

1 **Bringing it all together: Science priorities for improved understanding of**

2 **Earth system change and to support international climate policy.**

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72 **Abstract.** We review how the international modelling community, encompassing Integrated Assessment models, global and
73 regional Earth system and climate models, and impact models, have worked together over the past few decades, to advance
74 understanding of Earth system change and its impacts on society and the environment, and thereby support international
75 climate policy. We go on to recommend a number of priority research areas for the coming decade, a timescale that
76 encompasses a number of newly starting international modelling activities, as well as the IPCC 7th Assessment Report
77 (AR7) and the 2nd UNFCCC Global Stocktake. Progress in these priority areas will significantly advance our understanding
78 of Earth system change and its impacts, increasing the quality and utility of science support to climate policy.

79
80 We emphasize the need for continued improvement in our understanding of, and ability to simulate, the coupled Earth
81 system and the impacts of Earth system change. There is an urgent need to investigate plausible pathways and emission
82 scenarios that realize the Paris Climate Targets. For example, pathways that overshoot 1.5°C or 2°C global warming, before
83 returning to these levels at some later date. Earth System models need to be capable of thoroughly assessing such warming
84 overshoots, in particular, the efficacy of mitigation measures, such as negative CO₂ emissions, in reducing atmospheric CO₂
85 and driving global cooling. An improved assessment of the long-term consequences of stabilizing climate at 1.5°C or 2°C
86 above pre-industrial temperatures is also required. We recommend Earth system models run overshoot scenarios in CO₂-
87 emission mode, to more fully represent coupled climate - carbon cycle feedbacks and, wherever possible, interactively
88 simulate key Earth system phenomena at risk of rapid change during overshoot. Regional downscaling and impact models
89 should use forcing data from these simulations, so impact and regional climate projections cover a more complete range of
90 potential responses to a warming overshoot. An accurate simulation of the observed, historical record remains a fundamental
91 requirement of models, as does accurate simulation of key metrics, such as the Effective Climate Sensitivity and the
92 Transient climate response to cumulative carbon emissions. For adaptation, a key demand is improved guidance on potential
93 changes in climate extremes and the modes of variability these extremes develop within. Such improvements will most likely
94 be realized through a combination of increased model resolution, improvement of key model parameterizations, combined
95 with an enhanced representation of key Earth system processes. We propose a deeper collaboration across modelling efforts
96 targeting enhanced process realism and coupling, increased model resolution, parameterization improvement, and data-
97 driven Machine Learning methods.

98
99 With respect to sampling future uncertainty, increased collaboration between approaches that emphasize large model
100 ensembles and those focussed on statistical emulation is required. We recommend an increased focus on High Impact Low
101 Likelihood (HILL) outcomes. In particular, the risk and consequences of exceeding critical tipping points during a warming
102 overshoot and the potential impacts arising from this. For a comprehensive assessment of the impacts of Earth system

103 change, including impacts arising directly as a result of climate mitigation actions, it is important spatially detailed,
104 disaggregated information used to generate future scenarios in Integrated Assessment Models are available for use in impact
105 models. Conversely, methods need to be developed that enable potential societal responses to projected Earth system change
106 to be incorporated into scenario development.

107

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

112 **1 Introduction**

113 Given the rapidly developing climate crisis, and the negative consequences for planetary habitability and human well-being,
114 there is an increasing need for accurate, reliable, and actionable information encompassing the full spectrum of climate risk.
115 This information is required at global to local scales, near to long timescales, and needs to be tailored to inform critical
116 decision-making related to climate change mitigation and adaptation (e.g., in the context of UNFCCC negotiations, the UN
117 Global Stocktake, IPCC assessments, and the World Adaptation Science Program; WASP), as well as the growing needs of
118 climate service providers. Over the past few decades, coordinated by the World Climate Research Program (WCRP), the
119 international modelling community has worked together to contribute simulations, data and knowledge to support decision
120 making, in particular the cyclical IPCC Assessment Reports (AR). This has been achieved through a suite of interconnected
121 modelling projects and initiatives, with the most important of these listed in Table 1, along with project acronyms and
122 primary citations. Meehl (2023) discusses the synergistic interaction between climate science (particularly Global Climate
123 and Earth system modelling) and the IPCC over the past 4 decades.

124

125 With a new IPCC AR cycle (AR7) beginning, it is timely to review how the international modelling community has
126 supported climate policy in the past, including earlier AR cycles, and ask what advances can be made in the overall quality
127 and availability of science to support policy needs. In addition, it is pertinent to review our current understanding of, and
128 ability to model, coupled Earth system change, as well as the societal and environmental impacts associated with this change
129 and ask whether plausible, safe pathways can be developed for the Earth system that avoid the worst impacts of this change.
130 Many of the international projects listed in Table 1, that provide the scientific knowledge on which IPCC reports are based,
131 are beginning new cycles. For example, CMIP7 is starting to take shape, likely running through to ~2030. In this paper we
132 outline a number of areas we believe the international modelling community can significantly advance our understanding of,
133 and ability to simulate, past and future Earth system change, including the impacts of these changes. Progress in the
134 proposed areas will also allow an improved investigation of mitigation options for limiting long-term global warming and its
135 impacts to acceptable levels. Such developments will deliver enhanced scientific support to international climate policy,
136 during and beyond AR7. The advances we propose assume the *maintenance, expansion* and *integration* of a robust and
137 interconnected infrastructure ecosystem. Such an infrastructure has underpinned past international modelling collaborations
138 and is a fundamental requirement for realizing the ambitious goals outlined here. The specific science, and science for
139 policy, ambitions, as well as the necessary underpinning infrastructure, are discussed in more detail in subsequent sections.
140 Each proposed focus area can be summarized by the following key goals:

141

- 142 • **Provision of a coordinated, internally consistent set of simulations, data, and knowledge to support IPCC**
143 **assessments and international climate policy.** The resulting data sets and knowledge should be based on the most

144 recent and consistent set of Integrated Assessment Model (IAM) scenarios, global and regional Earth system model
145 (ESM) projections and simulated societal and environmental impacts. With consideration of impacts arising due to
146 the projected Earth system change, and directly from any mitigation actions assumed in the IAM scenarios.

- 147
- 148 ● **Improving understanding and guidance on future Earth system change, allowable emissions, net-zero**
149 **responses, and safe, long-term pathways for planet Earth.** Ensure global and regional ESMs, IAMs, and impact
150 models include the required level of process realism, process interactions, and consistent forcing data to accurately
151 simulate the response of the Earth system and human societies to future socio-economic, mitigation, emission, and
152 land-use scenarios. Develop and analyse a range of future pathways that limit long-term global warming to less than
153 1.5 or 2°C above pre-industrial levels, while minimizing the negative impacts on society and the environment.
- 154
- 155 ● **Improving our understanding of, and ability to simulate key climate processes, climate variability, extreme**
156 **events and regional impacts.** Ensure global and regional climate models (GCMs and RCMs) accurately represent
157 key processes, couplings, modes of variability and feedbacks that underpin global to regional climate change. Use
158 these models to deliver robust and detailed projections of regional climate change, including changes in extreme
159 events. Ensure the socio-economic information used to develop IAM mitigation and scenario data is suitably
160 disaggregated and combined with climate projection data to support national to regional scale impact assessment,
161 adaptation planning and climate services.
- 162
- 163 ● **Increasing collaboration across approaches to further improve global and regional Earth system and climate**
164 **models.** Ensure strong collaboration across efforts to; increase process realism and coupling in ESMs, increase
165 model resolution and improve physical parameterizations in climate models, and Machine Learning (ML) hybrid-
166 modelling approaches. Ensure each of these development paths are optimally combined to support development of
167 the next generation of Earth system models.
- 168
- 169 ● **Improving model simulations of the observational record and key metrics of climate change.** Ensure
170 improvement in the simulation and understanding of the observed, historical evolution of climate, particularly
171 historical global and regional warming, encompassing the forcings, processes, and feedbacks that determine the rate
172 and pattern of this warming. Improve our ability to constrain and simulate key climate change metrics, such as the
173 Effective Climate Sensitivity (EffCS), Transient Climate Response (TCR), the Transient Climate Response to
174 cumulative carbon Emissions (TCRE) and the Regional Warming to Global Warming ratio (RW/GW)
- 175
- 176 ● **Sampling and quantifying future uncertainty.** Develop and apply a hierarchy of models and methods to
177 efficiently explore the range of uncertainty inherent in future Earth system change and its impacts. Ensure regional
178 and national scale adaptation and mitigation is informed by a more complete sampling of the range of potential
179 climate futures, including rare (high impact, low likelihood) outcomes, their local climate signature, and the
180 potential consequences of these for society, the environment and climate policy.
- 181
- 182 ● **The underpinning technological infrastructure.** Further develop and maintain a robust, globally inter-connected
183 infrastructure ecosystem to ensure efficient co-production and co-exploitation of internally consistent model
184 simulations, via information, data and computational services that enable the rapid and reliable sharing of
185 requirements, knowledge, data, and analysis tools. Such sharing needs to be both within and across multiple

186 modelling projects and user communities, as well as providing suitable support to policymakers, planners, climate
 187 services, and the wider international research base.

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 Intercomparison Project	https://wcrp-cmip.org/	Earth system and Global Climate modelling	Eyring et al., 2016
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

