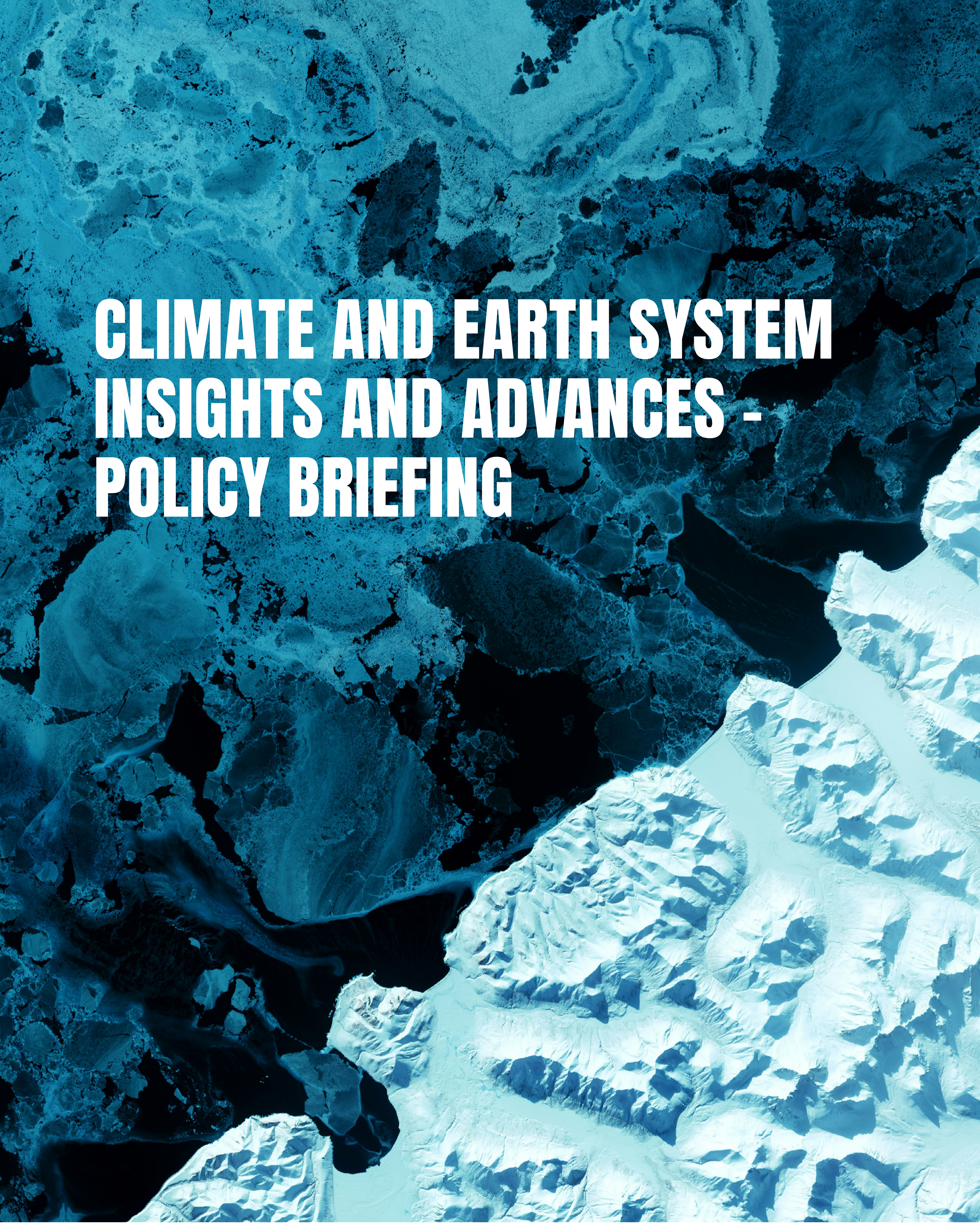


CLIMATE AND EARTH SYSTEM INSIGHTS AND ADVANCES - POLICY BRIEFING

4C Climate-Carbon Interactions in the Current Century

PROVIDE

CONSTRAIN
CONSTRAINING UNCERTAINTY OF MULTI-DECADAL CLIMATE PROJECTIONS

esm 2025 Earth System Models for the future

SUMMARY FOR POLICY MAKERS

Recent work in Earth Systems Modelling and climate research from four Horizon Europe funded projects – **ESM2025**, **CONSTRAIN**, **4C** and **PROVIDE** – has provided insights into how our climate system is responding to human-caused emissions of carbon dioxide (CO_2) and other greenhouse gases and aerosols. This work has provided important new findings:

1. **Carbon sinks may become less effective as the climate warms:** Global warming and associated changes in hydrology are possibly already reducing the efficiency of the current natural carbon sinks, meaning a higher proportion of emitted CO_2 remains in the atmosphere, which reinforces the warming. The Global Carbon Budget estimated that over the past decade the land carbon sink was about 20% less efficient and the oceans about 7%, contributing to warming being about 0.1°C higher than would have otherwise been the case.
2. **A revised 1.5°C carbon budget:** Most up-to-date estimates suggest the carbon budget to limit warming to 1.5°C with a 50% chance will be exhausted by 2030 at current annual levels of CO_2 emissions.
3. **The risks of climate overshoot:** Overshoot refers here to a climate strategy where global warming temporarily exceeds a long-term target such as 1.5°C before being reversed and brought back down below it. Research suggests a strong overconfidence in the narrative surrounding overshoot and its associated risks. Overshoot is still uncertain, particularly in terms of when it might happen, the availability and scalability of Carbon Dioxide Removal (CDR), whether warming will stop when net zero CO_2 is reached, and whether climate impacts are reversible. This overconfidence contributes to a lack of urgency in developing ambitious, policy-led mitigation action.
4. **The importance of reducing non-CO_2 greenhouse gases:** Methane has a shorter lifespan than CO_2 but is a more potent greenhouse gas. Near term warming can be significantly impacted by methane emissions. Pathways that limit warming to 1.5°C with no or limited overshoot reduce methane emissions by around 50% by 2050 relative to 2020 levels. Failing to achieve stringent methane reductions further reduces estimates of the remaining carbon budget in line with the Paris Agreement.

These developments have revealed a need for further research to better understand:

1. How the Earth system will continue responding to continuing or reducing CO_2 emissions, particularly how the carbon cycle and land and ocean mechanisms of carbon uptake will change with future warming.
2. What the climate impacts of overshooting 1.5°C of warming are compared to scenarios that avoid overshoot, and how mitigation benefits materialise over time as a function of CO_2 and non-CO_2 emissions.
3. Quantification of Earth system responses to negative emissions and different mitigation scenarios, including understanding whether climate impacts are reversible.
4. The differential impacts of incremental warming, particularly how local and regional climate impact drivers change with incremental warming (at 1.5°C, 1.6°C and higher levels of warming).
5. How mitigation and adaptation affect each other, with regional and sector-specific synergies and trade-offs, and how they benefit the planet and society.

INTRODUCTION

Through the Paris Agreement, countries collectively committed to keep warming well below 2°C and pursue efforts to limit it to 1.5°C above pre-industrial levels. Over the past decades, global emissions and temperatures have continued to increase, with global climate impacts consequently becoming more extreme and more frequent.

The 2023 UNEP emissions gap report[i] found that by following the pledged emissions reductions for 2030 known as National Determined Contributions (or NDCs), we are currently on track for a warming of 2.5-2.9°C above pre-industrial levels by the end of the century. As the window for limiting warming to 1.5°C is closing, the need to understand Earth system responses to increasing CO_2 levels and subsequent temperature increases becomes ever more important.

This briefing combines insights from four Horizon 2020 EU funded research projects: **ESM2025**, **CONSTRAIN**, **4C** and **PROVIDE**. These projects are all designed to provide policy relevant research to support or monitor the implementation of the Paris Agreement, as described in Box 1.

Below we highlight new research insights and remaining research gaps that need to be addressed to help identify effective and efficient pathways and responses to climate change.

