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Bringing it all together: Science and modelling priorities to support international climate policy.

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Abstract. We review how the international modelling community, encompassing Integrated Assessment models, global and regional Earth system and climate models, and impact models, have worked together over the past few decades, to advance understanding of Earth system change and its impacts on society and the environment, and support international climate policy. We then recommend a number of priority research areas for the coming ~6 years (i.e. until ~2030), a timescale that matches a number of newly starting international modelling activities and encompasses the IPCC 7th Assessment Report (AR7) and the 2nd UNFCCC Global Stocktake. Progress in these areas will significantly advance our understanding of Earth system change and its impacts and increase the quality and utility of science support to climate policy.

We emphasize the need for continued improvement in our understanding of, and ability to simulate, the coupled Earth system and the impacts of Earth system change. There is an urgent need to investigate plausible pathways and emission scenarios that realize the Paris Climate Targets, including pathways that overshoot the 1.5°C and 2°C targets, before later returning to them. Earth System models (ESMs) need to be capable of thoroughly assessing such warming overshoots, in particular, the efficacy of negative CO_2 emission actions in reducing atmospheric CO_2 and driving global cooling. An improved assessment of the long-term consequences of stabilizing climate at 1.5°C or 2°C above pre-industrial temperatures is also required. We recommend ESMs run overshoot scenarios in CO_2-emission mode, to more fully represent coupled climate - carbon cycle feedbacks. Regional downscaling and impact models should also use forcing data from these simulations, so impact and regional climate projections are as realistic as possible. An accurate simulation of the observed record remains a key requirement of models, as does accurate simulation of key metrics, such as the Effective Climate Sensitivity. For adaptation, improved guidance on potential changes in climate extremes and the modes of variability these extremes develop in, is a key demand. Such improvements will most likely be realized through a combination of increased model resolution and improvement of key parameterizations. We propose a deeper collaboration across modelling efforts targeting increased process realism and coupling, enhanced model resolution, parameterization improvement, and data-driven Machine Learning methods.

With respect to sampling future uncertainty, increased collaboration between approaches that emphasize large model ensembles and those focussed on statistical emulation is required. We recommend increased attention is paid to High Impact Low Likelihood (HILL) outcomes. In particular, the risk and consequences of exceeding critical tipping points during a warming overshoot. For a comprehensive assessment of the impacts of Earth system change, including impacts arising directly from specific mitigation actions, it is important detailed, disaggregated information from the Integrated Assessment Models (IAMs) used to generate future scenarios is available to impact models. Conversely, methods need to be developed to incorporate potential future societal responses to the impacts of Earth system change into scenario development.

Finally, the new models, simulations, data, and scientific advances, proposed in this article will not be possible without long-term development and maintenance of a robust, globally connected infrastructure ecosystem. This system must be easily accessible and useable across all modelling communities and across the world, allowing the global research community to be fully engaged in developing and delivering new scientific knowledge to support international climate policy.

1 Introduction

Given the rapidly developing climate crisis, and the negative consequences for planetary habitability and human well-being, there is an increasing need for accurate, reliable, and actionable information encompassing the full spectrum of climate risk. This information is required at global to local scales, near to long timescales, and must be tailored to inform critical decision-making related to climate change mitigation and adaptation (e.g., in the context of UNFCCC negotiations, the UNFCCC Global Stocktake, IPCC assessments, and the World Adaptation Science Program; WASP), as well as the growing needs of climate service providers. Over the past few decades, coordinated by the World Climate Research Program (WCRP), the international modelling community has worked together to contribute simulations, data and knowledge to support decision making, in particular the cyclical IPCC Assessment Reports (AR). This has been achieved through a suite of interconnected modelling projects and initiatives, with the most important of these listed in Table 1, along with project acronyms and citations.

With a new IPCC AR cycle (AR7) beginning, it is timely to review how the international modelling community has supported climate policy needs in the past, including earlier AR cycles, and ask what advances can be made in the overall quality and availability of science to support policy needs. In addition, it is also pertinent to review our current understanding of, and ability to model, coupled Earth system change, as well as the societal and environmental impacts associated with this change and ask whether plausible, safe future pathways for the Earth system can be developed that avoid the worst impacts of this change. In addition to a new IPCC AR7 cycle, many of the international projects listed in Table 1 that provide the scientific knowledge on which IPCC reports are based, are starting new cycles. For example, CMIP7 is beginning to take shape and will likely run through to ~2030. Assuming these approximate timescales (i.e. from now to ~2030, which encompass the IPCC AR7 cycle and the next UNFCCC Global Stocktake), we outline a number of areas where we believe the international modelling community can significantly advance our understanding of, and ability to model, past and future Earth system change, including the impacts of these changes, and develop scientifically robust options for mitigation pathways that limit long-term global warming and its impacts to acceptable levels. Such developments will deliver enhanced scientific support to international climate policy, during and beyond AR7. The advances we propose cannot be realized without the *maintenance, expansion* and *integration* of a robust and interconnected infrastructure ecosystem. Such an infrastructure has underpinned past international modelling collaborations and is a fundamental requirement for realizing the ambitious goals outlined below. The specific science, and science for policy, ambitions, as well as the underpinning infrastructure, are discussed in more detail below. The ambitions arising from each can be summarized by the following key goals:

- **A coordinated, internally consistent set of simulations, data, and knowledge to support IPCC assessments and international climate policy.** The resulting data sets and knowledge will be based on the most up to date, and consistent, set of Integrated Assessment Model (IAM) socio-economic, mitigation, emission and land-use scenarios, global and regional Earth system model projections, and the simulated impacts, on society and the environment, associated with the Earth system change and arising directly from mitigation actions implemented in the IAM scenarios.

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- **Improving understanding and guidance on future Earth system change, allowable emissions, net-zero responses, and safe landing pathways for planet Earth.** Ensure global and regional ESMs, IAMs, and impact models include the required level of process and feedback realism and forcing data to accurately simulate the response of the Earth system, and of societies and the environment, to future socio-economic, mitigation, emission, and land-use scenarios. Develop and analyse a range of safe future pathways that realize the Paris Climate Targets while minimizing negative impacts on the Earth system and society.

- **Improving our understanding of, and ability to simulate key physical climate processes, climate variability, extreme events and regional impacts.** Ensure global and regional climate models accurately represent key physical processes, couplings, modes of variability and feedbacks that underpin global to regional climate change, and deliver robust and detailed projections of regional climate change, including extreme events. Ensure aggregated, coarse scale IAM mitigation and scenario data is disaggregated and combined with climate projection data to support national to regional scale impact assessment, adaptation planning and climate services.

- **Increasing collaboration across approaches to improve global and regional Earth system and climate models.** Ensure strong collaboration across efforts to; increase process realism and couplings in ESMs, increase model resolution and improve physical parameterizations in climate models, and data driven Machine Learning (ML) hybrid-modelling approaches. Ensure the benefits from each of these development paths are optimally combined to support the next generation of Earth system models.

- **Improving model simulations of the observational record and key metrics of climate change.** Ensure improvement in simulations of the historical climate evolution, particularly historical global and regional warming, encompassing forcing, processes, and feedbacks determining the observed rate of warming. Improve our ability to constrain and simulate key climate change metrics, such as the Effective Climate Sensitivity (EffCS), Transient Climate Response (TCR), the Transient Climate Response to cumulative CO_2 Emissions (TCRE) and the Regional Warming to Global Warming ratio (RW/GW)

- **Sampling and quantifying future uncertainty.** Develop and apply a hierarchy of models and methods to efficiently sample the range of uncertainty inherent in future Earth system change and its impacts, to ensure regional and national scale adaptation is informed by a more complete sampling of the range of potential climate futures, including rare (high impact, low likelihood) outcomes, their local climate signature, and the consequences of these for society, the natural environment and climate policy.

- **The underpinning technological infrastructure.** Further develop and maintain a robust, globally inter-connected infrastructure ecosystem to ensure efficient production and exploitation of internally consistent model simulations, rapid and reliable sharing of data, knowledge and analysis tools across multiple projects, models, and modelling communities, as well as with the global research community, policymakers, planners, and climate services.

Acronym	Initiative or project name	Website	Main themes	Citation
IAMC	Integrated Assessment Modelling Consortium	https://www.iamconsortium.org	Future socio-economic pathways, emission and land use scenarios	Moss et al., 2010
WCRP CMIP	Coupled Model	https://wcrp-cmip.org/	Earth system and Global Climate	Eyring et al., 2016

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	Intercomparison Project		modelling	
ScenarioMIP	ScenarioMIP	https://wcrp-cmip.org/model-intercomparison-projects-mips/scenariomip/	Further develop IAM scenarios into emission, concentration and land-use scenarios for CMIP and CORDEX.	O'Neill et al., 2016
WCRP CORDEX	Coordinated Regional Downscaling Experiment	https://cordex.org	Regional climate downscaling	Giorgi et al., 2009
VIACS AB	Vulnerability, Impacts, Adaptation & Climate Services Advisory Board	https://viacsab.gerics.de/	Advisory body for linking CMIP and CORDEX to the impacts and climate services communities	Ruane et al., 2016
ISIMIP	Inter-Sectoral Impact Model Intercomparison Project	https://www.isimip.org	Global and regional impact modelling for multiple sectors	Frieler et al., 2017
ESGF	Earth System Grid Federation	https://esgf.llnl.gov/	Data curation and distribution system for CMIP and CORDEX	Balaji et al., 2018

Table 1. Examples of the main international projects contributing to the provision of simulations, data and scientific knowledge to support climate policy, particularly IPCC assessment reports, including a main reference for each activity. CMIP and CORDEX are coordinated by the World Climate Research Program.