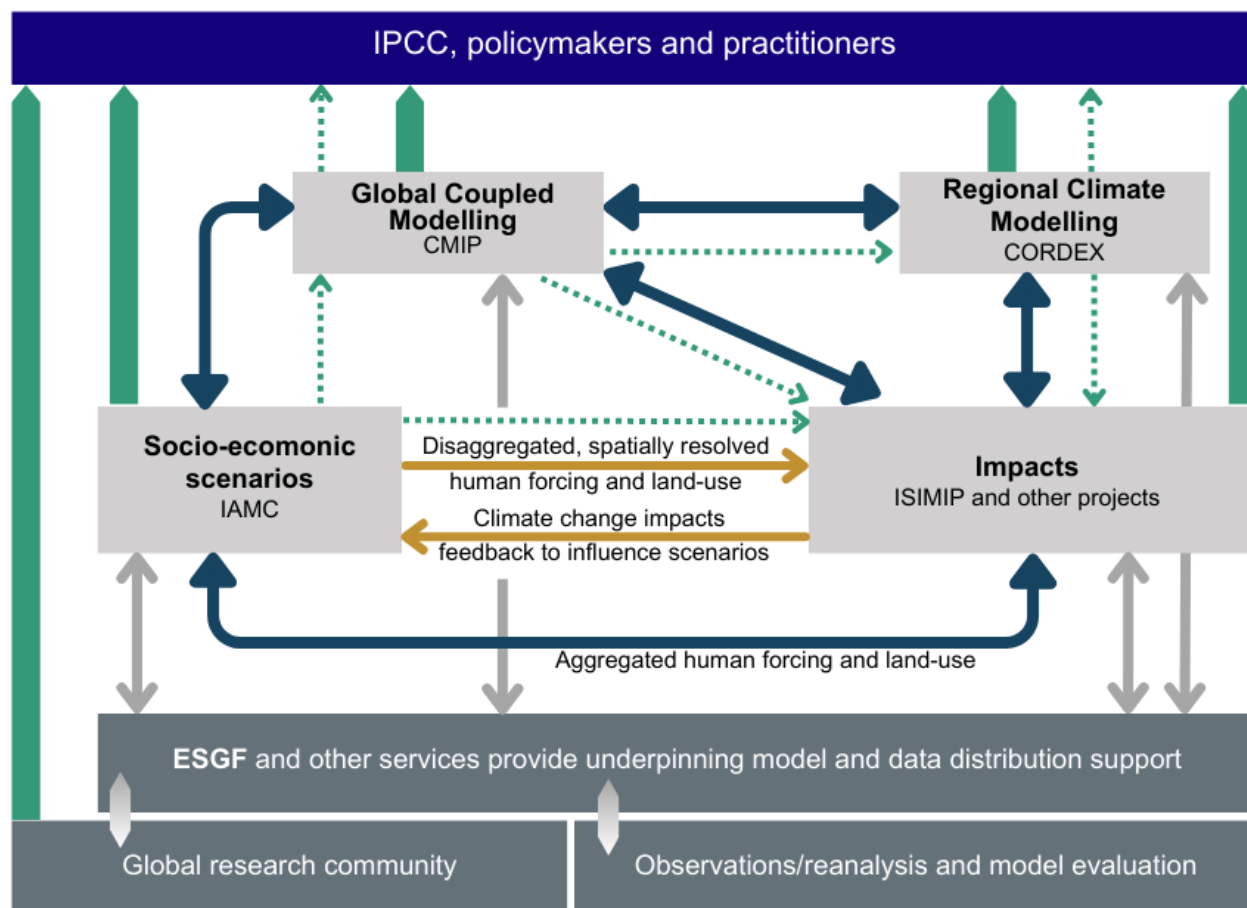
190
 191 **Table 1. Examples of the main international projects contributing to the provision of simulations, data and scientific knowledge to**
 192 **support climate policy, particularly IPCC assessment reports, including a main reference for each activity. CMIP and CORDEX**
 193 **are coordinated by the World Climate Research Program.**

194 The recommendations in this paper summarize the opinions of a group of European scientists who have been engaged in, and
 195 in a number of cases helped lead, major international modelling exercises that have delivered into past IPCC assessment cycles.
 196 Examples include; earlier and the latest (7th) phase of CMIP (including leadership of numerous CMIP MIPs; e.g. ScenarioMIP,
 197 C4MIP, HighResMIP, AerchemMIP), IAMC, CORDEX, and ISIMIP. Members of the group have also played a leading role
 198 designing and delivering the underpinning infrastructure required for such large, international modelling projects, in particular
 199 the Earth System Grid Federation (ESGF). While this perspective is therefore a European one, it is informed by many years of
 200 active involvement and collaboration in numerous international projects.

201 **2 Provision of a coordinated, internally consistent set of simulations, data, and knowledge to support IPCC**
 202 **assessments and international climate policy.**

203 The process by which the aforementioned activities have, in the past, delivered data and knowledge into the science and
 204 policy arenas is summarized in Fig. 1. IAMs develop a range of future global pathways, based on narratives for socio-
 205 economic, political, and technological development, as well as climate policy. For methodological reasons these scenarios do
 206 not (yet) consider the impacts of future climate change on human behaviour. The pathways are typically quantified in terms
 207 of highly aggregated information on future population and economic development, energy and food system development,
 208 and environmental consequences. For each pathway, marker anthropogenic emission and land-use scenarios are selected
 209 (van Vuuren et al., 2011; O'Neill et al., 2016; Riahi et al., 2017). These scenarios are combined with observation-based

210 estimates for the historical past, resulting in a time series of emission and land use data covering ~1850 to 2100 (Hurtt et al.,
 211 2011; Gidden et al., 2019). Using simple climate models (e.g. MAGICC; Meinshausen et al., 2011) and chemistry-climate
 212 models (Lamarque et al., 2011), the emissions are converted into atmospheric concentration time series. The concentration
 213 timeseries, along with the land-use scenarios, are used to “force” ESMs in CMIP to investigate potential changes in the Earth
 214 system arising from each scenario. The ESMs deliver time-varying, spatially discrete estimates of the past and future
 215 evolution of the Earth system, sampling the range of available emission and/or concentration scenarios (Tebaldi et al., 2021).
 216 CMIP simulations are extensively used to inform policymaking addressing global climate change risks. They are also made
 217 available to the international research community via the ESGF, where they are used to increase understanding of the Earth
 218 system and Earth system change, and to highlight areas requiring further model improvement.
 219



220
 221 **Figure 1: A schematic illustration of how earlier rounds of IAMC, CMIP, CORDEX and impact modelling activities, such as ISIMIP,**
 222 **have worked together to develop and apply future socio-economic and emission scenarios (IAMC), increase the scientific**
 223 **understanding of, and ability to simulate the coupled Earth system (CMIP and CORDEX), and investigated the impacts of Earth**
 224 **system change on societies and the natural environment (ISIMIP etc). In the figure dark blue lines illustrate the main (generally**
 225 **two-way) exchanges of scientific knowledge between the different projects. Dotted green lines indicate the main (simulation)**
 226 **data transfer between projects, while grey lines show the main data exchanges outside of these projects (e.g. onto the ESGF for open use**
 227 **by the global research community or into regional or national data distribution sites). Thin orange lines illustrate the new exchanges**
 228 **proposed in Sect. 2 of this paper. Finally, the thick green lines illustrate the main knowledge and data exchange routes between the**
 229 **different projects, the global research community, and the IPCC assessment process, as well as with multiple policymakers,**
 230 **practitioners, and climate service providers around the world.**

231
 232 CMIP simulations are used extensively as boundary forcing for regional downscaling (e.g. CORDEX) to generate climate
 233 information at spatial scales relevant for adaptation policy and climate services, as well as to drive impact model simulations
 234 (e.g. crop models in AgMIP (Ruane et al., 2017), fisheries and marine ecosystem models in FishMIP (Tittensor et al., 2018),
 235 and a range of impact models that contribute coordinated simulations to ISIMIP (Frieler et al., 2017), addressing impacts

236 such as, biome changes, water resources, human health, energy systems and biodiversity). Regional downscaling follows two
237 main pathways; (i) dynamical downscaling generate high-resolution regional simulations consistent with the ESM boundary
238 condition data (Ruti et al., 2016; Jacob et al., 2020; Teichmann et al., 2021) and (ii) empirical-statistical downscaling
239 (including ML methods) combine observations and models to translate large-scale features simulated by the ESMs to high-
240 resolution, local scale climate information (Gutiérrez et al., 2018; Lange, 2019; Karger et al., 2023). Impact models use both
241 CMIP and CORDEX climate data, as well as socio-economic data and information on mitigation actions from the IAM
242 scenarios (e.g. population distributions and land use patterns that include information on mitigation measures), as forcing to
243 assess the societal and environmental impacts arising from the range of simulated futures (Frieler et al., 2017).

244
245 The combined outcome of this international effort are a set of simulations, data and resulting knowledge covering the past
246 ~175 and future ~100 years (and sometimes longer) that sample; (i) plausible future global socio-economic development
247 pathways, (ii) emission, concentration and land-use scenarios commensurate with these pathways, (iii) global and regional
248 Earth system changes associated with each future pathway and (iv) the societal and environmental impacts arising from the
249 simulated Earth system changes, as well as direct impacts associated with the socio-economic and/or mitigation measures
250 applied in the IAM scenarios.

251
252 There are numerous challenges involved in running the number and variety of model simulations across this range of
253 activities, including cross-project and cross-model dependencies. As a consequence, to date it has not been possible to
254 develop a single, coordinated dataset of forcings, simulations and findings from all four activities (IAMs, CMIP, CORDEX,
255 impact modelling), based on a common set of socio-economic assumptions, scenarios, and driving data, within a single IPCC
256 Assessment cycle. This limitation reduces the overall consistency and utility of information entering the three IPCC working
257 groups (WGs). For example, Global (CMIP) and Regional (CORDEX) simulations are often out of sync, with CORDEX
258 RCMs using boundary data derived from an earlier phase of CMIP. A similar example holds for impact models that often
259 use a mix of global and regional forcing from different phases of CMIP and CORDEX. Furthermore, impact models forced
260 by CMIP/CORDEX climate data, do not include all the socio-economic and climate policy information that underpin the
261 driving IAM emission and land-use scenarios. This is particularly acute with respect to a number of direct human forcings.
262 These forcings are aggregated across multiple sectors and large spatial scales in the IAM scenarios, but need to be
263 disaggregated and harmonized with observed historical data, to more detailed spatial scales and individual sectors, to allow
264 an accurate estimate of their impact on society and the environment, in combination with the impacts due to Earth system
265 change (e.g. see *Direct Human Forcings*, as listed on Table 1, Frieler et al., 2024). An improved accounting of such direct
266 human forcings will be increasingly important as future scenario pathways include major (human) interventions likely
267 required to deliver the negative CO₂ emissions required to achieve the Paris Agreement targets. Such interventions
268 themselves can have important direct impacts on food production and biodiversity and therefore need to be accounted for in
269 impact assessments.

270
271 Partly for methodological reasons, the impacts of climate change (and the potential societal responses to these changes) have
272 not been included in IAM scenarios describing future socio-economic trajectories (i.e. Shared Socio-economic Pathways
273 (SSPs), O'Neill et al., 2020). As climate change is expected to have a considerable impact on society, it is important methods
274 are developed that allow these feedbacks to be included in future scenario development (Pirani et al., 2024). Ideally
275 information on the impacts of climate change would be fed back into the IAMs to iteratively generate new future socio-
276 economic and policy pathways that include the societal responses to both the applied climate mitigation measures and to the
277 impacts of climate change. For example, future land use will need to be adjusted to satisfy global food production, while
278 accounting for the impacts of climate change on crop yields and changes in available land resulting from any land-based

279 climate mitigation measures. These iterative adjustments to future socio-economic scenarios are one way to represent
280 societal adaptation to projected climate change. Given the tight timelines it will not be possible to fully develop such
281 iterative and interactive steps within the IPCC AR7 cycle. Nevertheless, we recommend urgently addressing this link as the
282 envisioned modification of workflows has the potential to significantly improve the overall coherency of future scenarios,
283 integrating important information across socio-economic, Earth system and impact projections.

