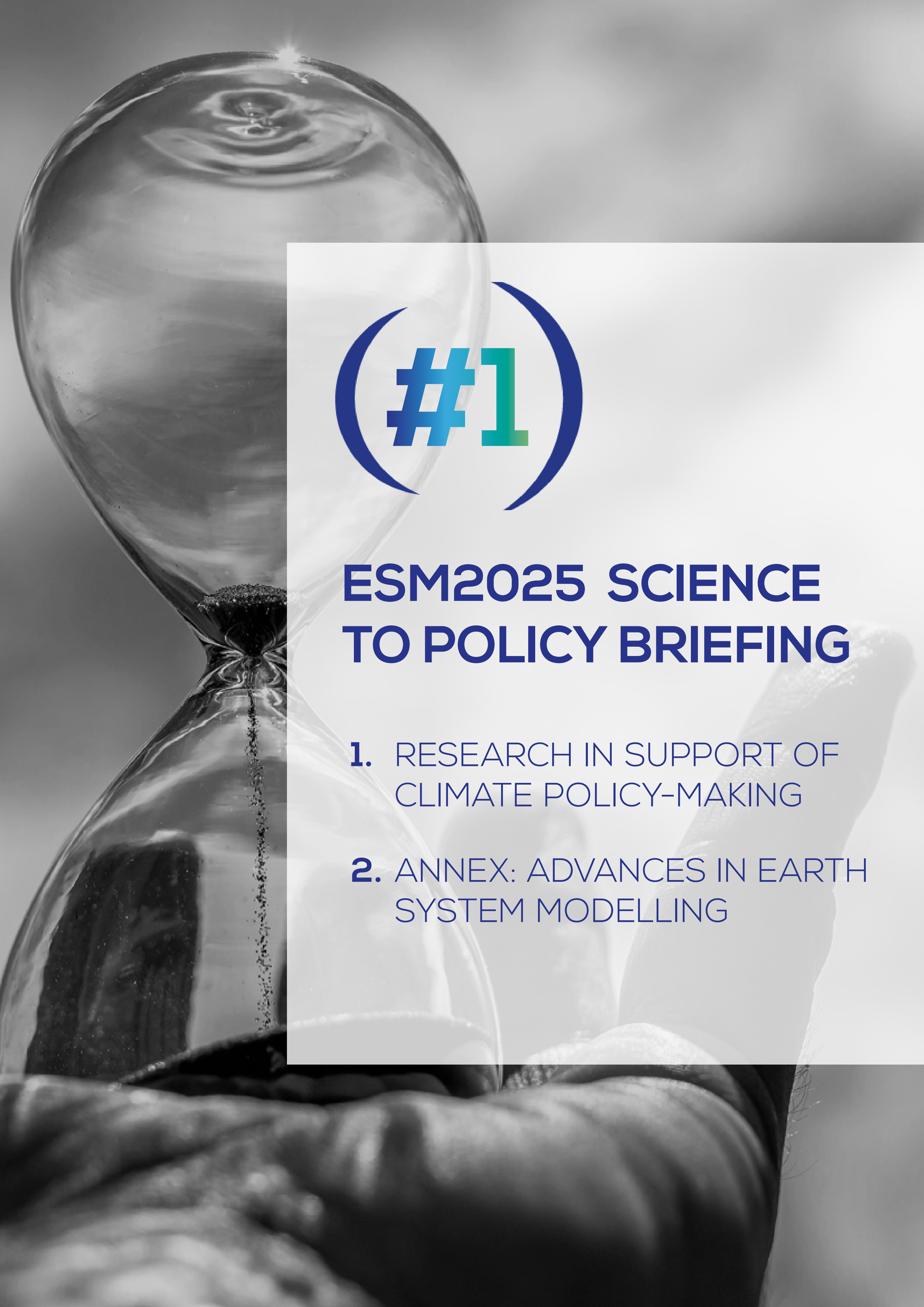

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ESM2025 SCIENCE TO POLICY BRIEFING

1. RESEARCH IN SUPPORT OF CLIMATE POLICY-MAKING
2. ANNEX: ADVANCES IN EARTH SYSTEM MODELLING

KEY MESSAGES

- ESM2025 addresses key limitations in current Earth System Models to enable an improved assessment of the climate outcomes of realising the Paris Agreement, and the potential consequences of exceeding the Paris temperature-targets.

