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CMIP7 Data Request: Earth System Priorities and Opportunities

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Abstract. This paper presents a comprehensive overview of the Coupled Model Intercomparison Project Phase 7 (CMIP7) request for data pertaining to Earth systems science, and provides justification for the resources needed to produce this data. Topics within the CMIP7 Earth system (CMIP7-ES) theme centre around tracking of flows of energy, carbon, water and other fluxes across domains, and constraining feedbacks between these cycles and the climate system. These topics are summarized in this paper as scientific 'opportunities' describing specific model intercomparison experiments and use cases for next-generation Earth System Model (ESM) output. These opportunities were submitted by modelling groups and scientific consortia following an extended public consultation process. Contained within each opportunity are requests for groups of Climate & Forecasting (CF) variables, which are bundled into variable groups representing all data required to address the

https://doi.org/10.5194/egusphere-2025-3246
Preprint. Discussion started: 16 July 2025

opportunities' needs. Novel opportunities in CMIP7 compared with previous phases will include running 'emissions-driven' simulations that integrate carbon emissions and removal scenarios with updated representations of the global carbon cycle, expanded variable groups needed to model marine trophic interactions and biogeochemistry, and data needed to understand the risk of global tipping points, among others. The production of these variables will close key gaps and uncertainties identified during previous rounds of CMIP, and support the 7th Intergovernmental Panel on Climate Change Assessment Report (AR7). We argue that CMIP7-ES data will be broadly used by scientific, policy, governmental, industry, and other communities that rely on climate model projections for research and decision making. As an author group we also reflect on the evolution of the CMIP7-ES data request as a part of a deliberative process in support of the global CMIP program.

1. Modelling Earth system cycles, feedbacks, and thresholds in CMIP7

1.1 Background

Based on a physical climate 'core,' Earth system models (ESMs) simulate numerous complex relationships and feedbacks among the atmosphere, biosphere and oceans to model energy and mass transfer across domains (Séférian *et al.*, 2019; Jones 2020). ESMs are critical tools for studying the role of anthropogenic forcing on interacting biogeochemical systems, and for predicting cascades of physical and ecological responses to global warming (Steffen *et al.*, 2018; Gillett *et al.*, 2016; Zhang *et al.*, 2024). Developed based upon a broad consultation process, the Coupled Model Intercomparison Phase 7 Earth System (CMIP7-ES) data request contains the requirements needed for the analysis of carbon, nitrogen, water and other cycles and their interactions with the physical climate, the biosphere and reservoirs (Juckes *et al.*, 2024; Friedlingstein *et al.*, 2025; Dunne *et al.*, 2024; Jones *et al.*, 2024). The data request is organized into scientific 'opportunities' representing specific research foci that each contain a variable group representing the data needed to fulfil the scientific objectives of each opportunity (MacKallah *et al.*, 2025; Data Request Task Team 2025). While many of these variables were produced as part of CMIP6, the new variables will enable the evaluation of climate sensitivity to forcing, detection and attribution of the impacts of climate change, and prediction of the likelihood of major tipping points under different emissions scenarios (Wunderling *et al.*, 2023, Steffen *et al.*, 2018). Moreover, while the CMIP6 data request included a large number of variables, most models did not output most variables meaning that many studies analysing multiple variables were often restricted to small subsets of models. By organising the CMIP7 data request around scientific opportunities, and omitting variables that were little used in CMIP6, the intention is that studies addressing these key opportunities will be able to draw on a much more complete set of CMIP7 data. Fulfilment of the CMIP7-ES data request will enable the study of a large number of terrestrial and marine ecological dynamics and their implications in the carbon cycle and climate system (Sanderson *et al.*, 2024). This will allow for ESMs to be benchmarked against observations of climate and ecological dynamics, serving both as validation of the processes represented by the models and their skill at predicting trajectories of global change (Fu *et al.*, 2022; Collier *et al.*, 2018).

https://doi.org/10.5194/egusphere-2025-3246
Preprint. Discussion started: 16 July 2025

Projecting Earth systems' responses to further forcing from anthropogenic emissions is at the centre of the CMIP7-ES data request. Emissions-driven, as opposed to concentration-driven, simulations that incorporate the removal of carbon from the atmosphere and reflect an advanced understanding of natural source-sink dynamics will explore the response of the climate system to human activities (Arora *et al.*, 2020; Sanderson *et al.*, 2024). Whereas in CMIP6, almost all scenario simulations were run with a single set of projected atmospheric CO_2 concentrations derived from an emulator (Meinshausen *et al.*, 2011a,b; O'Neill *et al.*, 2016), meaning that carbon cycle uncertainty was typically neglected when discussing uncertainties of the climate response to emissions, the emissions-driven interactive CO_2 simulations proposed as part of the Scenario Model Intercomparison Project for CMIP7 (Van Vuuren *et al.*, 2025) will allow the effects of carbon cycle uncertainty on future projections to be fully characterised. As carbon dioxide removal (CDR) technologies are becoming more feasible and necessary to avoid the worst climate impacts, modelling a range of Shared Socioeconomic Pathways (SSPs) that reflect up-to-date industrial and agricultural emissions and include mitigation to net-zero and net-negative emissions is a priority (Van Vuuren *et al.*, 2024; Riahi *et al.*, 2017). For example, these simulations will include explicit representation of the carbon cycle effects of afforestation and reforestation in ESMs (Van Vuuren *et al.*, 2025). An improved representation of the exchanges of CO_2 from sources to sinks, in particular into the oceans, will account for missing fluxes and reduce existing mass imbalances in models (Henson *et al.*, 2022; Jones *et al.*, 2016; Liddicoat *et al.*, 2021; Planchat *et al.*, 2023; Tang *et al.*, 2024). Adding nitrogen and phosphorous cycling to terrestrial ESMs will improve estimates of photosynthesis (Gier *et al.*, 2024), and adding methane emissions will ensure that major contributors to the greenhouse effect are represented (Davies-Bernard 2020; Lovato *et al.*, 2022; Sanderson *et al.*, 2024). Progress on these aspects of ESMs will help create wholistic representations of the climate-carbon system and improve predictions of near- and long-term climate impacts in response to future emissions.

Reducing uncertainty around marine and terrestrial carbon fluxes is critical to emissions-driven model deployment. The oceanic 'pump' of carbon export represents a crucial sink for atmospheric carbon, removing ~25% of the carbon added to the atmosphere since the start of the industrial revolution (DeVries 2022; Friedlingstein *et al.* 2025). The response of the marine carbon flux to additional warming is uncertain, reflecting differences in the underlying simulated variables and parameters in ocean biogeochemical modules (Rohr *et al.*, 2023; Wilson *et al.*, 2022). The 'solubility pump' of CO_2 into dissolved inorganic carbon (DIC) accounts for the majority of carbon present in seawater, functioning as a result of the disequilibrium concentration of carbon in the oceans and atmosphere (Egleston *et al.*, 2010; DeVries 2022). The rate at which the ocean and atmosphere equilibrate and remove anthropogenic carbon depends on water pH levels and sea surface temperatures (Weiss 1974). It is estimated that the oceans' buffering capacity has decreased substantially, but a large source of uncertainty remains in how seawater circulation will be affected by a warmer atmosphere, thereby influencing the ocean-atmosphere CO_2 flux (Archer 2005; Liao *et al.*, 2021). The 'biological pump' of carbon export via marine organisms, both as DIC from dissolved carbonate skeletons and as larger particles that precipitate into sediments, sequesters anthropogenic carbon at a rate of approximately 10 gigatons of carbon per year (DeVries 2022). Biological activity in the upper ocean is contingent on water chemistry (i.e. pH and nutrient availability), regional upwelling, and hemispheric-scale circulation patterns (Planchat *et al.*,

https://doi.org/10.5194/egusphere-2025-3246
Preprint. Discussion started: 16 July 2025

2023). Improved modelling of trophic interactions in the upper ocean from primary producers to higher trophic levels, responses to changing water chemistry, and factors affecting carbon export to deeper ocean reservoirs are critical for estimating the magnitude of ocean carbon storage in the future (Wilson *et al.*, 2022). Deliberately altering ocean water chemistry and circulation to enhance rates of carbon dissolution in seawater have been proposed as a method of reducing the greenhouse effect. More studies are needed to assess the feasibility, and estimate the impacts of ocean-based CDR on ecosystems, fisheries, and climate (Doney *et al.*, 2025).

Over land, Jones *et al.*, (2023) have shown that CMIP6 ESMs generally agree well with observations of regional mean fluxes and carbon stocks, although large spread across models is found. While improvements have been made in simulating terrestrial gross primary productivity (GPP), especially when including the nitrogen cycle, the net land-atmosphere carbon flux remains an uncertain component of ESMs (Gier *et al.*, 2024). ESMs without an interactive nitrogen cycle tend to overestimate the effect of elevated CO_2 on the land carbon sink (Kou-Giesbrecht and Arora, 2023). A broader representation of the interactive nitrogen cycle and inclusion of other limiting factors such as phosphorus (Fleischer *et al.*, 2019) are needed to better constrain the magnitude of the future land carbon sink (Kou-Giesbrecht and Arora, 2023; Gier *et al.*, 2024). The spatial distribution of the land carbon sink is still poorly represented with an underestimation of the sink in the Northern Hemisphere, and poor agreement between ESMs and observations of carbon fluxes and stocks over permafrost-covered regions (Jones *et al.*, 2023; Qiu *et al.*, 2023). Representing permafrost biogeochemistry is crucial to better represent future carbon fluxes, including methane, and feedbacks between fluxes and climate (Kleinen *et al.*, 2021; Schuur *et al.*, 2022). Improvements in the net land-atmosphere carbon fluxes are mainly attributed to improvements in the representation of GPP (Gier *et al.*, 2024), while carbon turnover (including processes such as respiration, mortality and soil carbon decomposition) remains a large source of uncertainty (Koven *et al.*, 2017; Canadell *et al.*, 2021; Spafford and MacDougal, 2021; Pugh *et al.*, 2020). With the exception of fire, tree mortality and demographic changes associated with climate-driven disturbances are poorly or not represented in ESMs resulting in uncertainties in the future response of the land carbon sink to climate change (Fisher *et al.*, 2021; Pugh *et al.*, 2020; Bonan *et al.*, 2024). Although fire processes are represented in some ESMs, changes in fire regimes constitute a significant source of uncertainty in simulating the carbon cycle. CMIP6 models systematically underestimate the total burned area observed via satellites, instead tending to estimate an increase in burned area and fire emissions, contrary to observations (Zheng *et al.*, 2021; Li *et al.*, 2024). Running ESM simulations assuming different levels of fire prevalence and comparing the output to satellite records and charcoal reconstructions will help to constrain its role in the carbon cycle and improve predictions for future fire prevalence worldwide (Rabin et al 2017; Li *et al.*, 2024). Soil respiration represents another source of uncertainty in terrestrial ESMs, reflecting a need for better representations of below-ground processes in CMIP7 (Ito *et al.*, 2020; Varney *et al.*, 2022). Closing nitrogen and phosphorous cycles, modelling carbon fluxes from soil respiration and vegetation uptake, ecological responses to fire and drought, and the role of land cover and land use change will all help to reduce uncertainty surrounding net primary production and feedbacks to climate (Boysen *et al.*, 2021; Song *et al.*, 2021; Qui *et al.*, 2023). Finally, reducing uncertainties on land-use and land-cover changes (LULCC) and corresponding emissions will

