



1 The Coupled Climate-Carbon Cycle Model 2 Intercomparison Project (C4MIP) experimental protocol 3 for CMIP7 4

5 Vivek K. Arora¹, Chris D. Jones^{2,3}, Pierre Friedlingstein^{4,5}, Tatiana Ilyina⁶, Guilherme L. Torres
6 Mendonça^{7,8,6}, Benjamin Sanderson⁹, Charles Koven¹⁰, Heather Graven¹¹, Michio Kawamiya^{12,13},
7 Victor Brovkin¹⁴, John Dunne¹⁵, Forrest M. Hoffman¹⁶, Julia Pongratz¹⁷, James T. Randerson¹⁸
8 Anastasia Romanou^{19,20}, Sönke Zaehle²¹, Kirsten Zickfeld²²
9

10 Correspondence: Vivek K. Arora (vivek.arora@ec.gc.ca), Chris D. Jones
11 (chris.d.jones@metoffice.gov.uk)

12 ¹Canadian Centre for Climate Modelling and Analysis, Climate Research Division, Environment
13 and Climate Change, Victoria, Canada

14 ²Met Office Hadley Centre, Exeter, EX1 3PB, UK

15 ³Geographical Sciences, University of Bristol, UK

16 ⁴Faculty of Environment, Science and Economy, University of Exeter, Exeter, EX4 4QF, UK

17 ⁵Laboratoire de Météorologie Dynamique, Institut Pierre-Simon Laplace, CNRS, École Normale
18 Supérieure, Université PSL, Sorbonne Université, École Polytechnique, Paris, France

19 ⁶Max Planck Institute for Meteorology, Hamburg, Germany

20 ⁷Center for Weather Forecasting and Climate Studies, National Institute for Space Research
21 (INPE), Cachoeira Paulista, SP, Brazil

22 ⁸Institute of Mathematics and Statistics, University of São Paulo, São Paulo, SP, Brazil

23 ⁹CICERO International Center for Climate Research, Oslo, Norway

24 ¹⁰Climate and Ecosystem Sciences Division, Lawrence Berkeley Laboratory, Berkeley, CA, USA

25 ¹¹Department of Physics, Imperial College London, London, UK

26 ¹²Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan

27 ¹³Advanced Institute for Marine Ecosystem Change, Tohoku University, Sendai, Japan

28 ¹⁴Max Planck Institute for Meteorology, Hamburg, Germany

29 ¹⁵NOAA/OAR/Geophysical Fluid Dynamics Laboratory, Princeton, NJ, USA

30 ¹⁶Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA

31 ¹⁷Ludwig-Maximilians-Universität München, Germany

32 ¹⁸Department of Earth System Science, University of California, Irvine, USA

33 ¹⁹NASA-Goddard Institute for Space Studies, New York, USA

34 ²⁰Dept of Applied Physics and Applied Mathematics, Columbia University, New York, USA

35 ²¹Biogeochemical Signals Department, Max Planck Institute for Biogeochemistry, 07745 Jena

36 ²²Department of Geography, Simon Fraser University, Burnaby, BC, Canada



37 Abstract

38 Model intercomparison projects (MIPs) have become an essential tool for systematically
39 comparing Earth system models (ESMs) by identifying, characterizing, and quantifying common
40 model behaviour through standardized experiments and metrics under idealized, historical, and
41 scenario-based forcing. Over the past few decades, community MIPs have become a
42 cornerstone of the broader climate modelling community and the Coupled Model
43 Intercomparison Project (CMIP). Here, we describe the scientific objectives of the Coupled
44 Climate-Carbon Cycle Model Intercomparison Project (C4MIP) in the context of the seventh
45 phase of CMIP (CMIP7) and present the complete suite of C4MIP experiments, including those
46 contributing to CMIP7's Assessment Fast Track (AFT) and those proposed for subsequent
47 analyses beyond the AFT. The proposed experimental protocol maintains backward
48 compatibility with previous CMIP phases while introducing new experiments. In addition to the
49 traditional biogeochemically (BGC) and radiatively (RAD) coupled versions of the 1pctCO₂
50 experiment, the new experiments include concentration-driven BGC and RAD variants of the
51 abrupt 2×CO₂ experiment, a suite of emissions-driven simulations that investigate carbon-cycle
52 behaviour under positive, zero, and negative emissions, and a large pulse experiment to
53 reassess the impulse-response of newer generation ESMs and update the widely-used function
54 from earlier model generations. Whereas earlier phases of C4MIP primarily focused on
55 quantifying the feedback metrics that describe interactions between the coupled carbon cycle
56 and the physical climate system, the scope of C4MIP has expanded to include the estimation of
57 the transient climate response to cumulative emissions (TCRE) and the zero-emissions
58 commitment (ZEC). These policy-relevant metrics are most naturally quantified using
59 emissions-driven ESM simulations. The increased emphasis on emissions-driven simulations
60 reflects both the growing policy relevance of these metrics and the ability of emissions-driven
61 simulations to represent carbon-climate interactions in a bi-directional manner. In particular,
62 changes in carbon sinks and evolution of feedback effects influence the atmospheric CO₂
63 concentration in emission-driven simulations, whereas these interactions are absent from
64 concentration-driven simulations, in which atmospheric CO₂ concentrations are prescribed. The
65 proposed experimental design attempts to balance scientific ambition with the computational
66 and storage resources required of participating climate modelling centres. The final suite of
67 experiments and associated protocols has been developed through extensive community
68 consultation and guidance from the C4MIP Scientific Steering Committee. As in previous CMIP
69 phases, the experiments are expected to enable a broad range of community-led investigations
70 of the coupled carbon-climate system.