- ESM2025 will assess the robustness of published mitigation pathways for meeting the Paris Agreement, including: exploration of the potential for continued warming after net zero emissions are reached; minimisation of climate risks in mitigation strategies; and the effectiveness of planned carbon dioxide removal measures (with a focus on land-based practices – e.g., bioenergy with carbon capture and storage or afforestation/reforestation).

- ESM2025 will provide new knowledge on the co-benefits and trade-offs inherent in a range of policies targeting climate change mitigation and future air quality.

esm 2025 Earth System Models for the future

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RESEARCH IN SUPPORT OF CLIMATE POLICY-MAKING

The Horizon 2020 EU project, **ESM2025, develops a new generation of Earth System Models tailored to supply policy-relevant information to support implementation of the Paris Agreement.**

A first stakeholder forum was held in October 2021, where current research priorities for climate policy were discussed. This briefing explores the questions raised during that first forum, detailing the contribution of ESM2025 to each of the following policy-relevant topics:

- **A. The impact of climate change at both global and regional scales;**
- **B. Long-term mitigation pathways and the need for negative emission technologies and nature-based mitigation solutions;**
- **C. The role of ESM2025 in international research initiatives such as the next phase of the Coupled Model Intercomparison Project (CMIP7).**

Throughout the project, ongoing dialogues with the stakeholder community will shape future policy-briefings, and help ensure ESM2025 fully supports policy needs.

What is ESM2025?

ESM2025 is an ambitious European research project that will build a new generation of Earth System Models designed to support the development of mitigation and adaptation strategies, in line with the goals of the Paris Agreement.

The project has two core scientific activities: **improving Earth System Models** and **establishing synergies between these models and other climate research communities** that use different modelling platforms to address their research questions (such as Integrated Assessment Models and Simple Climate Models). **Its goal is to produce a more reliable and policy-relevant set of ESMs and associated future climate projections, to contribute to more robust climate policy.**

Beyond climate research, the project will create **new, policy-relevant scientific knowledge** and contribute to the **development of innovative climate education** for European students and citizens.

A. AN IMPROVED ASSESSMENT OF CLIMATE CHANGE IMPACTS

A.1. Global warming, the risk of overshooting temperature targets and tipping points

ESM2025 will deliver **an improved assessment of future global warming associated with successful implementation of the Paris Agreement.** This includes **an improved assessment of climatic impact drivers** (such as regional temperature and rainfall) at **1.5°C and 2°C global warming**, and of the **consequences of temporarily exceeding the Paris temperature limits** for the severity and potential reversibility of any resulting climate impacts.

The new generation of ESM2025 models will simulate a more comprehensive range of processes and process-interactions that will significantly improve our ability to assess the climate response to anthropogenic greenhouse gas (GHG) emissions in a holistic manner, across a range of spatial and temporal scales. The new models will also enable **an improved assessment of the likelihood and consequences of triggering important climate tipping points**, such as **permafrost-thaw,** Greenland and Antarctica **ice sheets collapse** or **tropical forest dieback**.

A.2. A more comprehensive assessment of climate impacts

Global-scale information provided by the new generation of ESMs will provide **critical input to regional climate assessments** exploring climate risks and adaptation strategies. Through collaboration with relevant international research communities, **climate-relevant information will be delivered** for a range of climate impacts, including multi-driver compound events: **extreme precipitation events, flooding, sea-level rise, heatwaves, droughts, wildfires,** and their impact on **vegetation.**

New findings will inform the research community beyond the project, as well as support ongoing and future research into a range of High-Impact Low-Likelihood events (e.g., megafires or ice shelf collapse), **enabling the development of new knowledge for risk assessment and adaptation planning.**

A.3. New knowledge to support climate change mitigation and future air-quality policies

The improvement of key components of the ESM2025 Earth System Models will pave the way for new synergies with the air-quality research community, **enriching the assessment of the co-benefits and trade-offs of policies targeting climate change mitigation and future air quality.**

In particular, the representation of atmospheric chemistry in the new generation of ESMs will deliver policy-relevant knowledge on how different greenhouse gas mitigation strategies interact with air pollution strategies, **framing potential win-win strategies, with important benefits for human health.** This includes the assessment of strategies targeting methane and nitrous oxide emissions, or the development of a hydrogen economy, and their impact on regional air quality; as well as the assessment of the risks of compound extreme events in which heat, humidity and air pollution extremes occur simultaneously.