https://doi.org/10.5194/egusphere-2025-3246
Preprint. Discussion started: 16 July 2025

be crucial for emissions-driven runs. For example, Egerer *et al.*, (2025) found large spread in afforested and reforested area in CMIP6 models forced by the same underlying LULCC scenarios. Differences in the consideration of land-use transitions (gross vs. net) and of management processes can result in large spread in LULCC fluxes (Arneth *et al.*, 2017; Hartung *et al.*, 2021) Models should clearly report the underlying assumptions for estimating LULCC transitions and fluxes.

Beyond carbon cycle characterizations the CMIP7-ES data request will provide new insights into how changes in Earth's energy balance affect climate and biogeochemical cycling. In particular, it will enable study of how aerosol transport, deposition, and reactions with other heat-trapping gases within the atmosphere affect climate, the carbon cycle and ecosystems. How aerosol particulates and trace gases, stemming both from industrial processes and volcanism, modify global temperatures have been major source of uncertainty in transient simulations (Fyfe *et al.*, 2021; Hansen *et al.*, 2023; Clyne *et al.*, 2021). Improvements in the representation of aerosol forcing over multiple phases of CMIP had a large impact on temperature trends derived from models. Exclusion of forcing from volcanoes in early phases of CMIP5 resulted in simulations of global temperature that were significantly greater than observed trends (Domingues *et al.*, 2008; Schmidt *et al.*, 2014). CMIP6 experiments brought models into better agreement with respect to natural (i.e. volcanic) forcing, and indicated that anthropogenic aerosol emissions likely switched from driving a cooling trend over the twentieth century to driving a warming trend in the twenty-first century, due to improvements in air quality (Quass *et al.*, 2022; Fiedler *et al.*, 2023; Bellouin *et al.*, 2020; Zanchettin *et al.*, 2022; Bauer *et al.*, 2022). Although globally the cooling effect of aerosols has decreased (Bauer *et al.*, 2022), the spatial distribution of these changes is determined by regional emissions and meteorological dynamics (Williams *et al.*, 2022; Stier *et al.*, 2024). Downscaled and high-resolution models are needed to tie improvements in air quality with local and regional temperature trends and weather events (Roberts *et al.*, 2025). Although aerosol forcing as a physical process falls primarily within the Atmosphere theme, there are also direct and indirect interactions between atmospheres, oceans, and land. As examples, how aerosols nucleate moisture in the atmosphere, thus affecting regional hydroclimate, or how transport of dust particles fertilizes remote ecosystems are potential research topics that could be addressed by the data request (Samset et al 2024; Iles et. Al 2024; Bellouin *et al.*, 2020; Richardson *et al.*, 2016; Persad, 2023).

Next-generation ESMs will deepen our understanding of how anthropogenic and natural forcing drive climate variability, affect ocean-atmosphere circulation, and alter the risk of extreme events. It remains poorly-understood how changes in Earth's radiative balance translate into internal climate variability and affect climate on local to regional spatial scales (Boer *et al.*, 2016; Jain *et al.*, 2023). The inaccurate representation of patterns of internal variability on timescales ranging from days to decades hinders adaptation efforts when the full range of values for critical climate variables such as daily temperature and precipitation are not well-constrained (DeGroot *et al.*, 2021; Laepple *et al.*, 2023). Understanding the relationship between variability and forcing is also a critical component of climate change detection and attribution (D&A), which is needed to diagnose how anthropogenic emissions affect dynamical systems, such as the jet stream, Atlantic meridional overturning

https://doi.org/10.5194/egusphere-2025-3246
Preprint. Discussion started: 16 July 2025

circulation (AMOC), and other ocean-atmosphere circulation patterns (Gillett *et al.*, 2016; 2025). The Detection and Attribution Model Intercomparison Project (DAMIP v2.0) will include simulations with only land use change prescribed and simulations with only aerosol changes prescribed, in which atmospheric CO_2 is interactively modulated to allow for the effects of biogeochemical feedbacks on the responses to individual forcings to be analysed (Gillett *et al.*, 2025). Longer simulations will be of use to both the Paleoclimate Model Intercomparison Project (PMIP) for constraining natural and forced variability on decadal to millennial timescales (Kageyama *et al.*, 2018). The data request will also address the research needs of geoengineering experiments such as the Geoengineering Model Intercomparison Project (GEOMIP), enabling important research into the potential effects of direct intervention into radiative forcing (i.e. solar radiation management) and carbon dioxide removal on physical climate, ecosystems, and society (Visoni *et al.*, 2023).

Scenarios with higher warming levels raise the likelihood of triggering tipping points within the Earth system (Schleussner *et al.*, 2024; Ritchie *et al.*, 2021; Armstrong McKay *et al.*, 2022). Tipping elements of concern include the aridification of the Amazon basin, ratcheted loss of mass of the Greenland and West Antarctic ice sheets leading to rapid sea level rise, and a slowed AMOC due to the weakened oceanic thermal gradients (Wunderling *et al.*, 2024). If any of these thresholds are reached within the next century it would result in widespread social and economic damage (Dietz *et al.*, 2021). ESMs are the best source of information that we have about what tipping points might be reached under different warming scenarios. Building an understanding of the risk of tipping points, and of what cascades of impacts may result from them is crucial for building climate adaptation policies that accounts for uncertain but high-risk outcomes.

1.2 Scientific questions

Answering the following scientific questions are considered to be a high priority for CMIP7-ES. These questions flow from a series of opportunities (described in Section 4) proposed by members of the ES author group with community consultation, and are summarized in Fig. 1.

1) Cycles: How do the global carbon and other biogeochemical cycles respond to and feedback to changes in radiative forcing, and how does carbon cycle uncertainty contribute to uncertainty in projected warming?

2) Ecosystems: How will climate change and/or climate mitigation influence the ocean biological carbon pump, and how will marine ecosystems be affected? What dynamics and feedbacks govern the prevalence of fire on a global scale, and how do changing fire regimes alter the terrestrial carbon cycle?

3) Energy: How does energy move across realms (ocean, land, cryosphere, atmosphere), and can we optimize model output of the Earth's energy budget in a way that can be compared to observations? Can we keep track of the energy fluxes represented in water as it transfers between phase states and domains? How is energy stored and propagated between the atmosphere and oceans systems to produce internal climate variability on daily to decadal timescales, and can model hindcasts be used to improve multi-annual to decadal-scale predictability and the prediction of extremes?

https://doi.org/10.5194/egusphere-2025-3246
Preprint. Discussion started: 16 July 2025

4) Thresholds Under what climate forcing scenarios could major tipping points within the Earth system be reached? To what extent can currently stable ecosystems sustain future climate alterations?

