EARTH SYSTEM INSIGHTS

Policy Briefing

November 2025

SUMMARY

Earth System models are important tools underpinning evidence for policymaking that can determine:

i. whether we are on track to achieve the Paris Agreement goals,

ii. the potential effectiveness of different climate change mitigation strategies at helping us achieve the Paris Agreement goals, and

iii. the potential real-world climate impacts that we will have to live with.

Recent research in Earth Systems Modelling and climate change from six Horizon Europe funded projects – **ESM2025, ClimTip, TipESM, OptimESM, nextGEMS,** and **RESCUE** – has provided important new insights into the impact of human-caused emissions of greenhouse gases, such as carbon dioxide, on current and future climate change, including:

1. **Tracking key indicators of climate change** shows that levels of observed warming, human-induced warming, total greenhouse gas emissions, and the remaining carbon budget have all worsened since the IPCC 6th assessment in 2021.
2. **Reaching net zero carbon dioxide emissions early is our best chance of avoiding continued warming after net zero is reached.** Best estimates suggest that if global carbon dioxide emissions are reduced to net zero, global warming will stabilise – but not decrease. However, temperatures may still continue to rise even after reaching net zero. The higher the temperature at which net zero is achieved (that is, the longer we take to reach net zero), the higher the likelihood that temperatures will continue to increase.
3. **Existing models used to guide policy may be overestimating the effectiveness of carbon dioxide removal methods,** potentially leading to overoptimistic expectations of what emissions removal measures can deliver compared to what is achievable when implemented in reality. Accelerated early decarbonisation is key to hedging against this uncertainty.
4. **The risk of triggering tipping points rises with increasing levels of warming.** Some – such as the Greenland ice sheet and Atlantic Meridional Overturning Circulation (AMOC) – may not recover after net zero carbon dioxide emissions are reached, with severe impacts for the stability of global and regional climates.

These developments reveal a need for further research to improve our understanding of:

1. **Progress in key indicators of global change,** including the factors resulting in recent record-warm years.
2. **How the Earth System might respond to increasing (net positive) and decreasing (net negative) emissions.**
3. **Carbon dioxide removal.**
4. **Tipping points and abrupt Earth System changes.**

INTRODUCTION

The impacts of climate change continue to increase, with global temperatures rising and extreme weather events becoming increasingly frequent and severe. Up until 2024, human activities have caused the world to warm by approximately 1.36°C relative to pre-industrial levels.[1]

Earth System Models (ESMs) represent physical processes in the Earth's atmosphere, ocean, and land, as well as the interactions between them. Though imperfect, they are a key tool to understanding the causes, consequences, and potential responses to climate change.[2]

This briefing draws on work from six projects: **ESM2025, ClimTip, TipESM, OptimESM, nextGEMS,** and **RESCUE**. All six projects conduct policy-relevant climate change research using ESMs, in particular in relation to the Paris Agreement, as described in Box 1. In this briefing we first summarise some of the new research insights of these projects that help us understand:

i. how to track real-world progress in warming, greenhouse gas emissions, and carbon budgets;