2 A coordinated, internally consistent set of simulations, data, and knowledge to support IPCC assessments and international climate policy.

The process by which the aforementioned activities have, in the past, delivered data and knowledge into the science and policy arena is summarized in Fig. 1. Integrated Assessment Models (IAMs) develop a range of future global pathways, based on narratives for socio-economic, political, and technological development, as well as climate policy, which for methodological reasons do not (yet) consider the impacts of climate change. These pathways are typically quantified in terms of highly aggregated information on future population and economic development, energy and food system development, and environmental consequences. For each pathway, marker anthropogenic emission and land-use scenarios are selected (van Vuuren et al., 2011; O'Neill et al., 2016; Riahi et al., 2017). These scenarios are combined with observation-based estimates for the historical past, resulting in a time series of emission and land use data covering ~1850 to 2100 (Hurtt et al., 2011; Gidden et al., 2019). Using simple climate models (e.g. MAGICC; Meinshausen et al., 2011) and chemistry-climate models (Lamarque et al., 2011), the emissions are converted into atmospheric concentration time series. The concentration timeseries, along with the land-use scenarios, are used to "force" ESMs in CMIP to investigate potential changes in the Earth system arising from each scenario. The ESMs deliver time-varying, spatially discrete estimates of the past and future evolution of the Earth system, sampling the range of available emission/concentration scenarios (Tebaldi et al., 2021). CMIP simulations are extensively used to inform policy addressing global climate change risks and are also made available to the international research community via the ESGF, where they are used to increase understanding of Earth system change and highlight areas requiring further model improvement.

CMIP simulations are used as boundary forcing for regional downscaling (CORDEX) to provide climate information at spatial scales relevant for adaptation policy and climate services, as well as to drive impact model simulations (e.g. crop models in AgMIP (Ruane et al., 2017), fisheries and marine ecosystem models in FishMIP (Tittensor et al., 2018), and a range of impact models (e.g. addressing biomes changes, water resources, human health, energy systems and biodiversity) contributing coordinated simulations to ISIMIP (Frieler et al., 2017)). Regional downscaling follows two main pathways; (i) regional climate models (RCMs) generate high-resolution regional simulations consistent with the ESM boundary condition

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data (Ruti et al., 2016; Jacob et al., 2020; Teichmann et al., 2021) and (ii) statistical downscaling combines observations and models to translate large-scale features simulated by the ESMs to high-resolution, local scale climate information (Gutiérrez et al., 2018; Lange, 2019; Karger et al., 2023). Impact models use both CMIP and CORDEX climate data, as well as socio-economic data and information on mitigation actions from the IAM scenarios (e.g. population distributions and land use patterns that include information on mitigation measures), as forcing to assess the societal and environmental impacts arising from the range of simulated futures (Frieler et al., 2017).

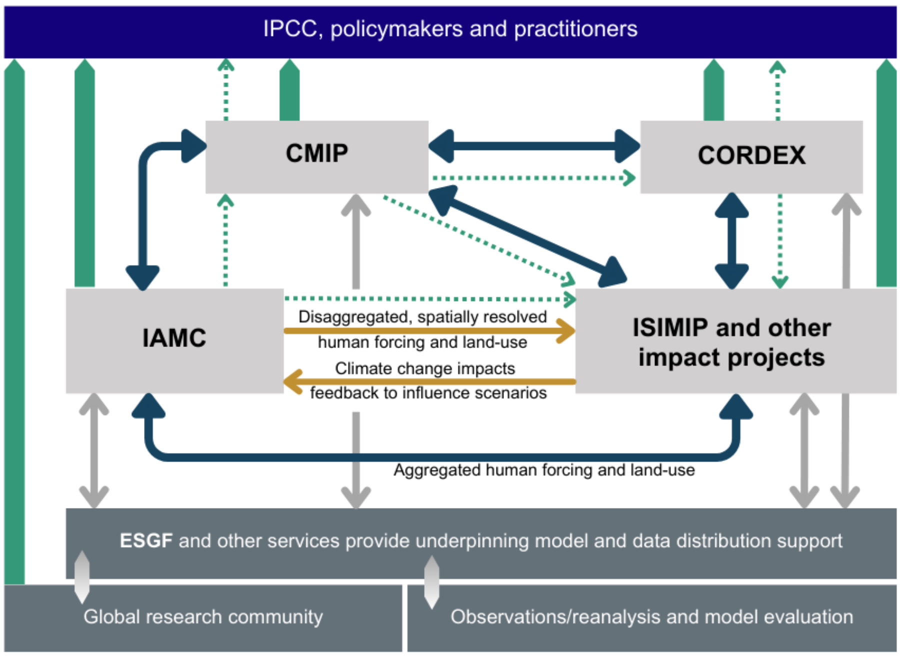

Figure 1: A schematic illustration of how earlier rounds of IAMC, CMIP, CORDEX and impact modelling activities, such as ISIMIP, have worked together to develop and apply future socio-economic and emission scenarios (IAMC), increase the scientific understanding of, and ability to simulate the coupled Earth system (CMIP and CORDEX), and investigated the impacts of Earth system change on societies and the natural environment (ISIMIP etc). In the figure dark blue lines illustrate the main (generally two-way) exchanges of scientific knowledge between the different projects. Dotted green lines indicate the main (simulation) data transfer between projects, while grey lines show the main data exchanges outside of these projects (e.g. onto the ESGF for open use by the global research community or into regional or national data distribution sites). Thin orange lines illustrate the new exchanges proposed in Sect. 2 of this paper. Finally, the thick green lines illustrate the main knowledge and data exchange routes between the different projects, the global research community, and the IPCC assessment process, as well as with multiple policymakers, practitioners, and climate service providers around the world.

The combined outcome of this enormous international effort are a set of simulations, data and resulting knowledge covering the past ~170 and future ~100 years (and sometimes longer) that sample a range of; (i) plausible future global socio-economic development pathways, (ii) emission, concentration and land-use scenarios commensurate with these pathways, (iii) global and regional Earth system change associated with each future pathway and (iv) the societal and environmental impacts arising from the simulated Earth system changes, as well as the direct impacts arising from the assumed socio-economic and/or mitigation measures in the IAM scenarios.

There are numerous challenges involved in running the number and range of model simulations across this range of activities, including cross-project and cross-model dependencies. As a consequence, to date it has not been possible to develop a single, coordinated dataset of forcings, simulations and findings from all four activities (IAMs, CMIP, CORDEX, impact modelling), based on the same socio-economic assumptions, scenarios, and driving data, within a single IPCC

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Assessment cycle. This limitation reduces the overall consistency and utility of information going into the three IPCC working groups (WGs). For example, Global (CMIP) and Regional (CORDEX) simulations are often out of sync, with CORDEX RCMs using boundary data derived from an earlier phase of CMIP. A similar example holds for impact models that use a mix of global and regional forcing from different phases of CMIP and CORDEX. Furthermore, impact models forced by CMIP/CORDEX projection data, do not include all the socio-economic and climate policy information that underpin the driving emission and land-use scenarios. This is particularly acute with respect to a number of direct human forcings, which are aggregated across multiple sectors and large spatial scales in the IAM scenarios, but need to be disaggregated and harmonized with observed historical data, to more detailed spatial scales and potentially individual sectors, to allow an accurate estimate of their impact on society and the environment in combination with the impacts due to Earth system change (e.g. see *Direct Human Forcings*, as listed on Table 1, Frieler et al., 2024). An improved accounting of such direct human forcings will be increasingly important as future scenario pathways include major (human) interventions to the carbon cycle necessary to realize the negative CO_2 emissions needed to achieve the Paris Agreement targets, which themselves can have major impacts on biodiversity and food production and therefore need to be accounted for in impact simulations.