284
285 The lack of consistency, of both data and knowledge entering IPCC and national climate change assessments, reduces its
286 overall utility and makes the interpretation of uncertainties across the various data sources a challenge. This can lead to
287 inconsistent data and knowledge being used to develop climate policy, with some data being more than 10 years old. We
288 believe the time is right to much more tightly link these key international activities, with more extensive and rapid sharing of
289 simulations, data, knowledge, tools, and personnel, moving such critical *science for policy* work towards an operational
290 footing. Such a change has been proposed earlier (e.g. Jakob et al., 2023; Stevens, 2024). We agree with these proposals but
291 stress the need for “*operationalization*” across the entire workflow involved in developing and delivering robust and useable
292 scientific knowledge. This includes; generation of IAM scenarios and associated forcing data, global and regional Earth
293 system model simulations based on these scenarios, impact model simulations, post-simulation evaluation and analysis,
294 uncertainty quantification, science to policy knowledge translation, and the technical infrastructure needed to support the
295 entire endeavour. To maximize the relevance and utility of the resulting science for policy, we further propose such
296 operational activities employ a co-development and co-exploitation approach, where a cross-section of intended users of the
297 science are involved throughout the process.

298
299 Such developments require support across a number of international coordinating bodies, as well as mechanisms to
300 coordinate or pool the significant funding required, for what is inherently an international, multi-institutional and multi-
301 disciplinary endeavour. The building blocks for this do exist, represented by IAMC, CMIP, CORDEX, VIACS, ISIMIP and
302 the ESGF. To date, the bulk of the effort to realize these interconnected projects have been funded through short-term,
303 competitive research grants, with the availability and international coordination of this funding arising partly by chance and
304 often thanks to common IPCC timelines (Meehl, 2023). While such a development requires significant effort, funding and
305 coordination, the long-term benefits for climate policy are potentially very significant. While moving the policy and service
306 oriented aspects of climate projections and impact assessment towards a more operational approach is important, we stress
307 the paramount importance of maintaining a strong science understanding, model improvement, and open data access,
308 approach across all these activities. This will help maintain global participation and ensure continual improvement in the
309 quality of data and knowledge entering the climate policy and service arenas. Fully achieving these goals on the timescale of
310 IPCC AR7 will not be possible. Nevertheless, a first step in this direction is under development as part of the planning for
311 CMIP7, which will operate a dual timescale approach. A set of CMIP7 Fast Track (FT) simulations, specifically intended to
312 support IPCC AR7, is under development. The CMIP7 FT aims for a small set of policy relevant experiments that can be
313 rapidly performed and made available for analysis by early 2027. In addition to the Fast Track, the bulk of CMIP7 will
314 operate on a slower timescale, roughly from 2025 to 2030, with individual science-oriented MIPs (Model Intercomparison
315 Projects) developing and realising a range of experiments and analyses to address outstanding questions and challenges in
316 Earth system modelling.

317
318 Starting to develop a more joined up and efficient workflow across projects, along with increased internal consistency of
319 data and knowledge emanating from these projects to support IPCC will be an important step towards a durable, more
320 operational approach to delivering scientific support to climate policy and climate services.

321 **3 Improving knowledge and guidance on future Earth system change, allowable emissions, net-zero responses,**
322 **and safe landing pathways for planet Earth.**

323 **3.1 The Paris Agreement: The risk of warming overshoot, allowable emissions, net-zero and negative emissions,**
324 **and Earth system feedbacks.**

325 The 2015 Paris Agreement (with an aim to limit long-term global warming to well below 2°C above pre-industrial
326 temperatures and pursue efforts to limit warming to 1.5°C; Riahi et al., 2021) focused the attention of policymakers and the
327 public onto the risks and consequences of exceeding these key targets. Partly in response to such policy needs, work
328 accelerated on quantifying allowable carbon emission budgets commensurate with the Paris goals (Millar et al., 2017; Rogelj
329 et al., 2019; Lamboll et al., 2023). It became increasingly clear that to provide accurate guidance on such allowable budgets,
330 Earth system models needed to improve their representation of the carbon cycle and its interaction with physical climate
331 processes. In addition, further improvement was required in representing non-CO₂ climate forcings, such as methane, nitrous
332 oxide and aerosols. Focus also turned to the risk of triggering feedbacks that might push temperatures further from a given
333 target, once the target was exceeded, as well as on the risk of exceeding Earth system tipping points, with potentially major
334 regional impacts. Lastly, recognition that international policy would likely lead to the climate being stabilized at
335 temperatures warmer than pre-industrial or present-day, stimulated work to better quantify the long-term consequences
336 associated with such a stabilized warmer world (King et al., 2021).

337
338 Over the past decade significant progress has led to several ESMs now including a full representation of the carbon cycle,
339 interactively coupled to the physical climate (Arora et al., 2020). This progress has motivated calls for CMIP7 to more
340 strongly focus on CO₂-emission driven simulations, where a more complete representation of future climate – carbon cycle
341 feedbacks can occur (Sanderson et al., 2023). A number of ESMs are also incorporating and coupling other Earth system
342 processes required to properly investigate future emission pathways that realise the Paris Targets, as well as the
343 consequences of long-term stabilization. Developments include; nutrient limitation on terrestrial carbon uptake (Lawrence et
344 al., 2019; Wiltshire et al., 2021), interactive methane cycles with the ability to run in emission-mode for methane (Folberth et
345 al., 2022), interactive treatment of nitrogen and iron cycles (Dunne et al., 2020), interactive permafrost (Burke et al., 2020,
346 Schädel et al., 2024), interactive fires (Mezuman et al., 2020; Teixeira et al., 2021), full atmosphere chemistry (Gettelman et
347 al., 2019; Archibald et al., 2020) coupled to advanced aerosol models (Mulcahy et al., 2020), as well as interactive
348 Greenland and Antarctic ice sheets (Smith et al., 2021; Muntjewerf et al., 2021). Many of these developments, occurring
349 across several ESMs, have either recently entered use in their coupled model, or are in an advanced stage of development
350 and planned for use in CMIP7. As a result, the Earth system modelling community, collectively, are entering a period where
351 simulation of the full Earth system during overshoot, recovery, and long-term stabilization can deliver critical new insights
352 that are urgently required by international climate policy.

353
354 An important focus for CMIP7 and ScenarioMIP (O’Neill et al., 2016; van Vuuren et al., 2023) therefore, is investigation of
355 plausible emission scenarios and global warming pathways that successfully realize the Paris Agreement. Key questions
356 within this activity encompass; What is the feasibility of actually realizing the Paris targets? Whether a temporary warming
357 overshoot is inevitable? And, if so, of what magnitude? Also, is it feasible to return to a target warming level on a reasonable
358 timescale once an overshoot has occurred (Bauer et al., 2023)? To provide robust policy guidance on the plausibility and
359 consequences of such pathways, several additional questions need to be addressed: Can accurate predictions of carbon
360 emission budgets (and budgets of other radiatively important greenhouse gases) be made that are commensurate with
361 different warming targets, with or without overshoot (Ramboll et al., 2023)? What is the role of anthropogenic aerosol
362 emissions with respect to future warming and achievability of the Paris targets (Jenkins et al., 2022) What is the risk of
363 amplifying feedbacks being triggered during overshoot (Melnikova et al., 2022), and is there a risk of exceeding tipping

364 point thresholds in the Earth system, society or the natural environment, during overshoot (Wunderling et al., 2023)? If
365 plausible negative emission pathways do exist, that return the Earth system to an acceptable temperature at an acceptable
366 rate, once overshoot has occurred, what will be the environmental consequences of following these pathways? Furthermore,
367 during the overshoot phase, if major changes or impacts (e.g. ecosystem degradation, population displacement, economic
368 damages) do occur, or tipping points are exceeded (either in society or the Earth system), are these changes reversible when
369 temperatures return back below a target level (Kim et al., 2022; Reed et al., 2023; Santana-Falcón et al., 2023) and how long
370 will such a recovery take (Albrich et al., 2020, Meier et al., 2012)?

371
372 Existing mitigation pathways that rely on negative CO₂ emissions assume a significant stimulation of terrestrial carbon
373 uptake through extensive modifications to land-use (Smith et al., 2016). How the carbon cycle will respond to these
374 interventions is not well quantified. Nor is the actual efficacy of these interventions in reducing temperatures (Schleussner et
375 al., 2023), or the ensuing impacts on the natural world, particularly biodiversity. A dominant part of the negative CO₂
376 emissions in present IAM scenarios is assumed to come from the AFOLU (agriculture, forestry and other land use) sector,
377 through large scale deployment of bioenergy with carbon capture and storage (BECCS). It is of the utmost importance
378 ESMs, with a comprehensive process-based representation of the carbon cycle, are used to assess the efficacy of such
379 AFOLU scenarios in terms of realized negative emissions and temperature response, accounting for interactions with the
380 natural carbon cycle and regional climate. Such major changes to the land surface will likely also lead to significant impacts
381 on water availability, biodiversity and a range of human activities (Séférián et al., 2018; Hof et al., 2018), both directly from
382 the change in land use and indirectly through induced changes in regional climates. Such potential impacts need to be
383 carefully assessed with impact models, with any negative impacts balanced against the positive impact of the mitigation
384 actions on global warming. New negative CO₂ emissions technologies that encompass marine-based CO₂ removal (mCDR)
385 are increasing in interest. Such approaches aim to increase marine carbon uptake through ocean alkalization (Kwiatowski
386 et al., 2023; Palmieri and Yool, 2024) or increase the storage of ocean carbon via marine afforestation (Bach et al., 2021).
387 These new approaches have the potential to reduce the demand on land-based CDR, reducing the impacts of these techniques
388 on the land. However, such ocean techniques can lead to negative consequences for marine ecosystems and organisms, by
389 altering marine nutrients cycles. It is important to emphasise that the full Earth system response to marine CDR is as
390 uncertain as its land counterpart. Uncertainties in its efficacy to remove and store CO₂ remain poorly quantified and
391 estimating the lifetime of CO₂ storage in the water column represents an additional challenge compared to the land-based
392 CDR, due to the complicating role of ocean circulation and potential redistribution of CO₂.

393
394 In addition to negative CO₂ emissions, Solar Radiation Management (SRM) has been proposed as an alternative (or
395 additional) route to limiting global warming to 1.5°C. While there remain concerns around the unintended consequences of
396 SRM (Bonou et al., 2023), as well as the long-term governance of such technology (Pasztor and Harrison, 2021), the
397 international SRM community recently designed a set of scenarios that allow investigation of both the efficacy and potential
398 climate impacts of such technology (MacMartin et al., 2022; Baur et al., 2023; Baur et al., 2024). The same community
399 recently proposed an experiment protocol for the CMIP7 Fast Track (Visioni et al., 2024) that targets recovery of the global
400 mean surface temperature to 1.5°C threshold after overshoot. As the world continues to get closer to the 1.5°C threshold,
401 interest in SRM and geoengineering more broadly is likely to increase. The science community will be asked to provide the
402 best possible guidance on the efficacy of SRM, the potential climatic and ecological impacts of SRM, as well as information
403 on the scales (temporal, spatial and quantity) required for this technology to deliver long-term, safe climate stabilization.
404 Such work on climate ‘solutions’ including SRM should be organized under the WCRP Lighthouse Activity on Climate
405 Intervention, which brings together international research communities focussing on both CDR and SRM.