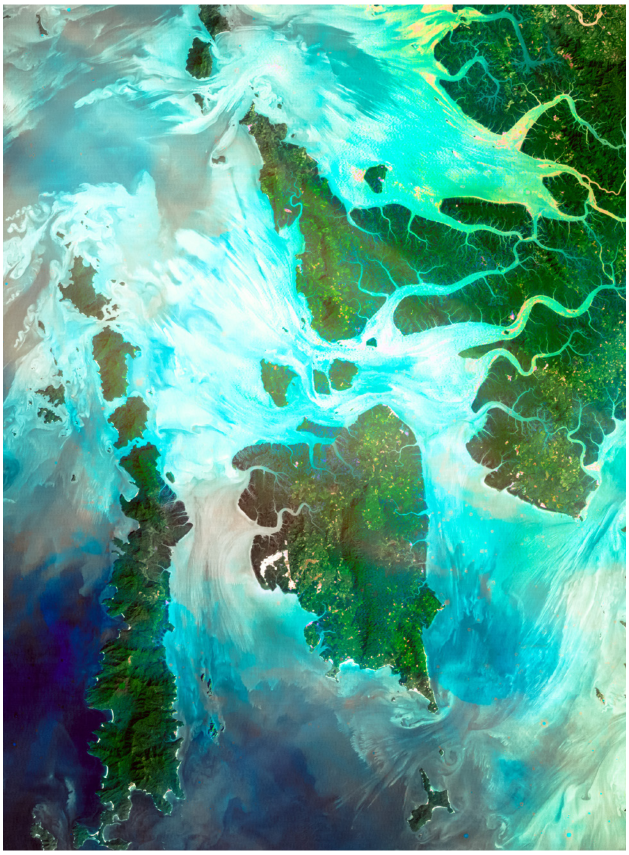
ii. expected future warming and the potential of measures to reduce concentrations of carbon dioxide in the atmosphere; and

iii. the stability of global and regional climates.

We then identify key research gaps that must be filled to predict future pathways and identify effective and efficient responses to climate change.

Box 1: The Paris Agreement

The Paris Agreement sets out a legally binding long-term temperature goal to limit global warming well below 2°C above pre-industrial levels and pursue efforts to limit warming to 1.5°C.[3] Under the Paris Agreement, countries make regular emissions reductions pledges in their Nationally Determined Contributions (NDCs). However, current commitments are not sufficient to meet the Paris Agreement temperature goal. The 2025 UNEP emissions gap report states that even if these NDCs are all met, we are likely to experience 2.3-2.5°C warming by the end of the century, and continued warming after that point.[4]



NEW RESEARCH INSIGHTS

Our new developments in Earth Systems Models and climate change research have allowed us to answer key questions regarding current and future climate change, including:

How can we track progress in the real world and anticipate risks?

The IPCC publishes comprehensive scientific assessment reports which quantify many key indicators of global climate change every 5-7 years.[5] However, to track real-world progress and accurately understand the risks involved with climate change, up-to-date information is required. The Indicators of Global Climate Change (IGCC) project uses IPCC methodologies to publish annual reports quantifying a set of key indicators of global climate change, including net greenhouse gas emissions, warming attributed to human activities, and the remaining carbon budget.[6] The latest IGCC data shows that:

- Human-induced warming is increasing at the unprecedented rate of approximately 0.27°C per decade.[7]
- Almost all observed warming between 2021 (when the IPCC 6th Assessment was conducted) and 2024 can be attributed to human activities.[8]
- The remaining carbon budget has decreased faster than predicted since 2021, in part due to record high temperatures in recent years.[9] (This is because the remaining carbon budget is calculated taking into account the difference between policy-relevant temperature targets – such as 1.5°C – and the amount of human-induced warming.[10])

These data suggest that human activities are consistently changing aspects of our climate system at unprecedented rates and scales.

How effectively will our actions result in a peak and decline in global warming?

How much warming is expected when we reach net zero?

Currently, our best estimate suggests that if global carbon dioxide emissions are reduced to net zero, global warming will be halted and temperatures will stabilise.[12] However, there is uncertainty around this estimate, meaning that there is a range of possible temperature change after net zero depending on how different aspects of the Earth System respond. This includes the possibility that temperatures may continue to rise. Moreover, regional climate in different parts of the world may still change after global temperature stabilisation, for example due to readjustments in ocean circulation patterns redistributing heat around the globe.[13]

Research suggests that the higher the temperature at which net zero carbon dioxide emissions are achieved, the larger the likelihood that global mean temperatures will continue to increase.[14] This would make it harder to reverse warming and is associated with higher climate risks and impacts which may be irreversible. For example, the Earth System may experience abrupt irreversible system changes (shifting from one state to another) if critical tipping points are reached.[15,16]