Partly for methodological reasons, the impacts of climate change (and potential societal responses to this change) have not been included in IAM scenarios describing future socio-economic trajectories (i.e. Shared Socio-economic Pathways (SSPs), O'Neill et al., 2020). As climate change is expected to have a considerable impact on society, it is important to develop methods that allow this feedback to be included in future scenario development (Pirani et al., 2024). Ideally information on the impacts of climate change would be fed back into the IAMs to iteratively generate new future socio-economic and policy pathways that incorporate the societal impacts associated with the applied climate mitigation measures and the remaining impacts of climate change. For example, land use patterns will have to be adjusted to satisfy global food production requirements, while accounting for the impacts of climate change on crop yields and changes in available land resulting from any assumed land-based climate mitigation measures. These iterative adjustments to future socio-economic scenarios are one way to represent societal adaptation to projected climate change. Given the tight IPCC timelines it will likely not be possible to develop such iterative and interactive steps within the AR7 cycle. Nevertheless, we recommend addressing this link as the envisioned adjustment of workflows has the potential to significantly improve the overall coherency of future scenarios, integrating relevant information across socio-economic, Earth system and impact projections.

The lack of consistency, of both data and knowledge entering IPCC and national climate change assessments, reduces its overall utility and makes the interpretation of uncertainties across the various data sources a challenge. Furthermore, this can lead to inconsistent data and knowledge being used to develop climate policy, with some of this data more than 10 years old. We believe the time is right to much more tightly link these key international activities, with much more extensive and rapid sharing of simulations, data, knowledge, tools, and personnel, moving such critical science to policy support towards a quasi-operational footing (Jakob et al., 2023). Achieving this will be a major challenge, requiring a step-change in the level and efficiency of realizing simulations, as well the workflow linking different model simulations through data and knowledge sharing between communities. While the evolving IPCC AR7 timescales appear to be very challenging, addressing this need for internal consistency across the various data and knowledge sources supporting IPCC Assessments, is an important requirement for the international modelling community to address both for AR7 and beyond.

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3 Improving knowledge and guidance on future Earth system change, allowable emissions, net-zero responses, and safe landing pathways for planet Earth.

3.1 The Paris Agreement: The risk of warming overshoot, allowable emissions, net-zero and negative emissions, and Earth system feedbacks.

An important focus for CMIP7 and ScenarioMIP (O'Neill et al., 2016; van Vuuren et al., 2023), also addressed in the WCRP Safe Landing Climates Lighthouse Activity (LHA https://www.wcrp-climate.org/safe-landing-climates), is the development and investigation of plausible future emission scenarios and global warming pathways to better inform mitigation and adaptation science. With respect to mitigation, a particular focus on future pathways that successfully realize the 2015 Paris Agreement (e.g. limiting long-term global warming to less than 1.5 or 2°C above pre-industrial temperatures; Riahi et al., 2021) is required. Key questions within this activity encompass; What is the feasibility of actually realizing the Paris targets? Whether a temporary warming overshoot is inevitable? And, if so, of what magnitude? Also, is it feasible to return to a target warming level on a reasonable timescale once an overshoot has occurred (Bauer et al., 2023)? To provide robust policy guidance on the plausibility and consequences of such pathways, several important additional questions need to be addressed: Can accurate predictions of carbon emission budgets (and budgets of other radiatively important greenhouse gases and aerosol precursors) be made that are commensurate with different warming targets, with or without overshoot (Ramboll et al., 2023)? What is the risk of amplifying feedbacks being triggered during an overshoot phase (Melnikova et al., 2022), and is there a risk of exceeding tipping point thresholds in the Earth system, society or the natural environment, during overshoot (Wunderling et al., 2023)? If plausible negative emission pathways exist that return the Earth system to an acceptable temperature at an acceptable rate, once overshoot has occurred, what will be the environmental consequences of following these pathways? Furthermore, during the overshoot phase, if major changes or impacts (e.g. ecosystem degradation, population displacement, economic damages) do occur, or tipping points are exceeded (either in society or the Earth system), are these changes reversible when temperatures return below a target level (Kim et al., 2022; Reed et al., 2023; Santana-Falcón et al., 2023) and how long will such a recovery take (Albrich et al., 2020, Meier et al., 2012)?

Most negative emission scenarios assume a significant stimulation of terrestrial carbon uptake through extensive modifications to land-use (Smith et al., 2016). How the carbon cycle will respond to these interventions is not well quantified, nor is the actual efficacy of these interventions in reducing temperatures (Schleussner et al., 2023), or the ensuing impacts on the natural world, particularly biodiversity. A dominant part of the negative CO_2 emissions in these scenarios comes from the AFOLU (agriculture, forestry and other land use) sector, through large scale deployment of bioenergy with carbon capture and storage (BECCS). It is of the utmost importance ESMs, with a comprehensive process-based representation of the carbon cycle, are used to assess the efficacy of such AFOLU scenarios in terms of realized negative emissions and temperature response, accounting for interactions with the natural carbon cycle and regional climate. Such major changes to the land surface will likely also lead to significant impacts on water availability, biodiversity and a range of human activities (Séférian et al., 2018; Hof et al., 2018), both directly from the change in land use and indirectly through induced changes in regional climates. Such potential impacts need to be carefully assessed using impact models, with any negative impacts balanced against the positive impact of the mitigation actions on global warming. Finally, once an "acceptable" warming level is reached, it remains to be established whether the Earth system can be stabilized long-term at this level (Jones et al., 2019)? If so, what will be the consequences across the Earth system and society from such long-term stabilization (King et al., 2021; Palazzo Corner et al., 2023)?

All these questions have major implications for global mitigation and adaptation policy. Reliable answers are urgently needed. The international research community is beginning to address such questions, and increasingly has the modelling

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tools capable of providing answers. We believe the new round of international modelling projects has the potential to make major advances towards delivering robust answers.

Past CMIP cycles, including the most recent phase CMIP6 (Eyring et al., 2016a), emphasized CO_2-concentration driven simulations, where atmospheric CO_2 concentrations are prescribed and model simulated carbon cycle – climate feedbacks are not allowed to influence atmospheric CO_2. This approach was taken largely for pragmatic and inclusivity reasons (i.e. there was only a small number of models with robust and stable coupled climate and carbon cycles). Thanks to efforts such as C4MIP (Arora et al., 2020), this is no longer the case, with a significant number of ESMs now including advanced carbon cycles coupled to their physical climate model (Sanderson et al., 2023). A few ESMs even extend to interactive cycles of other important gases, such as methane (Folberth et al., 2022), nitrogen and iron (Dunne et al., 2020). Due to the small carbon budgets involved in realizing the Paris targets, and uncertainty in how the carbon cycle will respond to negative and net zero emissions, it is imperative more ESMs in CMIP7 run in CO_2-emission mode, with full interaction between the physical climate and carbon cycle, including prognostic atmospheric CO_2 (Sanderson et al., 2023; Gier et al., 2024). This will enable an improved assessment of the interactions and feedbacks between the physical climate and the carbon cycle, including consequences for allowable carbon emissions, the negative emissions required after different overshoots to achieve stabilization targets, and for an assessment of the associated risks, impacts and potential for irreversible change across the Earth system and society. Only through such a coupled and prognostic approach can we properly connect anthropogenic CO_2 emission scenarios that are intended to realize (with or without overshoot) key warming targets, with the Earth system response and the impact these responses have on atmospheric CO_2 and thus the realized warming/cooling pathways.

We propose other important aspects of the coupled Earth system, at risk of rapid change, should also be run in a more *coupled and prognostic* manner in CMIP7. A detailed assessment of coupled interactions and risks across the entire Earth system, including potential tipping point risks (Ritchie et al., 2021), is severely lacking in earlier IPCC Assessment Reports. Giving greater emphasis to fully coupled and prognostic interactions across the Earth system (particularly those thought to play a major role in determining the magnitude of future Earth system change) in an internally consistent modelling framework will allow a more complete assessment of Earth system change beyond that solely focussed on the physical climate. The current scientific priorities with respect to such interactions, along with (in italics) the key phenomena, feedbacks and consequences such coupled simulation would enable an improved assessment of, are listed below:

(i) Water, vegetation and biogeochemical cycles of carbon, nitrogen, phosphorous; *improved estimates of vegetation change, terrestrial carbon uptake, regional water cycles and ecosystem tipping risks.*

(ii) Climate, vegetation, and fire: *improved assessment of future fire risk and carbon uptake, atmospheric composition and ecosystem tipping risks.*

(iii) Permafrost, climate, vegetation, and carbon: *stability of permafrost under warming and long-term warming stabilization, carbon/methane release from thawing permafrost, ecosystem expansion into thawing permafrost zones.*

(iv) Climate, ice, and sea level: *improved assessment of potentially irreversible loss of Antarctic and Greenland ice and consequences for sea level rise, ocean circulation and heat uptake.*

(v) Climate, atmospheric composition, and air quality (*internally consistent assessment of radiative forcing, climate change and air quality*).

(vi) Ocean physics, biogeochemistry and ecosystems: *assessment of ocean warming, marine carbon uptake and long-term storage, ocean acidification and impacts on marine ecosystems.*

(vii) The interplay between global change, regional climate variability, and changes in climate and weather extremes including full Earth system responses.