NEW RESEARCH INSIGHTS

Together, the development of Earth Systems Modelling and climate change research have provided insights into how our climate system is responding to emissions of CO_2. Our research provides an improved assessment of:

1. **CO_2 levels, temperature rise and carbon sinks**

As atmospheric CO_2 levels increase, currently, so too does the uptake rate of CO_2 into the surface and deep ocean and land ecosystems (plants and soil). However, these carbon sinks are themselves affected by climate change and associated changes in hydrology. We estimate that the historical climate change is already reducing the land sink by around 20% and the ocean sink by around 7% (relative to a counterfactual scenario with no climate change).[ii]
This means a higher proportion of emitted CO_2 remains in the atmosphere, reinforcing the warming (by about 0.1°C).[iii]

This complexity results in a significant uncertainty around future warming trends, particularly for:

a. How ocean and land sinks will respond to cumulative warming and CO_2 levels.

b. How much warming can still be expected once global CO_2 emissions reach net zero levels.[iv]

Global average temperature is currently increasing at a rate proportional to annual CO_2 emissions, but how carbon sinks respond to cumulative warming and CO_2 levels will determine whether this linear relationship will continue, or whether there are thresholds beyond which the system might see an increased warming per unit of CO_2 emitted.[v] This will have significant implications for understanding the potential for warming beyond net zero CO_2 emissions.

2. **The impact of non-CO_2 greenhouse gases (GHGs)**

The mitigation of non-CO_2 GHGs (such as methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride) can contribute significantly to limiting or delaying the likelihood of overshooting 1.5°C. For example, the main difference in temperature evolution between the two IPCC scenarios with the least future warming is due to differences in non-CO_2 GHG.

Central estimates of the remaining carbon budget (the total amount of CO_2 that can still be emitted while keeping warming below a specific limit) are of the order of 250 $GtCO_2$ from 2023 onwards for limiting warming to 1.5°C with a 50% chance. This estimate assumes that methane emissions are also reduced as deeply as possible. Reductions in methane of around 50% by 2050 relative to 2020 levels, combined with the disappearance of polluting cooling aerosols, mean that non-CO_2 emissions could contribute an additional 0.1°C to future warming relative to 2010-2019 temperatures. Without ambitious non-CO_2 GHG emission reductions, however, the remaining carbon budget for CO_2 becomes smaller, with recent research suggesting that the carbon budget to limit warming to 1.5°C could already be exhausted without rigorous methane emission reductions. [vi, vii]

3. **Reaching 1.5°C and the risks of climate overshoot**

If and when we will reach 1.5°C depends on how quickly we reduce emissions and how Earth systems respond. At current emission levels, our studies suggest that we will exhaust the budget for a 50% chance of limiting warming to 1.5°C by 2030.[viii]

The implications of exceeding 1.5°C are still uncertain, and research suggests a potential overconfidence in the narrative surrounding overshoot pathways (where warming temporarily exceeds 1.5°C before being reversed and brought back down below this level) and the associated risks.[ix] This contributes to a lack of ambitious, policy-led mitigation action. The uncertainty around overshoot falls in several areas:

a. **Identifying if and when overshoot has begun:** The remaining carbon budget and Earth system models are tools that allow us to estimate if and when global warming will reach or exceed key warming limits such as 1.5°C or 2°C. However, it will only be possible to identify *with confidence* that the 1.5°C limit is reached and has been surpassed in hindsight. The precisions of estimates of global warming are limited by observations and the challenge of disentangling inter-annual variations from the long-term trend. The Paris Agreement temperature limits therefore refer to the long-term temperature average, measured over decades.

b. **The availability and scalability of Carbon Dioxide Removal (CDR) techniques:** currently there are significant uncertainties, as well as energy and other resource constraints associated with CDR, which influence the scalability and capacity of the techniques to capture and store CO_2 particularly in terms of Carbon Capture and Storage (CCS). Meanwhile, the permanence of nature-based CDR is uncertain. This challenges the realism of large-scale net negative CO_2 emissions required to reverse warming in overshoot scenarios.

c. **Whether or not warming will halt when net zero CO_2 is reached:** new research indicates that there is a risk that we could continue to see additional warming after net zero CO_2 emissions are reached due to a complex interplay of Earth system feedbacks requiring larger than anticipated negative emissions to reverse warming.

d. **The extent to which climate impacts can be reversed if temperatures are reduced:** many climate impacts may not "go back to where they were" if temperature comes down in the future; some will be irreversible over long timescales (such as species extinctions, sea-level rise or melting of glaciers).[x]

