align climate targets with the full overshoot–peak–decline pathway.** GST2 should assess whether collective emissions pathways are sufficient to limit peak warming and enable a return towards 1.5°C. Parties should strengthen successive NDCs for rapid, economy-wide greenhouse-gas reductions, align long-term strategies with global net-zero CO_2 around mid-century, and adopt post-net-zero targets that contribute to sustained global net-negative emissions. To operationalise these targets, Parties should report gross emissions, residual emissions, and gross removals separately, with quantified milestones and timelines. This transparency would expose excessive reliance on removals and clarify whether national pathways collectively limit the magnitude and duration of overshoot.

- **Limit overshoot through immediate emissions cuts and planning beyond net zero.** Parties should combine deep cuts in *gross* emissions, including a rapid transition away from fossil fuels and deep methane reductions with quantified targets and timelines. These measures are essential for limiting peak warming. To shorten overshoot, long-term strategies should extend beyond net zero, specifying further reductions in residual emissions, CDR deployment, and contributions to sustained global net-negative emissions. CDR cannot justify delaying deep decarbonisation; given its costs and environmental and social trade-offs, it should counterbalance hard-to-abate residual emissions and contribute to subsequent atmospheric carbon drawdown, not substitute for stringent emissions reductions. Financial resources should therefore be redirected from new fossil-fuel and emissions-intensive infrastructure to low-emission alternatives, avoiding further carbon lock-in.

- **Establish coordination mechanisms tailored to the risks and limits of different CDR methods.** GST2 should assess CDR's collective role in post-net-zero pathways, including feasible and sustainable deployment ranges, mitigation-deterrence risks, equity, and support needs. For removals credited under the Paris Agreement Crediting Mechanism, the Article 6.4 Supervisory Body should continue reviewing methodologies and safeguards covering quantification, additionality, leakage, storage durability, and reversals. Parties should establish compatible national frameworks for all CDR counted towards NDCs and long-term strategies, separately reporting emissions and removals and addressing lifecycle emissions, monitoring, leakage, durability, reversals, liability, and grievance procedures. These frameworks should reflect method-specific risks and safeguard for social and environmental trade-offs.

- **Plan adaptation for peak warming and address unavoidable loss and damage.** National and subnational governments should use NAPs, infrastructure standards, and investment appraisals to stress-test long-lived assets against plausible peak-warming scenarios and persistent impacts, rather than assuming that returning to 1.5°C reverses risks. Authorities should prioritise anticipatory investment and use adaptive pathways, monitored decision triggers, and flexible designs, pursuing transformational responses where incremental measures approach their limits. Through the GGA, Parties should track progress under different warming scenarios. At COP31, Parties should strengthen finance, technical assistance, and accessible support through existing loss and damage arrangements for impacts that adaptation cannot prevent.

5 Bundled interventions can transform food systems for health and planetary stability

KEY MESSAGES

- Food systems are the central nexus connecting human health, Earth system processes, and social justice. Generating roughly 30% of human-driven greenhouse gas emissions, food systems are the leading driver of multiple planetary boundary transgressions. Transforming how food is produced and consumed is essential to achieving climate resilience, biodiversity protection, and fair livelihoods.
- Dietary change is the most decisive demand-side lever for transformation. Shifting demand away from resource-intensive animal sources towards more plant-rich diets reduces pressure on land and emissions, creating critical "option space" that makes supply-chain climate targets feasible, while simultaneously improving health outcomes.
- Bundling demand- and supply-side policy interventions can avert 182 million life-years lost annually by 2050, halve global nitrogen surpluses, and deliver a net social welfare gain equivalent to 7% of global gross domestic product (GDP).
- An anticipated side effect of these transformations is a likely acceleration of the ongoing decline in agricultural labour demand. Hence, forward-looking strategies for a just transition are essential to minimise social and economic disruption.

Transforming how food is produced and consumed offers a unique opportunity to address multiple global challenges at once. Food systems sit at the nexus of climate, environment, health, and social justice. Recent conflicts, extreme weather, and COVID-19 have revealed weaknesses in global food supply chains. A deep transformation could tackle this nexus of challenges together, while new insights are helping to identify and evaluate pathways towards a more sustainable future.

Food systems encompass production, processing, packaging, transportation, cooking, consumption, and disposal, as well as the actors involved at every stage. These activities sit at the heart of the Sustainable Development Goals and other socio-economic and environmental targets. Changes to the food system are essential for stronger food security, improved nutrition and health, environmental sustainability, climate resilience, and fairer livelihoods.

In its current state, the global food system is a major driver of climate change, accounting for around 30% of all human-caused greenhouse gas emissions when transport and energy use across the food chain are included. Food systems have also breached several "Planetary Boundaries", which mark the safe limits within which humanity can operate without destabilising the systems that keep the planet habitable. They are the leading cause of transgression for land-system change, biosphere

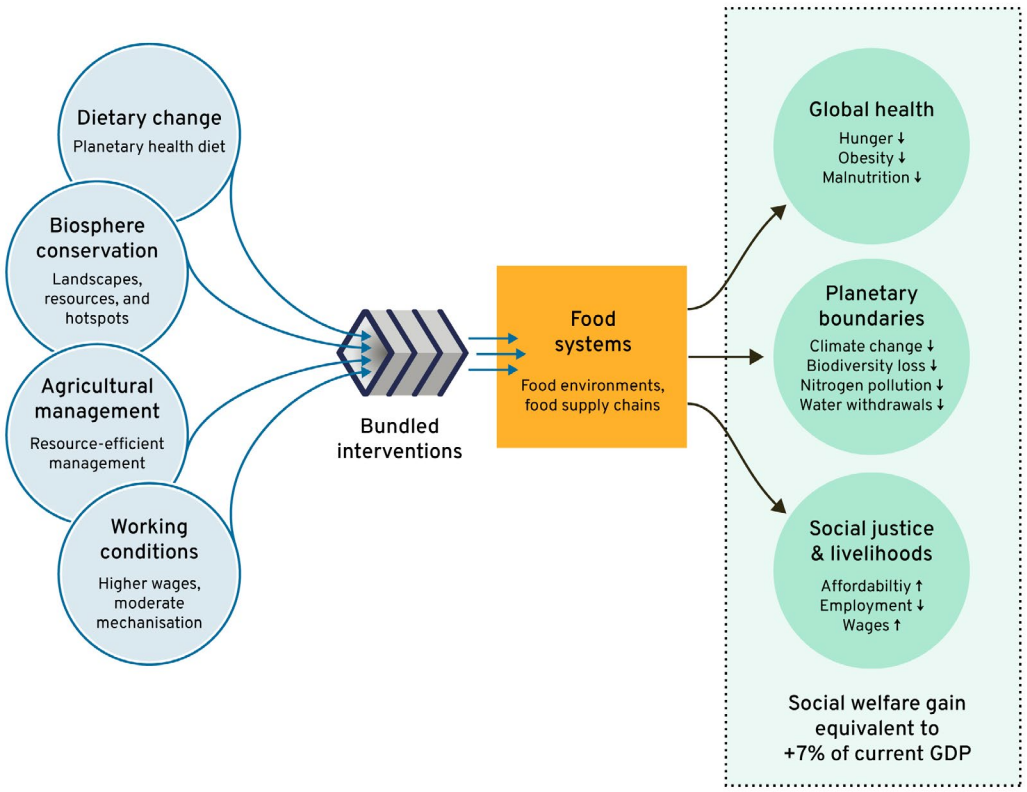


Figure 5. Bundled interventions for food systems transformation. Conceptual pathway linking diverse policy objectives with co-benefits in human health, planetary boundaries, and socioeconomic well-being, via bundled interventions for food systems transformation.

integrity, biogeochemical flows, freshwater change, and novel entities such as unsafe use of pesticides and antimicrobials, pushing societies further from a safe and just operating space.

Dietary change has been identified as one of the most powerful levers to ease pressure on these natural systems. The EAT-Lancet Commission's reports, backed by multi-model analyses, define the "Planetary Health Diet" as the scientific basis for transforming food systems, with far-reaching multiplier benefits for health, nutrition, and climate mitigation (Figure 5). Cutting back on resource-intensive animal-source foods and reducing food waste would cut demand more than enough to offset the extra production needed to tackle malnutrition elsewhere. These shifts, paired with supportive supply-side policies, could bring environmental benefits and help stabilise agricultural prices, while opening an "option space" that makes ambitious climate targets far more achievable.

Crucially, any global diet recommendations should remain flexible enough to adapt to the cultures and preferences of population groups within countries. Social and justice dimensions of food systems are also important: rights to a healthy environment (including the food environment people live in), to nutritious food, and to decent work through fair wages and transparent employment opportunities. Many populations are still denied these rights, and researchers are starting to quantify these gaps and explore pathways to a fairer transition. Encouragingly, global modelling shows that healthy, sustainable diets are already affordable at the food group level in most high-income countries, with plausible pathways to affordability in low-income countries as well. However, affordability is only one aspect of genuine access, alongside other factors such as education and proximity to fresh food options.