Using indicators observable over time (such as those monitored in the IGCC project), it is possible to anticipate how warming might evolve after net zero is reached:

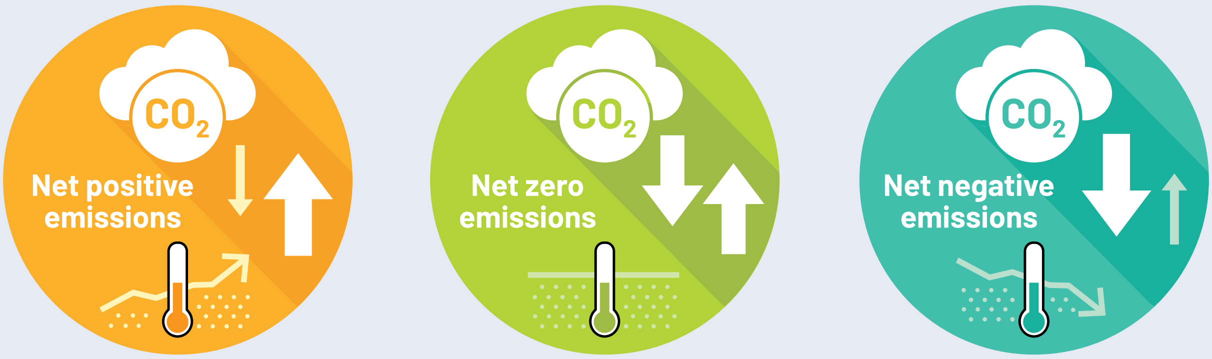
- Reaching net zero carbon dioxide emissions at 2.8-2.9°C of warming would give us a 1 in 2 (50%) chance of more warming after net zero.
- Reaching net zero at 2.2-2.3°C would give us a 1 in 3 (33.3%) chance of more warming after net zero.[17]

Box 2: The relationship between emissions and temperatures

Global warming is approximately proportional to the total amount of human-caused carbon dioxide emissions we ever emit. That means that temperatures will continue to rise as long as we continue to emit carbon dioxide into the atmosphere.

Achieving net zero carbon dioxide emissions means that no additional carbon dioxide is being added to the atmosphere. Our best estimate is that at this point, temperatures will plateau[11] (see below).

Since warming is now expected to exceed 1.5°C above pre-industrial levels, achieving the Paris Agreement's long-term temperature goal will require efforts to bring temperatures *back down again* in future. This will require achieving *net negative* carbon dioxide emissions which means that any remaining human-caused emissions are exceeded by active removal of carbon dioxide from the atmosphere.



How effective are measures to reduce levels of carbon dioxide in the atmosphere?

Scenarios compatible with the Paris Agreement often rely on substantial amounts of carbon dioxide being *removed* from the atmosphere via land-based projects like afforestation or Biomass Energy with Carbon Capture and Storage (BECCS). Advances in ESMs can be used to better understand the effectiveness of these measures.

BECCS: BECCS first involves some form of biomass (for example grasses or trees) being grown, removing carbon dioxide from the atmosphere in the process. This biomass feedstock can be sourced from waste biomass from other industries, such as agriculture, or can be grown specifically for the purpose of carbon removal. The biomass is combusted to produce energy, producing carbon dioxide in the process, which is then captured and permanently stored, resulting in a net reduction of carbon dioxide in the atmosphere.[18]

Integrated Assessment Models (IAMs) represent both human systems (including social, economic, and technological systems) and natural systems. IAMs are used to help answer policy questions such as 'how could we limit warming to 1.5°C'. Researchers compared the assumptions that underpin IAMs with results from the latest ESMs and found that the actual level of carbon dioxide removal from BECCS may be less than half than what is estimated by IAMs.[19] Thus, IAMs may be providing an overoptimistic view of the amount of carbon dioxide removal that could be delivered by BECCS. These differences would have knock-on consequences for the amount of carbon dioxide that would remain in the atmosphere and therefore the level of long-term global warming. IAMs project higher biomass yields (and hence estimate greater levels of carbon dioxide removal) compared to ESMs due to the following reasons:

- Incomplete coverage in IAM land models of factors that would limit plant productivity (such as ecological and physiological constraints like nutrient and water limitations, plant competition, and carbon dioxide acclimation).
- Inclusion of assumptions that might prove optimistic in terms of plant productivity (such as intensive crop management assumptions related to irrigation, fertilisation, and active crop management).