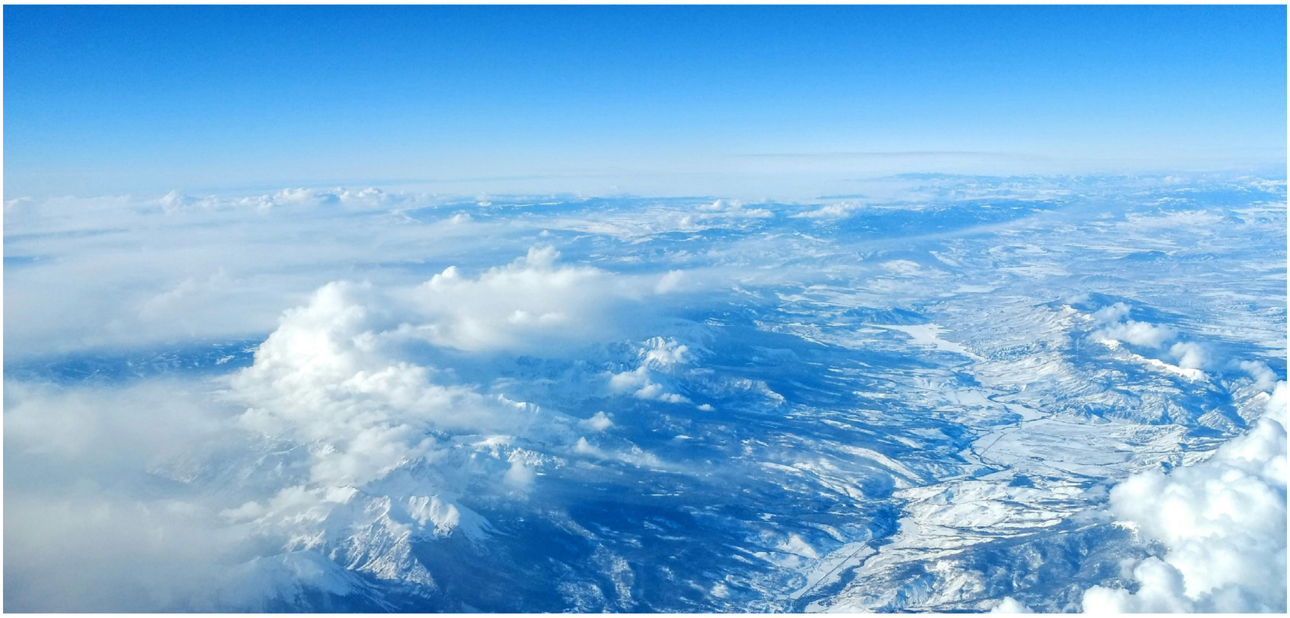
RESEARCH GAPS

Most climate modelling experiments to date have excluded uncertainties relating to the carbon cycle uncertainties by starting from the concentrations of greenhouse gases in the atmosphere instead of from emissions. To improve our understanding of the potential effectiveness of activities such as CDR and land-use policies, we need to **improve modelling experiments to better reflect the Earth system response to specific human activities, be they emissions, removals or land-use changes.**

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

1. **Gaining a better understanding of the near, medium and long-term response of land and ocean carbon sinks to increasing or decreasing atmospheric CO_2 levels and associated global warming through:**
   a. **Constraining the evolution of key processes in the coupled climate-carbon-cycle system** and quantifying how the amount of anthropogenic CO_2 emissions absorbed by carbon sinks will change in the future.
   b. **Understanding the dynamic response of the ocean and land carbon cycle** to negative emissions and declining atmospheric CO_2 in the context of overshoot scenarios.
   c. **Assessing the risk of irreversible changes in the carbon cycle** such as the release of carbon currently stored in permafrost or in tropical forests, or the export of carbon from the ocean surface to deeper ocean layers. This should include assessing risks under various overshoot pathways.
2. **Identifying the climate impacts of overshoot scenarios** and the global and regional implications for adaptation and loss and damage compared to scenarios that avoid overshoot.[xi]
3. **Quantifying Earth system responses to negative emissions and different mitigation scenarios,** including the potential rate of temperature change and what effects could be observed in response to mitigation action such as whether climate impacts are reversible.[xii]
4. **Simulating and analysing the effects of incremental warming, fractional degree changes to 1.5°C and beyond:** until now, much attention has been focused on studying the impacts at 1.5°C or 2°C of warming. However, smaller, fractional changes in warming rate and total warming can have significant implications for climate impacts and adaptation. We need to better understand differential impacts of incremental warming, particularly how local and regional climate impact drivers change with incremental warming (at 1.5°C, 1.6°C and higher levels of warming).
5. **Better characterising the effects and potential mitigation contributions of different GHGs and their interactions,** both in the near and long term[1].[xiii]
6. **Improving our understanding of how adaptation and mitigation interact and affect each other,** with regional and sector-specific synergies and trade-offs, and how their benefits for the planet and society could materialise over time.