To tackle the full nexus of food-related challenges, new insights can help prioritise and bundle measures more efficiently to quantify co-benefits such as biodiversity protection, nutrition, or social justice. For instance, recent methods and tools show that demand-side changes tend to bring benefits across many goals simultaneously, whereas supply-side measures that work well for one goal often carry trade-offs for others.

Looking ahead, food system pathways should aim to advance several goals at once, combining measures such as more diverse landscapes to

support biodiversity, higher fruit and vegetable consumption to improve nutrition, and higher agricultural wages to advance social justice. One global food-and-land system model identified 23 measures that could deeply transform the food system, with major benefits for health, environment, and inclusion. Individually, many of the measures involved trade-offs, but combined, they were projected to cut diet-related mortality by around 182 million life-years per year by 2050 (Box 3). They would also nearly halve global nitrogen surpluses and offset the poverty-increasing side effects that strong environmental protection can otherwise cause. A related analysis put the net welfare gains from such measures at the equivalent of 7% of global GDP.

Multi-model ensembles can now assess a wider range of measures and outcomes at once. They show that a shift to plant-based diets would substantially reduce demand for agricultural labour, particularly in livestock-producing regions, underscoring the need for structural change and income diversification strategies to support a just transition. Given the vast amounts of data and computing power required by these food system models, researchers have begun using "emulators": tools that apply mechanistic or deep-learning methods to existing model results. This development integrates narrower studies into a broader nexus view and broadens the opportunity to explore the decision space.

Despite advances, current models still hit limits when trying to achieve multiple nexus goals at once. The boundaries for nitrogen and for climate mitigation without overshoot look particularly hard to meet. Today's models also rely on very optimistic assumptions about early, globally coordinated policy action and efficient implementation by governments and the private sector. To better assess the feasibility of proposed transformation pathways, models must better reflect political economy realities, incorporating concrete socio-political barriers, such as corporate lobbying and market concentration, short-term electoral cycles, public resistance to food price increases, and labour displacement. Incorporating power dynamics, stakeholder agency, and regional policy trade-offs should result in more grounded simulations of alternative transformations, including their feasibility and uncertainty.

BOX 3. REGIONALLY DOWNSCALED FOOD SYSTEM TRANSFORMATION: CHINA AND INDIA

- In India, combining food system transformations with measures to improve education and incomes could reduce poverty and inequality and avert 50 million years of premature death by 2050 (reducing annual "years of life lost" from 72 million under business-as-usual to 22 million under a sustainable development pathway). However, as these food system transformations and broader socio-economic gains also accelerate the adoption of capital-intensive agricultural technologies, a steeper decline in agricultural employment is also expected: from 185 million in 2020 to 65 million in 2050, compared to 96 million under a business-as-usual scenario.

- Similarly, in China, a multi-sectoral food system transformation could cut diet-related premature mortality by 81% by 2050 (reducing annual "years of life lost" from 43 million under business-as-usual to 8 million and avoiding a 1.6% loss of projected GDP) while reducing the population living below USD 3.65 per day (purchasing power parity) by 90% relative to the 2050 baseline, down to 1 million people. Once again, the effects on labour are likely to be significant: a steeper structural decline in primary agricultural employment from 140 million in 2020 down to 32 million in 2050, compared to 47 million under a business-as-usual baseline (though an expanding bioenergy sector is projected to generate 5 million new jobs that could help absorb displaced workers).

POLICY IMPLICATIONS

- **Agriculture work at the UNFCCC should have an implementation and support mechanism.** Parties could extend the Sharm el-Sheikh joint work through a time-bound implementation roadmap that assigns deliverables to relevant UNFCCC bodies and financial institutions. They should strengthen its online portal as a country-led pipeline for matching implementation needs with finance, technology and capacity-building support, and report on support mobilised and actions implemented.

- **Include demand-side measures in national climate plans.** National governments, especially for countries with high-impact consumption patterns, should provide incentives to shift towards healthier and more sustainable diets, and incorporate this strategy in NDC implementation plans, long-term strategies, and associated sectoral policies. In practice, responsible ministries can set measurable targets and align public procurement, dietary guidelines, consumer information, waste regulation, and incentives across health, agriculture, and environment portfolios. These measures can reduce GHG emissions and pressure on land while supporting public health and making supply-side mitigation more feasible.

- **Bundle measures to manage trade-offs.** Coordinated policy packages combining dietary and food-waste measures, low-emission production, methane and nutrient management, ecosystem protection, and targeted social protection should be prioritised for maximising co-benefits and minimising trade-offs. While there may be a faster decline in agricultural labour demand as a result of less animal-intensive food systems, it is important to note that the underlying declining trend reflects broader structural change, technological developments, and changing production patterns. Hence, managing this requires similarly broad measures.

- **Finance just transitions for affected rural workers.** The UAE Just Transition Work Programme and the new Belém just transition mechanism explicitly cover transitions in agriculture and food systems, not only energy. National governments should identify exposed workers, producers, and regions through participatory transition planning and integrate corresponding measures into climate and development plans. Governments, climate funds, and multilateral development banks (MDBs) should then mobilise grants and concessional finance for income protection, skills development, rural economic diversification, and smallholder adaptation.

6 The social cost of carbon has been severely underestimated

KEY MESSAGES

- The social cost of carbon (SCC) has been significantly underestimated in widely used climate-economy models. Integrating state-of-the-art Earth system models yields estimates up to four times higher.
- Specifically, incorporating ocean-based systems, including marine ecosystems, fisheries, and marine infrastructure, nearly doubles the SCC compared to estimates that exclude them. Similarly, accounting for additional urban heat island effects can more than double the global SCC.
- New models linking GDP growth to weather variability and global mean temperature project substantially higher future economic losses, implying greater macroeconomic sensitivity than previously estimated.

What does an additional tonne of carbon dioxide really cost the world? Economists rely on a key metric, the SCC, which influences everything from national carbon prices to the economic case for climate action itself (Box 4). New research indicates that conventional approaches to calculating the SCC may significantly underestimate true costs, often because they oversimplify how a warming planet damages economies and ecosystems over the long term. The more we understand about the myriad connections between the physical, ecological, and economic worlds, the more our estimates of the true cost of carbon keep climbing (Figure 6). A more complete picture of the SCC can inform decisions about mitigation versus adaptation and guide climate investments that deliver the greatest long-term return.

In practice, climate damage estimates draw on a spectrum of approaches. At one end are structural models, which simulate how climate change would ripple through markets and the wider economy. At the other end are more empirical approaches, increasingly common in the literature, where researchers look directly at historical data to see how past weather, including extreme events and year-to-year variability, has affected economic outcomes, and then use those statistical relationships to project future damages. These estimates feed into integrated assessment models, which link today's emissions to future climate change, economic impacts, and ultimately, the SCC itself.

BOX 4. DEFINING THE SOCIAL COST OF CARBON

The SCC measures the economic cost to society of emitting one additional tonne of CO_2. It is typically expressed as the net present value of the total climate damage that tonne will cause over time. These damages include external costs borne by society, such as impacts on property, health, agricultural and labour productivity, the environment, and the broader economy. The SCC matters for climate policy because it allows the benefits of emissions reductions to be compared with the costs of regulation or mitigation.