71



72 1. Introduction

73

74 Model intercomparison projects (MIPs) provide a coordinated framework for systematically
75 comparing models following a common experimental protocol. The climate modelling
76 community has embraced MIPs for several decades through successive phases of the Coupled
77 Model Intercomparison Project (CMIP) (Covey et al., 2003; Eyring et al., 2016; Meehl et al.,
78 1997, 2005; Taylor et al., 2012). Beyond forming the basis for inter-model comparison, MIPs
79 have proven extremely useful in identifying, characterizing, and quantifying common emergent
80 behaviour, often through standardized metrics, in response to idealized, historical, and
81 scenario-based perturbations in climate and Earth system models (Eyring et al., 2016; Meehl et
82 al., 2005; Stouffer et al., 2017).

83 A key benefit of MIPs is the quantification and comparison of policy- and scientifically-relevant
84 climate metrics across models. Long-established examples are the transient climate response
85 (TCR) (Hansen et al., 1984; National Research Council, 1979) and the equilibrium climate
86 sensitivity (ECS) (Arias et al., 2021; Eyring et al., 2016; Meehl et al., 2007), which characterize
87 the response of the physical climate system to changes in atmospheric CO₂ concentration
88 ([CO₂]) under idealized forcing. ECS measures the equilibrium global temperature response to a
89 doubling of [CO₂] (in the CMIP abrupt 2XCO₂ experiment), while TCR measures the
90 temperature change at the time of [CO₂] doubling in a transient experiment in which [CO₂]
91 increases at a rate of 1% per year (the CMIP 1pctCO₂ experiment). Because the physical climate
92 system is still evolving at the time of [CO₂] doubling in this experiment, TCR is, by design,
93 smaller than ECS (Forster et al., 2021).

94 Although extremely useful for model comparison and for tracking the evolution of individual
95 model temperature responses to [CO₂] forcing across generations of MIPs, both ECS and TCR
96 may be seen as rather idealized definitions of climate sensitivity because they are designed to
97 quantify this sensitivity in specific model experiments where [CO₂] change is prescribed (Forster
98 et al., 2021). In the real world, [CO₂] has neither doubled instantaneously nor increased at a
99 rate of 1% per year. Over the historical period 1850–2024, the average growth rate of [CO₂] has



100 been approximately 0.28% per year, increasing to about 0.54% per year over the recent
101 2020–2024 period (calculated using data from [https://gml.noaa.gov/webdata/ccgg/trends/
102 co2/co2_annmean_mlo.txt](https://gml.noaa.gov/webdata/ccgg/trends/co2/co2_annmean_mlo.txt)). Although calculated from an idealized experiment, TCR has been
103 shown to have some utility in predicting near-term climate change (Jeevanjee et al., 2026). An
104 alternative measure of climate sensitivity that is not defined for an idealized experiment with
105 prescribed $[\text{CO}_2]$ change but instead takes into account how $[\text{CO}_2]$ prognostically evolves in
106 response to emissions and climate-carbon cycle interactions is the transient climate response to
107 cumulative emissions (TCRE), defined as the global temperature increase per 1000 GtC emitted
108 in the atmosphere ($^{\circ}\text{C} / 1000 \text{ Pg C}$) (Allen et al., 2009; Gillett et al., 2013; C. D. Jones &
109 Friedlingstein, 2020; Matthews et al., 2009). TCRE is approximately scenario independent (C. D.
110 Jones & Friedlingstein, 2020), so it can be calculated from idealized simulations but is
111 straightforwardly applicable to “real-world” scenarios. Hence, this metric is now routinely used
112 to estimate the “remaining carbon budget” – the cumulative amount of CO_2 that can still be
113 emitted while limiting global mean temperature increase below a specified level – and its
114 associated uncertainty (Forster et al., 2023, 2024; Rogelj et al., 2019).

115 The TCRE depends on both the fraction of emitted CO_2 that remains in the atmosphere and the
116 climate sensitivity to changes in atmospheric CO_2 . The airborne fraction is, in turn, governed by
117 climate-carbon cycle feedbacks. In the context of these feedbacks in Earth system models
118 (ESMs), model intercomparisons have focused on comparing two sensitivities. The first, the
119 carbon-concentration (biogeochemical) sensitivity (β , Pg C/ppm), quantifies the effect of
120 changes in atmospheric CO_2 on land and ocean carbon storage. At the global scale, β is a
121 positive quantity that creates a negative feedback for the climate system such that the initial
122 CO_2 perturbation of the atmosphere is dampened. When $[\text{CO}_2]$ increases, the land and ocean
123 take up some of the carbon from the atmosphere and only the remaining airborne fraction of
124 anthropogenic CO_2 emissions causes climate change. In response to increase in atmospheric
125 CO_2 , carbon uptake on land is driven primarily by CO_2 fertilization of terrestrial vegetation, and
126 carbon uptake in the ocean is driven by dissolution of CO_2 in sea water. Gregory et al. (2009)
127 and C.D. Jones and Friedlingstein (2020) showed that β is both the most important and most
128 uncertain carbon-cycle contribution to TCRE. The second, carbon-climate (radiative) sensitivity