The multiple modelling frameworks of ESM2025

One of the key aspects of ESM2025 is the use of **multiple modelling frameworks,** and the creation of bridges between different research communities.

Earth System Models extend physical Global Climate Models. They represent the **physics of the atmosphere and ocean** (e.g., winds, clouds, ocean circulation). In addition, they include numerical representations of key **global biogeochemical cycles, such as the carbon and nitrogen cycles,** as well as **representations of vegetation and land use, atmospheric chemistry, ocean ecology and continental ice sheets,** with all of these processes interacting with each other. Such developments enable a more complete assessment of the full **Earth system's response to anthropogenic GHG emissions and human land use.**

Integrated Assessment Models (IAMs) **are targeted policy models.** They are used to generate future GHG emissions scenarios as a function of different societal choices. Currently, these scenarios are **used in ESMs to generate climate change projections consistent with each emission scenario,** along with resulting climate impacts and the assessment of potential mitigation strategies. Likewise, climate information on the remaining carbon budgets to stay below 1.5°C and 2°C global warming are used in IAMs to define future climate policy.

IAMs simulate the dynamics of the global economy, energy and land-use systems, but include only a simplified representation of the climate system (and potential feedbacks back onto the economy).

Simple Climate Models, also known as climate emulators, **provide a simplified representation of the Earth system.** They are designed to rapidly emulate the response of a large ensemble of more complex ESMs. These models are routinely used in climate assessments to explore a wide range of emission scenarios, as they are able to rapidly integrate multiple lines of evidence into their projections (such as theoretical or observational constraints).

ESM2025 will bridge the gap between these three modelling platforms, ensuring an improved consistency between ESMs and IAMs for assessing the impacts of climate change and the potential mitigation strategies underpinning future GHG emissionsscenarios.

B. AN IMPROVED ASSESSMENT OF LONG-TERM MITIGATION PATHWAYS

ESM2025 will scrutinise the robustness of current published mitigation pathways for meeting the Paris Agreement temperature-targets.

B.1. Improved estimates of the remaining carbon budgets for limiting global warming to 1.5°C and 2°C and future warming commitment at net-zero

The project aims to improve the simulated **response of future warming to emissions of both CO_2 and non-CO_2 greenhouse gases.** Integrating this knowledge with expertise on long-term societal transformation pathways, ESM2025 will deliver an **improved estimate of the remaining carbon budget** (for limiting warming to below the Paris temperature-targets), a key geophysical constraint on future mitigation pathways and climate policy.

It remains uncertain how much warming can be expected once GHG emissions reach net-zero levels. Estimates of what will happen in such a situation depend on trade-offs between the distribution of energy and carbon across different components of the Earth system. The new generation of ESM2025 emission-driven models will improve this estimation with direct consequences for net-zero scenarios targeting the Paris Agreement (see Annex). Hence, the project will provide **novel insights into the consequences and risks of different net zero strategies and their timing.**

B.2. The necessity and feasibility of negative emission technologies

Bringing together Earth system and integrated assessment modelling teams, ESM2025 will contribute to the development of **new robust deep mitigation pathways,** in line with the Paris Agreement, that consider the **necessity and feasibility of negative emissions measures,** such as the production of bio-energy with carbon capture and storage, afforestation or direct air carbon capture and storage.