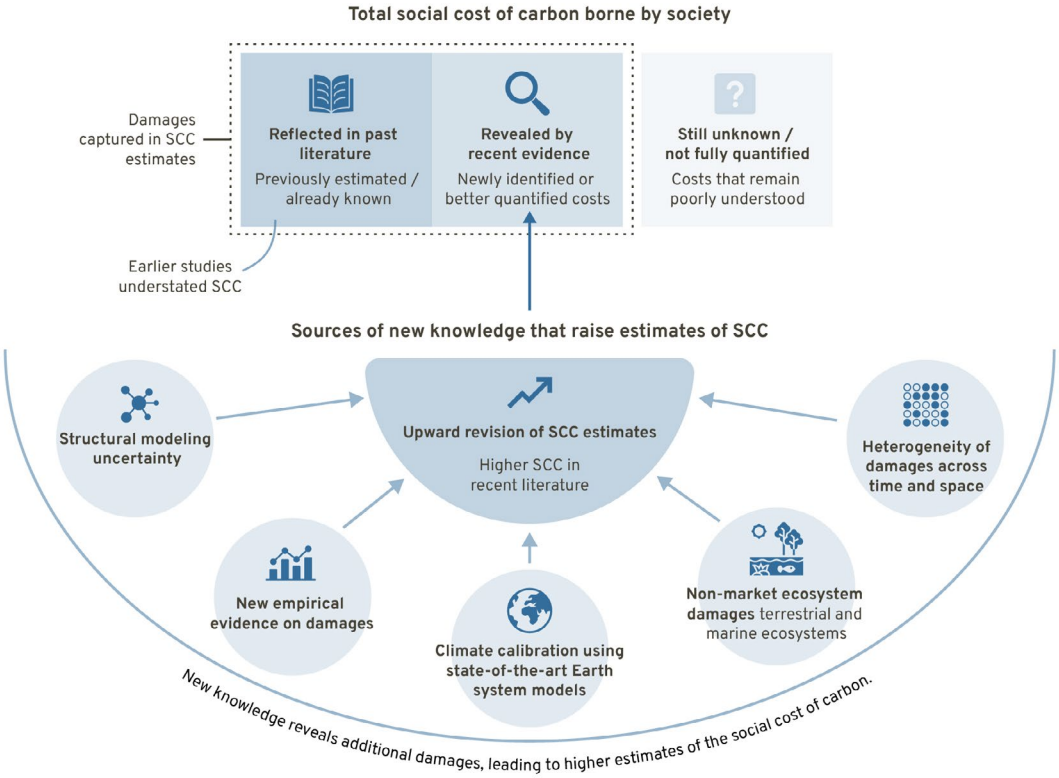


Figure 6. Methodological advances and improved evidence reveal higher SCC. New empirical evidence on climate damages, improved climate calibration, better treatment of structural uncertainty, and broader valuation of non-market, spatial and temporal impacts support upward revisions to the SCC.

When recent insights are incorporated into these models, estimated climate damages increase markedly. One key finding is that including global average temperature, not just local weather, in these statistical models leads to much higher projected GDP losses. The effect is substantial. Research shows projected economic losses under high-warming scenarios by 2100 jumped from around 11% to around 40% of GDP on average. According to this model, the cost of further mitigation would outweigh the damage it prevents at anything above 1.7°C, which is in line with the Paris Agreement targets. Separate research points to something equally striking. Using more realistic, up-to-date climate models, rather than the simplified versions built into most economic models, can change the SCC by up to four times over. The choice of climate model, therefore, matters just as much as the choice of economic model.

Climate impacts on ecosystems that do not carry an immediate price tag are also increasingly factored in. Accounting for the benefits provided by marine ecosystems, fisheries and maritime infrastructure, collectively known as ocean-based welfare, nearly doubles the SCC relative to estimates that leave these sectors out. Cities are also affected. Surfaces like concrete and asphalt can trap heat, pushing up cooling costs, reducing productivity in hot conditions, and straining public health systems. Once this urban heat island effect is factored into economic assessments in addition to global warming, the estimated damage per tonne of CO_2 rises from USD 187 to USD 490. In everyday terms, this means the economic loss from burning a single litre of petrol increases from USD 0.44 to USD 1.14. As urban populations continue to grow, cities are set to bear the brunt: they are projected to account for 78–93% of all global climate-related damages.

Recent country-level work tells a similar story. One major modelling effort, covering more than 50 regions worldwide (RICE50+), puts the 2025 global SCC at about USD 194 per tonne of CO_2, assuming the world follows an efficient, well-coordinated climate policy. Under the business-as-usual scenario, that figure jumps to about USD 437 per tonne. These figures are not directly comparable, but they indicate the scale of the risk. Of course, this does not mean that mitigation is free, but it does mean that money spent cutting emissions now would avoid far larger damages later if warming goes unchecked. That conclusion is reinforced by separate research showing that much of the disagreement between SCC estimates comes down to how the models are built, not just the data behind them.

It is also important to understand how damages are distributed across time, place, and sector. A single global figure can mask real differences in exposure and vulnerability, which matters for how the SCC is used in policy and investment decisions. Future damages caused by past emissions are estimated to be an order of magnitude larger than the damages those emissions have caused so far. This strengthens the case for updating carbon-price benchmarks, while underlining that national valuations can inform domestic policy but cannot substitute for coordinated international action. Climate stability is a shared global good.

Taken together, the evidence points to sobering findings. Emerging research that links human and natural systems more closely shows that the SCC is greater than we thought (Figure 6). Models that capture interconnections between economic and climate systems project far worse GDP damages at moderate to high warming, while models that truly account for uncertainty find that every extra tonne of CO_2 carries additional risk. As understanding of the SCC continues to grow, so should the ambition and urgency of decarbonisation.

POLICY IMPLICATIONS

- **Higher SCC estimates strengthen the economic case for earlier and deeper emissions reductions** by showing that conventional assessments omit or understate important damages. This is crucially important during the information-gathering phase of the GST2, which begins now. The 2035 NDCs should translate into funded sectoral implementation plans, and ambition should reflect a more robust understanding of the damages associated with additional GHG emissions and further global warming. Under Article 6, participating Parties should separately ensure environmental integrity and avoid prices that discourage higher-cost mitigation.

- **Update carbon values for other public decisions.** This includes those used by national governments and MDBs, which should reflect updated understanding of the "shadow carbon values". This is significant for regulatory assessments, budgets, procurement and infrastructure appraisal. Methodologies should account for global and intergenerational damages, spatial inequalities, non-market impacts and uncertainty, rather than relying on a single central estimate.

- **Scale climate finance using updated damage evidence.** Parties, developed-country contributors, MDBs and climate funds should use updated evidence on climate damages to strengthen the case for more grant-based, concessional and non-debt-creating finance. This evidence should inform implementation of the Baku-to-Belém Roadmap, including efforts to scale finance for developing countries towards the aspirational figure of USD 1.3 trillion annually by 2035. The Board and contributors to the FFRLD should also consider updated damage evidence when assessing needs and preparing the Fund's first replenishment, starting in 2027.

7 Advances in attribution science demonstrate individual emitters' climate impacts

KEY MESSAGES

- Attribution science has evolved enough to map the causal chain from emissions and emitters to the socio-economic impacts of weather events caused by climate change. This makes it possible to isolate specific harms resulting from the emissions of specific actors.
- These advances show that the emissions of "Carbon Majors" – large fossil fuel and cement producers – can be linked to ~50% of the increase in global heatwave intensity since the pre-industrial era. These emissions have already locked in substantial future impacts from climate change, such as sea level rise.
- Zooming in on the emissions arising from the consumption and investments of the wealthiest 10% shows they contributed seven times more to extreme heat than the average individual. However, the impacts disproportionately fall on low-income tropical regions.

Climate change attribution science has come a long way since it emerged as a distinct field in the 1990s. Today, it rests on three pillars. First, source attribution links past and present greenhouse gas emissions to changes in current and projected climate (Figure 7). It is, therefore, now understood that every tonne of CO_2 has a climate impact. Second, impact attribution bridges those physical changes to socio-economic outcomes, such as heat-related deaths or lost economic output. The third and most ambitious pillar, end-to-end attribution, brings these approaches together to trace a specific harm back to a specific actor's emissions (Box 5). This Insight highlights scientific advances that connect the full causal chain from emissions to impacts.

Research has shown that direct (Scope 1) and value-chain (Scope 3) emissions from large fossil fuel and cement producers, or "Carbon Majors", caused 24–37% of sea level rise to date, based on their activities between 1854 and 2020. Researchers have also calculated the intensity and probability of hundreds of historical extreme heat events with and without the emissions of Carbon Majors, finding these producers collectively responsible for around 50% of the increase in heatwave intensity since the industrial era (1850–1900). In fact, each Carbon Major has enough emissions to enable heatwaves that would have been virtually impossible without climate change.

Connecting physical hazards to impact models (Figure 7C, D) shows how changes in human health and economic outcomes can be attributed to climate change. A survey of 20 recent health studies found tens of thousands of deaths a year already attributed to climate change, despite covering only a limited range of health impacts. One study attributed to climate change 1,700 heat-related deaths in Zurich since 1969. Another found climate change directly caused around 6,000 deaths during the August 2003 heatwave in France.