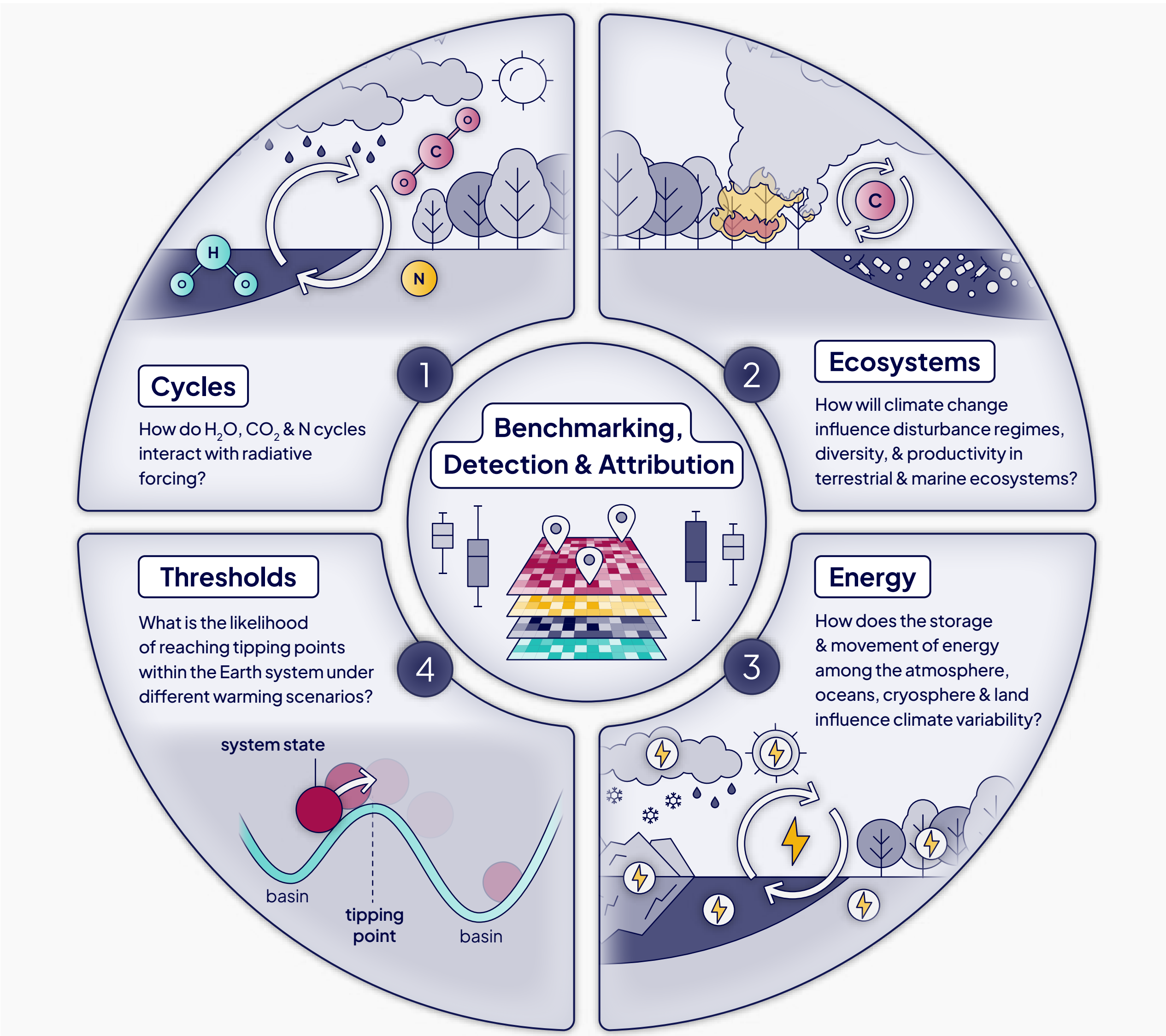

Fig. 1: Schematic diagram outlining questions at the centre of the CMIP7 Data Request for Earth systems research.

1.3 Scope of the data request

The CMIP7-ES theme deals primarily with Earth system cycles and interactions across domains, not with the physical climate itself (i.e., atmospheric dynamics and general circulation), which falls under the Atmosphere & Ocean and Sea Ice themes. Although related (e.g., marine ecosystems and fisheries), opportunities that deal with the social impacts of climate change

https://doi.org/10.5194/egusphere-2025-3246
Preprint. Discussion started: 16 July 2025

were determined best suited for the Impacts and Adaptation theme. Overlap exists with other themes in the area of ecological change and its associated impacts on biodiversity and ecosystem function. Any opportunity dealing chiefly with a single domain, i.e., cryosphere, land, or atmosphere, falls within other thematic areas as the ES theme emphasizes the transfer of energy and mass across domains.

1.4 Audience

The audience for the data request includes modelling centres with the expertise and capacity to generate ESM simulations, as well as a larger community of scientists and stakeholders who use model data for a variety of applications. Opportunities under the CMIP7-ES umbrella flow from the CMIP6 community of endorsed MIPs and research consortia, which represent both modelling centers and independent research activities (Eyring *et al.*, 2016). These include the Coupled Climate-Carbon Cycle Model Intercomparison Project (C4MIP), Fire Model Intercomparison Experiment (FireMIP), Fisheries and Marine Ecosystem Model Intercomparison Project (FishMIP), Paleoclimate Model Intercomparison Project (PMIP), Geoengineering Model Intercomparison Project (GEOMIP), Tipping Point Model Intercomparison Project (TIPMIP), Detection and Attribution Model Intercomparison Project (DAMIP), Decadal Climate Prediction Project (DCPP), (ScenarioMIP) and others. The opportunities described below, with their attendant requests for data from the modelling centres, have been contributed by the members of these experiments. Fulfilment of the data requirements described below is critical for the advancement of research activities within these longstanding research groups.

CMIP7-ES data will also be useful to the community of climate model data users. These include researchers involved in data-model comparison of observational, remotely sensed, and paleoclimate data. For data-model comparisons, CMIP data serves as an independent source of climate information, and findings from these activities cyclically drive model development by identifies areas of data-model disagreement. Non-academic audiences for ES model data include climate policy makers and private sector stakeholders, for example insurers involved in catastrophe risk modelling (Stoffel *et al.*, 2024). CMIP will continue to be an integral part of designing climate adaptation polity on national and international levels (IPCC 2021), and is increasingly being used by state and local governments to guide municipal planning for future climate impacts.

2 Approach and methodology

The CMIP7 Earth System thematic group was initiated through an open recruitment process that started with a public call that opened between February and March 2024 (https://wcrp-cmip.org/cmip7-earth-system-call/). This call specifically addressed the engagement of representatives from the wider Earth system science communities, with expertise on the carbon and nitrogen global cycles and the biogeochemical interactions between the physical climate and the biosphere. All the applications were collaboratively evaluated by representatives of selected MIPs (GEOMIP, DAMIP, PMIP) and Data Request

Task Team leaders and liaison members. A diverse team of 18 members was selected that included a spread of different scientific foci and encompassed a wide range of CMIP experiences, nationalities and career stages.

The author team was officially formed in late August 2024 and its activity began immediately after the closing of the first public consultation phase on the collection of community-based data request opportunities for the CMIP7 Fast Track (Turner et al, 2024). Members were requested to address the scientific groundings and data requirements of the proposed opportunities, as well as a proactive engagement with the reference communities and networks to sustain an effective participation in the composition of the Data Request. The team agreed on the use of a shared online spreadsheet to allow for the asynchronous completion of individual tasks, while periodic virtual meetings with a two to three-week frequency were devoted to summarizing ongoing activities and discussing shared, common responses to the actions emerging from each iteration of the evaluation process. CMIP7-ES Task Team liaisons edited the content of an Airtable database on behalf of the author team and returned to the group key outcomes emerging from the cross-thematic and Task Team meetings, and outlined actions to be undertaken after each public consultation phase.

3 Information management and decision making

After the closing of the first consultation phase in the end of August 2024, the main activity of the CMIP7-ES thematic team was to evaluate the clarity of the scientific scope presented in each opportunity and the consistency of requested variables and experiments groups. In a shared online spreadsheet, each member indicated the acceptance or rejection of an opportunity, along with comments related to scoping issues, requested variables, or potential overlaps with other themes. In the following online meetings, the team finalized the evaluation of those opportunities associated with the Earth System theme by pooling individual scores and the agreed responses were transferred to the public Airtable database. The review of all the comments raised by each thematic group was carried out in a coordinated cross-thematic effort in the middle of September 2024 to achieve a more consolidated set of opportunities by indicating potential aggregations or requesting revisions of proposed variable groups. In turn, the CMIP7-ES author team took charge of reporting back the outcomes of the cross-thematic activity to the proposers of opportunities to resolve identified criticalities and to interact with the reference science community when multiple instances had to be aggregated into a single coordinated action. A summary of the main decisions and comments that arose in the consultation phase of the initially proposed opportunities is reported in Annex 1.

Before the release of DR V1.0, the author team revised the consistency of experiments associated with each opportunity, along with time subset specifications and prioritization of variable groups by interacting with proposers and reference communities to better frame the requests. At the end of the public consultation on the first version of the Data Request (mid January 2025) an in depth revision of newly proposed variables was carried out by the liaison members of the thematic group in preparation

https://doi.org/10.5194/egusphere-2025-3246
Preprint. Discussion started: 16 July 2025

of the following sub-releases to fill technical gaps (e.g. missing CF definitions) and by including items proposed by the community consultation held in February and March 2025.

In the finalized Data Request at v1.2.1, the CMIP7-ES theme primarily accounts for 8 opportunities (Table 1) and it shares overlapping scientific objectives with 13 opportunities led by other thematic teams (CMIP Data Request Task Team; 2025). The details of the other thematic areas and variable groups included in the Data Request are provided in the companion manuscripts under the Rapid Evaluation Framework (CMIP Model Benchmarking Task Team 2024; Dunne *et al.*, 2024), Atmosphere (Dingley *et al.*, 2025), Land and Land Ice (Li *et al.*, 2025), Impacts & Adaptation (Raune *et al.*, 2025), and Ocean and Sea Ice (Fox-Kemper 2025) themes.

Table 1. Data Request opportunities primarily accounted within the Earth System theme scientific objectives, including total numbers of variable groups and experiments requested.

ID	Description	Variable Groups	Experiment Groups
18	Constructing a Global Carbon Budget	5	3
10	Benchmarking and Attributing Changes to Global Carbon and other Biogeochemical Cycles	11	3
31	Role of fire in the Earth system	2	6
44	Changes in marine biogeochemical cycles and ecosystem processes	8	4
29	Earth's Energy Budget	5	4
66	Water cycle/budget assessment	4	3
82	Robust Risk Assessment of Tipping Points	2	4
54	Multi-annual-to-decadal predictability of the Earth System and risk assessment of climate extremes	4	5

4.1 Constructing a global carbon budget (ID18)

A defining trait of an Earth system model is the ability to consider interactions between the physical climate system and the global carbon cycle. This coupling between carbon and climate can be represented in two main ways. The first is by allowing the atmospheric CO2 concentration to be prognostic in response to imposed emissions with land and ocean carbon reservoirs freely exchanging CO2 with the atmosphere, in an "emissions-driven" configuration. The second is to specify atmospheric CO_2 concentrations, such that fossil fuel CO_2 emissions are inferred as what is needed to balance out the change in carbon masses in the total land, ocean, and atmosphere system (a "concentration-driven" configuration) (see Fig. 2 in Jones *et al.*,

https://doi.org/10.5194/egusphere-2025-3246
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2016). In both emissions-driven and concentration-driven configurations, it is necessary to quantify changes to all of the carbon pools in the biosphere in order to ensure carbon mass conservation. The central goal of this opportunity is thus to track all carbon throughout the Earth system, ensure a closed carbon budget, and allow for calculating compatible fossil fuel CO_2 emissions in concentration-driven experiments.

The land and ocean variable groups for this opportunity are based on the variables defined following the CMIP6 C4MIP experiment in Jones *et al.*, (2016), their Fig. 5 (land carbon cycle) and Fig. 6 (ocean carbon cycle) (Table 2). On land, two new variables (*Lmon.cGeologicStorage* and *Lmon.fHarvestToGeologicStorage*), which were not present in the CMIP6 variable request, will allow tracking of carbon under intentional CDR such as bioenergy with carbon capture and storage (BECCS). In CMIP6, CDR fluxes were specified as forcings rather than simulated endogenously, and this is anticipated to be the case for most CDR methods in CMIP7 Fast Track experiments as well, with the exception of reforestation and afforestation fluxes (Van Vuuren *et al.*, 2024). Moreover, some modelling centres are experimenting with CDR representation for other approaches (e.g., Sanderson et al, 2024), and these new variables will allow the reporting of these fluxes for models and scenarios that treat them prognostically.