3.2 Regional Earth system change; assessing societal and environmental impacts.

In addition to changing how global ESMs are run, we propose RCMs in CORDEX also advance their representation of regional Earth system processes (beyond the physical atmosphere-land system, (Giorgi and Prein, 2022; Nabat et al., 2020; Sevault et al., 2014). To better sample the uncertainty range of future global projections, RCMs and statistical downscaling should preferentially use CO_2 emission-driven ESMs as boundary forcing and employ an efficient (as automated as possible) method to select an ESM ensemble for a given region and rapidly generate the required boundary condition data. The resulting combination of global emission-driven ESMs, regional ESMs, and advanced statistical downscaling, all running in a tightly linked framework, will allow a more complete assessment of potential changes across the global and regional environment at scales required by policymakers and planners. We further recommend impact models use a coordinated, multi-model ensemble of (global and regional) simulations, based on CMIP7 CO_2-emission driven ESMs, to sample a matrix of climate forcing better spanning the uncertainty in projected Earth system change. We further recommend that impact models sample multiple members from individual ESMs/RCMs to quantify the role of internal (natural) variability in regional impact assessments.

Forcing impact models, either directly by global ESM simulations or by RCM and/or statistically downscaled data, themselves driven by the same ESM simulations, will ensure global consistency of the impact simulations and comparability of impacts resulting from global and regional model forcing over the same region. In addition to coordinated forcing from ESM and downscaled data, a more complete, disaggregated set of IAM scenario data describing socio-economic development and potential mitigation or adaptation measures will ensure greater coherency between global and regional impact assessments and the underpinning IAM, ESM and regional forcing data. Furthermore, such model combinations can be used to assess the efficacy and potential impacts associated with proposed regional climate change mitigation or adaptation actions, offering much-needed scientific assessment of these proposed climate solutions.

4 Improving our understanding of, and ability to model key physical climate processes, climate variability, extreme events and regional impacts.

4.1 Improving key phenomena and couplings in global climate models.

Some of the key uncertainties in Earth system model projections relate to errors in simulating important regional climate processes and phenomena, including interactions across spatial scales and regions. For some of these phenomena, model resolution has been shown to be a key factor. Hewitt et al. (2022) showed that increasing ocean model resolution, in particular better resolving the ocean mesoscale, is important for accurately representing a number of key processes, including; ocean eddies in areas such as the Southern Ocean and North Atlantic (*with implications for simulated marine heat and carbon uptake, ice sheets and sea-level rise*), ocean deep water formation, such as in the Labrador and Nordic Seas and on the Antarctic shelf (*with implications for the global ocean overturning circulation and heat uptake*), the Atlantic Meridional Overturning Circulation (*with implications for heat and carbon uptake, as well as regional and global climate*), ocean upwelling regions (*with implications for marine carbon uptake, productivity and fisheries*). Increased resolution, in

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both the atmosphere and ocean, is also important for simulating large-scale hydrological processes (Vannière et al., 2019) (*with important implications for regional water cycles, water availability and food security*), and modes of climate variability, such as the El Niño Southern Oscillation (ENSO) and associated teleconnections (*with implications for the rate of ocean heat uptake and regional climate variability*). While increased model resolution (e.g. to better resolve the ocean mesoscale or the synoptic scale in the atmosphere) is an important component of reducing several systematic biases in coupled models, equally important is to improve key parameterization schemes for processes that continue to be unresolved, even at horizontal resolutions of ~10km/0.1° in coupled models. In particular, it is critical to ensure further improvement in parameterizations at the heart of uncertainty in the simulated Effective Climate Sensitivity (EffCS) and Transient Climate Response (TCR) (Meehl et al., 2020; see Sect. 6 of this paper)

Upscale effects from many of these processes can be important: for example, oceanic mesoscale eddies tend to drive atmospheric mesoscale storms in the extra tropics (Liu et al., 2021), while at larger scales the atmosphere can drive ocean variability (Frankignoul, 1985). These effects are apparent only in coupled systems and their large-scale consequences, such as the preferred location and orientation of the jet stream, mid-latitude storm tracks, and related air-sea fluxes, can only be captured in large-domain models with mesoscale or better resolution (Seo et al., 2023). Furthermore, couplings between the heat, water, and carbon cycles, means improving the representation (and parameterization) of physical processes will deliver important benefits for simulating the carbon, and other biogeochemical, cycles. In addition to the large-scale impacts, higher resolution models also offer an improved simulation of climate variability, in particular weather extremes such as; tropical cyclones (Roberts et al., 2020), extreme precipitation (You et al., 2023), atmospheric rivers (Liang and Yangyang, 2023), jet streams and atmospheric blocking (Schiemann et al., 2020) with consequences for the frequency and location of extreme weather (Athanasiadis et al., 2022). All these events have important impacts across the coupled Earth system, including upscale effects, e.g. drying of the atmospheric column by tropical cyclones over the Maritime Continent, with impacts on ENSO (Scoccimarro et al., 2021). Similarly, in the ocean increased resolution can improve the representation of important dynamical phenomena, such as marine heatwaves (Plecha and Soares, 2020) the representation of bottom water formation (Heuzé, 2021) and mixed layer eddies (e.g. Calvert et al., 2020).

Increasing model resolution alone does not guarantee improvement in all simulated metrics and leads to important challenges related to model spin-up, equilibration, calibration, and uncertainty quantification. Simulation improvements are often realized through a combination of increased model resolution and targeted improvement to key parameterization schemes. While the compute cost increases considerably as model resolution is increased, recent studies suggest increased resolution can deliver insights into some long-standing model biases, and perhaps reconcile mismatches between modelled and observed historic trends. Rackow et al (2022) show that resolving the ocean mesoscale improves the simulation of Antarctic sea-ice trends, Chang et al (2023) illustrate increased realism in ocean upwelling as model resolution is increased, and ongoing work suggests higher resolution simulations can better capture recent observed trends in the Eastern Pacific that are not captured in CMIP6 models (Seager et al., 2022). Such improvements will have important implications for predicting future extreme events, such as tropical cyclones, floods, droughts and heatwaves.

There is strong evidence a coordinated set of simulations for CMIP7, with resolutions enhanced over those typically used (e.g. 10-25 km in the atmosphere and ~0.1° in the ocean), can deliver an improved simulation and understanding of key regional climate processes and a more robust assessment of future changes in many of these processes, with benefits for impact and adaptation planning. Chang et al (2020) demonstrated that CMIP-length simulations, with an equilibrated coupled model, are now possible with models at resolutions of ~10-25km/0.1°. Many groups produced simulations following the CMIP6 HighResMIP protocol (Haarsma et al., 2016), though generally with very limited ensemble sizes. Given

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increased model efficiency and available compute resources, CMIP7 provides an opportunity to further investigate the benefits of increased coupled model resolution, alongside increased ensemble size, longer simulations, methods for improved model equilibration and initialization, and enhanced process realism. The aim is to optimize across these competing demands to deliver future projection data sets of maximum quality and utility for understanding the coupled Earth system, projecting future changes in the Earth system (globally and regionally), and for supporting climate change adaptation.

4.2 Increased model resolution from global to regional scales for regional impact assessment and adaptation.

Like their global counterparts, Regional Climate Models have also increased in resolution, with a growing set of models running at convection-permitting resolutions (~1-3km resolution; Ban et al., 2021; Hohenegger et al., 2023). In addition to an improved simulation of the convective scale, and interactions with the meso- and synoptic scales, such high-resolution itself brings direct benefits, by delivering climate information closer to impact and adaptation relevant scales and by better resolving local climate in regions of strong orographic forcing, complex land-sea-lake structures or heterogeneous land surface types. Moreover, explicitly resolving convective events, including the self-organization and self-intensification of these events, brings physical grounding to simulated precipitation extremes (Kendon et al., 2021; Caillaud et al., 2024), including the ability to evaluate models against observations at common spatial scales (Caillaud et al., 2021). A growing set of convection-resolving regional projections (Pichelli et al., 2021; Chapman et al., 2022; Kawase et al., 2023; Kendon et al., 2023) is shedding new light on interactions between future climate change and hydrological extremes. Convective-scale regional models can also be deployed for shorter, targeted purposes. For example, by focusing downscaling onto event sets where such high regional resolution is expected to add value to coarser scale models, or by sub-selecting particular global projections that allow a broad range of climate hazards, needed for robust adaptation, to be simulated regionally at impact relevant scales.

While such high-resolution coupled global climate models (~10-25 km in the atmosphere and ~0.1° in the ocean) and convection-permitting regional climate models (~1-3 km) are computationally very demanding, the potential to deliver radically new findings and policy support on present and future climate risks, at scales required by national and regional planners, means they are an increasingly important input to national climate scenarios, national adaptation planning and climate services. This is particularly the case with respect to societal risks associated with extreme weather events. In the next phase of CMIP7 and CORDEX, we propose a major emphasis be placed on increased collaboration, data and knowledge sharing between high-resolution (~10-25 km/0.1°) global climate models and convection-resolving regional climate models, with the goal of producing a coordinated ensemble of high-resolution global projections forcing an ensemble of convection-resolving RCMs. We further recommend the resulting high-resolution (global and regional) climate data are used to drive a range of global and regional impact models (e.g. in ISIMIP, AgMIP and FishMIP). As the future impacts felt by natural and human systems is not only dependent on climate change, but also on changes in the direct human forcing arising from the underpinning scenarios themselves, it will be equally important to represent these drivers with high spatial resolution. The resulting coordinated set of climate change and impacts data, delivered at unprecedented spatial resolution, will be of enormous value to national scale climate change impact assessments, adaptation planning and climate service providers.