129 (γ , Pg C/ $^{\circ}$ C), quantifies the effect of changes in climate characterized in terms of temperature
 130 change on carbon storage on land and in the ocean. At the global scale, γ is typically found to
 131 be a negative quantity that creates a positive feedback, which enhances the initial CO₂
 132 perturbation of the atmosphere. As climate warms due to increasing [CO₂], both the land and
 133 the ocean release carbon, thereby enhancing the initial atmospheric CO₂ perturbation. Over
 134 land, carbon release at the global scale is driven primarily by enhanced respiration in response
 135 to higher temperatures, although warmer temperatures also enhance vegetation productivity at
 136 high latitudes, where photosynthesis is currently temperature limited. In the ocean, higher
 137 temperatures due to warming of the atmosphere weaken the uptake of CO₂ in the sink regions
 138 (e.g., the North Atlantic Ocean) or strengthen CO₂ release in source regions (e.g., the tropical
 139 Pacific Ocean). In addition, warmer ocean temperatures due to atmospheric warming and lower
 140 salinities due to changes in the hydrological cycle, as well as freshwater inputs from melting sea
 141 ice and glacial melt, lead to increased ocean stratification. Increased stratification, in turn,
 142 inhibits deep convection and water mass transformations at high latitudes, which reduces
 143 transport of carbon from the surface into the deep ocean, and prevents upwelling that brings
 144 colder water to the surface, leading to less uptake of CO₂ by the ocean.

145 The β and γ sensitivities were first introduced in the seminal paper by Friedlingstein et al.
 146 (2003), marking the launch of the Coupled Climate-Carbon Cycle Model Intercomparison
 147 Project (C4MIP), and have since underpinned C4MIP analyses across subsequent CMIP phases
 148 and multiple studies (Arora et al., 2013a, 2020; Friedlingstein et al., 2006; Gregory et al., 2009;
 149 C. D. Jones & Friedlingstein, 2020; Schwinger et al., 2014). Both β and γ metrics can be
 150 quantified for the whole globe, separately for land and ocean, or in a geographically (Boer &
 151 Arora, 2010) varying manner. Although C4MIP and some other MIPs existed and operated
 152 during the third phase of CMIP, it was only during the fifth phase of CMIP (CMIP5) that C4MIP
 153 became a structured component of the CMIP framework (Taylor et al., 2012). Although
 154 quantities such as ECS, TCR, TCRE, and the carbon-cycle feedback sensitivities β and γ quantify
 155 the response of the system to a given perturbation, within the context of CMIP they also serve
 156 as standardized metrics for model intercomparison. Accordingly, we have used the term metric
 157 throughout this paper when referring to carbon-cycle feedback sensitivities β and γ .



158 Similarly to ECS and TCR, β and γ are also limited for characterizing real-world conditions. In
159 fact, β and γ are well-behaved only when CO_2 is continuously increasing (e.g., see Asaadi et al.,
160 2024) and even in that case the magnitude of these metrics depends on the rate of increase of
161 CO_2 , making them scenario-dependent (Gregory et al., 2009). During both CMIP5 and CMIP6
162 (Arora et al., 2013a, 2020), the C4MIP protocol used the **1pctCO2** experiment to quantify the
163 magnitudes of β and γ when $[\text{CO}_2]$ reaches two ($2\times\text{CO}_2$) and four ($4\times\text{CO}_2$) times its
164 pre-industrial value of around 285 ppm, although these metrics can be calculated at any time to
165 show their temporal evolution. As discussed above, when quantifying the sensitivity of climate
166 to an emissions perturbation, one may use TCRE rather than TCR or ECS, because TCRE appears
167 to be an intrinsic characteristic of the Earth system and is therefore applicable across different
168 perturbation scenarios. In a similar manner, climate-carbon feedbacks that represent intrinsic
169 properties of the coupled system make for better metrics than the current β and γ since they
170 are scenario-independent. Obtaining such metrics is one of the goals of C4MIP in CMIP7. As
171 with TCRE, these metrics should not depend on the type of perturbation imposed on the
172 coupled climate-carbon system. To robustly test this requirement, the CMIP7 experimental
173 design includes additional experiments that differ substantially from the traditional 1pctCO2
174 simulations (see Section 3.2).

175 Despite their scenario dependence and limited applicability in real-world situations, β and γ
176 have proved useful in comparing models and their evolution across phases of CMIP, and also
177 provided helpful insights for instance by quantifying the role of the nitrogen (N) cycle in
178 modulating the C cycle, especially over land. Going forward, one particular use of β and γ ,
179 despite their path dependence, is that they combine to form TCRE, which as mentioned is
180 approximately independent of pathway (C. D. Jones & Friedlingstein, 2020). This allows us both
181 to understand the cause of model spread in TCRE from its underlying components, and to
182 propagate constraints on individual terms, such as the constraint on tropical γ from inter-annual
183 variability in land-atmosphere CO_2 fluxes (Cox et al., 2013; Rödenbeck et al., 2018; Wang et al.,
184 2013) back onto TCRE.