Afforestation: While increasing forest cover is a commonly proposed mechanism for reducing levels of carbon dioxide in the atmosphere, the effectiveness of forest-based carbon storage is very limited compared to the large global emissions, and sensitive to multiple factors which may not be accounted for in existing scenarios or policy.[20] For example, if these forests are not healthy, stable, and undisturbed, the carbon stored in these forests may not remain stored permanently.[21] This could lead to an overoptimistic assessment of the amount of carbon dioxide removal that can be achieved through afforestation, potentially undermining carbon reduction plans. Model shortcomings include:

- A failure to account for natural forest disturbance, which is mainly caused by pests, drought, disease, and windfall.[22]
- Underestimating the level of human-induced forest disturbance, such as deforestation and degradation.[23]
- Overestimation of the level of carbon dioxide fertilisation (where increased levels of carbon dioxide in the atmosphere facilitate increased plant growth).[24]

Ultimately, accelerated early decarbonisation is key to hedging against the uncertainty associated with carbon removal projects, which may underdeliver on carbon dioxide removal compared to predictions.

How stable are global climate processes and what are the global and regional impacts of climatic instability?

New insights from ESMs reveal how key features of the Earth System are likely to respond in the future as global temperatures increase, or in a situation where achieving *net negative carbon dioxide emissions* (where carbon dioxide emissions are exceeded by the active removal of carbon dioxide from the atmosphere) brings global temperatures back down again. Changes in the behaviour of global climatic processes can have large-scale consequences due to abrupt Earth System changes and tipping points.

The stability and global climate impacts of key tipping elements

Greenland ice sheet: The melting of the Greenland ice sheet is a significant contributor to sea level rise and represents a critical tipping element in our Earth System.[25] Incorporating dynamic ice sheet changes into ESMs reveals how global warming will accelerate the melting of the Greenland ice sheet.[26] The ice sheet will continue to melt even once net zero carbon dioxide emissions are reached and global warming stabilises. This long-term legacy effect means that it is likely to continue to melt – albeit at a lower rate – even if carbon dioxide is removed from the atmosphere (net negative carbon emissions) and global warming is reversed.

Atlantic Meridional Overturning Circulation (AMOC): The AMOC is a system of ocean currents which, through its role in heat transport, is a key determinant of temperature and precipitation, particularly in Europe and Africa.[27] A collapse of the AMOC would likely result in decreased precipitation in heavily populated tropical monsoon regions[28], with devastating consequences for farming and agriculture.

Research finds that the AMOC will decline as temperatures continue to increase, though it may not fully collapse. The level of recovery of the AMOC when net zero carbon dioxide emissions are reached depends on the level of global warming reached and the specific ESM used. Even when global temperatures decrease the AMOC may not fully recover if total warming levels are high, and the speed of recovery is hard to estimate since it differs between ESMs. The AMOC is thus vulnerable to global warming and likely to experience greater perturbation as the level of warming increases.