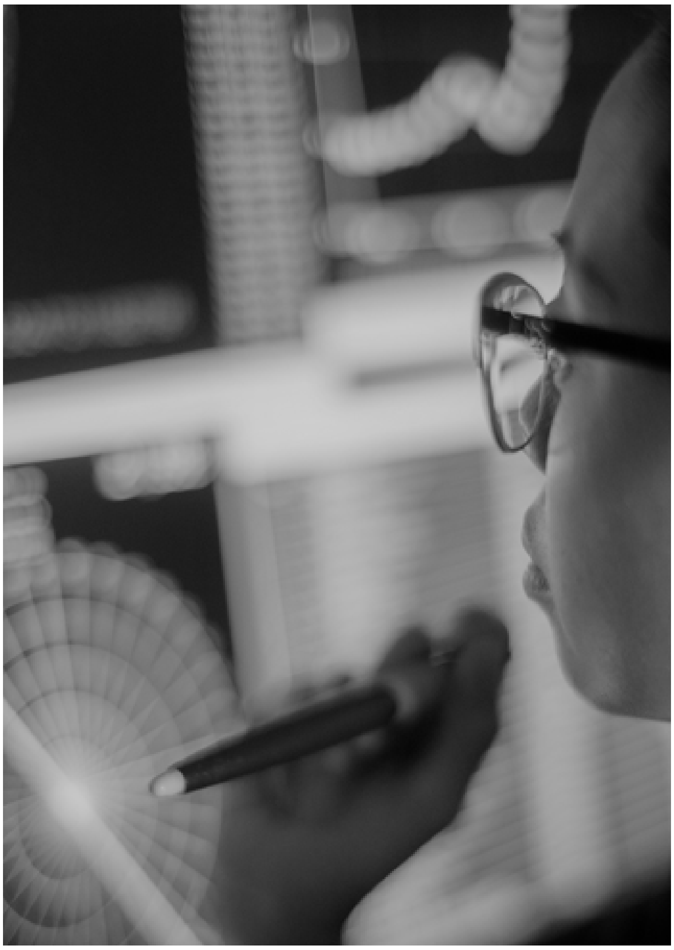
By improving the representation of land use and land management in the ESM2025 models, significant advances will be made in the **assessment of land-based mitigation strategies,** their impact on the climate system, and the risk of trade-offs between those strategies and other land-based activities, such as food production and water availability.

C. ESM2025: AN IMPORTANT EUROPEAN CONTRIBUTION TO CMIP7

CMIP (the Coupled Model Intercomparison Project), coordinated by the World Climate Research program (WCRP), brings together climate and Earth system modelling groups from across the world to perform a range of coordinated experiments addressing key scientific and policy questions. CMIP has now run over six phases, with each one targeting climate model improvement and the support of national and international climate change assessments. The next phase of CMIP (CMIP7) is expected to start around 2025.

ESM2025 will contribute to CMIP7 through several routes. First, by significantly **improving five European Earth system models** in advance of their use in CMIP7, where these improved models **will play a leading role in answering key science and policy questions.** This new generation of models will deliver a more complete simulation of the full Earth system response to emissions of CO_2 and other greenhouse gases, as well as to land use change, in contrast to CO_2 concentration-driven models that have dominated previous CMIP activities over the past decades. The resulting future projections will thus have greater direct policy relevance and will better inform mitigation strategies and risk assessment.

Second, by bringing together Earth system and integrated assessment modelling teams to work on the development of a new CMIP framework, the project will **facilitate cross-community research,** helping to break down existing barriers between climate change research communities (and corresponding IPCC Working Groups).



ANNEX: ADVANCES IN EARTH SYSTEM MODELLING

This associated annex provides the scientific background to the above policy brief "ESM2025: Research in support of Climate Policy-making", which describes how ESM2025 will support delivery of the Paris Agreement through science to policy guidance on the following topics:

A. **The impact of climate change at global and regional scales;**

B. **Long-term mitigation pathways, negative emission technologies and nature-based strategies;**

C. **The role of the ESM2025 community in international Research initiatives such as the next phase of the Coupled Model Intercomparison Project (CMIP7).**

The research plans described in this document are essential steps to deliver science-based support for these policy needs.

TACKLING KEY SOURCES OF UNCERTAINTY

Many of the core uncertainties in global mitigation pathways and optimal net-zero strategies still need to be assessed, with several of these strategies still at the very early stages of development. These core uncertainties depend on how the atmosphere, land, ocean, cryosphere and their interaction occur across the Earth system and are modelled within Earth System Models (ESMs).

ESM2025 aims to tackle uncertainties surrounding:

Atmospheric processes - by improving the **representation of aerosols** and aerosol precursors (such as nitrogen dioxide, sulphur dioxide, carbon monoxide and formaldehyde) in ESMs, with a focus on the interaction of aerosols with clouds (microphysics and radiation).

Land processes - by improving the **representation of the biogeochemical cycling of carbon and nitrogen** (the exchanges of carbon and nitrogen between living things and their environment), with an emphasis on nutrient control of land carbon uptake.