In addition to the land and ocean carbon cycle variables, atmospheric mole fractions of CO_2, as well as total fluxes of CO_2 between the atmosphere and the land and ocean, are needed to close the global carbon budget, particularly for emissions-driven ESM scenarios.

An emergent linear and path-independent relationship between global warming and cumulative CO_2 emissions (Allen *et al.*, 2009; Matthews *et al.*, 2009; Zickfeld *et al.*, 2009) underlies much of global climate policy, including the concept of a remaining carbon budget for climate stabilization (IPCC, 2021). In concentration-driven ESMs, fossil fuel CO_2 emissions must be inferred as the difference in the total stock of carbon in the combined land, atmosphere, and ocean systems over time. Thus, one key goal of tracking the carbon cycles through each of these systems is to infer the implied emissions for a given CO_2 concentration forcing pathway, and to diagnose relationships such as the Transient Climate Response to cumulative CO_2 emissions (TCRE, Arora *et al.*, 2020), which is the slope of the relationship between warming and cumulative emissions. Under emissions-driven ESM simulations, CO_2 emissions are specified rather than diagnosed, and it is necessary to have similar information about the response of the carbon cycle to the emissions. Such information will allow us to characterise the contribution of carbon cycle uncertainty to uncertainty in projections of future climate change under particular emissions scenarios. Moreover, this information could help us understand the processes contributing to this uncertainty and could also support the narrowing of such an uncertainty using emergent constraints, based for example on changes in carbon pools over the historical period.

Table 2. Variable groups needed for ID 18: Constructing a Global Carbon Budget

https://doi.org/10.5194/egusphere-2025-3246
Preprint. Discussion started: 16 July 2025

Variable group	Reason for inclusion
land_carbon_cycle_tier1	This set of variables includes a set of pools and fluxes that allow a complete accounting of the terrestrial carbon cycle
land_carbon_cycle_tier2	This set of variables allows greater resolution of carbon pools and fluxes based on, e.g. plant tissues, soil depth, land cover type, management practices
atmosphere_carbon_cycle_tier1	These atmospheric variables allow for accounting of CO_2 fluxes to the atmosphere and tracking of CO_2 transport in the atmosphere.
ocean_carbon_cycle_tier1	This set of variables include the pools and fluxes of carbon in the ocean system needed to allow a full accounting of the ocean carbon cycle, as well as other ocean biogeochemical tracers such as nutrients.
ocean_carbon_cycle_tier2	This set of variables includes more detail on ocean biogeochemistry than the tier 1 variables

4.2 Benchmarking and Attributing Changes to Global Carbon and other Biogeochemical Cycles (ID10)

Earth system models simulate a broad suite of carbon cycle feedbacks in response to changing climate and atmospheric CO_2 emissions, which are central to the projections of Earth system change into the future. Across several generations of coupled carbon-climate models, the carbon cycle feedbacks act as a large source of uncertainty in these projections (Friedlingstein *et al.*, 2006; Arora *et al.*, 2013; 2020). Reducing the uncertainty in these feedbacks is thus a key goal in narrowing projections of climate change in response to future CO_2 emissions, especially in the context of evolving ESMs (e.g. inclusion of N and CH_4 cycles) and more systematic use of emission-driven experiments. One approach to reducing this uncertainty is systematic benchmarking of land and ocean models against a broad range of historical observations at site to global scales, so that model fidelity can be assessed and tracked over time (Collier *et al.*, 2018; Fu *et al.*, 2022, Gier *et al.*, 2024) (Table 3).

Table 3. Variables needed for ID10: Benchmarking and Attributing Changes to Global Carbon and other Biogeochemical Cycles

Variable group	Reason for inclusion
land_carbon_cycle_tier1	This set of variables includes a set of pools and fluxes that allow a complete accounting of the terrestrial carbon cycle
land_carbon_cycle_tier2	This set of variables allows greater resolution of carbon pools and fluxes based on, e.g. plant tissues, soil depth, land cover type. These

https://doi.org/10.5194/egusphere-2025-3246
Preprint. Discussion started: 16 July 2025

	will allow for better understanding drivers of change and comparing to observations.
land_nitrogen_cycle_tier1	Land carbon and nitrogen cycles are closely intertwined, with nitrogen playing a strong role in limiting ecosystem productivity. These variables allow the construction of a global land ecosystem nitrogen budget, to benchmark models and understand the role of nitrogen in governing global carbon feedbacks and nitrogen dynamics under global change.
land_nitrogen_cycle_tier2	These nitrogen variables allow further detail on nitrogen stocks and fluxes, as resolved by plant tissues, soil depth, and land cover type.
carbon_isotopic_variables	Carbon isotopic variables allow tracing the flow of carbon through land and ocean ecosystems, and comparison to observed carbon isotopic patterns and responses to global change. In particular, ^{14}C variables allow comparison of both natural-abundance and patterns of historical anthropogenic ^{14}C enrichment (by nuclear reactions) and depletion (through burning of fossil fuels) of the biosphere; and ^{13}C variables allow comparison of both natural variation in ^{13}C and changes due to fossil fuel emissions.
land_benchmarking_and_landcover_variables_tier1	These variables include core biophysical variables, as well as land cover and other physical attributes of ecosystems. These govern water and energy exchange with the atmosphere, influence carbon and bother biogeochemical cycling, and can allow benchmarking of land models against observations.
land_benchmarking_and_landcover_variables_tier2	These variables include more finely-resolved land cover and physical variables.
atmosphere_carbon_cycle_tier1	These atmospheric variables allow for accounting of CO_2 fluxes to the atmosphere and tracking of CO_2 transport in the atmosphere.
ocean_carbon_cycle_tier1	This set of variables include the pools and fluxes of carbon in the ocean system needed to allow a full accounting of the ocean carbon cycle, as well as other ocean biogeochemical tracers such as nutrients.

https://doi.org/10.5194/egusphere-2025-3246
Preprint. Discussion started: 16 July 2025

ocean_carbon_cycle_tier2	This set of variables includes more detail on ocean biogeochemistry than the tier 1 variables
land_ch4_fluxes	CH_4 is a critical greenhouse gas, and ecosystems play a strong role in CH_4 emissions and uptake. These variables allow comparison against CH_4 observations, diagnosing ecosystem CH_4 budgets under global change, and understanding drivers of CH_4 flux changes.

4.3 Role of fire in the Earth system (ID31)

Fire is the primary terrestrial ecosystem disturbance globally and a critical Earth system process (Bowman *et al.*, 2009; Li and Lawrence, 2017; Li *et al.*, 2024). This opportunity enhances our understanding of past, present, and future fire changes and the role of fire in the Earth system, as well as the related uncertainties. The proposed variables are divided into two categories: fire variables and fire driver/impact variables. The fire variables (Table 5), (i.e., burned area fraction and fire carbon emissions) are of the highest priority and essential for understanding fire behaviour in ESMs. They serve two main aims: a) Analysing historical fire patterns and projecting future fire regimes under varying climate and socio-economic scenarios to inform long-term environmental planning and policy making; b) Benchmarking and evaluating fire simulations in coupled Earth system models, leading to improvements in future modelling systems to support more precise climate predictions and a deeper understanding of Earth system complexities. The fire driver and impact variables are currently used in Earth system modelling and strongly overlap with baseline variables. These include variables related to carbon, nitrogen, water, and energy cycles; vegetation distribution and structure; climate indicators (e.g., temperature, precipitation, wind speed, permafrost extent, active layer thickness, sea ice and snow coverage, sea surface temperature); and atmospheric circulation, composition, and chemistry. These variables will be analysed to: a) Assess the accuracy of models in capturing the relationship between fire and climate, ecosystems, and environmental factors; b) Understand the drivers of fire regime changes, the impacts of fire, and cross-sphere feedbacks between fire and various Earth system components. In addition, daily maximum temperature, precipitation, wind speed, and minimum relative humidity are required to calculate the Canadian Fire Weather Index (Quilcaille *et al.*, 2023). FWI is a method to represent the impact of weather and is related to fire's drivers. These variables are available in biodiv_land_daily, CFMIP-daily, and AgModelExpandedDaily.

Table 5. Variable groups for role of fire in the Earth system (ID31)

Variable group	**Reason for inclusion**

https://doi.org/10.5194/egusphere-2025-3246
Preprint. Discussion started: 16 July 2025

FireMIP_monthly	Monthly fire variables, along with fire driver and impact variables, are included to evaluate fire simulations, identify biases, and guide model development. They are also essential for understanding fire dynamics and their drivers across the past, present, and future, including uncertainty assessments. Additionally, these variables help quantify the cross-sphere impacts of fires and fire changes, as well as uncover the underlying mechanisms driving these interactions.
FireMIP_daily	Four cloud and aerosol variables influenced by fire activity, available only in the CMIP7 daily variable list, The daily variables in FireMIP include Cloud Droplet Number and the burden of black carbon (BC), organic carbon (OC), and primary organic aerosol (POA). These were added based on CMIP7 community comments. They are variables capturing fire impacts on atmospheric composition and process and for understanding the mechanisms through which fire influences surface climate.

4.4 Changes in marine biogeochemical cycles and ecosystem processes (ID44)

This opportunity is composed of a baseline set of variables that have already been widely used in CMIP6 and exist in most ESMs, along with a number of selected variable groups whose inclusion in the Data Request (Table 6) (see details in Annex 1) will extend the scientific purpose toward relevant ecosystem processes and downstream applications.