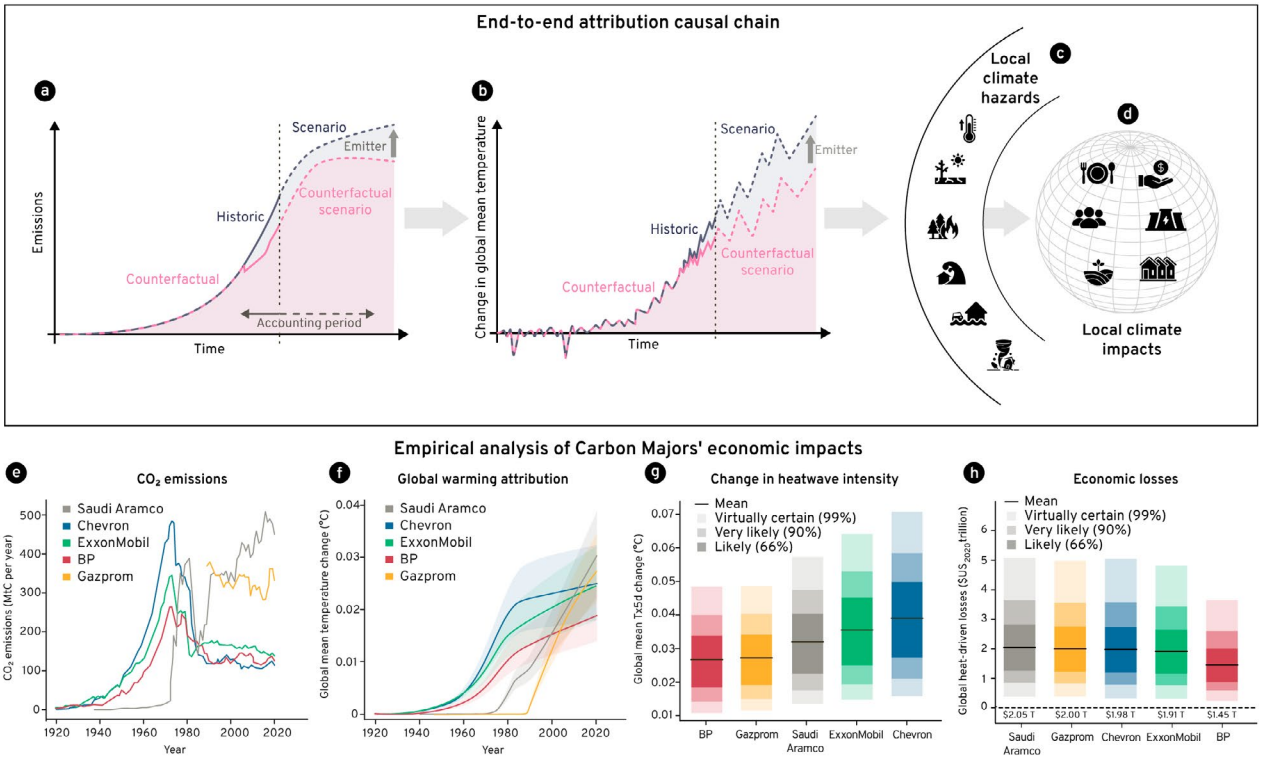


Figure 7. Illustration of the attribution causal chain and empirical evidence. Top panel: Source attribution links specific emissions (a) to changes in the global climate (b) and local climate hazards (c). Impact attribution links the global climate (b) to local climate hazards (c) and local climate impacts (d). End-to-end attribution connects the whole causal chain. Bottom panels (modified from Callahan & Mankin, 2025)[13] show: CO_2 emissions from the top five emitting fossil fuel companies ("Carbon Majors") (e); global warming magnitude attributable to cumulative emissions from each Carbon Major, (shading shows the 90% likelihood range across the simulation) (f); changes in the average temperature of the five hottest days each year (1991–2020) attributable to each carbon major (g) and cumulative global heat-driven economic losses attributable to the five largest fossil fuel emitters (h). Lines show the mean, and shading indicates uncertainty ranges.

BOX 5. END-TO-END ATTRIBUTION: THE HOLY GRAIL

In 1997, Brazil proposed assigning climate mitigation obligations based on countries' historical responsibility for warming, spurring scientists to link national emissions to global temperature rise. Two decades of attribution research have built on that foundation: first connecting emissions to physical climate change, then extending to specific emitters such as fossil fuel producers and to metrics like sea level rise and extreme weather, before linking that physical change to socio-economic harm. The next step, now within reach, is to trace the full causal chain.

Example: connecting a specific fossil fuel producer to rising global temperatures, to local heat extremes, and then to economic damages.

End-to-end attribution studies compare two versions of the world: the *factual*, the world as it actually is, and the *counterfactual*, a simulated world in which everything else stays the same but a specific actor's emissions never existed. The gap between the two reveals the climate change and harm attributable to that actor (Figure 7A, B). The field also exposes the disproportionate burden low-income regions bear despite contributing the least to warming, while often lacking the data to document their own losses.

13 Callahan, C. W., & Mankin, J. S. (2025). Carbon majors and the scientific case for climate liability. *Nature*, 640(8060), 893–901.

End-to-end studies can now attribute human impacts to individual high-emitting entities directly (Figure 7A–D). Counterfactual estimates of global economic growth without Carbon Majors' emissions show trillions of dollars in losses attributable to the largest producers. Losses are concentrated in tropical regions that are generally warmer, lower-income, and least responsible for warming. It is important to note that uncertainties compound at each step of the causal chain, often producing wide ranges of plausible local impacts. Future work will need to calculate these uncertainties meticulously and communicate conclusions with caution.

It is also becoming possible to examine the consumption and investment behaviour of high-income individuals. Simulating climate hazards with and without emissions from top income groups reveals that the wealthiest 10% increased the likelihood of extreme heat sevenfold relative to the average person, a striking contrast between consumption- and production-based accounting. Again, these attributable hazards fall disproportionately on lower-income tropical regions least responsible for warming.

Research also shows that future impacts from past emissions can substantially exceed the historical impacts of those same emissions because CO_2's warming effect persists for centuries. Past emissions from Carbon Majors have already committed an additional 0.26–0.55 m of sea level rise by 2300. For a pulse of CO_2 emitted in 1990, around 90% of its economic damage has yet to be realised.

Attribution science is increasingly entering the courtroom. Linking specific emitters to specific impacts can support evidence-based decision-making in climate lawsuits, many of which seek financial redress or injunctions to prevent further emissions. Attribution advances can also provide scientific grounding for polluter-pays legislation, as in certain US states, and can inform a fairer approach to international loss-and-damage negotiations.

Looking ahead, challenges remain for attribution science. Most studies focus on extreme heat and sea level rise because of clearer links to emissions; other hazards, such as floods, droughts, and tropical cyclones, remain challenging to assess and are understudied. Simpler methods that use the near-linear relationship between cumulative CO_2 emissions and global temperatures can attribute impacts to individual emission sources, e.g., the warming contribution of individual fossil fuel projects. However, these methods cannot capture nonlinearities or time lags, and some processes, such as those involving aerosols, require alternative approaches.

Another limitation is that most attribution analyses have concentrated on high-income regions while data scarcity persists in low- and middle-income countries. Systematic attribution methods may expand coverage, but disaster databases remain globally incomplete. Notably, most health attribution studies focus on high-income countries, despite disproportionate burdens elsewhere, partly because epidemiological models require high-resolution data that are not globally available.

Despite these challenges, attribution science increasingly provides robust evidence to inform decision-making, legal questions, and climate negotiations. It cannot resolve normative or political questions, but it sharpens understanding of the physical evidence underpinning them. Future work will further extend end-to-end attribution, move beyond temperature-related impacts, broaden geographical coverage, and improve coordination across research communities.

POLICY IMPLICATIONS

- **Build open, locally led attribution capacity**. UNFCCC bodies and the Parties should invest in public climate observations, disaster-loss databases, socioe-conomic data and locally led modelling institutions, particularly in vulnerable low-income countries. Together, these bodies should support open tools, regional research hubs, and sustained training.
    - At COP31, the Paris Committee on Capacity-building, which identifies and coordinates responses to capacity gaps, should convene technical partnerships; the Santiago Network should provide country-requested assistance; and the Warsaw International Mechanism should compile methods, data standards, and good practices.
- **Use attribution to inform, not condition, loss and damage funding.** The FRLD and its funders should use attribution evidence to improve loss assessments, needs estimates, and project design ahead of its first replenishment process in 2027. However, attribution should not be a condition of support. Funding should remain based primarily on vulnerability and need because unequal observational data and modelling capacity could otherwise exclude those least equipped to produce complex evidence.
- **Integrate attribution evidence into law, regulation, and policy design.** National legislatures and regulators can use attribution evidence when designing polluter-pays levies, climate-damage funds, corporate disclosure requirements, and permitting rules; courts can consider it when assessing causation under applicable law. However, scientific estimates alone do not determine legal breach, liability, or compensation. These questions should generally be addressed through domestic and international law outside the UNFCCC.
    - The International Court of Justice's 2025 advisory opinion on *Obligations of States in Respect of Climate Change* clarified states' duties of due diligence and cooperation, finding that a state's failure to take appropriate action to avoid climate change may constitute an internationally wrongful act under international law.

8 Climate clubs can limit carbon leakage, but fairness shapes their feasibility and effectiveness

KEY MESSAGES

- Climate clubs and club-like arrangements have been proposed to address carbon leakage and carbon pricing disparities across countries. These arrangements leverage market power, trade rules, and exclusive benefits to incentivise participation and make ambitious climate action more politically and economically viable.
- Carbon border adjustment mechanisms (CBAMs) are emerging as influential governance instruments that can reduce carbon leakage and encourage global climate policy convergence. However, their effectiveness depends on careful design that addresses trade law and the disproportionate impact on low-income countries.
- Fairness is key to the feasibility and effectiveness of these arrangements and essential for avoiding unintended consequences across trade, emissions, and development.