Atmospheric Circulation: Atmospheric circulation is a key factor determining weather patterns and extreme weather events. New research reveals that atmospheric circulation will continue to change even after net zero carbon dioxide emissions are reached, with knock-on consequences for weather, including extreme weather events. Further work is needed to understand the drivers of these changes and to predict the specific impacts of different warming levels on weather patterns and extreme weather events.[29]

Low cloud feedback: Low clouds reflect sunlight away from the Earth, contributing to what is known as the planet's albedo (the amount of sunlight reflected back into space) and cooling the planet.[30] However, the strength of this cooling effect may be reduced by global warming[31], potentially increasing global temperatures more than predicted by levels of greenhouse gas emissions. Recent work identifies a record-low planetary albedo, mainly due to reduced low-cloud cover, as the dominant cause of the record high temperatures of 2023.[32]

Understanding changes in low cloud cover enables us to better predict levels of future warming. Recent work projected low cloud cover over a 60-year study period under the Shared Socioeconomic Pathway (SSP) 370[33], which combines relatively high radiative forcing (associated with greenhouse gas emissions, high aerosol emissions, and land use change) with high societal vulnerability[34]. The authors found that low (and mid-level) cloud cover decreased by around 2.5% over the study period. Though albedo is determined by multiple factors, including aerosol concentrations, these results suggest that the cooling effect of low cloud cover may decrease under global warming.

Would a stable global climate also imply stable regional climates?

The impacts of tipping points and abrupt Earth System changes may differ between regions. Early evidence from a recent systematic search and classification of abrupt changes using climate simulations found that the polar regions were most vulnerable to abrupt transitions, mainly due to regional sea ice collapses. Abrupt ocean circulation changes in the North Atlantic were also identified in the study.[35]

Notably, abrupt changes and transitions in some models occurred even when the simulated level of warming was held below 1.5°C.[36] If these tipping points are reached, we are likely to see severe impacts on regional climates. It is worrying, therefore, that some observational evidence suggests that the stability of several key Earth System components has decreased over the last century, making reaching and exceeding these tipping points (including the Greenland ice sheet, AMOC, and South American monsoon) more likely.

The stability of regional climates

Regional climates are likely to be unstable in the future. Insights from ESMs suggest that:

- As greenhouse gas emissions increase, European temperatures will likely increase more than the global mean temperature.
- When net zero carbon dioxide emissions are reached there is no consistent temperature signal across models, making it difficult to predict how European temperatures will change.
- European temperatures are predicted to decrease again when we have net negative emissions.[37]

Projecting temperature change in multiple European cities over the next 30 years also suggests that regional climates are likely to change. City-scale climate information is key to addressing the city-scale regional impacts of Earth system changes – the model used in this study is one of the first to enable this. The study found that most cities showed a decreased urban heat island effect (smaller temperature difference between a city and its surrounding area). However, some cities, such as Milan, showed the opposite trend. Causes for this contrasting behaviour and the specific urban factors that determine how a city's climate will evolve in the future are being investigated.[38]

Regional differences in climate change are therefore expected to be large, and cities and rural regions will show pronounced differences in their response to climate change.

Research Gaps

To ensure that climate change mitigation is effective, policymakers are best served by tools which integrate the knowledge and expertise of multiple disciplines, bridging gaps in understanding. To guide this, **understanding how human activities and the Earth System will interact and impact our climate in the future as levels of greenhouse gas emissions and sequestration change, and as climate tipping points are potentially reached, is key.**

We believe there would be benefit from developing advanced Earth system modelling and climate science to address the following needs:

1. **Monitoring progress,** including:
   - Continuing to quantify key indicators of global change to provide up-to-date information to inform evidence-based policy.
   - Improving our understanding of the factors resulting in recent record-warm years, including the role of clouds, aerosols, ocean feedbacks, and internal variability of the climate system (such as El Niño/La Niña events and natural forcings like volcanic activity).
2. **Improving our understanding about how the Earth System might respond to increasing and net negative emissions.** This includes designing climate strategies that deliver effective adaptation and mitigation despite diverse and persistent Earth system uncertainties.
3. **Improving our understanding about carbon dioxide removal,** including its effectiveness and reliability in a changing climate, as well as creating long-term structures to govern it.
4. **Improving our understanding about tipping points,** in particular **conducting a consultation on developing a tipping points risk register.** This would:
   - Highlight the key risks and their consequences for different parts of the world, aiming to provide a plausibility assessment of certain tipping points occurring at different warming levels.
   - Assess key features of the Earth System including the AMOC, Greenland Ice Sheet, West Antarctic Ice Sheet, and Amazon.
   - Aim to assess associated impact sectors, such as:
     - Human health (including heat stress and infectious diseases)
     - Ecosystems (including biomes and fire and biodiversity)
     - Food systems (including crop indices)
     - Water (including hydrological drought and flooding)
     - Infrastructure and Energy (including hydropower)
     - Marine and Coastal (including ports and marine heat waves, and storm surges)
     - Economy