185 The historical development of C4MIP and the protocol for its CMIP6 simulations are
186 documented in C. D. Jones et al. (2016). C4MIP continues to play a central role in the seventh



187 phase of CMIP (CMIP7). Its core simulations (BGC and RAD versions of the 1pctCO₂ experiment)
188 form part of the Assessment Fast Track (AFT), designed to inform the Intergovernmental Panel
189 on Climate Change's (IPCC) Seventh Assessment Report (AR7) (Dunne et al., 2025). While
190 C4MIP's primary objective remains the characterization of land and ocean responses to changes
191 in [CO₂] and climate in a fully coupled climate–carbon cycle framework, its scope has expanded
192 to include the quantification of TCRE and the zero-emissions commitment (ZEC) (C. D. Jones et
193 al., 2019; MacDougall et al., 2020; Williams et al., 2025a). In CMIP7, TCRE and ZEC, along with
194 ECS and TCR, will be systematically calculated by the Rapid Evaluation Framework (REF) from
195 the relevant emissions-driven experiments on the Earth System Grid Federation (ESGF)
196 (Hoffman et al., 2026). These will be achieved using constant emissions of 10 Pg C/yr following
197 the flat10 emissions-driven experiment design protocol of Sanderson et al. (2025). In addition,
198 C4MIP seeks to improve understanding of Earth system responses under declining, zero, and
199 net-negative CO₂ emissions, with particular emphasis on the processes governing reversibility
200 and symmetry in carbon-cycle and climate response (Zickfeld et al., 2016, 2021). This focus on
201 emissions-driven runs is highlighted in the paper documenting CMIP7's key scientific objectives
202 in support of enhanced scientific understanding but also informing policy-making and climate
203 services (Dunne et al., 2025).

204

205 In line with this mandate, and with the need to further develop carbon cycle related metrics
206 with clear real-world applicability, this paper presents and summarizes the full suite of C4MIP
207 simulations to be performed as part of CMIP7, including those contributing to AFT and those
208 contributing to subsequent analyses beyond AFT as summarized later in Table 1. In addition, the
209 proposed experimental protocol explicitly attempts to maintain backward compatibility with
210 feedback metrics used in previous phases of CMIP while incorporating new experiments for
211 novel analyses with a focus on emissions-driven simulations. As always, careful consideration is
212 given to balancing scientific aspirations against the practical computational and data storage
213 burden on participating climate modelling groups. The selection of experiments, data requests,
214 and the associated protocols reflect community input and extensive guidance from the C4MIP
215 Scientific Steering Committee (SSC). Finally, as in previous CMIP phases, many of the scientific



analyses enabled by C4MIP are expected to be led by the broader climate modelling community, with the C4MIP Scientific Steering Committee coordinating the experimental design and a core set of analyses.

2. The foundational basis for biogeochemically- and radiatively-coupled simulations

Consider the globally summed and vertically integrated carbon budget quantities

$$\frac{dC_A}{dt} + \frac{dC_L}{dt} + \frac{dC_O}{dt} = E \quad (1)$$

where the global carbon pool $C_A + C_L + C_O$ is the sum of carbon in the atmosphere, land, and ocean reservoirs (Pg C) and E is the rate of anthropogenic CO_2 emission (Pg C/yr) into the atmosphere assuming that land-use change emissions and removals are modelled interactively in ESMs and included in the $\frac{dC_L}{dt} = F_L$ term. The rate of change of carbon is given by the fluxes into and out of the respective pools as

$$\frac{dC_A}{dt} = F_A + E \quad (2a)$$

$$\frac{dC_L}{dt} = F_L \quad (2b)$$

$$\frac{dC_O}{dt} = F_O \quad (2c)$$

where $F_L + F_O = -F_A$ are the fluxes between the atmosphere (A) and the underlying land (L) and ocean (O), taken to be positive into the components. Upon integration over time equation (2) yields

$$\Delta C_A = \int F_A dt + \int E dt \quad (3a)$$



$$\Delta C_L = \int F_L dt \quad (3b)$$

$$\Delta C_O = \int F_O dt \quad (3c)$$

239

240 The diagnosis of feedbacks between the carbon cycle and the physical climate system within
 241 the C4MIP framework follows the methodology introduced by Friedlingstein et al. (2006)
 242 (referred to as F06 from hereon). The F06 approach is based on separating the response of land
 243 and ocean carbon cycles to changes in $[CO_2]$ from their response to changes in the resulting
 244 climate by expressing the changes in pools C_X ($X = L, O$) as functions of change in
 245 globally-averaged temperature (ΔT) and change in atmospheric CO_2 concentration (Δc (ppm) =
 246 ΔC_A (Pg C)/2.12) . ΔT itself is represented in terms of Δc as $\Delta T = \alpha \Delta c$, where α is the linear
 247 transient climate sensitivity to CO_2 in K/ppm. The response of the land and ocean carbon cycles
 248 to changes in $[CO_2]$ alone (expressed in terms of carbon gained or lost per unit area or globally)
 249 is termed the *biogeochemical* response, whereas their response to climatic changes arising
 250 from the radiative effects of increasing $[CO_2]$ is referred to as the *radiative* response. In a
 251 standard fully-coupled simulation with increasing CO_2 , the land and ocean carbon cycles
 252 respond through both mechanisms. The magnitude of this combined response in a
 253 fully-coupled (COU) simulation can be separated into its biogeochemical and radiative
 254 components using two additional simulations with some caveats, which have been previously
 255 identified in several studies (Arora et al., 2013a, 2020; Gregory et al., 2009) and are mentioned
 256 briefly below. In the biogeochemically-coupled (BGC) simulation the physical climate doesn't
 257 directly respond to increases in $[CO_2]$; only the land and ocean biogeochemical processes do. In
 258 a complementary radiatively-coupled (RAD) simulation only the physical climate responds to
 259 increases in $[CO_2]$ while the land and ocean biogeochemical processes do not. Equation (4)
 260 summarizes this concept mathematically, which has been extensively documented in various
 261 forms (Friedlingstein et al., 2006; Gregory et al., 2009; Arora et al., 2013a, 2020) in earlier
 262 C4MIP and related publications but provided here for context for later discussion. For the case



of the **1pctCO2** simulation in which $[\text{CO}_2]$ increases at a rate of 1% per year (and broadly following the F06 methodology which was originally applied for emissions-driven simulations), the changes in land or ocean carbon pools $\Delta C_X (X = L, O)$, using three equations corresponding to the COU, BGC, and RAD experiments, are written as shown in Eq. (4).