406

407

408 Finally, once an “acceptable” warming level is reached, it remains to be established whether the Earth system can be
409 stabilized, long-term at this level (Jones et al., 2019)? And, if so, what the consequences across the Earth system and for
410 society will be from such stabilization (King et al., 2021; Palazzo Corner et al., 2023)? All these questions have major
411 implications for international climate policy. Reliable answers are urgently needed. The international research community is
412 beginning to address such questions, and increasingly has the modelling tools capable of providing answers. We believe the
413 new round of international modelling projects have the potential to make major advances towards delivering robust answers.
414

415 Past CMIP cycles, including the most recent phase CMIP6 (Eyring et al., 2016a), emphasized CO₂-concentration driven
416 simulations, where atmospheric CO₂ concentrations are prescribed and simulated carbon cycle – climate feedbacks cannot
417 influence atmospheric CO₂. This approach was taken largely for pragmatic and inclusivity reasons (i.e. there was only a
418 relatively small number of models with robust and stable coupled climate and carbon cycles). Thanks to efforts such as
419 C⁴MIP (Friedlingstein et al., 2006, Arora et al., 2020), this is no longer the case, with a significant number of ESMs now
420 including advanced carbon cycles coupled to their physical climate (Sanderson et al., 2023). Due to the small remaining
421 carbon budgets involved in realizing the Paris targets, and uncertainty in how the carbon cycle will respond to negative and
422 net zero emissions, it is imperative more ESMs in CMIP7 run in CO₂-emission mode, with full interaction between the
423 physical climate and carbon cycle, including prognostic atmospheric CO₂ (Sanderson et al., 2023; Gier et al., 2024). This
424 will support an improved assessment of feedbacks involving the physical climate and the carbon cycle, addressing
425 consequences for allowable future carbon emissions, the amount of negative emissions required after different overshoot to
426 achieve different stabilization targets, and the associated risks, impacts and potential for irreversible change across the Earth
427 system. Only through such a coupled, prognostic approach can anthropogenic CO₂ emission scenarios, intended to realize
428 key warming targets, be connected with the Earth system response and the impact of these on atmospheric CO₂ and realized
429 warming/cooling pathways.
430

431 We propose other important aspects of the coupled Earth system, at risk of rapid change, should also be run in a more
432 *coupled and prognostic* manner in CMIP7. Assessment of coupled interactions and risks across the entire Earth system,
433 including potential tipping point risks (Ritchie et al., 2021), is severely lacking in earlier IPCC Assessment Reports. Giving
434 greater emphasis to coupled and prognostic interactions across the Earth system (particularly those thought to play a major
435 role in determining the magnitude of future change) in an internally consistent framework will allow a more complete
436 assessment of Earth system change, beyond that focussed solely on the physical climate. In addition, we emphasize the need
437 to assess the impact of specific and targeted human actions (designed to mitigate future climate change or to adapt to
438 expected future change) on regional climate, as well as on other aspects of the coupled Earth system, including resilience of
439 the natural environment, biodiversity, and consequences for other human activities (e.g. food security, energy production or
440 air quality). The current scientific priorities with respect to such interactions, along with (in italics) the key phenomena,
441 feedbacks and consequences such coupled simulation would enable improved assessment of, are listed below:
442

443 (i) Water, vegetation and biogeochemical cycles of carbon, nitrogen, phosphorous; *improved estimates of vegetation*
444 *change, terrestrial carbon uptake, regional water cycles and ecosystem tipping risks.*
445

446 (ii) Climate, vegetation, and fire: *improved assessment of future fire risk and interactions with carbon uptake,*
447 *atmospheric composition and ecosystem tipping risks.*
448

- 449 (iii) Permafrost, climate, vegetation, and carbon: *stability of permafrost under warming and long-term warming*
450 *stabilization, carbon/methane release from thawing permafrost, ecosystem expansion into thawing permafrost zones.*
451
- 452 (iv) Climate, ice sheets, and sea level: *improved assessment of potentially irreversible loss of Antarctic and Greenland ice*
453 *mass and consequences for sea level rise, ocean circulation and ocean heat uptake.*
454
- 455 (v) Climate, atmospheric composition, and air quality: *internally consistent assessment of regional radiative forcing,*
456 *climate change and air quality.*
457
- 458 (vi) Ocean physics, biogeochemistry and ecosystems: *assessment of ocean warming, marine carbon uptake and long-term*
459 *storage, ocean acidification and impacts on marine ecosystems.*
460
- 461 (vii) Human-Earth System interaction: *assessment of the direct impact of human activities on the Earth system, regional*
462 *climate, society, and the environment. e.g. Mitigation actions designed to address air quality and/or climate change,*
463 *such as major land use change, nature-based solutions, climate interventions (geoengineering). Adaptation measures*
464 *designed to address regional to national scale climate risk.*
465
- 466 (vii) The interplay between global change, regional climate variability, changes in climate and weather extremes, and
467 resulting impacts across the Earth system.

468 **3.2 Regional Earth system change; assessing societal and environmental impacts.**

469 In addition to changing how global ESMs are run, we propose that regional downscaling (for example dynamical
470 downscaling or Regional Climate Modelling, as used in CORDEX) also advance their representation of key regional Earth
471 system processes (beyond the physical atmosphere-land system; Giorgi and Prein, 2022; Nabat et al., 2020; Sevault et al.,
472 2014). Here we refer to regional climate modelling or dynamical downscaling in the broadest sense, encompassing any
473 physics-based dynamical model targeting a fine-scale representation of the climate over a specific region of the world. This
474 includes limited-area models (LAM), variable-resolution GCMs (VRGCM) and, more recently, regional earth system
475 models, convection-permitting regional models, and two-way coupled systems. In addition, atmosphere-land only global
476 models are beginning to run for decadal timescales (and likely longer in the coming decade) and can be driven by sea surface
477 temperatures and sea ice derived from ESM projections, providing a global downscaling option for coupled ESM
478 projections. Whatever the technical choices used to perform such dynamical downscaling in future projection mode, forcings
479 from global ESMs and GCMs will always be required, either as lateral, surface, or inner model boundary condition data.
480 Similarly, we use the term statistical downscaling in a very broad sense, covering established statistical methods for
481 transferring simulated large-scale climate data to local scales, as well as the increasing range of machine learning (ML)
482 techniques, including recent deep learning applications (Gerges et al., 2023, Soares et al., 2024).

483
484 To better sample the uncertainty range of global projections, dynamical and statistical downscaling should preferentially use
485 CO₂ emission-driven ESMs as boundary forcing and employ an efficient (as automated as possible) method to select an ESM
486 ensemble for a given region and rapidly generate the required boundary condition data. The resulting combination of global
487 emission-driven ESMs, regional ESMs, and advanced statistical/ML-based downscaling, all running in a tightly linked
488 framework, will allow a more complete assessment of potential changes across the global and regional environment at scales
489 required by policymakers and planners. Given the rapid development of a diversity of dynamical, statistical and ML-based
490 methods to generate high-resolution regional data, it is important a common evaluation framework is developed that is

491 applicable across global to local scales (and across the implied model resolutions) as well as being agnostic to the methods
492 employed, so different downscaling approaches can be objectively evaluated against each other, region by region and
493 application by application.

494
495 We further recommend impact models use a coordinated, multi-model ensemble of (global and regional) simulation-data,
496 based on the CMIP7 CO₂-emission driven ESMs, that capture a representative fraction of the uncertainty space of global and
497 regional projections. In addition, impact models should aim to sample multiple members of individual ESMs, and the
498 downscaling of these ESMs, to better quantify the importance of internal (natural) variability in regional climate impacts.
499 Forcing impact models, either directly by global ESM output or by appropriately downscaled data, themselves driven by the
500 same ESM simulations, will ensure global consistency of the impact simulations and comparability of impacts resulting from
501 global and regionally downscaled forcing over the same region. In addition to coordinated forcing from ESM and
502 downscaled data, a more complete, disaggregated set of IAM scenario data describing socio-economic development and
503 potential mitigation or adaptation measures will ensure greater coherency between global and regional impact assessments
504 and the underpinning IAM, ESM and regional forcing data. The resulting global models and downscaling combinations can
505 be also used to assess the efficacy and potential impacts associated with different regional climate change mitigation or
506 adaptation actions, offering scientific assessment of such proposed climate solutions.

507 **4 Improving our understanding of, and ability to model key climate processes, climate variability, extreme** 508 **events and regional impacts.**

509 **4.1 Improving key phenomena and couplings in global climate models.**

510 Some of the key uncertainties in Earth system model projections relate to errors in simulating important regional climate
511 processes and phenomena, including interactions across spatial scales and regions. For some of these phenomena, model
512 resolution has been shown to be a key factor. Hewitt et al. (2022) showed that increasing ocean model resolution, in
513 particular better resolving the ocean mesoscale, is important for accurately representing a number of key processes,
514 including; ocean eddies in the Southern Ocean and North Atlantic (*with implications for simulated marine heat and carbon*
515 *uptake, ice sheets and sea-level rise*), ocean deep water formation in the Labrador and Nordic Seas and on the Antarctic shelf
516 (*with implications for the global ocean overturning circulation and heat uptake*), the Atlantic Meridional Overturning
517 Circulation (*with implications for heat and carbon uptake, as well as regional climate*), ocean upwelling regions (*with*
518 *implications for marine carbon uptake, productivity and fisheries*). Increased resolution, in both the atmosphere and ocean, is
519 also important for simulating large-scale hydrological processes (Vannière et al., 2019) (*with important implications for*
520 *regional water cycles, water availability and food security*), as well as modes of climate variability, such as the El Niño
521 Southern Oscillation (ENSO) and associated teleconnections (*with implications for the rate of ocean heat uptake and*
522 *regional climate variability*). While increased model resolution (to better resolve the ocean mesoscale or the synoptic scale
523 in the atmosphere) is an important component of reducing several systematic biases in coupled models, it is equally
524 important to improve key parameterization schemes for processes that continue to be unresolved, even at horizontal
525 resolutions of ~10km/0.1° in coupled models. In particular, it is critical to ensure further improvement in parameterizations
526 at the heart of uncertainty in simulated Effective Climate Sensitivity (EffCS) and Transient Climate Response (TCR) (Meehl
527 et al., 2020; see Sect. 6 of this paper)

528
529 Upscale effects from many of these small-scale processes can be important. For example, oceanic mesoscale eddies tend to
530 drive atmospheric mesoscale storms in the extra tropics (Liu et al., 2021), while at larger scales the atmosphere can drive
531 ocean variability (Frankignoul, 1985). These effects are apparent only in coupled systems and their large-scale

532 consequences, such as the preferred location and orientation of the jet stream, mid-latitude storm tracks, and related air-sea
533 fluxes, can only be captured in large-domain models with mesoscale or better resolution (Seo et al., 2023). Furthermore,
534 couplings between the heat, water, and carbon cycles, means improving the representation (and parameterization) of physical
535 processes will deliver important benefits for simulating the carbon, and other biogeochemical, cycles. In addition to the
536 large-scale impacts, higher resolution models also offer an improved simulation of climate variability, in particular weather
537 extremes such as; tropical cyclones (Roberts et al., 2020), extreme precipitation (You et al., 2023), atmospheric rivers (Liang
538 and Yangyang, 2023), jet streams and atmospheric blocking (Schiemann et al., 2020) with consequences for the frequency
539 and location of extreme weather (Athanasiadis et al., 2022), which both depend on SST realism delivered by resolving the
540 ocean mesoscale. All these events have important impacts across the coupled Earth system, including upscale effects, e.g.
541 drying of the atmospheric column by tropical cyclones over the Maritime Continent, with impacts on ENSO (Scoccimarro et
542 al., 2021). Similarly, in the ocean increased resolution can improve the representation of important dynamical phenomena,
543 such as marine heatwaves (Plecha and Soares, 2020) the representation of bottom water formation (Heuzé, 2021) and mixed
544 layer eddies (Calvert et al., 2020).