5 Increasing collaboration across approaches to improve global and regional Earth system and climate models.

The accuracy of numerous Earth system and biogeochemical phenomena strongly depends on the quality of simulated physical climate drivers (Doney et al., 1999). Examples of such dependencies include, but are not limited to; (i) vegetation growth/loss, terrestrial carbon uptake, and the simulated water cycle; (ii) wildfires and simulated precipitation, soil moisture and winds; (iii) marine productivity and the dynamics of ocean upwelling, (iv) mass loss from marine ice sheets and regional ocean circulation; (v) global ocean overturning and heat and carbon uptake, and representation of deep water formation, (vi) regional air pollution and modes of atmospheric circulation. Conversely, in the real-world, carbon cycle – climate feedbacks (and other Earth system feedbacks) change the fraction of anthropogenic emitted CO_2 (and other GHGs, such as CH_4 or N_2O) that remain in the atmosphere to cause warming, and thereby influence the magnitude of physical climate feedbacks (e.g. water vapour, lapse-rate, cloud or sea ice feedbacks). Furthermore, while an accurate simulation of the mean climate (in time and space), as well as trends in this measure of climate, are extremely important, an accurate representation of variability (in both time and space) of the underpinning physical climate can often be as important for simulating the Earth system response to a changing climate. Such variability is also a critical driver of the impacts of climate change, both on society and the natural environment. Regional climate variability, particularly the width of the distribution of such variability (i.e. the extreme tails of future climate distributions), is generally better represented as resolution is increased, both in global and regional models (Wehner et al., 2014; Doblas-Reyes et al., 2021; Ban et al., 2021).

High-resolution coupled global climate models (~10-25 km in the atmosphere and ~0.1° in the ocean) can be viewed as the physical core of the next generation of Earth system models, offering an improved simulation of the driving physical climate, including climate variability and extreme events. Collaboration across the development of high-resolution physical climate models, and Earth system models that emphasize enhanced process-realism, needs to deepen both in CMIP7 (with respect to global models, Dunne et al., 2023) and CORDEX (with respect to regional models). Such collaboration can benefit from and feed into ongoing efforts under the WCRP LHA Explaining and Predicting Earth System Change (https://www.wcrp-climate.org/epesc), and offers an unprecedented opportunity to bring advances from both areas together to support development of the next generation of Earth system models. Such a meeting point between these two model development paths offers a unique testbed for assessing technological advances (e.g. hybrid-resolution ESMs, Berthet et al., 2019; AI-based emulation approaches, Son et al., 2024) and conceptual challenges (e.g. in quantifying and optimizing the benefits and trade-offs between resolution, complexity and ensemble size) in Earth system modelling. Machine Learning (ML) offers the potential to reduce long-standing systematic errors in ESMs and enhance the overall projection capability of these models. This needs to be further explored (Eyring et al., 2023a), with increased sharing of methodologies and findings across ML-based, and more traditional approaches, to model development. Better collaboration and knowledge sharing across these efforts will lead to a step change in our overall community-ability to provide robust climate information that meets the needs of mitigation and adaptation across spatial scales (Eyring et al., 2023b).

A number of initiatives are beginning to develop “Digital Twins of the Earth”, (e.g. the WCRP Digital Earth LHA, https://www.wcrp-climate.org/digital-earths) targeting an optimal fusion of Earth system modelling and observations, to deliver fit-for-purpose and actionable information to society. These approaches combine forward modelling, data assimilation, and machine learning tools with user models designed to answer specific questions. A major challenge is to bring users, and their tools, to the data, which is of unprecedented size and complexity. A number of models (global and regional) are beginning to provide samples of km-scale information, but only a few efforts are trying to develop two key aspects of digital twins by linking inputs to observations and outputs to human systems. In Europe, Destination Earth (https://destination-earth.eu/) experiments with weather and climate twins, down to resolutions of 2.5 km, and aims to make its experimental design respond to user needs, so models store a minimal amount of data, but are re-run on a regular basis, incorporating the latest data requests in each update. In the US, the Department of Energy has tested combining physical models (e.g. the Energy Exascale Earth System Model, E3SM (Golaz et al., 2022)) with human system models, including Integrated Assessment or Energy Grid models. In addition, ultra-high-resolution global storm-resolving models (GSRMs,

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Stevens et al., 2019) run at 1-5 km resolution may provide further understanding and insights into biases, complementing CMIP7/CORDEX simulations. Due to the extreme computational cost, we do not expect GRSM models to run CMIP7 historical and future projection simulations. Nevertheless, while the approaches employed and timescales involved are somewhat different, sharing of methodologies, successes, and problem-solving across communities will benefit all strands of work, improving our combined ability to model the coupled Earth system and deliver robust and actionable climate information to policymakers and society.

6 Improving model simulations of the observational record and key metrics of climate change

To increase confidence in future projections it is important models accurately reproduce the observed historical record. This requirement encompasses multiple variables and timescales, with long-term trends in global mean surface air temperature (GMSAT), including the forcings and feedbacks controlling these trends, of first order importance. In CMIP6 a number of ESMs exhibited EffCS values (of 5°C or greater) that are higher than the 5-95% range, as assessed by multiple lines of evidence (Sherwood et al., 2020). Some of these models also simulated global warming rates over recent decades (~1980 to 2014) greater than seen in observations (Tokarska et al., 2020), leading to suggestions these "hot models" were unrealistic and should be filtered out from climate impact assessments (Hausfather et al., 2022). Cloud feedbacks are the largest contributor to uncertainty in EffCS. Perhaps surprisingly, CMIP6 ESMs with high EffCS often evaluate better against observations for present-day clouds than earlier or lower EffCS models (Bock and Lauer, 2023; Kuma et al., 2023), and also accurately reproduce recent trends in cloud-radiation when driven by observed sea surface temperatures (SSTs, e.g. Loeb et al., 2020). These ESMs also represent a number (though not all) cloud feedback processes more accurately than earlier models, particularly those related to mixed phase clouds over the Southern Ocean (Jiang et al., 2023). Nevertheless, studies continue to highlight problems across the majority of CMIP6 models with respect to Southern Ocean clouds (Schuddeboom and McDonald, 2021) and, in particular, low-level tropical marine clouds (Konsta et al., 2022), with observation-based constraints of the latter cloud type suggesting an EffCS closer to 3°C (Myers et al., 2021). It is possible some high EffCS CMIP6 models improved one cloud feedback (e.g. mid-latitude, mixed phase clouds leading to a less negative cloud phase feedback) that exposed other feedback errors (e.g. too positive low-level, tropical marine cloud feedback) that previously compensated each other with respect to the total cloud feedback. Such one-sided improvement can result in an increased positive total cloud feedback and high EffCS. Continued improvement in the representation of cloud processes and feedbacks across all relevant cloud types, including exploitation of new observational data and analysis methods, will be crucial for better constraining EffCS in CMIP7 and improving simulation of historical climate and rates of global warming. While a number of high EffCS models in CMIP6 simulated too strong global warming over the period ~1980 to 2014, establishing a direct link between EffCS and historical warming is not straightforward. This is mainly due to the confounding role of aerosol cooling over the historical period, as well as the important role played by natural variability. In CMIP7 historical forcings are planned to be extended to 2022 (i.e. 8 years longer than in CMIP6). Recent studies indicate anthropogenic effective radiative forcing (ERF) has become more positive, by ~50%, between the decades 2000-2009 and 2010-2019, mainly due to a reduction in the negative aerosol ERF (Jenkins et al., 2022). This change has been accompanied by almost a doubling of the GMSAT warming trend between these two decades. Jenkins et al. (2022) suggest that while some of the increased GMSAT trend is very likely due to reduced aerosol cooling, long-term variability in ENSO may also contribute. Kang et al. (2023a, b) suggest the SST pattern observed in the Pacific between ~1979 and 2013, which induces a negative cloud feedback term and is not captured in most coupled ESMs, is linked to cooling SST trends in the Southern Ocean over this period (also not captured in coupled ESMs). They suggest that as Southern Ocean SSTs begin to warm, the tropical Pacific SST pattern may decay, resulting in a more positive cloud feedback and potentially an increased rate of global warming. Understanding, and simulating in coupled ESMs, the drivers of such SST trends, as well as their interaction

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with, and impact on, climate feedbacks and global warming, will be crucial to address in CMIP7 to increase confidence in future projections.