$$\text{Fully coupled} \quad \Delta C'_X(t) = \int F'_X(t) dt = \beta_X(t) \Delta c'(t) + \gamma_X(t) \Delta T^+(t) \quad (4a)$$

$$\text{Biogeochemically coupled} \quad \Delta C^*_X(t) = \int F^*_X(t) dt = \beta_X(t) \Delta c'(t) \quad (4b)$$

$$\text{Radiatively coupled} \quad \Delta C^+_X(t) = \int F^+_X(t) dt = \gamma_X(t) \Delta T^+(t) \quad (4c)$$

270

Here F' , F^* , and F^+ are the CO_2 flux changes (PgC yr^{-1}); $\Delta C'_X$, ΔC^*_X , ΔC^+_X , and the changes in global carbon pools (Pg C) in the COU, BGC, and RAD simulations; ΔT^+ the global temperature change ($^\circ\text{C}$) in the RAD simulation (assumed approximately equal to that in the COU simulation because the BGC global temperature change ΔT^* is small; see comments below); and the subscript $X = L, O$ refers to either the land or ocean model components. $\Delta c'$ is the change in $[\text{CO}_2]$ (equal in the BGC and COU simulations for the 1pctCO2 experiment). The time dependence is explicitly indicated to emphasize that in particular β_X and γ_X are not constants (see discussion below). Here and elsewhere uppercase C is used to denote pools and lowercase c is used to denote atmospheric CO_2 concentration, $[\text{CO}_2]$. All changes are defined relative to a preindustrial equilibrium state represented by the preindustrial control simulation. There is no $\Delta c'$ term in the RAD simulation since there the biogeochemistry sees the preindustrial value of $[\text{CO}_2]$ although ΔT^+ is a function of increasing $\Delta c'$ that is seen only by the radiative transfer calculations. If we make the questionable assumption that γ estimated from the RAD simulation is the same as that estimate from COU and BGC simulations, then the two β and γ sensitivities



285 can be found using any two of the three equations (for the COU, BGC, and RAD cases) as done
286 in Arora et al. (2020).

287 There are several caveats with equation (4). First, the global temperature change in the BGC
288 simulation (ΔT^*) is not zero, but typically slightly positive due to vegetation changes associated
289 with enhanced productivity (e.g. increased leaf area index) and reduced transpiration
290 associated with stomatal closure in a higher $[\text{CO}_2]$ environment (Arora et al., 2020; Varney et al.,
291 2024). Because at global scale this BGC temperature change is small compared to that in the
292 COU/RAD simulations (Zarakas et al., 2020), in the standard framing one assumes it negligible,
293 so that no temperature term shows up in equation (4b) (Adloff et al., 2018; Friedlingstein et al.,
294 2003, 2006; Gregory et al., 2009; e.g., Varney et al., 2024). While attempts have been made to
295 account for this small ΔT^* in the formulation (Arora et al., 2013a, 2020) to calculate γ_x , this
296 may not be straightforward because it has recently been argued that climate evolves differently
297 in BGC and COU/RAD setups and the resulting γ_x values depend on this time evolution (Reick &
298 Torres Mendonça, 2025). A second caveat is that, while ΔT^* is small in the global mean, it can be
299 larger regionally and seasonally, particularly in regions and during periods of the year when
300 transpiration rates are high. In addition, the spatial pattern of ΔT^+ is different from that of ΔT^* .
301 The former shows the typical global warming pattern with higher warming over land than over
302 ocean, and higher warming over polar regions compared to the rest of the globe. The spatial
303 pattern of ΔT^* is in response to changes in transpiration and therefore follows vegetation
304 distribution. As a result, for example, γ derived from the combination of RAD and BGC
305 simulations versus the combination of BGC and COU simulations is different. Finally, the
306 formulation of the β and γ terms in equation (4) has been critiqued and evaluated in multiple
307 publications (Gregory et al., 2009; Zickfeld et al., 2011; Arora et al., 2013a; Schwinger et al.,
308 2014; Adloff et al., 2018; Reick & Torres Mendonça, 2025). In fact, although this formulation
309 was originally introduced as a linearization of the system's response into CO_2 and temperature
310 forcings, it can be shown that, because of the memory of the climate-carbon system, for the
311 transient scenarios of interest the linear terms actually vanish so that the formalism is fully



nonlinear (Reick & Torres Mendonça, 2025). A consequence of this nonlinearity is that even for small forcing sizes the response does not scale with the forcing; hence, the β and γ values, defined as response-to-forcing ratios, are not constant but vary with forcing and time (e.g., Arora et al., 2013a, their Figure 6; Randerson et al., 2015). For this reason β and γ cannot be understood as intrinsic properties of the system but rather as simple diagnostics enabling comparison of ESMs carbon cycle sensitivities under a common set of forcing scenarios (Reick & Torres Mendonça, 2025).