4.4.1 Baseline BGC Variables

The baseline BGC variables represent the informational backbone of marine biogeochemical research, as carried out using previous generations of CMIP simulations. These variables allow us to examine how projected biogeochemical quantities and their level of uncertainty have changed with each CMIP iteration (e.g. Doney *et al.*, 2012; Bopp *et al.*, 2015; Kwiatkowski *et al.*, 2020), and if there have been improvements in simulated historical values in comparison to observations (e.g., Séférian *et al.*, 2020). This variable group contains the necessary variables to calculate the air-sea flux of carbon via abiotic carbon cycling (i.e "the solubility pump") (DeVries 2022). Furthermore, these variables allow continued research on the role of marine biogeochemical cycles in relation to the inner ocean carbon inventories and acidification (Gehlen *et al.*, 2014; Kwiatkowski and Orr, 2018; Jiang *et al.*, 2023), trends in oxygen consumption (Cocco *et al.*, 2013; Buchanan and Tagliabue 2021, Takano *et al.*, 2023), and lower ecosystem dynamics represented by ESMs (Henson *et al.*, 2021; Petrik et al, 2022; Kim *et al.*, 2023).

https://doi.org/10.5194/egusphere-2025-3246
Preprint. Discussion started: 16 July 2025

4.4.2 Ecological and Biogeochemical Processes in the Surface Ocean

Marine ecosystems in the upper ocean provide key ecosystem services such as food production and tourism. Additionally, ecosystems form the basis for net primary production (NPP) and generation of organic matter that leads to carbon sequestration in the ocean. CMIP6 model projections of NPP are uncertain in both direction and magnitude, as demonstrated by Ryan-Keogh *et al.*, (2025). One of the largest sources of inter-model uncertainty in the marine biogeochemistry realm in CMIP6 was found to be phytoplankton-specific loss rates to zooplankton grazing (Rohr *et al.*, 2023). Grazing affects both the transfer of energy to higher trophic levels and the export of carbon to the seafloor, where it can be sequestered long-term.

An additional set of variables have been defined, such that when combined with marine_bgc_baseline (Sect 4.4.1), they contain the minimum set of variables needed to perform an assessment of climate impacts on marine ecosystems. These variables allow projections of the effects of climate change on marine ecosystems and biodiversity, as well as a process-based understanding, which align with the goals of FishMIP under ISIMIP. The CMIP6 FishMIP ensemble included 9 global models and >40 regional models that vary with respect to their input forcing (Tittensor *et al.*, 2018, 2021, Ortega-Cisneros 2025). Surface and/or depth-integrated variables were shown to be not sufficient because some models represent distinct epipelagic, mesopelagic, and seafloor communities. Also, 3-D is needed over 2-D integrations because the vertical habitats (e.g. 0-200 m, 200-2000 m) of these communities differ by model. The full water column also provides the opportunity for potential future studies of deep-sea organisms and processes that have so far been ignored (bathypelagic and bathybenthic communities, deep-sea carbon export, seafloor mining, etc). A few new variables have been included in this variable group. The carbon concentration of all of the phytoplankton and zooplankton types are needed because many models use, e.g. small and large phytoplankton, as input forcing and these vary by individual biogeochemical model. A devoted nanophytoplankton group was requested as some BGC models' small phytoplankton are picoplankton, while others are nanoplankton. The variables "phynano" and "intppnano" explicitly track nanophytoplankton biomass and NPP, rather than putting it in the vague "phymisc" variables. Similarly, "zmisc" was created to account for the few BGC models that have zooplankton groups that they would categorize as neither microzooplankton nor mesozooplankton. The downward flux of particulate organic carbon to the ocean seafloor ("expcob", Section 4.4.3) is necessary for many models that simulate seabed communities of fishes and invertebrates.

The variable group "ISIMIP_oceanforcing_3hr" is needed to bias-adjust oceanic forcing. The bias adjustment is particularly critical for the regional marine ecosystem and fisheries models in FishMIP that are calibrated by observational data. We expect this variable group to be useful for driving a much larger set of impact models for uses beyond fish modelling.

Although sea ice was considered biogeochemically inert within most of CMIP6 Earth System Models (Lannuzel *et al.*, 2020) but not all of them (Boucher *et al.*, 2020; Stock *et al.*, 2020), the role of polar marine biogeochemical cycles has been shown to impact specific pathways of air-ice-sea carbon exchange on the global carbon cycle and to significantly interact with the

https://doi.org/10.5194/egusphere-2025-3246
Preprint. Discussion started: 16 July 2025

pelagic ecosystem (Vancoppenolle and Tedesco, 2017; Hayashida *et al.*, 2021; Willis *et al.*, 2023). An essential set of metrics was selected for the variable group "marine_bgc_seaice" to enable the possibility of storing novel sea ice biogeochemical data within Earth System Grid Federation (ESGF) and enable the scientific community to analyse and attribute the seasonal dynamics of polar sympagic ecosystems.

4.4.3 Biogeochemical Cycling in the Ocean Interior and Sediments

The cycling of organic and biogenic inorganic matter fluxes from the surface across the ocean interior, collectively known as the "Biological (Carbon) Pump", and within seafloor sediments contributes to carbon sequestration over centennial to millennial timescales and impacts major biogeochemical cycles such as dissolved oxygen. With fluxes expected to be sensitive to climate change in both magnitude and direction, as well as forming the basis for proposed marine carbon dioxide removal (mCDR) actions, we need to better understand the role that the ocean interior and sediments play in biogeochemical cycles and the wider carbon-climate system.

In CMIP6, downward particulate fluxes were typically quantified across a 100 m depth horizon (epc100, epcalc100 for organic carbon and calcite respectively), equating to "export production" (e.g., Henson *et al.*, 2022). Export production of organic carbon is a good proxy for new production under the steady-state assumption that exported nutrients are balanced by an influx of nutrients, rather than nutrients regenerated within the euphotic zone by the microbial loop that support recycled production (Dugdale & Goering 1967, Eppley & Peterson 1979). New production quantifies the energy available for higher trophic levels (fishes, squids, benthic invertebrates) and export production fuels mesopelagic, bathypelagic and benthic food webs (see Section 4.4.2). However, export production has been shown to be a poor predictor of carbon storage (Wilson *et al.*, 2022) because the cycling of organic carbon within the ocean interior can be decoupled from export production (Henson *et al.*, 2024). Additionally fluxes at 100 m give little to no insight into fluxes at the seafloor. 3D fields of fluxes (such as expc) were available in CMIP6 but assigned a lower priority output than fluxes at 100 m (Orr *et al.*, 2017). As such, depth-resolved particulate fluxes were only available from a subset of models limiting the applicability of outputs. There were no seafloor-related variables available in CMIP6.

A series of new CF variables have been defined to address the scientific questions around interior and seafloor fluxes (Table A2). These replicate the export production variables in CMIP6 across key depth horizons. They have been defined such that modelling centres are likely to already generate as diagnostics or are modest in requirements to create and store (e.g., 2-D instead of 3-D). Alongside the previous fluxes defined at 100 m, variables have been added at 1000 m to better characterize carbon storage by the biological pump (Wilson *et al.*, 2022) and fluxes at the ocean bottom (Table A2). New CF variables for sediments (expcalcob, expcob, expfeob, expnob, exppob, expsiob, exparagob) have abbreviations that include "ob" (= ocean bottom) to delineate the bottom of the grid cell instead of its centre. Dissolved oxygen concentration ("O2") and dissolved

https://doi.org/10.5194/egusphere-2025-3246
Preprint. Discussion started: 16 July 2025

oxygen concentration at saturation ("O2sat") are needed to calculate Apparent Oxygen Utilisation (AOU), which can be used to estimate carbon storage by the biological carbon pump.

Table 6. Variable groups for changes in marine biogeochemical cycles and ecosystem processes (ID44)

Variable group	Reason for inclusion
marine_bgc_baseline	Baseline variables that are needed to fully characterise biogeochemical cycles and ecosystem processes. Each one plays an important role in validation, monitoring, comparison against observations, and understanding ecosystem services.
marine_bgc_seaice	Provide comprehensive representation of the seasonal dynamics of sea ice biogeochemistry
marine_bgc_sediments	Essential variables used for evaluating the loss of organic and inorganic carbon, nitrogen, phosphorous, and iron to the sediments.
marine_bgc_carbon_sink	Variables required to characterise the cycling of biogenic material in the ocean interior. This includes new variables to better link sinking particulate fluxes with carbon storage associated with the Biological Carbon Pump (BCP).
marine_bgc_pp_uncertainty	Constrain CMIP projections of changes in ocean net primary production and enable the attribution of the uncertainty drivers across models.
marine_bgc_fishmip	Support the modelling of marine ecosystem and fisheries by FishMIP to investigate changes and impacts
marine_bgc_fisheries	Daily and monthly variables to support the downstream implementation of fisheries and other impact models.

4.5 Earth's Energy Budget (ID29) and Water cycle/budget assessment (ID66)

The consistent simulation of the energy and water cycles by numerical models of the Earth System is fundamental as their flows across atmosphere, land, cryosphere and oceans tightly interact to shape the climate and its future changes (Trenberth, 2014). It is well established that global precipitation and evaporation changes are controlled by Earth's energy balance, while water vapour is a relevant gaseous absorber in the atmosphere that in turn plays a primary role in the global radiative budget (Allan *et al.*, 2020). The very large latent energy fluxes also tie together Earth's energy and water cycles, meaning that they should be considered in concert. The growing volume of information provided by satellite Earth observation systems will increase our capability to understand and better constrain the uncertainties related to water and energy budgets in modelled historical changes (Stephens *et al.*, 2023).

These two interconnected opportunities primarily rely on the production of the *baseline_climate_variables* group, which contains the main variables central to the implementation of the energy budget framework and the water cycle analyses as described in the Sixth IPCC Assessment Report (Foster *et al.*, 2021; Douville *et al.*, 2021). Similarly, the core variable groups requested by other ES opportunities (Sec. 4.1 and 4.2) could be further exploited to closely investigate the land surface heat and energy budgets. Complementary variable groups, namely *seaice_budget_energy_monthly* and *seaice_budget_freshwater_monthly*, address the need to specifically describe the flows of energy and water in sea ice to reach a better closure of the global budgets, while the *int_ocean_budgets* variables set was designed to refine the computation of oceanic budgets in the light of recent model advancements and to improve the comparison with observations on non-hydrostatic pressure levels.