Constraining future feedbacks and evaluating model processes controlling these feedbacks is a difficult challenge. Emergent Constraints, which use a multi-model ensemble to identify relationships between observable Earth System variations and projected future changes, are an attractive way to constrain future feedbacks based on observations (Hall et al., 2019; Nijsse et al., 2020) and thereby reduce uncertainty in future projections. To date, assumed emergent relationships are often simple linear regressions. Machine Learning techniques are a promising route for identifying multi-dimensional, non-linear relationships between contemporary observables and the future state of the Earth System (Schlund et al., 2020) and may therefore improve the constraints on future feedbacks and even allow an evaluation of model processes that control these feedbacks. An improved simulation of the historical past, combined with improved constraints on key feedbacks, including the processes controlling these feedbacks, will increase confidence in ESM projections and improve model estimates of key climate change metrics such as EffCS, TCR and TCRE with important implications for estimates of allowable carbon emissions commensurate with different policy targets.

Both global and Regional ESMs struggle to accurately represent observed regional climate trends, as underlined for Western Europe by recent literature (Ribes et al., 2022; Schumacher et al., 2023; Vautard et al., 2023). This may be partly linked to poor quality lateral and surface boundary conditions (e.g. most recently from CMIP6 ESMs), but may also be a result of missing, or poorly represented, regional forcings and/or feedbacks in the RCMs (Nabat et al., 2014; Boé et al., 2020; Taranu et al., 2022, e.g. the representation of aerosol-cloud interactions or the simulation of regional/coastal SST trends). For RCMs too short evaluation runs and lack of adequate calibration strategies may also contribute to these problems. Tackling such weaknesses is important for increasing trust in high-resolution, regional climate projections that underpin numerous national climate scenarios, impact assessments and adaptation planning.

7 Sampling and quantifying future uncertainty

Multi-model ensemble projections (MME), such as those from CMIP and CORDEX, sample a number of plausible IAM emission and land-use scenarios. The MMEs often include a small number of ensemble members per individual model, each sampling internal variability (as represented by that model). The MME approach, to a limited extent, also addresses structural modelling uncertainty. The degree this aspect of uncertainty is sampled is ultimately constrained by the resolution and process realism of the models involved, and by the degree of commonality of approaches to representing unresolved and uncertain model processes (Merrifield et al., 2023).

7.1 High Impact Low Likelihood (HILL) outcomes.

While such MMEs sample a fraction of the uncertainty in future Earth system change, this sampling is far from complete, particularly with respect to the extreme, low-likelihood end of potential Earth system change. Such responses are referred to as HILL (High Impact, Low Likelihood) outcomes (Wood et al., 2023). While HILL outcomes have a low likelihood of happening, there remains a small chance they will occur. One example would be if the Earth's equilibrium climate sensitivity (ECS) turned out to be ~5°C. While this outcome is highly unlikely (IPCC AR6 quotes the *very likely range* (5-95% probability) of ECS as between 2°C and 5°; see Fig. 7.18, in IPCC, 2021, Ch7, Forster et al. 2021), if it did occur the impacts on society would be extremely large.

HILL events may also occur at lower levels of warming (Armstrong-McKay, 2020) and impact numerous parts of the Earth system across a range of regions and timescales. For example, a HILL event may be triggered if a threshold of Antarctic ice loss is exceeded, which may then accelerate and become irreversible, with important consequences for sea level rise and coastal communities (Garbe et al., 2020; Taherkhani et al., 2020). Similar, poorly quantified, and poorly understood, risks exist for other potential Tipping Points in the Earth system, such as collapse of the Atlantic Meridional Overturning Circulation (AMOC, Klose et al., 2023), dieback of the Amazon rainforest (Parry et al., 2022), or rapid permafrost thaw (Turetsky et al., 2020). Tipping points also exist in the natural environment and in society and may be triggered at modest levels of warming. Examples include climate driven species loss already occurring at today's levels of global warming (e.g. first species extinction attributed to climate change; IPCC 2023 SPM), mass mortality in coral reef ecosystems (Donner et al., 2017; Hughes et al., 2018; Hughes et al., 2019), shift from kelp- to urchin-dominated coastal communities (Rogers-Bennett and Catton, 2019; McPherson et al., 2021). HILL events, both in the natural Earth system and society are not only sensitive to changes in the mean climate, but also to changes in climate variability. Increased inter-annual variability can have major impacts on society and ecosystems (von Trentini et al., 2020). Systematic shifts, even in sub-seasonal climate can significantly impact society (e.g. changes in the frequency distribution of hot summer days and nights, human mortality; Schär et al., 2004).

The signal of natural internal variability (in models expressed as internal variability across a model ensemble) increases in importance, relative to the signal of human forced climate change, as spatial and temporal averaging scales decrease, and projection timescales become shorter (Hawkins and Sutton, 2009). A consequence of this is that larger ensembles are required to reliably detect a forced climate change signal from an extreme realization of natural variability. The shorter duration and/or rarer the event, the larger the ensemble size likely required to be confident a (forced) signal is outside the range of natural variability. This is important information for reliable and cost-effective adaptation to potential future climate risks. Several groups have produced large ensembles covering the historical past and future (Olonscheck et al., 2023; Maher et al., 2021; Deser et al., 2020), using 50 to 100 realizations, often started from different initial conditions taken from the model's pre-industrial simulation. Such large ensembles are ideal for detecting forced regional changes (as simulated by the particular model) from internal (natural) variability (also as simulated by the particular model). Due to the high computational cost involved, to date such large ensembles are generally based on relatively low-resolution models that do not carry the process complexity of full ESMs. This can limit their overall utility. For example, low resolution models struggle to simulate intense weather events, such as tropical cyclones or extreme precipitation. As a result, their utility for investigating changes in extreme weather is limited, although this limitation could be addressed, for specific regions at least, by building ensembles consisting of both Global and Regional models run in tight coordination.

Recently single model initial condition large ensembles (SMILEs) have been combined to form multi-model ensembles of SMILEs (Lehner et al., 2020), increasing the sampled uncertainty beyond internal variability to also encompass (to some degree) structural model uncertainty. Techniques have been developed to optimally combine individual SMILEs, with different ensemble numbers, to produce an unbiased multi-model SMILE that even considers present-day model performance in its design (Merrifield et al., 2020). New Machine Learning techniques offer the potential for a more efficient and comprehensive assessment of the future projection uncertainty space and can be used to guide, and in some cases realise, the creation of large ensembles, including ones targeted onto extreme event risks (Eyring et al., 2023a).

7.2 Internal variability, parameter uncertainty and model structural uncertainty.

An additional approach for investigating modelling uncertainty is the Perturbed Parameter Ensemble (PPE) (Murphy et al., 2007). In the PPE approach uncertain, often difficult to constrain, model parameters are varied within reasonable limits, where possible constrained by observations (Booth et al., 2017). The resulting PPE members can be further filtered to retain only skilful members in terms of present-day climate and/or historical trends (e.g., Sexton et al., 2021; Peatier et al., 2022). Recent advances in model calibration (e.g., Hourdin et al., 2021, 2023) will be instrumental in better designing future PPE. Using the PPE approach, it is sometimes possible to mimic key measures of future projection uncertainty (e.g. the range of climate feedbacks and ECS in a CMIP MME) using only a single model (Collins et al., 2011). Applying the PPE approach across multiple global and regional model systems allows probabilistic regional climate projections that sample a significant fraction of future projection uncertainty (Evi et al., 2021). Such approaches support assessment of potential regional impacts sampling uncertainty in the future driving regional climate, including changes in climate variability and extreme weather.

In addition to physically based models, advanced statistical methods such as emulators (Meinhausen et al., 2011; Leach et al., 2021) and Machine-Learning (ML) (Watson-Parris, 2021; Eyring et al., 2023a) are increasingly being used to more fully, and rapidly, investigate uncertainty in future Earth system change. Emulators and ML methods can be trained either on an individual model or an ensemble of historical and future projections made by ESMs (Beusch et al., 2020; Nath et al., 2022) or RCMs (Doury et al., 2022, 2024) and used to investigate a large range of future emission and land-use scenarios, or to focus on specific aspects of projection uncertainty (e.g. high ECS futures). Observations can also be brought into the emulation process, enabling the resulting emulators to mimic the behaviour of the more complex ESMs, while weighting this behaviour towards better performing models (Beusch et al., 2020; Sanderson et al., 2017). Statistical emulation approaches are also used to assess the sensitivity of ESMs to uncertain model parameters (expanding the PPE approach), both for parameterization development (Silva et al., 2021; Rasp et al., 2018) and for developing and selecting ESMs that combine acceptable present-day performance with constraints on their future response (e.g. constraining ECS to lie within a specified range (Peatier et al., 2022)). Emulators were used extensively alongside global and regional projections in IPCC AR6 to deliver observation-constrained future projections (Nicholls et al., 2022). Emulators and ML tools can enhance the provision of climate information (Pfleiderer et al., 2024) and support interdisciplinary integration, allowing direct coupling to IAM scenarios and thus support cross-working group collaboration in IPCC AR7 and beyond.