To drive deep carbon reductions at scale, the rules of global trade need to keep pace. One major challenge to address is carbon leakage, in which firms import from or relocate production to jurisdictions with weaker carbon policies, simply shifting emissions to another part of the world.

Today, we are at a critical moment. On the one hand, leakage incentives are declining as carbon-pricing mechanisms emerge and the gap in country emission intensities narrows. On the other hand, substantial disparities in carbon prices persist, even among countries that have implemented carbon pricing (Figure 8). Left unaddressed, leakage and competitiveness concerns can undermine support for ambitious carbon pricing. One trend that could help address these issues is the rise of climate clubs and club-like arrangements.

The concept of climate clubs carries multiple meanings. At the more ambitious end are transformational clubs, which grant exclusive benefits, such as trade privileges or access to technology for members that meet climate commitments (potentially imposing costs on outsiders). In this Insight, we assess the potential of the transformational club type conceptualised by Nobel Prize–winning economist William Nordhaus.

The IPCC Sixth Assessment Report (AR6) concluded that climate clubs could accelerate mitigation, while noting that real-world examples remained limited. Research since AR6 broadly splits into two camps: theoretical and model-based studies assess the effectiveness of mitigation, trade leverage, participation incentives, and legitimacy, while design-oriented studies and analyses of existing initiatives examine the gap between idealised potential and practice.

Given the shortage of real-world climate clubs, we can look to examples in other environmental areas. A high-profile example is the Montreal Protocol, which regulates the production and consumption of ozone-depleting substances. This landmark agreement achieved near-universal participation, illustrating how restricting trade privileges to parties can incentivise accession and higher stand-

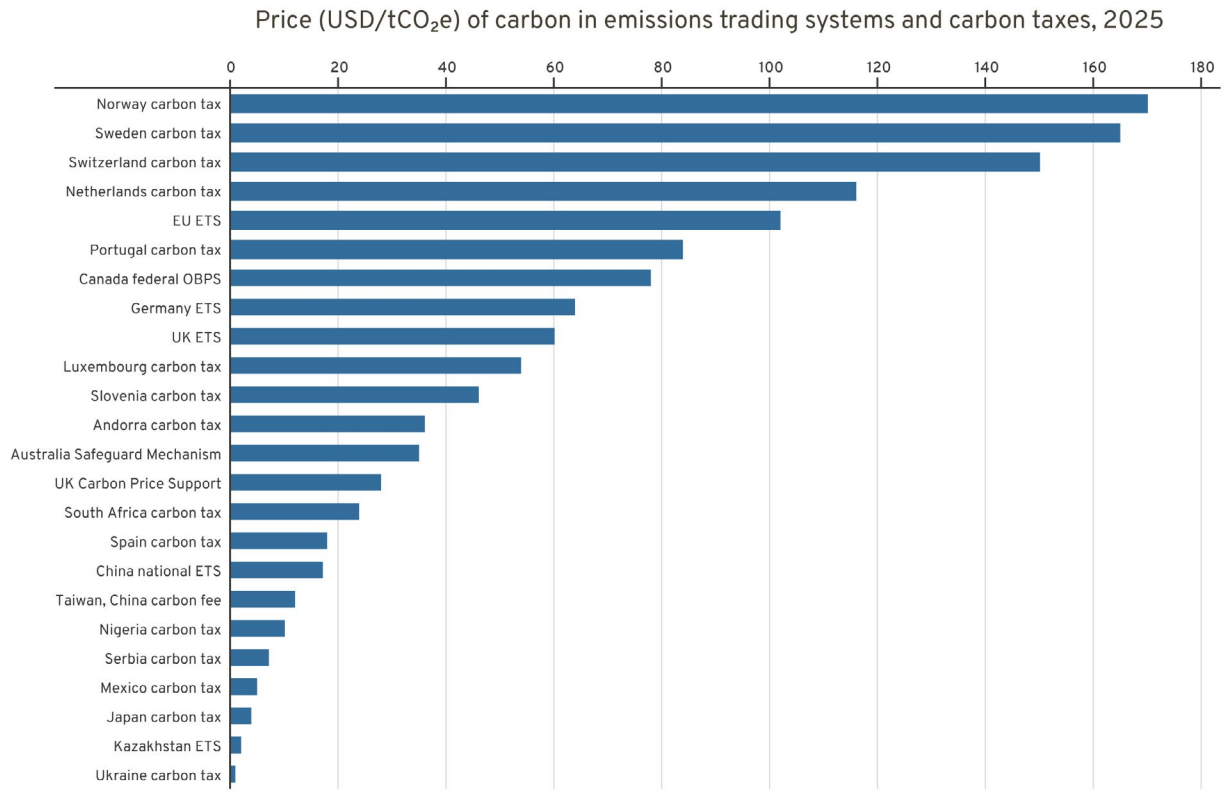


Figure 8. Price of carbon in emissions trading systems and carbon taxes, 2025. Carbon prices (USD/tCO_2e) across jurisdictions with operational carbon pricing instruments as of 2025. Significant price disparities persist. Source: World Bank. (2026). Carbon Pricing Dashboard. https://carbonpricingdashboard.worldbank.org/dashboard

ards. Elsewhere, in the fisheries sector, evidence suggests that clubs succeed when monitoring is credible and benefits are tangible. Agreements that incorporate trade provisions attract more accessions and undergo more frequent regulatory upgrades.

To date, there is no comprehensive climate club that combines high ambition with extensive global participation. However, various existing initiatives and policy proposals exhibit club-like features. Examples include the Agreement on Climate Change, Trade and Sustainability (ACCTS), the proposed EU–US agreement on low-carbon steel and aluminium, and proposed versions of a fossil fuel non-proliferation treaty. Although these examples differ in design, they all link stronger climate commitments to excludable benefits, most commonly through trade measures with participation incentives.

Another avenue is the inclusion of climate provisions in broader trade agreements. Although conceptually distinct from climate clubs, they also incentivise decarbonisation by linking trade benefits to climate commitments. Preferential trade agreements, especially those the EU negotiates, increasingly embed commitments linked to the Paris Agreement and fossil fuel subsidies. Beyond politics, investment agreements increasingly include climate-related clauses.

To date, the consequences of climate-related provisions in trade agreements are mixed. If well designed and enforced, they can shift trade towards cleaner exports, support firms' green transition, and increase energy efficiency. However, trade liberalisation often relocates pollution, rather than eliminating it, and low-income countries often remain excluded from low-carbon technology. Climate provisions also do little to promote additional climate cooperation, as governments have paid limited attention to these commitments when implementing economic agreements.