3. Key scientific objectives for C4MIP in CMIP7

There are five key scientific objectives for C4MIP in the context of CMIP7: (1) quantification of feedback metrics, comparing with previous CMIP phases, and understanding the mechanisms that determine them; (2) identification of new feedback metrics that more realistically represent intrinsic properties of the coupled climate–carbon cycle system; (3) quantification of TCRE and ZEC using emissions-driven simulations; (4) analysis of carbon-cycle behaviour under declining, zero and net-negative emissions; and (5) analysis of CO₂ emissions- and concentration-driven historical and future scenario simulations, with a focus on carbon budgets and evaluation of the magnitude of carbon-cycle components, including pool sizes, against observation-based estimates. Together, these objectives provide the rationale for the experiments proposed for inclusion in C4MIP as part of CMIP7, which are detailed in the following sections. C4MIP’s overall motivation remains to better understand the carbon cycle and its interaction with the physical climate system.

3.1 Comparison of feedback metrics with previous CMIP phases

Despite their limitations, the β and γ feedback metrics (Section 2) provide a useful framework for comparing models within a given CMIP phase, tracking the evolution of individual models across successive CMIP phases, and diagnosing and comparing related metrics. In addition, the TCRE (which also has been historically determined using the **1pctCO2** experiment) can also be interpreted in terms of the underlying climate-carbon feedback sensitivities α , β , and γ (C. D.



339 Jones & Friedlingstein, 2020; Tachiiri, 2020) which provides a formal connection between
340 traditional feedback decomposition and the cumulative emissions and temperature change
341 scaling used for the calculation of remaining carbon budgets.

342 To maintain backward compatibility with previous CMIP phases, in which β and γ were
343 diagnosed using the **1pctCO2** experiment and its radiatively and biogeochemically coupled
344 variants, the **1pctCO2-rad** and **1pctCO2-bgc** experiments have been proposed and approved for
345 inclusion in the CMIP7 AFT. These experiments therefore provide continuity with earlier CMIP
346 phases and enable evaluation of changes in the strength of feedback metrics arising from
347 changes in structure and process-level developments in ESMs. Because β and γ are defined as
348 sensitivities to changes in CO₂ concentration (ppm), it is natural to compare them across models
349 by prescribing CO₂ as the boundary condition. In contrast, TCRE is defined per unit of
350 cumulative emissions, while ZEC characterizes the climate response after emissions cease,
351 following a specified amount of cumulative emissions. The flat10 experiments therefore
352 prescribe emissions, making them the natural framework for estimating these emissions-based
353 metrics.

354

355 **3.2 Identifying intrinsic climate-carbon feedback metrics**

356

357 As briefly discussed above, Reick & Torres Mendonça (2025) make the case why β and γ are not
358 intrinsic properties of the coupled climate and carbon cycle system, as they are both
359 scenario-dependent and time-dependent within a given scenario. Reick & Torres Mendonça
360 (2025) also illustrate that these limitations arise from the long characteristic timescales of
361 carbon-cycle components. As a result, until the system approaches equilibrium, its response to
362 a CO₂ perturbation depends not only on the instantaneous forcing but also on the history of
363 prior CO₂ changes. This is indeed the case when [CO₂] is rising.

364 One possible approach to address this limitation is to formulate α , β and γ as feedback functions
365 within a linear convolution framework that explicitly incorporates system history effects (I.



Enting & Clisby, 2019; I. G. Enting, 2022; Rubino et al., 2016; Torres Mendonça et al., 2024).

Mathematically, in this framework equations (4) generalize to

$$\text{Fully coupled} \quad \Delta C'_X(t) = \int \chi_\beta^X(\tau) \Delta c'(t - \tau) d\tau + \int \chi_\gamma^X(\tau) \Delta T^+(t - \tau) d\tau \quad (5a)$$

$$\text{Biogeochemically coupled} \quad \Delta C_X^*(t) = \int \chi_\beta^X(\tau) \Delta c'(t - \tau) d\tau \quad (5b)$$

$$\text{Radiatively coupled} \quad \Delta C_X^+(t) = \int \chi_\gamma^X(\tau) \Delta T^+(t - \tau) d\tau \quad (5c)$$

with

$$\Delta T^+(t) = \int \chi_\alpha(\tau) \Delta c'(t - \tau) d\tau. \quad (5d)$$

Here, the scenario-dependent sensitivities α , β and γ become the generalized sensitivities χ_α , χ_β and χ_γ (for $X = L, O$), inherent system characteristics from which in principle the biogeochemical and radiative feedbacks can be uniquely quantified: these generalized sensitivities combine into scenario-independent feedback functions f_β and $f_{\gamma\alpha}$ that describe the feedback strength at different timescales. Such formulation also leads to generalized definitions of the airborne fraction and TCRE, by which the climate-carbon dynamics may be systematically investigated (Torres Mendonça et al., 2024).

The idea behind such an attempt is that a feedback framework that truly reflects intrinsic properties of the coupled climate–carbon cycle system should be scenario invariant. This means that estimates of feedbacks should be consistent across different scenarios and, by using feedback metrics derived from a particular simulation, one should be able to predict land and ocean carbon uptake and airborne fraction of emissions in others. To facilitate evaluation of the



scenario-independence of any future proposed feedback functions/metrics, C4MIP for CMIP7 includes a diverse set of concentration- and emissions-driven experiments. In addition to the **1pctCO₂** experiment and its RAD and BGC coupled versions, these include concentration-driven abrupt **2xCO₂** experiments requested jointly with Cloud Feedback MIP (CFMIP) along with their RAD and BGC versions, instantaneous 500 Pg C pulse experiments under pre-industrial conditions (**esm-pi-pulse-500**) and its BGC version, emissions-driven simulations with constant emissions of 10 Pg C/yr (**esm-flat-10**) and its RAD and BGC version, and concentration-driven **hist-CO₂** (a specified concentration hist simulation based on the CMIP protocol but with only atmospheric CO₂ increasing over the historical period) and its BGC version. These experiments are graphically illustrated in Figure 1: panel (a) for concentration-driven simulations and panel (b) for emissions-driven simulations. The protocol for these and other experiments are presented in detail in a later section.