7.3 Assessing uncertainty across all the steps in providing actionable climate information.

The new round of international projects presents an opportunity to bring together the range of approaches and methods used to assess and quantify uncertainty across IAM models and scenarios, global and regional models (considering internal model variability, parameter uncertainty and structural model differences), and impact models (both in terms of the climate forcing used and uncertain model parameters). This collaboration should also extend to work closely with communities developing and applying emulators and simple climate models. Collaboration across communities and activities will help increase the range of uncertainty space that can be analysed, and lead to a more systematic and coordinated approach to uncertainty assessment across the full suite of modelling activities that delivers science knowledge and data to climate policy and climate services. We further recommend significant effort be devoted to the communication of uncertainty and conversely, communication of what is expected to occur in the future, and the level of certainty/confidence that can be attached to these outcomes, with the target audiences being climate change policymakers, planners, and practitioners.

Going forwards, a key demand on the international modelling community, with respect to supporting IPCC AR7 and the UNFCCC Global Stocktake, will be the development and analysis of realizable future pathways that limit global warming to the targets of the Paris Agreement. These pathways are likely to include an overshoot of the warming targets and therefore the need for negative CO_2 emissions (i.e. active removal of CO_2 from the atmosphere). How these negative emissions will be realized in practice and what magnitude is feasible, remain open questions. A thorough analysis and quantification of the full cascade of uncertainty associated with such pathways is an important demand of the science community. This analysis needs

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to encompass uncertainty in; how the necessary negative CO_2 emissions will be realized (i.e. the mitigation actions themselves), the response of the carbon cycle to decreasing atmospheric CO_2, the efficacy of any CO_2 removal in reducing global temperatures, and the regional climate responses that may arise from such cooling pathways. In addition, uncertainties in the (expected) reduction in the societal and environmental impacts of Earth system change, as global warming is reduced, need to be assessed, and the impacts avoided compared to any impacts arising directly from the mitigation actions used to achieve the negative CO_2 emissions. Along the entirety of this chain of events and responses there is deep uncertainty. The science community needs to analyse, quantify, and communicate this uncertainty as thoroughly and clearly as possible.

Robust climate adaptation requires information on the range of potential future changes (which represent the climate hazard in risk decision frameworks). Whilst great strides have been made in quantifying global and large-scale impacts arising from the range of climate change drivers, this has only been partially successful with respect to translating the range of these impacts to the local scales needed to assess climate impact and develop adaptation plans. CMIP7 offers an opportunity to more fully include and propagate the wider CO_2-emission driven uncertainties through to local-scale climate information (as outlined in Sect. 3.2). An equally important dimension is the role natural variability plays in climate change, especially on the timescale of the next 10 to 40 years (that frames many adaptation decisions). On these timescales and at the local scale, natural variability typically dominates the forced climate change signal, for example for precipitation and temperature. This information is ever more critical as society adapts to climate change in a mitigating world, where such mitigation aims to limit the climate change signal. Large initial condition ensembles are a key tool for understanding and quantifying the role natural variability plays. The expense (computational, data storage) of generating and sharing Lateral Boundary Conditions (LBCs) required to drive Regional Climate models has limited the availability of LBC data, and hence the potential for regional scale simulations (such as CORDEX) to sample the role of regional natural variability in the context of the wider climate hazard space, at impact relevant scales. Commitments for new LBCs are often made before a simulation's credibility can be assessed and before any understanding of where the realisation of variability plus feedbacks places the particular simulation in the wider potential projection space. There will be value, therefore, in exploring iterative approaches between ESM and regional modelling groups to identify optimal ESM simulations to be rerun for LBC generation.

Statistical downscaling may provide the most effective route to link wider ESM projections to what they imply at the local level (Gutiérrez et al., 2019), as these approaches are not restricted by the limited availability of LBCs. Emerging Neural Network Machine Learning techniques trained on existing regional (RCM and Convection Permitting RCM (CPM)) simulations, are showings promise in capturing spatial and temporal climate change, at local scales, based on large scale drivers simulated by ESMs (Baño-Medina et al., 2021; Doury et al., 2022). Whilst there is still work to be done (e.g. achieving multi-variate coherence (González-Abad et al., 2023), transferability to other ESMs (Baño-Medina et al. 2024), building frameworks to verify ML downscaled results) their emergence is likely to represent a transformative change in how the international community provides local scale climate information for impact and adaptation decision making, as they enable the production of this information to be determined by realisations that can inform on the range of local scale climate hazard (bottom up) rather than the limited availability of LBCs by ESM modellers (top down) as is currently done. ML-based downscaling therefore has the potential to translate coarse-scale Earth system model output directly to spatial scales of utility for impact models, impact assessment and local adaptation planning (Eyring et al., 2023b). Such developments can be transformative in other senses, too. For example, given adequate prior ESM to RCM/CPM training data, CMIP7 has the potential to be downscaled almost as soon as the ESM simulations are completed, something which could help inform, for the first time, IPCC AR7 with consistent global and regional projection data, and associated impact simulations (see Sect. 2). Similarly, ML may offer ways to address the prohibitive storage costs of conventional high resolution local data by enabling the availability of such data on demand based on large scale variables (which are much cheaper to store). Ultimately, incorporating Machine Learning into the production of high-resolution regional climate information is likely to open further benefits due to the flexibility such tools enable. For example, ML downscaling will be amenable to approaches that use observations to bias correct the regional data, directly. Similarly, as insights from new modelling (e.g. resolving convective scales, interactive atmosphere-shelf sea-wave models) come online, similar ML downscaling tools may be able to produce new high resolution regional climate data reflecting these insights, if the new modelling experiments are designed to inform the required ML training.

8 The underpinning technological infrastructure

The ambitious science and science for policy goals discussed above cannot be realized without a state-of-the-art underpinning computational and data infrastructure, supported by experienced personnel. Our recommendations require the production, quality-control and sharing of numerous datasets from a diverse range of modelling systems, between producers and a heterogenous set of consumers separated in time and space. An aspiration for IPCC AR7, as described earlier is to deliver a coordinated and coherent set of data from across the most recent IAM scenarios, global (CMIP7) and regional (CORDEX) simulations, as well as impact model results based on these scenarios and climate forcing. To achieve this will require a more efficient and rapid sharing of data across communities. We therefore stress the need to improve the underpinning infrastructure ecosystem that supports these international modelling efforts to enable rapid production, evaluation, and exploitation of datasets, which themselves can be used as input to other simulation workflows, with different production, validation, and exploitation cycles. This will need to be realized for far more numerous and larger volume datasets, and across a broader and more disparate set of communities than previously, for example, with respect to delivering solely CMIP6 simulations during IPCC AR6.

CMIP6, like CMIP5, benefited from a globally coordinated data infrastructure, the Earth System Grid Federation (ESGF), linked to a large array of other important and necessary services (Balaji et al., 2018). The CMIP6 ESGF is now more than a decade old, largely not maintained and is therefore not fit for the scale of the challenge outlined above. The array of services linked to the ESGF include: standards-based data, model and experiment descriptions; citation and errata services for simulation data and derived products; and data quality control procedures (addressing the presence of required data, standards compliance etc, not to be confused with procedures for assessing the scientific quality of the data). The data infrastructure itself needs to support systematic (and efficient) simulation evaluation, and support replication of data from source to “super-nodes” that can host large volumes of multi-model data and provide sufficient local computational resource to allow analysis with minimal requirement for data movement (Eyring et al., 2016). To realize the ambitions outlined in this paper, the volumes of data that will need to be hosted at such super-nodes will be significantly larger than for CMIP6, and the services will need to be easier to navigate for a more heterogeneous community, extending beyond the modellers and analysts of earlier CMIP cycles. To fully take advantage of modern computing, both the underlying models and the analysis systems also need substantial investment to efficiently exploit modern computing systems, for example accelerators such as GPUs.

There are several activities underway that aim to address some of these requirements. Notable amongst these are the development of reusable evaluation and analysis workflows such as ESMValTool (Eyring et al., 2020; Righi et al., 2020) with the goal of fully integrating these into the CMIP publication workflow (Eyring et al., 2016b), the democratisation of the use of cloud computing via Pangeo (Abernathy et al., 2021), the use of new data formats such as HealPix (Chang et al., 2023), and the development of new technologies aimed at a future ESGF (Hoffman et al., 2022). However, there are also

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significant areas where little or no development is underway. These include enhanced documentation, errata, and citation services, many of which are relying on best efforts and need dedicated investment and effort in new techniques and modes of deployment. Considerable work will be required to bring all of these strands together into a coherent system that can be deployed and supported world-wide and sustained throughout the next IPCC cycle (and beyond).