545
546 Increasing model resolution alone does not guarantee improvement in all simulated metrics and leads to important challenges
547 related to model spin-up, equilibration, calibration, and uncertainty quantification. Simulation improvements are often best
548 realized through a combination of increased model resolution and targeted improvement to key parameterization schemes.
549 While the compute cost increases considerably as model resolution is increased, recent studies suggest increased resolution
550 can deliver important insights into some long-standing model biases, and perhaps reconcile mismatches between simulated
551 and observed historic trends. For example, Rackow et al. (2022) show that resolving the ocean mesoscale improves the
552 simulation of Antarctic sea-ice trends, Chang et al. (2023) illustrate increased realism in ocean upwelling as model resolution
553 is increased, and ongoing work suggests higher resolution simulations can better capture recent observed trends in the
554 Eastern Pacific that are not captured in CMIP6 models (Seager et al., 2022). Such improvements will have important
555 implications for predicting future extreme events, such as tropical cyclones, floods, droughts and heatwaves.

556
557 There is strong evidence a coordinated set of simulations for CMIP7, with resolutions enhanced over those typically used
558 (e.g. 10-25 km in the atmosphere and $\sim 0.1^\circ$ in the ocean), can deliver an improved simulation and understanding of key
559 regional climate processes and a more robust assessment of future changes in many of these processes, with benefits for
560 impact and adaptation planning. Chang et al. (2020) demonstrated that CMIP-length simulations, with an equilibrated
561 coupled model, are now possible at resolutions of $\sim 10\text{-}25\text{km}/0.1^\circ$. Many groups produced simulations following the CMIP6
562 HighResMIP protocol (Haarsma et al., 2016), though generally with very limited ensemble sizes. Given increased model
563 efficiency and available compute resources, CMIP7 provides an opportunity to further investigate the benefits of increased
564 coupled model resolution, alongside increased ensemble size, longer simulations, methods for improved model equilibration
565 and initialization, and enhanced process realism. Given current structural limitations of coupled climate models, of whatever
566 resolution, sampling model diversity, through multi-model CMIP-style exercises, remains critical for providing robust
567 estimates of projection uncertainties and risks (see Section 7). This is particularly the case with respect to regional climate
568 change, where processes may be resolution-dependent (e.g. Chamarro et al., 2021) and therefore sensitive to biases common
569 across lower resolution models. A diversity of enhanced resolution coupled models thus needs to be promoted, but also
570 optimized across the competing demands for delivering future projection data that is of maximum quality and utility both for
571 the science and policy communities.

572

573 **4.2 Increased model resolution from global to regional scales for regional impact assessment and adaptation.**

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

587
588 While the combination of high-resolution coupled global climate models (~10-25 km in the atmosphere and ~0.1° in the
589 ocean) and convection-permitting regional climate models (~1-3 km) are computationally demanding, the potential to deliver
590 radically new findings and policy support, at scales required by national and regional planners, means they are an
591 increasingly important input to national climate scenarios, adaptation planning, and climate services. This is particularly the
592 case with respect to risks associated with extreme weather events. In the next phase of CMIP and CORDEX, we propose a
593 significant emphasis be placed on increasing collaboration, as well as data and knowledge sharing, between high-resolution
594 global climate models, convection-resolving regional models, and statistical/ML-based downscaling, with the goal of
595 producing a coordinated ensemble of high-resolution global projections, downscaled by an ensemble of convection-resolving
596 regional models, augmented by state of the art statistical and ML-based downscaling. We further recommend the resulting
597 high-resolution (global and regional) projection data are used to force a range of impact models (e.g. in ISIMIP, AgMIP and
598 FishMIP). As the future impacts felt by natural and human systems is not only dependent on climate change, but also on the
599 direct human forcing of climate arising from the underpinning scenarios themselves, it will be important to also represent
600 these drivers at high spatial resolution. The resulting set of climate change and impacts data will be of enormous value to
601 national climate change impact assessments, adaptation planning and climate services. To maximize the quality and
602 consistency of this multi-scale, multi-method data set, it is important systems are developed and employed to allow careful
603 evaluation of the cascade of information across systems, scales, regions, as well as from climate to impacts, highlighting
604 both value-added and consistency-lost across the entire chain.

605
606 **4.3 Global Storm Resolving models and the path to global km-scale**

607 Global models with grid spacing in the range 1-10km are often referred to as Global Storm Resolving Models (GSRMs, e.g.,
608 Hohenegger et al., 2020; Judt et al., 2020; Caldwell et al., 2021). GSRMs running at ~3-5km global resolution currently
609 achieve a throughput of ~0.5 simulated years per day (SYPD), with an aim to reach 1 SYPD in the coming years. GSRMs
610 originated within the international DYAMOND initiative (Stevens et al., 2021) and the GRSM community are currently
611 designing year-long experiment protocols (Takasuka et al., 2024, submitted). In addition, within the EU-sponsored
612 Destination Earth (DestinE; Wedi et al., 2022) two coupled GCMs have run a reduced HighResMIP experiment (for the
613 period 1990 to 2040) with grid spacing of 5km.

614
615 Examples of scientific highlights realised by GSRMs include; a realistic representation of the interannual frequency of
616 Tropical Cyclones (TC) in major basins, comprising a realistic distribution of all severity categories (Judt et al., 2020), as

617 well as realistic representation of the rate of TC intensification, possible as resolutions reach 3km or better. Recent
618 comparative studies among km-scale ocean models show large-scale features that affect the storm tracks and air-sea coupling
619 (e.g., Gulf Stream separation) are more consistent in these models than in coarser resolution ocean models. Internal
620 variability is also substantially larger in eddy-rich models (Chang et al., 2020; Jüling et al., 2021), including stronger SST
621 responses to AMOC variations. In terms of coupled phenomena, realistic representation of the North Atlantic storm track has
622 been shown to be sensitive to resolution of the ocean mesoscale, including instantaneous features (eddies) and climatological
623 features (western boundary currents) (Moreno Chamorro et al., 2022). Representation of the full spectrum of precipitation
624 processed by cyclones, including their frontal structures, organised convection, such as Mesoscale Convective Systems and
625 squall are generally more realistic as model resolution is increased (Vellinga et al., 2016).

626
627 Many of these achievements have been in the realm of convection-permitting Regional Climate Models (see section 4.2) for
628 the past ~5 years. GSRMs offer the additional value of being able to simulate upscale effects from small scales onto larger
629 scales, e.g. how the Hadley and Walker circulations are affected, including meridional transports of energy, as well as
630 implications for global teleconnections, mediated by atmospheric wave propagation. Many of these achievements were
631 realised thanks to the development of new dynamical cores, capable of reducing the total number of computations, by use of
632 uniformly spaced global grids, or by models running more efficiently through advanced numerical schemes in time and
633 space, and by exploiting multiple parallelisation paradigms on the latest supercomputers, including those equipped with
634 GPUs. With the advent of even more powerful new classes of GPU, such as the NVIDIA Hopper or AMD MI300 series,
635 completing a selection of typical CMIP6 experimental protocols at ~3km resolution, with a total turnaround of order of one
636 year, will soon be possible.

637
638 Data output and analysis constitutes a major challenge at these resolutions: output of order petabytes per day are
639 commonplace, and storing multiple ensemble members for centennial-scale simulations is not feasible. Multiple approaches
640 are being tested to alleviate this problem, such as performing the most data-intensive and multi-variate analyses while the
641 models are running, reduced data precision, or holding data on fast disks for very brief time periods to allow immediate
642 consumption by users. Other approaches include the use of hierarchical data layers, which can be output and handled in
643 parallel, with incremental expense, as exemplified by the HEALPIX standard.

644 An ambitious vision for addressing such data challenges, including co-design, co-production, and global access, is provided
645 in the Earth Virtualisation Engines concept (Stevens et al., 2024).

646

647 **5 Increasing collaboration across approaches to improve global and regional Earth system and climate models.**

648 The accuracy of numerous simulated Earth system and biogeochemical phenomena strongly depends on the quality of
649 simulated physical climate drivers (Doney et al., 1999). Examples of such dependencies include, but are not limited to; (i)
650 vegetation growth/loss, terrestrial carbon uptake, and the simulated water cycle; (ii) wildfires and simulated precipitation,
651 soil moisture and winds; (iii) marine productivity and the dynamics of ocean upwelling, (iv) mass loss from marine ice
652 sheets and regional ocean circulation; (v) global ocean heat and carbon uptake, and representation of deep water formation,
653 (vi) regional air pollution and modes of atmospheric circulation. Conversely, in the real-world, carbon cycle – climate
654 feedbacks (as well as other Earth system feedbacks) change the fraction of anthropogenic CO₂ (and other gases, such as CH₄
655 or N₂O) that remain in the atmosphere to cause warming, and thereby influence the magnitude of physical climate feedbacks
656 (e.g. water vapour, lapse-rate, cloud or sea ice feedbacks). Furthermore, while an accurate simulation of the mean climate (in
657 time and space), as well as trends in this measure of climate, are extremely important, an accurate representation of
658 variability (in both time and space) of the underpinning physical climate can often be as important for simulating the Earth
659 system response to a changing climate. Such variability is also a critical driver of the impacts of climate change. Regional
660 climate variability, particularly the width of the distribution of such variability (i.e. the extreme tails of future climate

661 distributions), is generally better represented as resolution is increased, both in global and regional models (Wehner et al.,
662 2014; IPCC, Doblas-Reyes et al., 2021; Ban et al., 2021).