Table 4. Earth's Energy Budget (ID29) and Water cycle/budget assessment (ID66)

Variable group	Reason for inclusion
seaice_budget_energy_monthly	This includes heat fluxes relevant to sea ice both from the sea ice and the atmospheric components, as the full decomposition of different fluxes might be available only in one of these components depending on the considered model.
seaice_budget_freshwater_monthly	Variables needed for assessing the sea ice freshwater budget at monthly timescale to understand the sea ice interactions within the global hydrological cycle,
int_ocean_budgets	These are fundamental to correctly compute the budgets in the light of recent ocean numerical schemes and vertical discretizations, along with the adopted equation of state.

4.6 Rapid Evaluation Framework (ID55)

The CMIP Rapid Evaluation Framework (REF) was created to evaluate and benchmark the CMIP7 Assessment Fast Track (CMIP7 AFT) simulations as soon as they are uploaded to the ESGF with metrics and diagnostics that are available through different open-source evaluation and benchmarking tools (Hoffman *et al.* 2025). This opportunity contains the set of variables that are needed for the planned diagnostics and metrics for the REF (CMIP Model Benchmarking Task Team, 2024). The suggested metrics/diagnostics for the REF to be available for all CMIP7 AFT experiments will allow basic evaluations. The exact selection of variables was also made consistent with the model evaluation diagnostics in Chapter 3 of the latest IPCC report (Eyring *et al.*, 2021). Due to the fixed timeline for the CMIP7 AFT simulations there is only a short time period for the technical implementation of the REF, and therefore the available metrics and diagnostics in this first version of the REF will be limited to a temporal resolution of monthly mean data and about five metrics/diagnostics per realm based on a community selection. The realms were chosen specifically to be consistent with the realms used for the data request.

Table 8. Variable groups for the Rapid Evaluation Framework

Variable group	Reason for inclusion
ref_earth_system	This is the set of variables that would be needed for the planned earth system diagnostics and metrics for the Rapid Evaluation Framework. The variable group will be linked with the "Rapid Evaluation Framework" opportunity, and is essential for the evaluation of the new CMIP7 AFT simulations on a routine basis.

4.7 Robust Risk Assessment of Tipping Points (ID82)

This opportunity has been submitted by the Tipping Point Modelling Intercomparison Project (TIPMIP). As part of the CMIP7-ES theme, this opportunity comprises two variable groups which are also relevant to the Atmosphere, Land & Land Ice, Ocean & Sea Ice themes (Table 9).

The concept of "tipping point" or "critical transition" appears in several fields of science: in ecology, for example, it appears in the form of mass extinction and rapid desertification (Scheffer *et al.*, 2001; Arumugam *et al.*, 2024); human physiology offers examples such as seizures and the abrupt increase in inflammatory response (Scheff *et al.*, 2013); examples from the geosciences include potential events such as the dieback in the Amazon rainforest or the decline and collapse of polar ice sheets (Lenton *et al.*, 2008). These seemingly disparate events share phenomenological attributes, which are understood to be defining characteristics of a tipping point or critical transition (Scheffer et al, 2009; Kuehn, 2011). A tipping point is reached when there is an abrupt qualitative change in the system's dynamics which is rapid compared to the system's normal evolution, and beyond this threshold the system enters a new dynamical state which is qualitatively different from the previous state. More recent studies have supported the existence of tipping points for certain Earth System components, as described for example by Lenton *et al.*,(2008): such as polar ice sheets (Bradley & Hewitt, 2024; Petrini *et al.*, 2025), and the Atlantic Meridional Overturning Circulation (van Westen *et al.*, 2024; Ditlevsen & Ditlevsen, 2023). Wunderling *et al.*, (2024) have also highlighted the possibility of interactions between these components of the Earth System, whereby one component crossing its tipping threshold could destabilize other components, triggering a so-called "tipping cascade."

Given the fact that the Earth system components are complex non-linear systems in their own right, that they are coupled to one another, and interact across many different spatio-temporal scales, giving a precise characterization of what critical transitions (or tipping events) could occur, or when they could occur, is at present very difficult (Ben-Yami et al, 2024). Yet the fact that such transitions might occur cannot be excluded, as several components of the Earth system may be susceptible to reaching a critical threshold beyond which amplifying feedbacks could result in abrupt and/or irreversible changes

https://doi.org/10.5194/egusphere-2025-3246
Preprint. Discussion started: 16 July 2025

(Armstrong McKay *et al.*, 2022). This could have far-reaching impacts on the global climate, ecosystems, and humankind. Recent assessments have highlighted the increasing risk for potential tipping events, in particular beyond 1.5°C global warming, and also stressed the large uncertainties involved in any projection regarding the future occurrence of such events (IPCC AR6, Eyring *et al.*, 2021). Addressing these uncertainties will necessitate a systematic effort to evaluate our understanding of Earth system dynamics and their evolution under sustained exogenous forcing, so that we may be better able to quantify the likelihood of tipping events and therefore the risks and impacts associated to them. This will be crucial for developing effective strategies to mitigate and adapt to the impacts of global environmental change.

The variables included in this opportunity will serve two major purposes: (1) The analysis of Earth System models (ESMs) with respect to tipping points, and (2) Serving as forcing input for uncoupled/offline component models (e.g. standalone ice sheet models) in follow-up tailored tipping experiments. There is a strong overlap between the variables in the opportunity and existing baseline_climate_variables, minimising additional computational costs while providing the base for a cross-domain analysis of tipping points.

This opportunity will allow the evaluation of key large-scale tipping elements such as ice-sheet collapse, permafrost carbon release, tropical forest dieback and shutdown of the Atlantic Meridional Ocean Circulation (AMOC), as well as possible feedbacks associated with each individual tipping element. Outputs will be used to evaluate the uncertainties associated with identifying the existence of tipping points in the biogeophysical Earth system; the critical thresholds and warming levels that may induce tipping; as well as the interactions and feedbacks between (possible) tipping elements. Outputs may be then used by impact models and other end-user groups to evaluate the downstream consequences of tipping points in the Earth system on human society.

Table 9. Variable groups for Robust Risk Assessment of Tipping Points (ID82)

Variable group	Reason for inclusion
tipmip_baseline	These 45 variables allow for analyses of ESM output data, predominantly in the atmospheric and ice sheet components. They are also WCRP priority variables, hence they are grouped as baseline variables.
tipmip_extended	These 43 variables, which are not in the WCRP priority list, allow for offline, domain-specific experiments. They are focused on the soil and ocean components of ESMs.

4.8 Multi-annual-to-decadal predictability of the Earth System and risk assessment of climate extremes (ID54)

As the magnitude of climate changes are strongly determined by the cumulative emissions (Allen et al, 2009; Notz et al, 2020), differences between various emission scenarios will have relatively little impact in the near term. This makes the prediction of climate over the next few decades an initial value problem, and decadal predictions are created operationally (Smith et al, 2013). Such predictions are made not only for atmospheric variables, but across the earth system, including for ocean variables such as the Atlantic Meridional Overturning Circulation (AMOC; WMO, 2024), cryospheric variables such as sea ice concentration (WMO, 2024), and biogeochemical variables such as CO_2 uptake (Li *et al.*, 2016; Gooya *et al.*, 2024) (Table 7). Understanding the nature and limits of the predictability across the Earth System is key to delivering the maximum skill in these forecasts. The Decadal Climate Prediction Project (DCPP) defines experiments to allow the quality of climate prediction systems to be assessed through the use of hindcasts, as well as to assess as the inherent predictability of the Earth System (Boer et al, 2016). As part of CMIP7 Fast Track, a prediction initialised in 2025 and comprising of 10 ensemble members is requested (dcppB-forecast-cmip6), but only from models who have also performed a hindcast.

This opportunity was submitted by DCPP, and incorporates two different variable groups that both span multiple themes. The essential variable group will allow analysis of key climate aspects of the decadal forecast, including modes of climate variability such as the Pacific Decadal Oscillation and AMOC that have substantial low-frequency components. The wider opportunity pushes beyond mean climates to assess the predictability of climate extremes.

Table 7. Variable groups for Multi-annual-to-decadal predictability of the Earth System and risk assessment of climate extremes (ID54)

Variable group	Reason for inclusion
DCPP_Essential	These 66 variables are considered essential to assess the the predictability of the Earth System, with 33 of them also being part of the Baseline data request. They are overwhelming at monthly resolution, with the remaining variables being mainly daily resolution needed to assess extremes.
DCPP_Wider	These 133 variables will allow a broader assessment of hindcast performance including ocean biochemistry. They cover all aspects of the Earth System, and again are predominantly at monthly resolution, but with a greater utilisation of daily data (41 fields).

https://doi.org/10.5194/egusphere-2025-3246
Preprint. Discussion started: 16 July 2025

5 Discussion

5.1 Reflections from the data request process

5.1.1 Prioritization process

The Earth System Author Team was tasked with harmonizing among different the author teams for preparation of the CMIP7 AFT. The main goal of this process was to streamline the variable list presented in the data request, so that most modelling centres will be able to output the core variables. As part of streamlining, several opportunities needed to be merged into larger, more general opportunities (more details in Annex 1). These included agricultural carbon monitoring, which was merged into the global carbon cycle, and several opportunities related to ocean biodiversity and fisheries, which were merged into on opportunity focused on marine biogeochemistry and ecology. Opportunities related to climate variability and extreme events were effectively split between Earth Systems, Ocean and Sea-ice and Impacts & Adaptation, where Paleodata assimilation (ID 52), Robust risk assessments of extreme climate (ID 59), and Coupled climate variability (ID 23) were transferred, but Multi-annual-to-decadal predictability of the Earth System and risk assessment of climate extreme (ID 54) remained.

5.1.2 Challenges

By its very nature the Earth System theme has links and overlaps with several other themes, requiring careful consideration of scope. The push towards running scenarios in emissions mode, with a full representation of the carbon cycle, means that all CMIP7 activities could interact with the Earth System theme. For example, atmospheric chemistry, which is included in the Atmosphere theme, also has impacts on water and carbon cycles, thus overlapping with the Earth System domain. Many of the impacts of warming, for example on ecosystem function and biodiversity overlap with the Impacts and Adaptation area. These overlaps were a challenge during the data request process, as they made it difficult to determine when exactly an opportunity falls within the Earth System, and which were better suited for other thematic areas.