This new ecosystem will need to support and coordinate efficient methods for data reduction and sharing, cross model analysis and evaluation, with an emphasis on bringing together existing and new observational and reanalysis datasets, models, emulators, and advanced analysis tools for rapid and in-depth analysis and exploitation. The new system will need to interface with other major data holdings, for example those of the WCRP Lighthouse activities[1] (Flato et al., 2023), the Destination Earth[2] data holdings, the existing ISIMIP data repository[3], the Copernicus Climate Change Service (C3S)[4] and new data holdings that may arise from the EVE (Earth Visualization Engines)[5] initiative. It will need to conform to FAIR (*Findable, Accessible, Interoperable, and Reusable*) principles (Wilkinson et al., 2016) and meet the needs and requirements arising not just from CMIP7, but from the range of communities involved in IAMC, CORDEX and VIACS/ISIMIP. Critically, the system will need to be fully supported by dedicated data managers, capable of addressing community questions pertaining to data quality, model and data documentation, as well as supporting users of embedded infrastructure tools to facilitate the rapid use and reuse of data and tools across communities. It is this rapid use and reuse that will deliver the internal consistency, across models and research communities, key to the transformative impact expected for international climate policy from the science and modelling efforts proposed in this article.

9 Summary and recommendations for the way forward

Over the past three decades, internationally coordinated modelling projects have delivered a wealth of simulations, data, and scientific knowledge to support policy actions addressing climate change mitigation and adaptation, from global to regional to national scales. As a new round of these projects start up, and a new 7th IPCC assessment cycle is beginning, we have reviewed how these projects have collectively provided science support to international climate policy. We propose a number of science, technology and collaboration priorities that we believe these projects should jointly focus on from now through to ~2030. Progress in these key areas will increase the quality and usability of science support to climate policy and maximize our understanding of Earth system change, including the impacts on society and the natural world, as well as our ability to reliably project such future changes and the associated impacts.

One key proposal is for the involved modelling communities, spanning integrated assessment, scenario generation, global and regional Earth system modelling, and impacts modelling, to work much more closely together during the next round of projects, with an aim to deliver a coordinated set of scenarios, projections and impact assessments all based on the same underpinning socio-economic and mitigation scenarios and using the most up to date model configurations. This will significantly improve the quality and internal consistency of scientific knowledge available to the upcoming (AR7) and future IPCC assessments, as well as to the periodic Global Stocktakes of the Paris Agreement. Fully realizing this ambition within the AR7 timeframe will be a major challenge. Nevertheless, significant effort to achieve such internal consistency and sharing of data, knowledge and personnel will result in future workflows much better suited to routinely realising this ambition. We further highlight the need for impact models to receive more detailed information (spatially and sectorially

[1] https://www.wcrp-climate.org/lha-overview
[2] https://destination-earth.eu/
[3] https://data.isimip.org/
[4] https://cds.climate.copernicus.eu/
[5] https://eve4climate.org/

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disaggregated) on the socio-economic assumptions underpinning different IAM scenarios. Conversely, increased effort is required to allow knowledge of potential future climate impacts, and the societal responses to these impacts, to be iteratively incorporated into the generation of emission and land-use scenarios.

The programme of work outlined here addresses numerous key priority knowledge gaps identified in IPCC AR6 (IPCC, 2021). Exploitation of CMIP6 was identified as limited, so there is a need to support and better focus coordinated international modelling projects, including links between projects. Plausible overshoot scenarios that return to the Paris Climate targets by the end of the century or later, were limited in CMIP6 and need to be a much greater focus of CMIP7. To properly address this, it is crucial ESMs are extended to allow a more thorough assessment of the efficacy of proposed land and ocean CO_2 removal techniques in reducing atmospheric CO_2, decreasing net radiative forcing and driving global cooling, while accounting for potential Earth system feedbacks (IPCC 2021; Canadell et al., IPCC 2021). ESMs need to be capable of assessing both CO_2 and non-CO_2 feedbacks during overshoot (e.g. changing efficiency of CO_2 uptake by natural reservoirs as CO_2 is removed from the atmosphere, or methane release from wetlands or permafrost (Canadell et al., IPCC 2021)), as well as the potential for, and consequences of, rapid change in key Earth system components, such as ice sheet mass loss or tropical forest dieback, during overshoot (Canadell et al., IPCC 2021; Fox-Kemper et al., IPCC 2021). Such analysis needs to be complemented by analysis of the (societal and environmental) impacts of a warming overshoot, the degree of reversibility of impacts once cooling to a target level is achieved, and the impacts resulting from long-term stabilization at this warming level. Finally, the impacts on society and the environment, arising directly from the CO_2 removal actions themselves needs to be contrasted with the impacts avoided from the forced reduction in global warming. Projections beyond 2100 were also not comprehensively covered in CMIP6 (Chen et al., IPCC 2021). In particular, ice sheets represent the largest uncertainty in future sea-level projections. It is vital these are better modelled in CMIP7, and that projections are extended beyond 2100, particularly for long-term warming stabilization, so committed, long-term changes in sea-level can be properly assessed (Fox-Kemper et al., IPCC 2021).

More accurately simulating the observed evolution of the climate system (i.e. reducing systematic model biases), including the forcings and feedbacks driving observed warming, is crucial for increasing confidence in model future projections, as well as for maximizing the use observational data in model improvement. Associated with this, we advocate the use of new approaches (e.g. combining Machine Learning and Emergent Constraints) to enable more extensive use of observations in constraining model projections and future feedbacks, as well as the processes underpinning these feedbacks. A key target is an improved (tighter) constraints on key metrics of Earth system sensitivity (e.g. EffCS, TCR, TCRE and the Regional to Global Warming ratio) and that global and regional ESMs more accurately simulate these metrics and the processes controlling their magnitude.

Due to their exceptional impact, we highlight the need for improved knowledge of, and ability to simulate, extreme weather events, including potential future changes in such events. We further stress the importance of assessing the impact of changing extreme events on society and the environment, considering the level of uncertainty inherent in future projections of (rare) extreme events. This requirement extends to understanding and simulating the key modes of climate variability that extreme events occur within (including future changes and extreme realizations of these modes). Looking towards the next generation of Earth system and climate models, we propose a significantly increased collaboration is required across communities investigating increased Earth system process realism and coupling, those working on increased model resolution and physical parameterizations, and groups working on ML-based hybrid modelling. Such collaboration will optimize benefits from each of the approaches with respect developing the next generation of Earth system models. This recommendation holds equally for global and regional modelling communities, including collaboration across these two communities.

With respect to uncertainty, in future socio-economic and emission scenarios, in Earth system change and in the ensuing impacts, we propose extensive collaboration across approaches addressing this issue, wherever possible assessing, quantifying, and emulating uncertainty as it propagates through the stages of IAM scenarios, ESM and RCM projections and impact assessment so a more complete sampling and quantification can provided to policymakers. Again, due to the extreme level of impact, we highlight the need for improved models and improved assessment of the risk and consequences of future High Impact Low Likelihood (HILL) outcomes, with the potential exceedance of tipping points in the Earth system, in the natural environment, or in society of critical importance. Given some level of uncertainty about the future will always be present, it is important to also focus on the communication of uncertainty, or possibly more importantly, communication of what is expected in the future and with what level of confidence. This is a key area to address in the science to policy interface.

The transformative goals outlined in this paper require the support of a robust, efficient, and internationally connected infrastructure. While components of such an infrastructure exist, much work is needed to design, build, deliver and sustain an integrated system that both meets the objectives outlined here, and maximises the benefits of existing initiatives and investments. The resulting infrastructure must exploit common tools and standards and be designed and delivered with both a long-term perspective and a well-trained workforce. It will need to handle increased volumes of data, support the use of new techniques for data analysis (such as the remote analysis of big-data using ML and AI techniques), and facilitate the easy exchange of data knowledge and analysis tools. Without such an infrastructure, many of the goals discussed here will not be met in a timely manner, if at all.

Finally, to expand the reach and benefits of international modelling, including the uptake and use of model simulations and projections, to a truly global scale and thus deliver a global impact on climate policy, there is an urgent need for increased involvement of global South scientists. WCRP leads a number of efforts in this area. These need to be ramped up significantly and put on a sound long-term footing. Given the global nature of the climate crisis, the magnitude of the impacts on society and the natural environment, combined with the fact these impacts are, and will continue to be, most strongly felt by global South countries, makes a globally inclusive response a necessity. This makes both scientific sense (e.g. to draw on local expertise and local observations for understanding and modelling local Earth system change and its impacts), as well as political sense (e.g. climate policy is generally better tailored to a specific country's needs if it is based on local expert advice that is easily accessible over the long-term). We therefore strongly encourage governments and funding agencies in the global North (i.e. economically wealthy countries) to provide sufficient, long-term financial support to maintain a strong and truly globally inclusive scientific and modelling collaboration over the coming decades.

Author contribution

All co-authors provided ideas and comments to the manuscript. CJ, SJ, BN, RS, TK, KF, BS, BB, SS, DVV, HH, EOR, FA, MR, PF, PLV, VE and PC conceived and developed the original ideas and recommendations in the paper. CJ and HJ wrote the paper, with regular input form the list of people under (2) and periodic input from all other co-authors.

Competing interests

Two co-authors are on the ESD editorial board: Roland Seferian and Richard Betts.

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