663
664 High-resolution coupled global climate models can be viewed as the physical core of the next generation of Earth system
665 models, offering an improved simulation of the driving physical climate, including climate variability and extreme events.
666 Collaboration across the development of high-resolution physical climate models, and Earth system models that emphasize
667 enhanced process-realism, needs to deepen both in CMIP7 (with respect to global models, Dunne et al., 2023) and CORDEX
668 (with respect to regional models). Such collaboration can benefit from, and feed into, ongoing efforts under the WCRP LHA
669 Explaining and Predicting Earth System Change (<https://www.wcrp-climate.org/epesc>), and offers an unprecedented
670 opportunity to bring advances from both areas together to support development of the next generation of Earth system
671 models. Such a meeting point between these two model development paths offers a unique testbed for assessing
672 technological advances (e.g. hybrid-resolution ESMs, Berthet et al., 2019; AI-based emulation approaches, Son et al., 2024),
673 as well as conceptual challenges in Earth system modelling (e.g. in quantifying and optimizing the benefits and trade-offs
674 between resolution, complexity and ensemble size). Machine Learning (ML) has the potential to reduce long-standing
675 systematic errors in ESMs and enhance the overall projection capability of these models. This needs to be further explored
676 (Eyring et al., 2023a), with increased sharing of methodologies and findings across ML-based, and more traditional
677 approaches, to model development. Increased collaboration and knowledge sharing across these efforts will lead to a step
678 change in our overall ability to provide robust climate information that meets the needs for mitigation and adaptation across
679 spatial and temporal scales (Eyring et al., 2023b).

680
681 A number of initiatives are beginning to develop “Digital Twins of the Earth” (DTEs), (e.g. the WCRP Digital Earth LHA,
682 <https://www.wcrp-climate.org/digital-earths>) targeting an optimal fusion of Earth system modelling and observations, to
683 deliver fit-for-purpose and actionable information to society. These approaches combine forward modelling, data
684 assimilation, and machine learning tools with user models designed to answer specific questions. A number of (global and
685 regional) DTEs are beginning to provide samples of km-scale information, with the majority of DTEs to-date being
686 atmosphere-land only models. For application to future climate change, such models presently require sea surface and sea ice
687 boundary condition data (or atmospheric boundary conditions) derived from coupled ESM projections. As DTEs further
688 develop to include other components of the Earth system (e.g. oceans, cryosphere, carbon cycle etc) it will be important they
689 are carefully evaluated against existing approaches to deliver high-resolution future climate information (either via
690 uninitialized projections or observation-initialised predictions). It will also be important to document the uncertainties in
691 DTE projections/predictions arising from different modelling choices, different external forcings and emission scenarios, as
692 well as from internal variability. This is particularly important with respect to predicted or projected changes in future
693 extreme weather events, which by definition are rare occurrences, with low predictability.

694
695 Only a few efforts to date are trying to develop two key aspects of digital twins; linking inputs to observations and outputs to
696 human systems. In Europe, Destination Earth (<https://destination-earth.eu/>) experiments with weather and climate twins,
697 down to resolutions of 2.5 km, and aims to make its experimental design respond to user needs, so models store a minimal
698 amount of data, but are re-run on a regular basis, incorporating the latest data requests in each update. In the US, the
699 Department of Energy has tested combining physical models (e.g. the Energy Exascale Earth System Model, E3SM (Golaz
700 et al., 2022)) with human system models, including Integrated Assessment or Energy Grid models. In addition, ultra-high-
701 resolution global storm-resolving models (GSRMs, Stevens et al., 2019; Lee and Hohenegger, 2024) run at 1-5 km
702 resolution may provide further understanding and insights into biases, complementing CMIP7/CORDEX simulations. While
703 the approaches employed and timescales involved are somewhat different, sharing of methodologies, successes, and

704 problem-solving across communities will benefit all strands of work, improving our combined ability to model the coupled
705 Earth system and deliver robust and actionable climate information to policymakers and society.

706 **6 Improving model simulations of the observational record and key metrics of climate change**

707 To increase confidence in future projections it is important models accurately reproduce the observed historical record. This
708 requirement encompasses multiple variables and timescales, with long-term trends in global mean surface air temperature
709 (GMSAT), including the forcings and feedbacks controlling these trends, of first order importance. In CMIP6 a number of
710 ESMs exhibited EffCS values (of 5°C or greater) that are higher than the 5-95% range, as assessed by multiple lines of
711 evidence (Sherwood et al., 2020). Some of these models also simulated global warming rates over recent decades (~1980 to
712 2014) greater than seen in observations (Tokarska et al., 2020), leading to suggestions these “hot models” were unrealistic
713 and should be filtered out from climate impact assessments (Hausfather et al., 2022).

714
715 Cloud feedbacks are the largest contributor to uncertainty in EffCS. Perhaps surprisingly, CMIP6 ESMs with high EffCS
716 often evaluate better against observations for present-day clouds than earlier or lower EffCS models (Bock and Lauer, 2023;
717 Kuma et al., 2023), and also accurately reproduce recent trends in cloud-radiation when driven by observed sea surface
718 temperatures (SSTs, e.g. Loeb et al., 2020). These ESMs also represent a number (though not all) cloud feedback processes
719 more accurately than earlier models, particularly those related to mixed phase clouds over the Southern Ocean (Jiang et al.,
720 2023). Nevertheless, studies continue to highlight problems across the majority of CMIP6 models with respect to Southern
721 Ocean clouds (Schuddeboom and McDonald, 2021) and, in particular, low-level tropical marine clouds (Konsta et al., 2022),
722 with observation-based constraints of the latter cloud type suggesting an EffCS closer to 3°C (Myers et al., 2021). It is
723 therefore possible some high EffCS CMIP6 models improved one cloud feedback (e.g. mid-latitude, mixed phase clouds
724 leading to a less negative cloud phase feedback) that exposed other feedback errors (e.g. too positive low-level, tropical
725 marine cloud feedback) that previously compensated each other with respect to the total cloud feedback. Such one-sided
726 improvement can result in an increased positive total cloud feedback and high EffCS. Continued improvement in the
727 representation of cloud processes and feedbacks across all relevant cloud types, including exploitation of new observational
728 data and analysis methods, will be crucial for better constraining EffCS in CMIP7 and improving the simulation of historical
729 climate and rates of global warming.

730
731 While a number of high EffCS models in CMIP6 simulated too strong global warming over the period ~1980 to 2014,
732 establishing a direct link between EffCS and historical warming is not straightforward. This is mainly due to the
733 confounding role of aerosols, as well as the important role played by natural variability. In CMIP7 historical forcings are
734 planned to be extended to 2022 (i.e. 8 years longer than in CMIP6). Recent studies indicate anthropogenic effective radiative
735 forcing (ERF) has become more positive, by ~50%, between the decades 2000-2009 and 2010-2019, mainly due to a
736 reduction in the negative aerosol ERF (Jenkins et al., 2022; Hodnebrog et al., 2024). This change has been accompanied by
737 almost a doubling of the GMSAT warming trend between these two decades. Jenkins et al. (2022) suggest that while some of
738 the increased GMSAT trend is very likely due to reduced aerosol cooling, long-term variability in ENSO may also
739 contribute. Modelling studies by Wang et al. (2023) further suggest that decreasing aerosol emissions may outweigh
740 decreasing CO₂ emissions in terms of their impact on warming and climate extremes during the path to global net-zero
741 carbon emissions. Kang et al. (2023a, b) suggest the SST pattern observed in the Pacific between ~1979 and 2013, which
742 induces a negative cloud feedback term (that is not captured in most coupled ESMs), is linked to cooling SST trends in the
743 Southern Ocean over this period (also not captured in coupled ESMs). They suggest that as Southern Ocean SSTs begin to
744 warm, the tropical Pacific SST pattern may decay, resulting in a more positive cloud feedback and potentially an increased

745 rate of global warming. Understanding, and simulating in coupled ESMs, the drivers of such SST trends, as well as their
746 interaction with climate feedbacks and global warming, will be crucial to increase confidence in future projections.

747
748 Constraining future feedbacks and evaluating model processes controlling these feedbacks is a difficult challenge. Emergent
749 Constraints, which use a multi-model ensemble to identify relationships between observable Earth System variations and
750 projected future changes, are an attractive way to constrain future feedbacks based on observations (Hall et al., 2019; Nijssen
751 et al., 2020) and thereby reduce uncertainty in future projections. To date, assumed emergent relationships are often simple
752 linear regressions. Machine Learning techniques are a promising route for identifying multi-dimensional, non-linear
753 relationships between contemporary observables and the future state of the Earth System (Schlund et al., 2020) and may
754 therefore improve the constraints on future feedbacks and even allow an evaluation of model processes controlling these
755 feedbacks. An improved simulation of the historical past, combined with improved constraints on key feedbacks and the
756 processes controlling these feedbacks, will increase confidence in ESM projections and improve estimates of key climate
757 change metrics such as EffCS, TCR and TCRE with implications for estimates of allowable carbon emissions for different
758 policy targets.

759
760 Both global and Regional ESMs struggle to accurately represent observed regional climate trends, as underlined for Western
761 Europe by recent literature (Ribes et al., 2022; Schumacher et al., 2023; Vautard et al., 2023). This may be partly linked to
762 poor quality lateral and surface boundary conditions (e.g. most recently from CMIP6 ESMs), but may also be a result of
763 missing, or poorly represented, regional forcings and/or feedbacks in the RCMs (Nabat et al., 2014; Boé et al., 2020; Taranu
764 et al., 2022, e.g. the representation of aerosol-climate interactions or the simulation of regional/coastal SST trends). For
765 RCMs too short evaluation runs and lack of adequate calibration strategies may also contribute to these problems. Tackling
766 such weaknesses, combined with development of an evaluation system applicable across the scales and downscaling
767 methods involved, will be important for increasing trust in high-resolution, regional climate projections that will be used in
768 numerous national climate scenarios and impact assessments.

769 **7 Sampling and quantifying future uncertainty**

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

776 **7.1 High Impact Low Likelihood (HILL) outcomes.**

777 While such MMEs sample a fraction of the uncertainty in future Earth system change, this sampling is far from complete,
778 particularly with respect to the extreme, low-likelihood end of potential Earth system change. Such responses are referred to
779 as HILL (High Impact, Low Likelihood) outcomes (Wood et al., 2023). While HILL outcomes have a low likelihood of
780 happening, there remains a small chance they will occur. One example would be if the Earth's equilibrium climate sensitivity
781 (ECS) turned out to be $\sim 5^{\circ}\text{C}$. While this outcome is highly unlikely (IPCC AR6 quotes the *very likely range* (5-95%
782 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
783 on society would be extremely large.

784

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

800

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

816

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

824 **7.2 Internal variability, parameter uncertainty and model structural uncertainty.**

825 An additional approach for investigating modelling uncertainty is the Perturbed Parameter Ensemble (PPE) (Murphy et al.,
826 2007). In the PPE approach uncertain, often difficult to constrain, model parameters are varied within reasonable limits,

827 where possible constrained by observations (Booth et al., 2017). The resulting PPE members can be further filtered to retain
828 only skilful members in terms of present-day climate and/or historical trends (e.g., Sexton et al., 2021; Peatier et al., 2022).
829 Recent advances in model calibration (e.g., Hourdin et al., 2021, 2023) will be instrumental in better designing future PPE.
830 Using the PPE approach, it is sometimes possible to mimic key measures of future projection uncertainty (e.g. the range of
831 climate feedbacks and ECS in a CMIP MME) using only a single model (Collins et al., 2011). Applying the PPE approach
832 across multiple global and regional model systems allows probabilistic regional climate projections that sample a significant
833 fraction of future projection uncertainty (Evi et al., 2021). Such approaches support assessment of regional impacts sampling
834 uncertainty in the future driving global and regional climate, including changes in climate and weather variability.