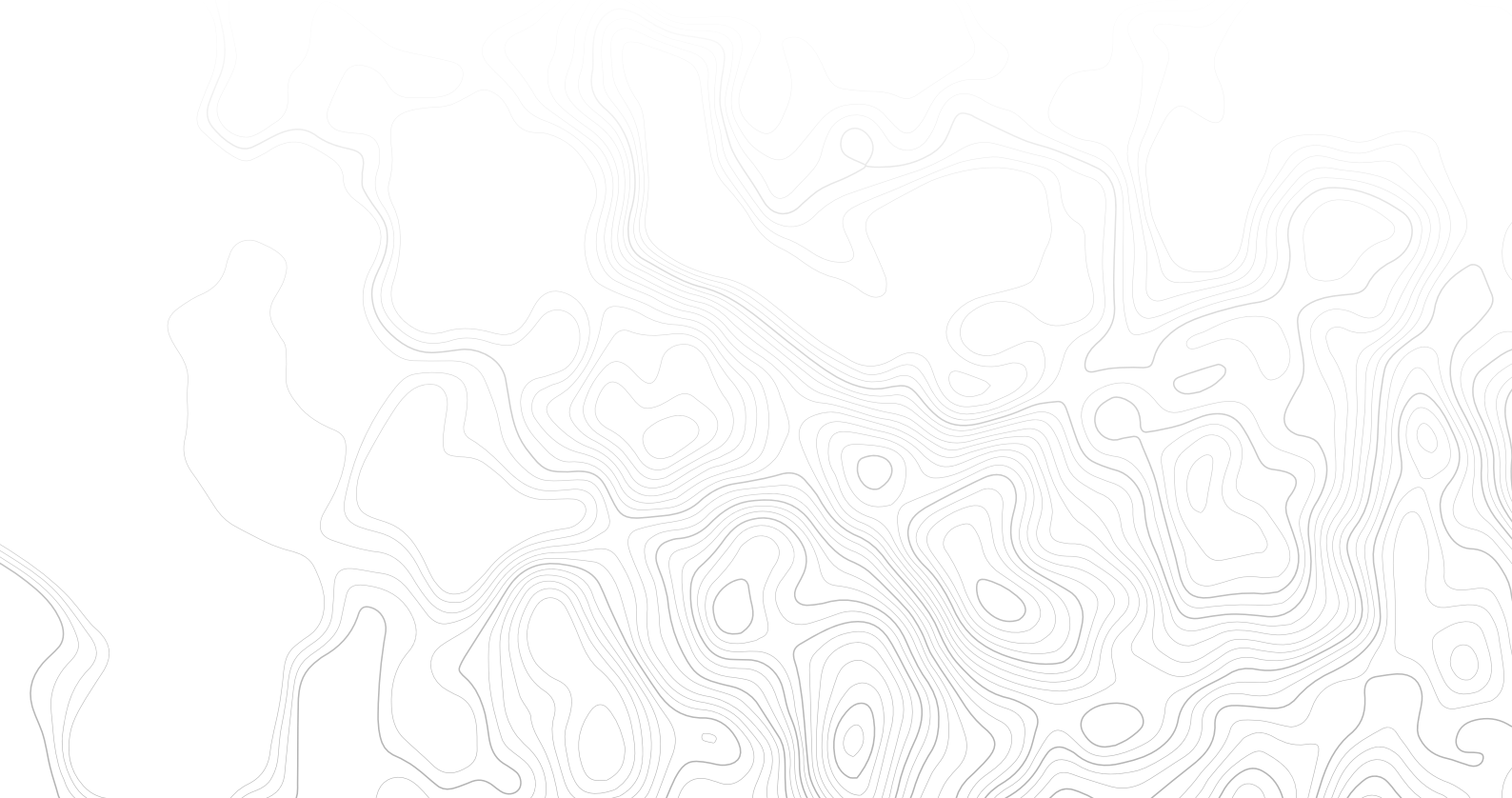
More broadly, trade agreement rules can limit governments' legal capacity to grant decarbonisation subsidies, pursue green industrial policy, and mandate fossil fuel phase-outs. Adding additional constraints risks deepening global climate inequalities, given that climate policies rely on state intervention and institutional quality. In response, economists have proposed new forms of climate clubs that would create greater policy space for participating states by relaxing or modifying

constraints imposed by international economic law, or by coordinating industrial policies among club members.

Though not a climate club in the strict sense, carbon border adjustment measures are gaining ground globally as a tool to counter carbon leakage. The EU's Carbon Border Adjustment Mechanism (CBAM), fully operational since January 2026, requires importers of select energy-intensive goods to purchase certificates that match the EU carbon price, while accounting for carbon prices already paid abroad. This aligns import costs with those of EU producers and discourages firms from relocating solely to avoid it. Critics have raised concerns about CBAM's unilateral governance and whether it conflicts with World Trade Organization rules, with several countries formally challenging the measure. Nevertheless, attitudes to CBAM have evolved from early controversy towards more nuanced, practice-based acceptance.

Early studies suggest CBAM's direct effects on emissions appear modest, though the mechanism may support climate ambition indirectly by reinforcing EU carbon pricing and encouraging other countries to adopt carbon pricing of their own. Concerns remain, however, that it could amplify existing global inequalities. Developing economies countries face a "triple burden" of compliance costs, weaker institutions, and social inequality, which could widen carbon-trade divides unless paired with financial transfers or differentiated treatment.

In summary, early examples of club-like climate arrangements reveal a gap between theoretical expectations and messy real-world implementation. The concepts are promising, but we need to avoid unintended consequences across trade, emissions, and development. Future research should integrate Global South scholars' perspectives more deeply and examine alternative designs. Ultimately, climate clubs and border adjustment mechanisms will only gain global approval if they are fair.



POLICY IMPLICATIONS

- **Anchor climate clubs in Paris Agreement implementation.** Participating governments and governing bodies should align club mandates and work programmes with members' NDCs and long-term strategies, maintain transparent, open accession criteria, and present concrete sectoral deliverables. This would position clubs as voluntary implementation vehicles within a "two-tier multilateralism", where UNFCCC consensus sets direction and legitimacy, while smaller coalitions advance issues that consensus cannot yet resolve, recognising that success depends as much on ambition as on how the costs and benefits are distributed.
    - An appropriate space to showcase club-based industrial cooperation could be the green-industrialisation track under the GCAA, one of the ten COP Presidency-defined priority themes for 2026.
- **Combine positive incentives with interoperable carbon accounting.** Climate clubs should embed concessional finance, technology cooperation, and coordinated demand for low-emissions materials alongside comparable emissions-accounting methods, support for monitoring, reporting and verification, and quality-infrastructure capacity in developing economies.
    - *The Climate Club*, launched at COP28, is an open intergovernmental forum focused on industrial decarbonisation. It is well placed to support the adoption of interoperable accounting standards for low-emissions materials. Through its Global Matchmaking Platform it matches requests from developing economies with technical and financial support.
- **Embed distributional safeguards and international revenue recycling in CBAM design.**
    - Jurisdictions implementing CBAMs should assess distributional impacts, including trade exposure, compliance costs, employment effects and institutional capacity, before implementation and at regular review points. These assessments should inform adjustments to CBAM design and targeted support for affected countries.
    - To foster fairness and effectiveness, a defined share of CBAM revenue should be earmarked for affected country partners or appropriate multilateral funds, rather than retaining it entirely as domestic revenue to finance emissions measurement and verification, clean energy, and industrial upgrading. This will support affected exporters' compliance with CBAM requirements and decarbonise production.
- **Institutionalise dialogue and accountability on climate–trade interactions.** UNFCCC Parties should use the 2026–2028 Climate and Trade Dialogue series, mandated at COP30, to examine how trade can support climate action. Parties should address tensions surrounding measures such as CBAMs and green industrial subsidies, including friction over perceived unilateral measures, as illustrated by BRICS opposition to the EU CBAM.
    - The outgoing and incoming COP Presidencies could link these formal discussions with practical cooperation under the Integrated Forum on Climate Change and Trade, launched at SB64 in Bonn, and will reconvene at COP31.
    - Parties can also request that the Response Measures Forum and its Katowice Committee of Experts assess the cross-border economic, employment, and distributional effects of climate-related trade measures to inform relevant UNFCCC decisions and the implementation of the just transition.

9 Organised obstruction prevents effective climate policy through denial, delay, dilution, and distraction

KEY MESSAGES

- Climate obstruction refers to intentional efforts to block or slow climate action and policies. These efforts range from outright science denial to more subtle tactics focused on delay, dilution, and distraction.
- High-emissions industries have been found to fund and collude with a wide range of networks to influence media, promote climate mis- and disinformation, and shape public opinion to block climate policy action.
- Legal action is increasingly targeting climate-related disinformation, with dozens of lawsuits filed against major oil and gas companies for historical deception and delay. Legislative efforts to curb obstruction are also emerging.

Failure to act decisively on climate change is not simply a result of human nature or technological constraints; it is fundamentally a political problem. "Climate obstruction" refers to intentional efforts to slow or block climate policies that align with the scientific understanding of what is needed to avoid dangerous levels of global warming. Tactics range from outright denial of climate science to more subtle forms of delay, dilution, and distraction. Such obstruction is a central reason why decarbonisation has lagged so far behind international emissions goals.

Enabling these activities are high-emissions industries, chiefly oil and gas but also coal, utilities, carmakers, aviation, and agribusiness, along with their commercial suppliers and customers, who have funded an extensive network of trade associations, PR firms, law firms, think tanks, consultants, and university-linked researchers. Together, these actors lobby governments, make political contributions, and shape media content and research, thereby influencing public opinion and leading to climate inaction (Figure 9). As climate action has globalised, so has obstruction, with transnational networks linking actors across the Global North and South. The full extent of climate obstruction continues to emerge.