The diversity of this suite of experiments will serve the key objective of obtaining strong evidence for the true scenario independence of any new feedback metrics. On one hand, the suite includes two concentration-driven experiments with a continuous increase in atmospheric CO₂: the traditional **1pctCO₂** experiment, relevant for its compatibility with previous CMIP phases, and the **hist-CO₂** experiment, from which one can evaluate the applicability of the new feedback metrics over the historical period. The suite also incorporates the concentration-driven abrupt **2xCO₂** experiment, especially relevant in this context for many reasons: first, this experiment will provide a rather extreme test case for the feedback metrics where CO₂ concentrations are abruptly increased, which allows for assessing the ability of the metrics to predict fast modes of the system; second, the **2xCO₂** experiment is particularly suitable for deriving generalized sensitivities such as those defined in Eq. (5) along with their timescale spectra, from which process contribution to the large-scale response may be quantified (see e.g., Torres Mendonça et al. (2021)); third, such experiment may allow for determining equilibrium carbon feedbacks and thereby obtain a framework completely consistent with that of physical feedbacks (Reick & Torres Mendonça, 2025). Finally, the suite includes emission-driven experiments, also with quite different scenarios (**esm-pi-pulse-500**

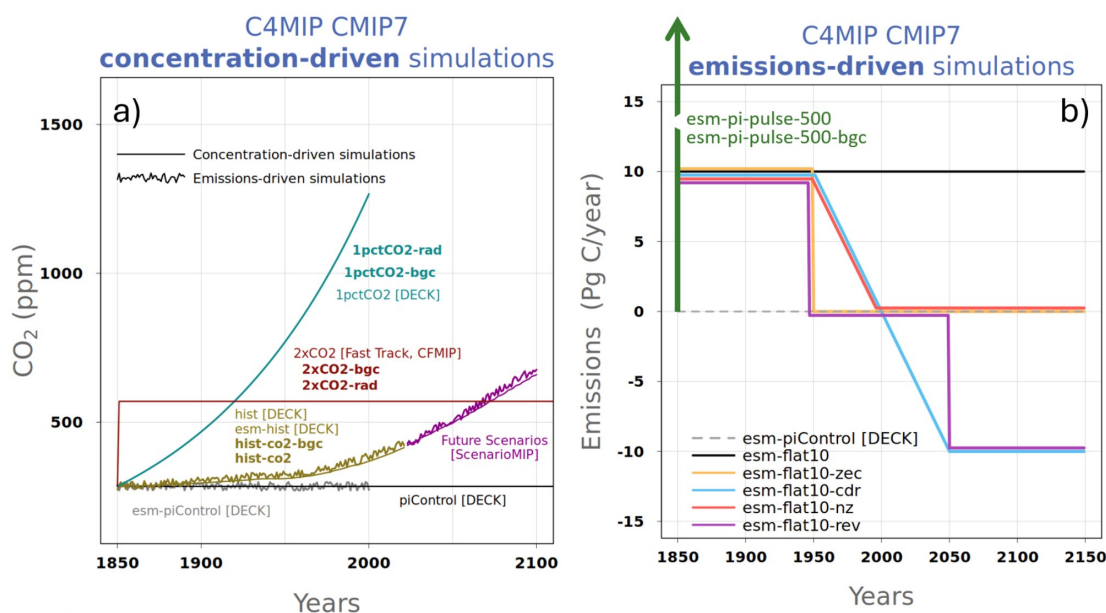


Figure 1: Proposed C4MIP concentration-driven (panel a) and emissions-driven (panel b) simulations for CMIP7. The emissions for all esm-flat10 configurations for years 1850-1950 are 10 Pg C/yr but plotted with slightly different values to avoid overlapping lines and facilitate identification of individual scenarios. This is also done when emissions become zero.

3.3 Focus on emissions-driven simulations for calculating TCRE and ZEC

Both TCRE and ZEC are emissions-relevant quantities. Yet for CMIP6, TCRE was calculated using cumulative diagnosed emissions from the concentration-driven **1pctCO2** experiment at the time when atmospheric CO₂ concentration doubled in approximately 70 years. The cumulative diagnosed emissions (Pg C) are based on integration of equation (1) from time 0 to 70 years (corresponding to the time period 1850-1919, since most modelling groups start their **1pctCO2** simulation in the year 1850)



$$\int_0^{70} E \, dt = \Delta C_A + \Delta C_L + \Delta C_O \quad (6)$$

where ΔC_A is the prescribed change in $[\text{CO}_2]$ (equal to around $285 \times (1.01^{70} - 1) \times 2.12 = 608.3 \text{ Pg C}$), and ΔC_L and ΔC_O are the carbon uptakes by land and ocean over the 70-year period in this case. TCRE is then calculated as

$$TCRE = \frac{\Delta T'_{70}}{\int_0^{70} E \, dt} \quad (7)$$

where $\Delta T'_{70}$ is the global-mean temperature change, averaged over 20 years, in the fully-coupled **1pctCO2** experiment centered at year 70.