Ocean processes - by improving the **representation of small-scale ocean mixing** and **marine biogeochemical cycling of carbon and nitrogen.**

Cryosphere processes: by improving the **representation of Antarctic and Greenland ice-sheets** and their interaction with the oceans.

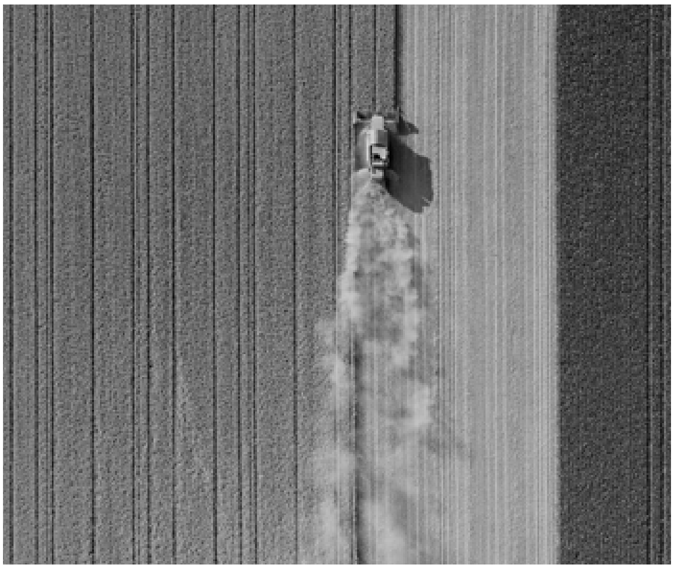
The development of ESM parameterizations ("simplified representations of complex processes") is a fundamental activity of ESM2025. The above research will support policy objectives A, B and C.

TOWARDS EMISSION-DRIVEN EARTH SYSTEM MODELS

Current ESM experiments generally prescribe atmospheric concentrations of both CO_2 and non-CO_2 greenhouse gases (GHG). As a result, a range of Earth system feedbacks that may alter the future atmospheric concentration of these gases are not included. This has multiple limitations, both for estimating remaining carbon and other GHG budgets, and for quantifying the climate outcomes associated with comprehensive net-zero strategies.

To overcome these limitations, **ESM2025 will develop an emission-driven Earth System Modelling framework, where the concentration of both CO_2 and non-CO_2 gases in the atmosphere** (e.g., methane, nitrous oxides, aerosols and other gases) **are internally simulated by the models.** These models will express more explicitly the links between climate change mitigation strategies, emission reductions, and climate change responses and impacts.

The development of a new emission-driven ESM framework will deliver new knowledge to support policy objectives B and C.



IMPROVED REPRESENTATION OF LAND-USE IN ESMS AND IAMS

Current ESMs have not been used systematically to assess the effectiveness of carbon sequestration as a climate mitigation measure. Moreover, existing scenario frameworks do not represent how land-use mitigation is impacted by climate change or if these measures themselves alter local to regional climate. This is of particular importance for nature-based solutions (e.g., afforestation/reforestation). At the same time, current IAMs (which define the socioeconomic mitigation scenarios that underpin future GHG emission scenarios) poorly represent key Earth system processes, such as water and nutrient availability, or interactions between land use and climate.

The current modelling paradigm of ESMs and IAMs renders the representation of both land and land use inconsistent across the full model chain, raising questions about the feasibility of stringent mitigation pathways that employ a massive deployment of nature-based solutions.

ESM2025 will **improve the representation of land-use and land-based mitigation strategies** (e.g., biomass energy production with carbon capture and storage) **in both ESMs and IAMs by including state-of-the-art parameterizations** (“representations”) **of human land-use in the new generation of ESMs** and **by enhancing the consistency of land and land-use modelling across ESMs and IAMs.**

Improving the representation and consistency of land and land-use processes across ESM and IAM modelling platforms will support the policy objectives B and C.

ACKNOWLEDGEMENTS

This report has been prepared by: Roland Séférian, Mariana Rocha and Anna Vermunt (Météo France/CNRM); Hazel Jeffery and Colin Jones (University of Leeds); Katrine Petersen and Joeri Rogelj (Imperial College London); Ben Sanderson (CICERO); and Chris Jones (MetOffice).

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