In the late 1990s and early 2000s, academics began documenting the roles of contrarian scientists, conservative think tanks, and the media. By the 2010s, investigative journalism and research into barriers to climate action had expanded significantly, and in 2022 the IPCC's Working Group III report identified vested interests and incumbent actors as barriers to mitigation. That same year, the US House Committee on Oversight and Reform released documents showing that Chevron and BP were greenwashing to obscure their long-term fossil fuel investments. Meanwhile, the Commission on Human Rights of the Philippines found that major oil and gas producers had "engaged in wilful obfuscation and obstruction to prevent meaningful climate action". Most recently, the Australian Senate

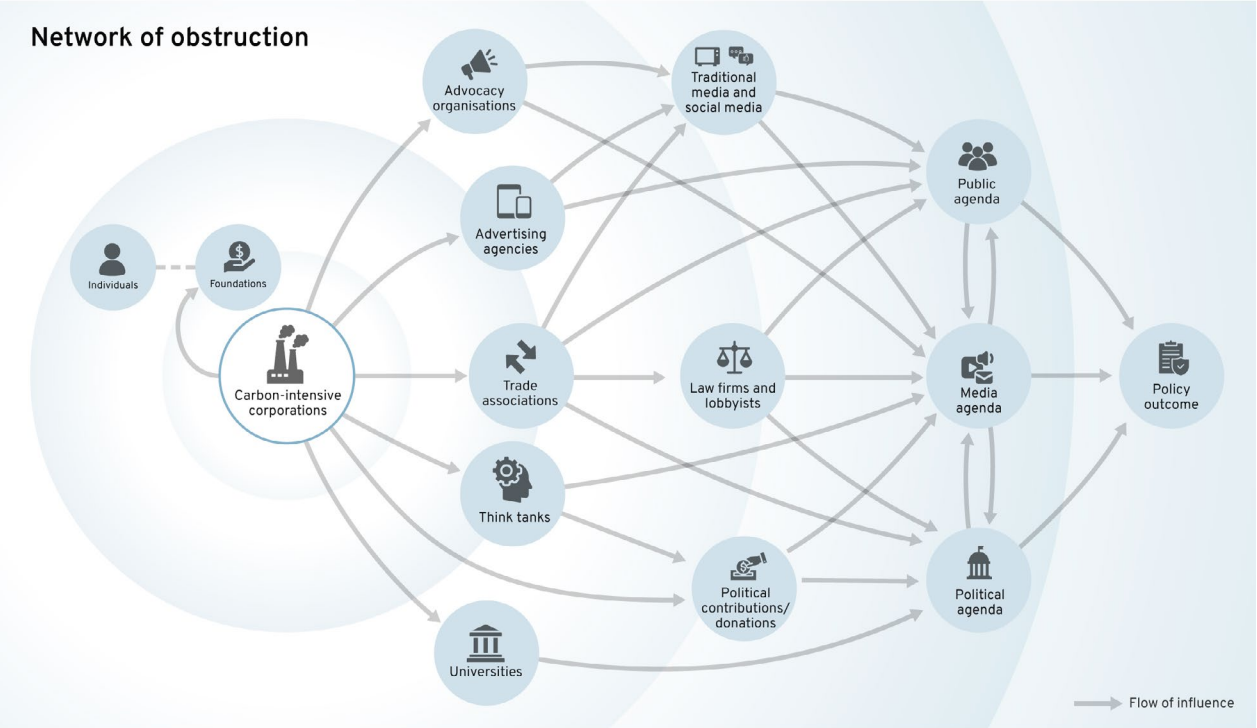


Figure 9. Network of obstruction depicting the financial flows and other forms of influence stemming from carbon-intensive corporations (and the foundations and individuals associated with these), through various organisations affecting agendas, and ultimately shaping policy outcomes with the intention of obstructing climate policy. Based on Brulle (2021)[14].

concluded that the country's democracy is being undermined by misinformation and disinformation on climate change and energy, often traceable to the fossil fuel industry.

As political and economic conditions evolve, so too do the tactics of climate obstruction. Outright denial of the basic science peaked before the 1997 Kyoto conference, when a successful deal would have triggered a rapid shift away from fossil fuels. Today it persists mainly among far-right voters and parties, and arguably, in continued fossil fuel expansion, which runs counter to the case for rapid decarbonisation. From the 2000s onwards, industry increasingly turned to "discourses of delay", publicly accepting the science but blocking action by other means, such as framing regulation as economically harmful or shifting responsibility onto individual consumers.

As climate litigation and ambitious legislation have mounted in the post-Paris era, the industry has escalated a well-established strategy of promoting "false solutions" (such as algae farming and end-of-pipe carbon capture) to project voluntary climate leadership while simultaneously pre-empting stricter regulation and continuing to expand fossil fuel production. The latest phase of climate obstruction includes misleading net-zero pledges, greenwashing, and "futurewashing": claims that lack short-term targets and are vulnerable to future retreat. Combined, these actions are designed to make voluntary corporate action appear sufficient and thus pre-empt regulation.

The channels through which obstruction reaches the public have shifted too. As mainstream media became less willing to present climate science and denial as equally credible, denial migrated to spaces with weaker editorial gatekeeping – first blogs, then social media. Platforms have profited from fossil fuel advertising and contrarian content has been algorithmically amplified with little accountability. They are also enabling "participatory misinformation", in which ordinary users share and amplify denialist talking points engineered to exploit economic anxiety and cultural resentment. Generative artificial intelligence adds a further complication by

14 Brulle (2021), *The Structure of Obstruction: Understanding Opposition to Climate Change Action in the United States*, CSSN Primer

drastically lowering the cost of producing disinformation at scale, though it may also help detect disinformation, increase the visibility of corporate conduct, and counter conspiracy beliefs.

The nature of obstruction varies with national and local contexts, as evidenced by empirical data across the Global South. In Brazil, climate denial often fuses far-right politics with Christian nationalism, echoing patterns seen in the USA. In Argentina, obstruction extends well beyond fossil fuels to agribusiness and energy more broadly, with "developmentalist" promises of a better future frequently pitched against environmental concerns. A similar dynamic plays out in Indonesia, where the palm oil and coal-mining industries are part of the government's development agenda, slowing the shift towards renewable energy.

What is being done about all this? Alongside research into obstruction, legal action is gathering pace. Dozens of lawsuits filed by US cities and states against major oil and gas companies are ongoing, and similar cases are emerging elsewhere. Brazil leads the Global South in climate litigation, with more than 80 cases filed so far. Some cases seek damages from producers, claiming they knew the risks and downplayed them, echoing tobacco litigation; others target greenwashing claims, as recently enforced in a Parisian court ruling against TotalEnergies. Regulation is advancing too, with Amsterdam becoming the first city to ban fossil fuel advertising. Looking ahead, much more is needed to curb the political influence of carbon-intensive industries and their vast networks. Our ability to identify and remove obstructions will strongly influence the pace of climate action in the years ahead.

POLICY IMPLICATIONS

- **Institutionalise UNFCCC integrity and conflict-of-interest reforms.** Parties should mandate disclosure of delegate affiliations, establish conflict-of-interest frameworks, and reform observer modalities to prevent fossil fuel interests from delaying UNFCCC negotiations. COP31's Action Agenda should establish a dedicated track on democratic governance and integrate the Global Initiative for Information Integrity on Climate Change into Action for Climate Empowerment (ACE) mandates.

- **Embed anti-obstruction safeguards in NDCs and governance.** To prevent 'false solutions' and greenwashing from substituting for deep mitigation, integrity criteria should be considered for the NDC updates and Article 6 market mechanisms. Guidelines should require Parties to report on corporate lobbying, enforce "say–do" consistency checks, and prevent carbon offsets from delaying domestic fossil fuel phase-outs.

- **Regulate corporate political influence and financial contributions from carbon-intensive industries to ensure transparency.** National and subnational policymakers must target structural drivers of delay by banning deceptive greenwashing, restricting corporate lobbying and campaign contributions, and enforcing strict financial disclosures. Furthermore, regulatory oversight should extend beyond fossil producers to banks, private equity, and asset managers funding high-emissions assets.

- **Reorient climate finance to neutralise obstruction in the Global South.** To counter domestic political narratives that frame decarbonisation as an economic threat, MDB lending, bilateral support, and climate finance must fund low-carbon economic diversification and social safety nets, as concrete elements of just transitions.

10 Just energy transition threatened by geopolitical risks and fragmentation

KEY MESSAGES

- Geopolitical risk and instability can have varying impacts on a country's energy transition. They can, for example, act as structural brakes that reverse decarbonisation efforts and encourage fossil fuel investments or as catalysts that accelerate domestic renewable energy adoption. The type of impact is highly dependent on countries' institutional maturity, financial strength, and access to resources and technology.
- Overall, evidence suggests that heightened geopolitical risk hinders the global energy transition by driving market volatility, disrupting supply chains, and redirecting policy priorities.
- Geopolitical fragmentation, reflected in a decline in multilateralism, can compound asymmetries in energy transition progress and global inequalities. Wealthy nations consolidate their advantage and diversify their energy portfolios, while neutral and sanctioned economies face heightened instability and slower decarbonisation, raising important justice concerns.

Will global conflict and geopolitical risk slow down or speed up the shift towards renewable energy? The answer, it seems, depends heavily on a nation's economic circumstances and the policies in place before a shock hits. While the direction of these effects remains ambiguous, advancing a just energy transition is non-negotiable in the face of escalating global socio-ecological crises and countries' commitments under the Paris Agreement. To some extent, international tensions can trigger a structural brake on decarbonisation, with leaders doubling down on fossil fuels. Conversely, they can also become a catalyst for accelerated investment in domestic renewables. Studies of how these opposing reactions play out globally reveal how distributional asymmetries can exacerbate inequalities, placing the just (energy) transition at risk.