835

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

851 **7.3 Assessing uncertainty across all the steps in providing actionable climate information.**

852 The new round of international modelling projects presents an opportunity to bring together the range of approaches and
853 methods used to assess and quantify uncertainty across IAM models and scenarios, global and regional models (considering
854 internal model variability, parameter uncertainty and structural model differences), and impact models (both in terms of the
855 climate forcing used and uncertain model parameters). This collaboration should also extend to work closely with
856 communities developing, improving and applying emulators and simple climate models (Séférián et al., 2024). Collaboration
857 across communities and activities will help increase the range of uncertainty space that can be analysed, and lead to a more
858 systematic and coordinated approach to uncertainty assessment across the full suite of modelling activities that delivers
859 science knowledge and data to climate policy and climate services. We further recommend significant effort be devoted to
860 the communication of uncertainty and conversely, communication of what is expected to occur in the future, and the level of
861 certainty/confidence that can be attached to these outcomes, with the target audiences being climate change policymakers,
862 planners, and practitioners.

863

864 Going forwards, a key demand on the international modelling community, with respect to supporting IPCC AR7 and the
865 UNFCCC Global Stocktake, will be the development and analysis of realizable future pathways that limit global warming to
866 the targets of the Paris Agreement. These pathways are likely to include an overshoot of the warming targets and therefore
867 the need for negative CO₂ emissions (i.e. active removal of CO₂ from the atmosphere). How these negative emissions will be
868 realized in practice and what magnitude is feasible, remain open questions. A thorough analysis and quantification of the full

869 cascade of uncertainty associated with such pathways is an important demand on the science community. This analysis needs
870 to encompass uncertainty in; how the necessary negative CO₂ emissions will be realized (i.e. the mitigation actions
871 themselves), the response of the carbon cycle to decreasing atmospheric CO₂, the efficacy of any CO₂ removal in reducing
872 global temperatures, and the regional climate responses that may arise from such cooling pathways. In addition,
873 uncertainties in the (expected) reduction in the societal and environmental impacts of Earth system change, as global
874 warming is reduced, need to be assessed, and the impacts avoided compared to any impacts arising directly from the
875 mitigation actions themselves. Along the entirety of this chain of events and responses there is deep uncertainty. The science
876 community needs to analyse, quantify, and communicate this uncertainty as thoroughly and clearly as possible.

877

878 Robust climate adaptation requires information on the range of potential future changes (which represent the climate hazard
879 in risk decision frameworks). While great strides have been made in quantifying global and large-scale impacts arising from
880 the range of climate change drivers, this has only been partially successful with respect to translating the range of these
881 impacts to the local scales needed to assess climate impact and develop local to national adaptation plans. CMIP7 offers an
882 opportunity to more fully include and propagate the wider CO₂-emission driven uncertainties through to local-scale climate
883 information (as outlined in Sect. 3.2). An equally important dimension is the role natural variability plays in climate change,
884 especially on the timescale of the next 10 to 40 years (that frames many adaptation decisions). On these timescales and at the
885 local scale, natural variability typically dominates the forced climate change signal, for example for precipitation and
886 temperature. This information is ever more critical as society adapts to climate change in a mitigating world, where such
887 mitigation aims to limit the climate change signal. Large initial condition ensembles are a key tool for understanding and
888 quantifying the role natural variability plays. The expense (computational, data storage) of generating and sharing Lateral
889 Boundary Conditions (LBCs) required to drive Regional Climate models has limited the availability of LBC data, and hence
890 the potential for regional scale simulations (such as CORDEX) to sample the role of regional natural variability in the
891 context of the wider climate hazard space, at impact relevant scales. Commitments for new LBCs are often made before a
892 simulation's credibility can be assessed and before any understanding of where the realisation of variability plus feedbacks
893 places a particular simulation in the wider potential projection space. There will be value, therefore, in exploring iterative
894 approaches between ESM and regional modelling groups to identify optimal ESM simulations to be rerun for LBC
895 generation.

896

897 Statistical downscaling may provide the most effective route to link wider ESM projections to what they imply at the local
898 level (Gutiérrez et al., 2019), as these approaches are not restricted by the limited availability of LBCs. Emerging Neural
899 Network Machine Learning techniques trained on existing regional (RCM and Convection Permitting RCM (CPM))
900 simulations, are showing promise in capturing spatial and temporal climate change, at local scales, based on large scale
901 drivers simulated by ESMs (Baño-Medina et al., 2021; Doury et al., 2022). Whilst there is still work to be done (e.g.
902 achieving multi-variate coherence (González-Abad et al., 2023), transferability to other ESMs (Baño-Medina et al., 2024),
903 building frameworks to verify ML downscaled results) their emergence is likely to represent a transformative change in how
904 the science community provides local scale climate information, as they enable the production of this information to be
905 determined by realisations that can inform on the range of local scale climate hazard (bottom up) rather than the limited
906 availability of LBCs by ESM modellers (top down) as is currently done. ML-based downscaling therefore has the potential
907 to translate coarse-scale Earth system model output directly to spatial scales of utility for impact models, impact assessment
908 and local adaptation planning (Eyring et al., 2023b). Such developments can be transformative in other senses, too. For
909 example, given adequate prior ESM to RCM/CPM training data, CMIP7 has the potential to be downscaled almost as soon
910 as the ESM simulations are completed, something which could help inform, for the first time, IPCC AR7 with consistent
911 global and regional projection data, and associated impact simulations (see Sect. 2). Similarly, ML may offer ways to

912 address the prohibitive storage costs of conventional high resolution local data by enabling the availability of such data on
913 demand based on large scale variables (which are much cheaper to store). Ultimately, incorporating Machine Learning into
914 the production of high-resolution regional climate information is likely to open further benefits due to the flexibility such
915 tools enable. For example, ML downscaling will be amenable to approaches that use observations to bias correct the regional
916 data, directly. Similarly, as insights from new modelling (e.g. resolving convective scales, interactive atmosphere-shelf sea-
917 wave models) come online, similar ML downscaling tools may be able to produce new high resolution regional climate data
918 reflecting these insights, if the new modelling experiments are designed to inform the required ML training.

919 **8 The underpinning technological infrastructure**

920 The ambitious science and science for policy aims discussed in this paper cannot be realized without a state-of-the-art
921 underpinning computational and data infrastructure, supported by experienced personnel. Our recommendations require the
922 co-design of certain experiments, followed by the production, quality-control and sharing of numerous datasets from a
923 diverse range of modelling systems, between producers and a heterogeneous set of consumers separated in time and space. An
924 aspiration for IPCC AR7, as described earlier, is to deliver a coordinated and coherent set of data from across the most recent
925 IAM scenarios, global (CMIP7) and regional (CORDEX) simulations, as well as impact model results based on these
926 scenarios and climate forcing. To achieve this will require more efficient and rapid sharing of both requirements and data
927 across all communities, including where feasible user communities. We therefore stress the need to improve the
928 underpinning infrastructure ecosystem that supports these international modelling efforts to enable the co-development of
929 suitable experiment protocols, followed by the production, evaluation, and exploitation of datasets, which themselves can be
930 used as input to other simulation workflows, with different production, validation, and exploitation cycles. This will need to
931 be realized for far more numerous and larger volume datasets, and across a broader and more disparate set of requirements
932 and communities than was previously the case.

933
934 CMIP6, like CMIP5, benefited from a globally coordinated data infrastructure, the Earth System Grid Federation (ESGF),
935 linked to a large array of other important and necessary services (Balaji et al., 2018). The CMIP6 ESGF is now more than a
936 decade old, largely not maintained and is therefore not fit for the scale of the challenge outlined above. The array of services
937 linked to the ESGF include: standards-based data, model and experiment descriptions; citation and errata services for
938 simulation data and derived products; and data quality control procedures (addressing the presence of required data,
939 standards compliance etc, not to be confused with procedures for assessing the scientific quality of the data). The data
940 infrastructure itself needs to support systematic (and efficient) simulation evaluation, and support replication of data from
941 source to “super-nodes” that can host large volumes of multi-model data and provide sufficient local computational resource
942 to allow analysis with minimal requirement for data movement (Eyring et al., 2016). Local computing services will need to
943 include both specific “well known” computational services such as those necessary to generate on-demand statistics, and
944 those necessary to support user-generated analysis pipelines that may include AI and ML techniques. To realize the
945 ambitions outlined in this paper, the volumes of data that will need to be hosted at such super-nodes will be significantly
946 larger than for CMIP6, and the services will need to be easier to navigate for a more heterogeneous community, extending
947 beyond the modellers and analysts of earlier CMIP cycles.

948
949 There are several activities underway that aim to address some of these requirements. Notable amongst these are the
950 development of reusable evaluation and analysis workflows such as ESMValTool (Eyring et al., 2020; Righi et al., 2020)
951 with the goal of fully integrating these into the CMIP publication workflow (Eyring et al., 2016b), the democratisation of the
952 use of cloud computing via Pangeo (Abernathy et al., 2021), the use of new data formats such as HealPix (Chang et al.,

953 2023), and the development of new technologies aimed at a future ESGF (Hoffman et al., 2022). However, there are also
954 significant areas where little or no development is underway. These include enhanced documentation, errata, and citation
955 services, many of which are relying on best efforts and need dedicated investment and effort in new techniques and modes of
956 deployment. Considerable work will be required to bring all of these strands together into a coherent system that can be
957 deployed and supported world-wide and sustained throughout the next IPCC cycle (and beyond).

958
959 This new ecosystem will need to support and coordinate efficient methods for data reduction and sharing, cross model
960 analysis and evaluation, with an emphasis on bringing together existing and new observational and reanalysis datasets,
961 models, emulators, and advanced analysis tools for rapid and in-depth analysis and exploitation. The new system will need to
962 interface with other major data holdings, for example those of the WCRP Lighthouse activities¹ (Flato et al., 2023), the
963 Destination Earth² data holdings, the existing ISIMIP data repository³, the Copernicus Climate Change Service (C3S)⁴ and
964 new data holdings that may arise from the EVE (Earth Visualization Engines)⁵ initiative. It will need to conform to FAIR
965 (*Findable, Accessible, Interoperable, and Reusable*) principles (Wilkinson et al., 2016) and meet the needs and requirements
966 arising not just from CMIP7, but from the range of communities involved in IAMC, CORDEX and VIACS/ISIMIP.
967 Critically, the system will need to be fully supported by dedicated data managers, capable of addressing community
968 questions pertaining to data quality, model and data documentation, as well as supporting users of embedded infrastructure
969 tools to facilitate the rapid use and reuse of data and tools across communities. It is this rapid use and reuse that will deliver
970 the internal consistency, across models and research communities, key to the transformative impact expected for
971 international climate policy from the science and modelling efforts proposed in this article.