Participants listed the time constraints for proposing new variables as a barrier to contributing opportunities. Opportunity proposers found the process of creating new CF variables to be challenging and unintuitive, requiring first the creation of a new physical parameter and then a new variable. If one was unfamiliar with CF naming conventions, this also posed a problem. For example, some participants were not able to complete this process before the Data Request closed. Authors suggest that in the future, the proposal of new CF variables should be separate from the Data Request and occur much in advance of it, so that the new variables can be included in proposed opportunities.

Another challenge of the data request process was weighing of large volume of data requested against the scientific interests of the community. We recognize the pressure of a large data request on modelling centres, especially when multiple tracers are needed from ESMs including biogeochemical cycles (with the associated storage and computing costs). Yet it is also

https://doi.org/10.5194/egusphere-2025-3246
Preprint. Discussion started: 16 July 2025

critical to carry out CMIP7 experiments to their fullest potential, leveraging the efforts of modelling groups into recent model developments, and providing researchers and policymakers with up-to-date climate information. To reflect both of these considerations, priority levels of variable groups were attributed based on the diverse expertise of the Earth System thematic group. Variable groups containing variables not output by any centres in CMIP6 were given lower priority.

5.2 Outstanding gaps and applications of Earth system process knowledge

Activities associated with CMIP7 will close critical gaps in our knowledge of the Earth System and its response to anthropogenic perturbation. This will set the stage for research in the event of significant mitigation efforts to slow the rate of warming. At present, there are still many sources of uncertainty in ESM simulations surrounding interactions among emissions, radiative forcing, and elemental cycling. In ocean models, there is uncertainty in how marine primary productivity relates to carbon storage, and the role of biogeochemical and ecological processes in deep ocean sediments (DeVries 2022). In terrestrial models, soil and plant respiration, their interactions with the nitrogen cycle and response to warming and rising CO_2 are sources of model disagreement (Jones *et al.*, 2016). Together, differences in the parametrization of carbon-climate feedbacks over land account for an order of magnitude greater uncertainty than ocean carbon-climate feedbacks (Arora *et al.*, 2020) representing uncertainty in land use and biophysical processes. The possibility of CDR raises questions regarding carbon cycle responses to rapid drawdown in atmospheric CO_2 concentrations under net-zero or net negative scenarios (van Vuuren *et al.*, 2025; Koven *et al.*, 2022). Variables requested here will also support analysis of the carbon uptake effects of reforestation and afforestation, which will be simulated explicitly in ScenarioMIP simulations for CMIP7 (Van Vuuren *et al.*, 2025) How changes in radiative forcing, not only from CO_2 but also associated with aerosols (e.g. dust, industrial pollutants and trace gases) are transported from point-source and distributed, and how this feeds back in to climate is another source of uncertainty in warming trajectories, especially at local to hemispheric spatial scales (Hansen *et al.*, 2025; Zhao *et al.*, 2022; Bauer *et al.*, 2022). In the event of interference with solar forcing via SRM, having strong understanding of how aerosols propagate through Earth systems will help anticipate potential interactions. In the absence of mitigation, downscaling, regional climate modelling, and detection and attribution will link anthropogenic forcing to impacts with increased specificity. Finally, tying ecosystem changes, severe weather events, and atmospheric dynamics to satellite observations will help track impacts in real time and serve as external validation of model performance.

Sustained efforts in these areas will help address the needs of a diverse community of stakeholders. The scientific community has an interest in basic climate research, but CMIP7 should also support provision of ESM data to a variety of non-academic sectors (Lea *et al.*, 2024). Climate policymakers have relied on scenario-based simulations to predict some probable range of outcomes that can be built into policy and planning for decades (IPCC 2021; Durack *et al.*, 2024). While this has been true at the national and international levels, industry and local and regional governments represent new users of ESM output. For example, fire risk predictions serve the insurance industry by providing scientific basis for risk assessment and management strategies. In the context of marine ecosystems, the biological carbon pump of carbon sequestration in microorganisms is related to trophic dynamics at higher levels. Thus, modelling primary and secondary producers in the surface ocean supports fisheries management (Blanchard *et al.*, 2024). Participants in international carbon markets, such as those mandated under the European Union Emissions Trading scheme could use CMIP7 variables that model rates of carbon cycling. Carbon sequestration data from soils, forests and oceans and coastlines (i.e. 'blue carbon') could be leveraged for use in these markets, although constraints remain regarding output resolution and flux uncertainty (Hilmi *et al.*, 2021; Michaelowa *et al.*, 2023). Improvements in model water budgets, in particular for fresh water, is of use to water managers (Shao *et al.*, 2023; Onyutha *et al.*, 2021). Regional climate models and dynamical downscaling of coarser-resolution products will allow for CMIP7 data to be used on socially and politically-relevant spatial scales, for example cities, municipalities, and states.

6 Conclusions

The ES author team identified the model variables needed to fully represent the carbon cycle and achieve greater clarity surrounding how changes in radiative forcing propagate through the Earth system. These include the core set of baseline variables along with specialized variables that may receive less attention from modelling centres, but will be necessary for achieving a detailed picture of ES responses to forcing. As the number of climate variables and model outputs continues to grow, it is important to establish clear guidelines for selecting which variables should be included in future requests. Rather than having a fixed set of variables, future CMIP requests could be more dynamic, allowing the inclusion of new variables as research needs evolve. Future work under CMIP7 may focus on improving model resolution, integrating new climate processes and strengthening collaboration across sectors. Next steps could prioritize data management and accessibility, including the adoption of cloud-based systems and artificial intelligence, and standardized variable definitions. Recommendations for variable management include broadening the range of model outputs, improving the integration of observations and ensuring robust quantification of uncertainty. These efforts will ultimately improve the accessibility of CMIP data, enabling better decision-making for climate adaptation and mitigation strategies.

Future work beyond CMIP7 includes increasing the spatial and temporal resolution of climate models in order to capture fine-scale processes such as ecosystem change, regional variability and extreme weather events. As we transition into the next generation of climate models (e.g., CMIP7+ and CMIP8), advancements in model complexity, resolution, and process representation have the potential to further improve our understanding of biological feedbacks to the climate system. For example, interactive simulations of nitrogen and methane dynamics is in development in some models and it is anticipated that these may not be complete in CMIP7. As computational power increases combined with the development of AI, next-generation models will likely have much higher spatial and temporal resolution and will incorporate better Earth system components, allowing for fine-scale representations of the relationship between human activities and the climate system. Carbon fluxes associated and-use change, deforestation, and ocean upwelling patterns could all be better constrained using finer-scaled model products. Benchmarking ecological and climate changes against observational data and model hindcasts

https://doi.org/10.5194/egusphere-2025-3246
Preprint. Discussion started: 16 July 2025

will help to assess model skill, and improve our fundamental understanding of the carbon-climate system. With benchmarking and downscaled data, CMIP7 will continue to play an essential role in bridging the gap between scientific research and public policy.

Annex 1

A1. Opportunity processing

The processing of opportunities proposed in the open call of August 2024 was carried out by revising the evaluation of each thematic author team within a cross-thematic meeting in mid of September 2024. The indications and comments resulted in the acceptance or rejection of certain opportunities as well as the request to evaluate the merging of those with commonalities in the scientific objectives and research domain. In a subsequent step, an interactive discussion was held between the leading author teams and the proposers or reference communities to harmonize the initially proposed opportunities and improve their description and data requirement.
The following table summarises the key processing actions and decisions with specific reference to a working copy Airtable database available at the following link https://bit.ly/CMIP-DR-Opportunities.

Action taken	Description	Meeting decision made (DD-MM-YYYY)	Notes from consultation	Notes from Author team
Accepted				
ID 10	Benchmarking and Attributing Changes to Global Carbon and other Biogeochemical Cycles	Author team meeting 24-11-2024	Request is too bespoke to be merged into the Rapid Evaluation Framework opportunity.	The rational is clear, although the amount of data requested is rather big and should be revised.
ID 18	Constructing a Global Carbon Budget	Author team meeting 24-11-2024	Well explained and justified and tiered variables. A lot of variables requested. Earth System to clarify if this is standalone	Improve the prioritization of requested variables and the experiment list. Too big to be merged with others.

https://doi.org/10.5194/egusphere-2025-3246
Preprint. Discussion started: 16 July 2025

			opportunity or C4MIP focused.	
ID 29	Earth's Energy Budget	Author team meeting 02-10-2024	Author team very supportive of the science this opportunity. Multiple, full baseline variable groups still included but may not all be necessary.	The proposed variable group should be revised to include only the relevant variables.
ID 31	Role of fire in the Earth system	Author team meeting 24-11-2024	A key Earth System Process and emerging area of science. Need to add more atmospheric variables.	A more descriptive title for this opportunity should be provided. Variable list may be reduced to focus more on fire related parameters.
ID 44	Changes in marine biogeochemical cycles and ecosystem processes	Author team meeting 02-10-2024 https://github.com/CMIP-Data-Request/Harmonised-Public-Consultation/issues/32	Potential to merge with other BGC opportunities - author team following up with proposers.	Revise original name, include additional marine variable groups and merge in this other opportunities
ID 54	Multi-annual-to-decadal predictability of the Earth System and risk assessment of climate extremes	Author team meeting 24-11-2024	This request has selected the entire fast track. If the data volume is a problem, I expect this can probably be narrowed down to a more refined set of	This opportunity involves a broad list of variables, which may be split into separate and smaller groups by redesigning in favour of a subset of more

https://doi.org/10.5194/egusphere-2025-3246
Preprint. Discussion started: 16 July 2025

			experiments that are of most relevance.	specific opportunities.
ID 66	Water cycle/budget assessment	Author team meeting 02-10-2024	Author team very supportive of the science this opportunity. Multiple, full baseline variable groups still included but may not all be necessary.	This deal mainly with physical processes that should be addressed by the cross-thematic group. Clearly we do recognize the relevance of the proposed opportunity.
ID 82	Robust Risk Assessment of Tipping Points	Author team meeting 24-11-2024	TipMIP set of experiments will be added once available on the controlled vocabularies system.	The objectives are clear and the proposed set of variables is consistent.
Merged				
ID 6	Agricultural carbon monitoring	Cross-thematic meeting 20-29-2024 Merge in ID 18	Could consolidate with Constructing a Global Carbon Budget Opportunity.	The scope is clear and the requested data are overlapping with other opportunities (e.g., ID 18 or ID 19) that can be likely combined into a larger one.
ID 12	Biological Carbon Sink in the Ocean	Author team meeting 27-09-2024 Merge in ID 44	Review potential to merge opportunity IDs 65 and 44	This could be merged with the others marine opportunities

https://doi.org/10.5194/egusphere-2025-3246
Preprint. Discussion started: 16 July 2025