TRANSLATION FOR POLICY

The goal of these six EU projects is to provide integrated research in support of climate policymaking. This requires ensuring that the science is presented in a format that is digestible for policy makers and audiences beyond the climate modelling community. Future projects should work on inter-project collaboration and ongoing engagement between researchers and policymakers. This is particularly important at the outset, research design phase and through the ongoing provision of key policy-relevant resources, for example:

i. Factsheets – Presenting the main concepts behind the science.

ii. Outlooks – Publishing key outcomes from projects.

iii. Science summaries – Highlighting relevant results and translating them for policymakers (such as the ZERO IN report series produced by CONSTRAIN[39]).

iv. Outreach material – Infographics, explainers, video content and so on.

v. Information platforms – Including data visualisation tools and portals.

Importantly, the production of these resources should be supported by dissemination and engagement efforts to reach relevant communities. This should involve researchers engaging with stakeholders and policymakers to understand their information needs and clarify timelines for input. Future projects should allocate adequate resources to take part in key national and international policy forums, meetings and policy debates.

PROJECTS

Box 3: The 6 projects contributing insights to this briefing

1. The ESM2025 project is building a new generation of Earth System Models (ESMs) to support the development of mitigation and adaptation strategies in line with the commitments of the Paris Agreement.
2. The ClimTip project assesses climate tipping points to inform global assessments (IPCC/IPBES), as well as climate adaptation and mitigation strategies.
3. The TipESM project aims to improve our understanding of climate tipping points in the Earth system in order to understand their impacts and the indicators and pathways that minimise the risk of exceeding these tipping points.
4. The OptimESM project seeks to understand the processes that drive the impacts of climate change and associated abrupt Earth system changes on regional and global scales using advanced digital technologies.
5. The RESCUE project investigates the environmental consequences of reducing greenhouse gas emissions to net zero and below to provide science-based policy-relevant recommendations on the future role of carbon dioxide removal.
6. The nextGEMS project builds storm- and eddy-resolving Earth System Models to advance science, guide policy, and inform applications to support the sustainable management of our planet.

Visit our websites for more information on each project:

ESM2025: https://www.esm2025.eu

ClimTip: https://www.climate-tipping-points.eu/

TipESM: https://tipesm.eu/

OptimESM: https://optimesm-he.eu/

RESCUE: https://www.rescue-climate.eu/

nextGEMS: https://nextgems-h2020.eu/

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- TipESM "Exploring Tipping Points and Their Impacts Using Earth System Models". Grant Agreement number: 101137673.
- OptimESM "Optimal High Resolution Earth System Models for Exploring Future Climate Changes". Grant Agreement number: 101081193.
- ClimTip "Climate Tipping Points: Uncertainty-aware quantification of Earth system tipping potential from observations and models and assessment of associated climatic, ecological, and socioeconomic impacts". Grant Agreement number: 101137601.
- NextGEMS "Next Generation Earth Modelling Systems". Grant Agreement number: 101003470.
- RESCUE "Response of the Earth System to overshoot, Climate neUtrality and negative Emissions". Grant Agreement number: 101056939.

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FURTHER READING

Senses Toolkit. Primer: Climate change Scenarios.

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ClimTip. Our key messages to the world: 13 Statements on the Science Basis of Climate Tipping Points and Implications and Policy Relevance

RESCUE Policy Brief (November 2024) New scenarios shed light on the role of carbon dioxide removal

TipESM. Factsheets and Infographics.

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