972 **9 Summary and recommendations for the way forward**

973 Over the past three decades, internationally coordinated modelling projects have delivered a wealth of simulations, data, and
974 scientific knowledge to support policy actions addressing climate change mitigation and adaptation. As a new round of these
975 projects start up, and a new 7th IPCC assessment cycle begins, we have reviewed how these projects have collectively
976 provided science support to international climate policy. We propose a number of science, technology and collaboration
977 priorities that we believe these projects should jointly focus on over the coming decade. Progress in these areas will increase
978 the quality and utility of science support to climate policy, while increasing our understanding of Earth system change,
979 including the impacts on society and the natural world, as well as our ability to project such future changes and the
980 associated impacts.

981
982 One key proposal is for the involved modelling communities, spanning integrated assessment, scenario generation, global
983 and regional Earth system modelling, and impacts modelling, to work much more closely together during the next round of
984 projects, with an aim to deliver a coordinated set of scenarios, projections and impact assessments all based on the same
985 underpinning socio-economic and mitigation scenarios and using the most up to date model configurations. This will
986 significantly improve the quality and consistency of scientific knowledge available to the upcoming (AR7) and future IPCC
987 assessments, as well as to the 5-yearly UNFCCC Global Stocktakes. Building on interactions developed over the past 5-10
988 years, and the increasing suggestion that simulations supporting international climate policy become more operational in
989 structure, we suggest the time is right to actively develop a tighter and more efficient set of links across the relevant

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/>

990 modelling projects. Fully realizing this ambition within the AR7 timeframe is likely not possible. Nevertheless, significant
991 effort to achieve such internal consistency and efficient sharing of data, knowledge, and personnel, will lead to future
992 workflows better suited to fully realize this ambition. In addition, we highlight the need for impact models to receive more
993 detailed information (disaggregated, spatially and by sector) on the socio-economic assumptions underpinning the IAM
994 scenarios. Conversely, increased effort is required to allow knowledge of projected future climate impacts, and the societal
995 responses to these impacts, to be iteratively incorporated into the generation of emission and land-use scenarios. Thanks to
996 CMIP5 and CMIP6 cycles, there is an increasing set of well-established links between IAM scenario production teams, Earth
997 system modelling groups, CORDEX downscaling teams, and impact modellers, with the majority of the modelling in these
998 activities using a common data infrastructure system. These established connections and shared infrastructure make the
999 potential for a more efficient, inter-connected workflow across all these activities a real possibility in the coming years.

1000

1001 The programme of work we outline addresses numerous key knowledge gaps, several of which were highlighted in IPCC
1002 AR6 (IPCC, 2021). Given the increasing number of ESMs capable of running in CO₂-emission mode, including simulation
1003 of the climate and carbon cycle as well a range of other Earth system phenomena, combined with an increasing number of
1004 coupled GCMs running for centennial timescales at ~10km resolution, we believe many of these knowledge gaps can be
1005 successfully addressed over the coming decade. Exploitation of CMIP6 was identified as limited in AR6, pointing to a need
1006 to support and better focus coordinated international modelling projects, including links between projects. Plausible
1007 overshoot scenarios that return to the Paris Climate targets by the end of the century or later (e.g. by 2130), were limited in
1008 CMIP6 and need to be a greater focus of CMIP7. To address this, it is crucial ESMs are extended to allow a more thorough
1009 assessment of the efficacy of proposed land and marine CO₂ removal techniques in reducing atmospheric CO₂ and driving
1010 global cooling, while accounting for potential Earth system feedbacks (IPCC 2021; Canadell et al., IPCC 2021). ESMs need
1011 to be capable of assessing both CO₂ and non-CO₂ feedbacks during overshoot (e.g. a changing efficiency of CO₂ uptake by
1012 natural reservoirs as CO₂ is removed from the atmosphere, or methane release into the atmosphere from wetlands or
1013 permafrost (Canadell et al., IPCC 2021)), as well as the potential for, and consequences of, rapid change in key Earth system
1014 components during overshoot, such as ice sheet loss or forest dieback (Canadell et al., IPCC 2021; Fox-Kemper et al., IPCC
1015 2021). In addition, interactions between CO₂ warming and trends in aerosol emissions need to be thoroughly assessed, so the
1016 impact of decreasing aerosol emissions on the near-term rate of global warming and achievability of the Paris targets can be
1017 better quantified. Such analysis needs to be complemented by analysis of the (societal and environmental) impacts of a
1018 warming overshoot, the degree of reversibility of these impacts once cooling to a target level is achieved, and the impacts
1019 resulting from long-term stabilization at a warming level (assuming it is warmer than today). The majority of IAM scenarios,
1020 designed to realize the Paris Agreement, assume extensive deployment of land-based (and in a very limited number of cases,
1021 marine-based) atmospheric CO₂ removal technology. The direct impact of these mitigation actions on society and the
1022 environment needs to be assessed and contrasted with the impacts avoided from the resulting reduction in global warming.
1023 An additional set of approaches to limit the magnitude of future warming, referred to as geoengineering, are increasingly
1024 discussed in policy circles and the media. The most widely known being Solar Radiation Management (SRM; Lawrence et
1025 al., 2018; Vioni et al., 2023). While there remain concerns around the safety and governance of such actions, it is
1026 increasingly important the research community actively assesses the efficacy of these approaches, including the risks and
1027 potential consequences of deployment of this technology at the scales required. Projections beyond 2100 were not
1028 comprehensively covered in CMIP6 (Chen et al., IPCC 2021). This is important for understanding committed changes and
1029 the consequences of long-term stabilization at temperatures warmer than today. This is particularly acute with respect to sea-
1030 level rise (Fox-Kemper et al., IPCC 2021), with Antarctic and Greenland ice sheets representing the largest uncertainty in
1031 future sea-level projections. It is vital these systems are better modelled in CMIP7 and beyond.

1032

1033 More accurately simulating the observed, historical evolution of the climate system (i.e. reducing systematic model biases),
1034 including the representation of the forcings and feedbacks driving the observed warming, is crucial for increasing confidence
1035 in model projections and for maximizing the use observations in model improvement. Associated with this, we advocate the
1036 use of new approaches (for example, combining Machine Learning and Emergent Constraint techniques) to enable more
1037 extensive use of observations to constrain model projections and future feedbacks. A key requirement remains improved
1038 constraints on key metrics of Earth system sensitivity (e.g. EffCS, TCR, TCRE and the Regional to Global Warming ratio)
1039 and that models accurately simulate these metrics, as well as the processes underpinning them.

1040
1041 Due to their exceptional impact, we highlight the need for improved knowledge of, and ability to simulate, extreme weather
1042 events, including potential future changes in such events. We further stress the importance of assessing the impact of
1043 extreme events on society and the environment, considering the level of uncertainty inherent in projections of such rare
1044 events. This requirement also extends to the modes of climate variability that extreme events develop within (including
1045 natural variations, future changes and extreme realizations of these modes). Looking towards the next generation of Earth
1046 system and climate models, we propose significantly increased collaboration across communities investigating enhanced
1047 Earth system process realism, those working on increased model resolution, and improved physical parameterizations, as
1048 well as groups working on ML-based hybrid modelling. Increased collaboration across these communities will optimize
1049 findings from each approach for development of the next generation of Earth system models. This recommendation holds
1050 equally for global and regional modelling, including collaboration between these two communities.

1051
1052 With respect to uncertainty, in future emission scenarios, in Earth system change, and in the impacts, we propose extensive
1053 collaboration across the range of approaches addressing these issues. Wherever possible work should assess, quantify, and
1054 emulate uncertainty as it propagates through the stages of IAM scenarios, ESM projections, regional downscaling, and
1055 impact simulations, so a more complete assessment of total uncertainty can be provided to policymakers. An additional
1056 consideration is to better quantify what can be predicted (i.e. based on model predictions started from observed initial
1057 conditions) versus projected (i.e. changes in future climate statistics relative to simulated past or present statistics due to a set
1058 of external forcings). An important challenge in this area is to accurately quantify the level of predictability for different
1059 variables and regions, and at what lead times and spatial scales. We highlight the need for improved modelling and
1060 assessment of the risk and consequences of potential future High Impact Low Likelihood (HILL) outcomes, with the
1061 possible exceedance of tipping points in the Earth system, the environment, or society, being of critical importance. Given
1062 there will always be some level of uncertainty in the future climate, it is important to focus on the communication of this
1063 uncertainty, or possibly more importantly, communication of what is expected in the future and with what level of
1064 confidence. This is a key area in the science-policy interface.

1065
1066 The transformative goals outlined in this paper require the support of a robust, efficient, and internationally connected
1067 infrastructure. While components of such an infrastructure exist, much work is needed to design, build, deliver and sustain
1068 an integrated system that meets the objectives outlined here, and maximises the benefits of existing initiatives and
1069 investments. The resulting infrastructure must exploit common tools and standards and be designed and delivered with both
1070 a long-term perspective and a well-trained workforce. It will need to handle increasing volumes of data, support the use of
1071 new techniques for data analysis (such as remote analysis of big data using ML and AI techniques), and facilitate the easy
1072 exchange of data, knowledge, and analysis tools. Without such an infrastructure, many of the aims outlined here will not be
1073 met in a timely manner, if at all.

1074

1075 Finally, to expand the reach and benefits of international modelling, including the uptake and use of model simulations, to a
1076 more truly global scale and thus deliver underpinning scientific support for global climate policy, there is an urgent need for
1077 increased involvement of Global South scientists. WCRP leads a number of important efforts in this area. These need to be
1078 ramped up significantly and put on a sound long-term footing. Given the global nature of the climate crisis, that the impacts
1079 are, and will continue to be, most strongly felt by Global South countries, a globally inclusive response is a necessity. This
1080 makes both scientific sense (to draw on local expertise for understanding and predicting local Earth system change and its
1081 impacts), as well as political sense (climate policy is generally better tailored to a specific country's needs if it is based on
1082 local expert advice that is accessible over the long-term). We (this group of scientists all working in Europe) encourage our
1083 governments and funding agencies to provide sufficient, long-term support to further develop and maintain a strong and
1084 globally inclusive scientific collaboration over the coming decades.

1085 **Author contribution**

1086 All co-authors provided ideas and comments to the manuscript. CJ, HJ, SJ, BNL, RS, TK, KF, BS, BB, SS, DVV, HH, EOR,
1087 FA, MR, PF, PLV, VE and PC conceived and developed the original ideas and recommendations in the paper. CJ and HJ wrote
1088 the paper, with regular input from the 17 other people listed in the first 19 co-authors and periodic input from all other co-
1089 authors.

1090 **Competing interests**

1091 Two co-authors are on the ESD editorial board: Roland Seferian and Richard Betts.

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