ID 21	Core fisheries modelling output	Author team meeting 27-09-2024 Merge in ID 44	Request proposers to merge with Fisheries board on additional fisheries modelling and impacts (ID32) and Fisheries board on advanced mariculture and species model (ID33) into one Opportunity.	This is part of a wider action and it can be consolidated with others
ID 23	Coupled climate variability	Author team meeting 24-11-2024 Merge in ID 55	Merge into the Merge into the REF Opportunity Opportunity.	Variable groups of this opportunity largely overlap with the 'Rapid Evaluation Framework' one, so it can be merged in there or revised to account only for additional variables.
ID 32	Fisheries board on additional fisheries modelling and impacts	Author team meeting 27-09-2024 Merge in ID 44	Request proposers to merge with Core fisheries modelling output (ID21), and Fisheries board on advanced mariculture and species model (ID33) into one Opportunity.	Integrate with companion opportunity ID33

https://doi.org/10.5194/egusphere-2025-3246
Preprint. Discussion started: 16 July 2025

ID 33	Fisheries board on advanced mariculture and species model	Author team meeting 27-09-2024 Merge in ID 44	Request proposers to merge with Core fisheries modelling output (ID21) and Fisheries board on additional fisheries modelling and impacts (ID32) into one Opportunity.	Integrate with companion opportunity ID32
ID 60	Role of ocean sediments in global ocean biogeochemical cycles	Author team meeting 27-09-2024 Merge in ID 44	Coordinate opportunity consolidation with Marine Biogeochemistry (ID 44) Opportunity	This is complementary to other opportunities dealing with marine biogeochemistry and can be coordinated with other variable groups.
ID 65	Uncertainty in changing net primary production	Author team meeting 27-09-2024 Merge in ID 44	Potential to merge with other BGC opportunities (changing net primary production, biological carbon sink in ocean and Marine BGC)	This could be coordinated/merged with the others marine biogeochemical opportunities.

665

https://doi.org/10.5194/egusphere-2025-3246
Preprint. Discussion started: 16 July 2025

Annex 2

A.2 New Variable description

670 The variables that are newly introduced in CMIP7 are tabulated below. The Coordinate Specifications column lists special aspects of the time and spatial requirements for each variable. The full grid specifications can be found in v1.2 of the CMIP7 Data Request (Data Request Task Team, 2025b).

Variable CMOR name	**CF standard name**	**Description**	**Further detail to aid compute**	**Coordinate specifications**
expcalcob	sinking_mole_flux_of_calcite_in_sea_water	Downward sinking flux of calcite at ocean bottom	Downward sinking flux of calcite reaching the seafloor	longitude, latitude, time, depthSeaFloor
exparagob	sinking_mole_flux_of_aragonite_in_sea_water	Downward sinking flux of aragonite at ocean bottom	Downward sinking flux of aragonite reaching the seafloor	longitude, latitude, time, depthSeaFloor
expcob	sinking_mole_flux_of_particulate_organic_matter_expressed_as_carbon_in_sea_water	Downward sinking flux of particulate organic carbon at ocean bottom	Downward sinking flux of particulate organic carbon reaching the seafloor	longitude, latitude, time, depthSeaFloor
expfeob	sinking_mole_flux_of_particulate_iron_in_sea_water	Downward sinking	Downward sinking flux	longitude,

https://doi.org/10.5194/egusphere-2025-3246
Preprint. Discussion started: 16 July 2025

		flux of particulate iron at ocean bottom	of particulate iron reaching the seafloor	latitude, time, depthSeaFloor
expnob	sinking_mole_flux_of_particulate_organic_nitrogen_in_sea_water	Downward sinking flux of particulate organic nitrogen at ocean bottom	Downward sinking flux of particulate organic nitrogen reaching the seafloor	longitude, latitude, time, depthSeaFloor
exppob	sinking_mole_flux_of_particulate_organic_phosphorus_in_sea_water	Downward sinking flux of particulate organic phosphorus at ocean bottom	Downward sinking flux of particulate organic phosphorus reaching the seafloor	longitude, latitude, time, depthSeaFloor
expsiob	sinking_mole_flux_of_particulate_silicon_in_sea_water	Downward sinking flux of particulate silicon at ocean bottom	Downward sinking flux of particulate silicon reaching the seafloor	longitude, latitude, time, depthSeaFloor
frfe	minus_tendency_of_ocean_mole_content_of_iron_due_to_sedimentation	Flux of iron from the ocean into the sediments	Iron loss from the ocean to the sediments through	longitude, latitude, time,

https://doi.org/10.5194/egusphere-2025-3246
Preprint. Discussion started: 16 July 2025

			sedimentation.	depthSeaFloor
frfn	minus_tendency_of_ocean_mole_content_of_elemental_nitrogen_due_to_denitrification_and_sedimentation	Flux of nitrogen from the ocean to the sediments by denitrification	Nitrogen loss from the ocean to the sediments through denitrification and sedimentation	longitude, latitude, time, depthSeaFloor
intppnanon	net_primary_mole_productivity_of_biomass_expressed_as_carbon_by_nanophytoplankton	Net Primary Organic Carbon Production by Nanophytoplankton	Vertically integrated primary (organic carbon) production by the nanophytoplankton component alone	longitude, latitude, time
phynano	mole_concentration_of_nanophytoplankton_expressed_as_carbon_in_sea_water	Mole Concentration of Nanophytoplankton Expressed as Carbon	Carbon concentration from the nanophytoplankton (2-20 um) component alone	longitude, latitude, olevel, time

https://doi.org/10.5194/egusphere-2025-3246
Preprint. Discussion started: 16 July 2025

		in Sea Water		
zmisc	mole_concentration_of_miscellaneous_zooplankton_expressed_as_carbon_in_sea_water	Mole Concentration of Other Zooplankton Expressed as Carbon in Sea Water	Carbon from additional zooplankton components (e.g. not categorized as micro or meso) concentrations alone. Since the models all have different numbers of components, this variable has been included to provide a check for intercomparison between models since some zooplankton groups are supersets.	longitude, latitude, olevel, time
sichl	sea_ice_mass_content_of_ice_algae_expressed_as_chlorophyll	Mass Concentration of Ice	Mass Concentration of Ice	longitude,

https://doi.org/10.5194/egusphere-2025-3246
Preprint. Discussion started: 16 July 2025

		Algae Expressed as Chlorophyll in Sea Ice	Algae Expressed as Chlorophyll in Sea Ice	latitude, time
sialgc	sea_ice_mole_content_of_ice_algae_expressed_as_carbon	Mole Concentration of Ice Algae Expressed as Carbon in Sea Ice	Mole Concentration of Ice Algae Expressed as Carbon in Sea Ice	longitude, latitude, time
sino3	sea_ice_mole_content_of_nitrate	Mole concentration of nitrate	Mole concentration means moles (amount of substance) per unit area	longitude, latitude, time
sisi	sea_ice_mole_content_of_silicon	Mole concentration of silicate	Mole concentration means moles (amount of substance) per unit area	longitude, latitude, time
sigpp	gross_primary_productivity_of_biomass_expressed_as_carbon_due_to_ice_algae_in_sea_ice	Total Gross Primary Productio	Total Gross Primary Production of	longitude, latitude, time

https://doi.org/10.5194/egusphere-2025-3246
Preprint. Discussion started: 16 July 2025

		n of Ice Algae in Sea Ice	Ice Algae in Sea Ice	
t17d	depth_of_isosurface_of_sea_water_potential_temperature	Depth of 17 degree Celsius Isotherm	Depth of 17 degree Celsius Isotherm	longitude, latitude, time
fHarvestToGeologicStorage	mass_flux_of_carbon_from_biomass_into_geological_storage	Harvested Biomass That Goes into Geological Storage	Flux of carbon harvested from biomass that goes into geologic storage for the purposes of intentional carbon dioxide removal, via efforts such as bioenergy with carbon capture and storage (BECCS) or biomass removal and storage (BiCRS). The definition of	longitude, latitude, time

			geologic storage here is that the resulting carbon be stored for a period of time that is long relative to that of the simulation.	
cGeologicStorage	carbon_mass_content_of_geological_storage	Carbon Mass in Geologic Storage	Mass of carbon that has been intentionally sequestered in geologic storage. The definition of geologic storage here is that it be stored for periods of time that are long as compared to the simulation.	longitude, latitude, time
Note nbp change	surface_net_downward_mass_flux_of_carbon_dioxide_expressed_as_carbon_due_to_all_land_processes	Carbon Mass Flux	In CMIP6, there were	

https://doi.org/10.5194/egusphere-2025-3246
Preprint. Discussion started: 16 July 2025

		out of Atmosphere Due to Net Biospheric Production on Land	two equivalent variables: nbp and netAtmosLandCO2Flux. For CMIP7, we ask that all modeling centers use nbp to report the net carbon flux from the atmosphere to the land.	

Code and data availability

The variables and their metadata included latest CMIP7 Assessment Fast Track Data Request can be accessed at https://doi.org/10.5281/zenodo.14774070. At the time of this publication, the latest major release is v1.2 (Data Request Task Team, 2025a; accessed at https://doi.org/10.5281/zenodo.15116894), and the latest minor release is v1.2.1 (Data Request Task Team, 2025b; accessed at https://doi.org/10.5281/zenodo.15288187).

Author contributions

MM led the writing of this manuscript with support in writing of the original draft from AB, CD, CMB, CMP, FLh, JDW, JLS, OA, FL, BH, and TL. Review and editing support from CDK, CMB, CMP, JCK, JDW, JLS, MM, NPG, OA and TL. CDK and TL led the conceptualization, investigation, methodology, and data curation with contributions from CD, CMB, CMP, FLh, JCK, JDW, JLS, MK, and OA. The vizualisation was contributed by CMP, FL, FLh, JCK and MM. BT provided resources and project administration support.

Competing interests

The authors declare that they have no conflict of interest.

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