This apparent paradox can be explained by two theories of how political priorities interact in times of volatility. "Geoeconomics theory" holds that geopolitical risk accelerates the transition. It proposes that reliance on imported fossil fuels exposes a strategic weakness, prompting willing and resource-rich governments to invest in renewables to strengthen energy independence. In contrast, "energy security theory" suggests that nations are driven towards rapid fixes to keep the lights on during supply shortages and rising prices. Often this means prioritising domestic fossil fuel production or subsidies, thereby delaying or reversing clean energy progress.

Empirical evidence, on balance, suggests that heightened geopolitical risk hinders the transition. It drives market volatility, disrupts supply chains for critical minerals needed in renewables, and redirects policy priorities towards military spending and immediate material security. This slowdown is sharpest when capital earmarked for green infrastructure gets diverted to conflict costs, causing a collapse in the readiness of countries actively advancing their transition. But the picture is complicated by studies that also document the reverse effect. Energy-importing countries with strong technological capacity have used geopolitical

shocks to accelerate towards energy independence. See Box 6 for how the two trends played out within the EU following Russia's full-scale invasion of Ukraine in 2022.

Much depends on institutional readiness and sustainable innovation capacity, particularly on whether countries can step up public research and development investment to build domestic technological leadership. The BRICS nations offer a case in point. In these countries, geopolitical instability has suppressed fossil fuel use and driven a strategic shift towards renewables, in pursuit of long-term energy security. Unfortunately, this "strategic adaptation" is not available to most nations. Lower-income economies, lacking the fiscal space and institutional maturity to absorb these shocks, may end up slowing their green transitions. The net effect is a widening gulf. Geopolitical risk becomes a security booster for well-placed countries, while triggering a structural brake for others, as macro-financial pressures raise the cost of capital and tighten the fossil trap.

This asymmetry is compounded by geopolitical fragmentation. In recent years, we have seen a shift away from a cooperative, integrated global system towards one of economic segmentation and competing, walled-off blocs. The results can reinforce existing inequalities. Wealthy nations consolidate their advantage and diversify their energy portfolios, while neutral and geopolitically isolated economies face heightened instability and slower decarbonisation. This raises profound climate justice concerns, as the burdens of the transition – energy price shocks and stranded fossil fuel assets – often land disproportionately on the most vulnerable.

What can global institutions do to ensure a fairer transition? Unlike the oil crises of the 1970s and 1990s, which were managed within established multilateral frameworks, today's fragmentation is straining the institutions built to coordinate a global response. The clearest example is the USA's withdrawal from the Paris Agreement, first in 2020 and again in 2026, which has reduced financial support for low-income nations through mechanisms like the Green Climate Fund. This creates a leadership vacuum that risks prompting others to weaken their own commitments.

In light of these developments, we urgently need to build geopolitical risk, evolving power relations, and societal dynamics explicitly into both short-term and long-term transition strategies and scenarios, rather than treating them as an afterthought to techno-economic planning. Similarly, fragmentation must be treated not as a passing disruption but as the new normal – one that requires stronger institutional capacity. Closer coordination between civilian and military planning, and between public and private investment, would also help countries break more decisively from fossil fuels during periods of crisis. Ultimately, coordinated international action remains essential for a just energy transition. In practice, this means giving low-income and emerging economies real access to risk-mitigation tools and climate finance, as well as ensuring meaningful participation and a real seat at the decision-making table. If we fail to do this, we risk global inequalities growing ever wider, which is not in line with a just transition, and the energy transition getting further out of reach.

BOX 6. THE EU ENERGY CRISIS UNDER GEOPOLITICAL INSTABILITY

The EU's response to the 2022 energy crisis, triggered by Russia's full-scale invasion of Ukraine, is a case study in the push and pull of fossil fuels. Governments first scrambled for short-term security by rapidly expanding fossil fuel infrastructure, as exemplified by Germany's "Liquefied Natural Gas (LNG) Acceleration Act", which expanded liquefied natural gas supplies. Such measures were clearly at odds with long-term climate targets.

However, the shock also forced a reorientation. The green transition shifted from an environmental choice to an urgent security strategy, formalised in the REPowerEU Plan, which mobilised between EUR 210 billion and EUR 300 billion to fast-track renewables and diversify supply. Renewable energy capacity expanded at historically high rates in 2025, with approximately 70 gigawatts (GW) added during the year. Solar power drove this growth, with total installed capacity reaching 359 GW at year-end, up by 19% from 2024, equivalent to an additional 56 GW. Wind capacity, encompassing both onshore and offshore installations, increased to 244 GW, marking a 6% rise over the previous year, or 13 GW in absolute terms.

The 2024 Israel–Iran escalation and ongoing conflict around the Strait of Hormuz further underscore how vulnerable global energy markets are to a handful of critical chokepoints. Again, however, these events have also strengthened the EU's long-term commitment to renewables and decarbonisation as a means to safeguard economic resilience.

POLICY IMPLICATIONS

- **Centre decarbonisation as a pillar of energy security.** National governments should treat renewable energy, energy efficiency, electricity grids, storage and demand flexibility as strategic resilience assets that reduces exposure to fuel-price shocks and supply disruptions.
    - The energy outcomes of the GST1, i.e., tripling renewable capacity, doubling the rate of energy-efficiency improvements, and transitioning away from fossil fuels, offer directives to guide sectoral policies and investment plans.
    - COP31 is an opportunity for the Presidency to gather support towards the voluntary "35 by 35" electrification target. Important spaces for these discussions are the GCAA's "Clean Energy Transition and Electrification" track and the "Climate Implementation Bridge", which helps countries turn NDC priorities into investable/finance-ready projects.
- **Include resilience mechanisms in energy transition planning to anticipate geopolitical tensions.** NDC implementation plans and national energy strategies should include mechanisms to prevent short-term crises/shocks (e.g., armed confrontations, sanctions, trade restrictions, supply-chain disruptions, and capital-cost shocks) from causing long-term carbon lock-in.
    - Before approving any "emergency fossil fuel infrastructure", Parties should be required to provide an assessment of lower-carbon alternatives, compatibility with the country's NDC and long-term low-emission development strategy, financial and stranded-asset risks, and a time-bound decommissioning or conversion plan.
    - Any significant changes to Parties' energy policy should be reported through their Biennial Transparency Reports, so their collective effects can be considered in the GST2.
- **Climate finance flows should be resilient to geopolitical shocks.** Pledges and risk-mitigation tools must feature contingency mechanisms to protect vulnerable economies and critical mechanisms such as the Loss and Damage Fund in the face of geopolitical shocks. An agreement on near-term milestones for implementing the Baku-to-Belém Roadmap (COP29: USD 1.3 trillion annually by 2035) is a central priority.
- **Scale transition finance in hard-to-abate sectors.** Broader investment across countries in energy transitions and clean technology could help avoid new geopolitical dependencies and long-term carbon lock-in.
- **Develop secure, just mineral supply chains and protect regulatory space for the transition.** Mineral-producing and importing nations, development banks, and companies should diversify critical-mineral supply and processing; expand recycling and material substitution; and support local processing, skills, and value creation in producer countries, while applying safeguards on human rights, Indigenous rights, and environmental protection.
    - Because investment treaties and investor–State dispute settlements fall largely outside the UNFCCC's mandate, governments should pursue treaty renegotiation and relevant UN processes and multilateral fora. Talks should seek to protect the right to regulate, narrow investment-protection standards and consider excluding fossil fuel investments from treaty protection.

Abbreviations

ACCTS – Agreement on Climate Change, Trade and Sustainability

ACE – Action for Climate Empowerment

BECCS – bioenergy with carbon capture and storage

CBAM – carbon border adjustment mechanism

CDR – carbon dioxide removal

CERES – Clouds and the Earth's Radiant Energy System

COP – Conference of the Parties

CO_2 – carbon dioxide

EEI – Earth's energy imbalance

FRLD – Fund for Responding to Loss and Damage

GCAA – Global Climate Action Agenda

GDP – gross domestic product

GGA – Global Goal on Adaptation

GMSLR – global mean sea level rise

GRACE – Gravity Recovery and Climate Experiment

GST – Global Stocktake

IPCC – Intergovernmental Panel on Climate Change

MDBs – multilateral development banks

MYD – multi-year drought

NAP – National Adaptation Plan

NDC – Nationally Determined Contributions

OHC – ocean heat content

SCC – social cost of carbon

SSP – Shared Socioeconomic Pathway

TWS – total water storage

UNFCCC – United Nations Framework Convention on Climate Change

WMO – World Meteorological Organization

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Acknowledgements

The making of this report was led by Future Earth, The Earth League, and the World Climate Research Programme. We acknowledge the work of the following individuals in their respective capacities:

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