Research of this kind will help to inform the development of more realistic emissions pathways and impact assessments; it can deliver not only quantifiable impact assessments of a range of emissions scenarios, but also provide a means for the analysis and visualisation of mitigation benefits in terms of avoided impacts and anticipation of adaptation requirements.



TRANSLATION FOR POLICY

The goal of these four 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 policy makers. This is particularly important at the outset, research design phase and through the ongoing provision of key policy-relevant resources, for example:

a. **Factsheets –** Presenting the main concepts behind the science.
b. **Outlooks –** Publishing key outcomes from projects.
c. **Science summaries –** Highlighting relevant results and translating them for policymakers (such as the ZERO IN report series produced by CONSTRAIN[xiv]).
d. **Outreach material –** Infographics, explainers, video content and so on.
e. **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. Future projects should allocate adequate resources to take part in key national and international policy forums, meetings and policy debates.

PROJECTS

1. The **CONSTRAIN** project has recently finished, having been focused on understanding the impact of natural and human-caused changes to the climate system driven by both CO_2 and non-CO_2 GHG emissions, specifically highlighting the next few decades.
2. **4C**, which has just concluded, aimed to better understand the climate response to increasing CO_2 emissions, with focus on the carbon cycle and the future efficiency of land/ocean carbon sinks.
3. **ESM2025** is developing a new generation of Earth System Models (ESMs) to assess global climate impacts and various mitigation scenarios.
4. **PROVIDE** gives an assessment of the risks associated with overshooting a global temperature increase of 1.5°C and the associated reversible or irreversible impacts as well as adaptation needs.

Visit our websites for more information on each project:

CONSTRAIN: www.constrain-eu.org

4C: 4c-carbon.eu

ESM2025: www.esm2025.eu

PROVIDE: www.provide-h2020.eu

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REFERENCES AND FURTHER READING

i. United Nations Environment Programme (2023). Emissions Gap Report 2023: Broken Record – Temperatures hit new highs, yet world fails to cut emissions (again). Nairobi. **https://doi.org/10.59117/20.500.11822/43922**.

ii. Friedlingstein, P. *et al.* **Global Carbon Budget 2023**. *Earth System Science Data.* 15, 5302-5369 (2023).

iii. Jones, C.D. and Friedlingstein, P. **Quantifying process-level uncertainty contributions to TCRE and carbon budgets for meeting Paris Agreement climate targets.** *Environmental Research Letters*, *15*(7), p.074019 (2020).

iv. Palazzo Corner, P. *et al.* **The Zero Emissions Commitment and climate stabilization**. *Frontiers in Science.* 1, 1-26 (2023).

v. 4C, **Policy Brief: Science needs to help reduce persistent uncertainties in climate projections**. (2023).

vi. IPCC (2023) Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35-115, doi: **10.59327/IPCC/AR6-9789291691647**.

vii. Rogelj, J; Lamboll, R, D. **Substantial reductions in non-CO_2 greenhouse gas emissions reductions implied by IPCC estimates of the remaining carbon budget**. *Communications in Earth & Environment*. 5(35), (2024).

viii. Lamboll, R, D. et al. **Assessing the size and uncertainty of remaining carbon budgets**. *Nature Climate Change*. 13, 1360-1367 (2023).

ix. Schleussner, C. et al. **Overconfidence in climate overshoot**. *ESS Open Archive.* (2023).

x. PROVIDE. Deliverable 4.1: **Four review reports on key overshoot adaptation challenges in Iconic Regions and Cities**. (2022).

xi. ibid.

xii. ESM2025. **From Earth System Models to Integrated Assessment models: Bridging the gap in climate modelling**. (2023).

xiii. Ibid.

xiv. **ZERO IN** report series, CONSTRAIN.