The real world is emissions-driven and $[\text{CO}_2]$ exhibits a seasonal cycle as well as geographical variations. This spatial and temporal structure of $[\text{CO}_2]$ is absent in concentration-driven simulations, which prescribe the same $[\text{CO}_2]$ at a given time at all given atmospheric levels and on the globe. Globally-averaged $[\text{CO}_2]$ exhibits a seasonal cycle and its annual amplitude is about 6 ppm. This amplitude is substantially larger in the Northern Hemisphere extratropics (30° to 90° N), and varies from 10 to 25 ppm due to the dominance of terrestrial biospheric fluxes (Keeling & Piper, 2001; Lin et al., 2020). In emissions-driven simulations, the spatial and temporal structure of atmospheric CO_2 evolves prognostically in response to atmospheric transport, anthropogenic and natural carbon fluxes, and changes in climate rather than the globally uniform CO_2 concentrations prescribed in concentration-driven simulations. As a result, because emissions-driven simulations represent the spatial and temporal evolution of atmospheric CO_2 more realistically, as well as its interactions with the land and ocean carbon reservoirs, they provide a more physically consistent framework for estimating TCRE than concentration-driven simulations. Unlike ECS, which quantifies the climate response to a prescribed atmospheric CO_2 concentration change, TCRE is fundamentally an emissions-based metric. Furthermore, the compatible CO_2 emissions implied by a **1pctCO2** concentration pathway are substantially larger than recent historical emissions, reaching around 20 Pg C/yr at year 70 of the experiment compared with the observed fossil-fuel emissions of 9.8 Pg C/yr over



the past decade (Friedlingstein et al., 2026). As a result, the path-dependent metrics estimated from the **1pctCO2** experiment may be less directly relevant to climate policy than those derived from emissions-driven simulations with emission rates closer to historical rates of fossil-fuel emissions.

A similar issue arises with estimation of the ZEC. For CMIP6, rather than using simulations in which emissions ceased in an emissions-driven framework to calculate ZEC, the free-CO₂ simulations were initialized from concentration-driven **1pctCO2** runs at the point when diagnosed cumulative emissions reached a specified threshold. Emissions were then set to zero, allowing atmospheric CO₂ to evolve freely. Consequently, the atmospheric CO₂ field transitioned abruptly from a spatially uniform prescribed concentration to a fully interactive, spatially heterogeneous field with seasonal and interhemispheric structure. Although this artificial transition is unlikely to strongly affect the magnitude of simulated ZEC, it introduces an inconsistency between forcing methodologies and somewhat complicates the physical interpretation of results.

Proposed emissions-driven experiments in CMIP7 avoid this inconsistency altogether by estimating both TCRE and ZEC in an emissions-driven framework in which CO₂ evolves freely. The 320-year **esm-flat10** experiment in which emissions are prescribed at a constant rate of 10 Pg C/yr is designed specifically to estimate TCRE (calculated from **esm-flat10** as the 20-year mean temperature change centred on year 100 divided by 1000 Pg C). A related objective of C4MIP for CMIP7 is to compare TCRE estimates from the **1pctCO2** and **esm-flat10** experiments, thereby evaluating whether future assessments could estimate TCRE from **esm-flat10** experiments alone, provided that the resulting TCRE values are consistent with those derived from the **1pctCO2** experiment. For **esm-flat10** experiments, when global temperature change is plotted against time, the slope of the resulting relationship is proportional to TCRE because the time axis is directly proportional to cumulative emissions (see Figure 3a of Sanderson et al. (2025)). For quantification of the ZEC, the emissions-driven **esm-flat10-zec** experiment sets emissions to zero at the beginning of year 101 (after 100 years of emissions at 10 Pg C/yr, corresponding to 1000 Pg C of cumulative emissions in the **esm-flat10** simulation), and the simulation is then continued for a further 220 years. In this context, ZEC50 and ZEC100 are



485 defined as the 20 year average centered on years 150 and 200 respectively. ZEC is known to be
486 dependent on both cumulative emissions level and emissions rate (Williams et al., 2025b).
487 flat10-based ZEC values are expected to be substantially different from the 1pctCO₂-based
488 ZECMIP design used in CMIP6, where cumulative emissions at the point of cessation were
489 model dependent, with emissions rates which were significantly larger than present day levels
490 (Sanderson et al., 2025). Together, these emissions-driven experiments provide a physically and
491 internally consistent framework for estimating emissions-relevant TCRE and ZEC metrics. Figure
492 1b illustrates the emissions pathway for the **esm-flat10** and **esm-flat10-zec** experiments along
493 with other variants of the flat10 experiment that are discussed in the next section.

494

495 3.4 Carbon-cycle behaviour under zero and net-negative emissions

496 In addition to the **esm-flat10** and **esm-flat10-zec** experiments, C4MIP proposes several
497 additional emissions-driven variants to analyze the behaviour of the coupled climate-carbon
498 cycle system under zero and net-negative emissions scenarios. These experiments are designed
499 to explore how the system responds to different pathways toward net zero and carbon dioxide
500 removal (CDR), and whether that response is reversible or exhibits hysteresis (see Figure 1b).

501 The **esm-flat10-cdr** experiment emulates large-scale CDR by linearly decreasing emissions over
502 a 100-year period, from +10 Pg C yr⁻¹ at year 100 to -10 Pg C yr⁻¹ by year 200. The CDR methods
503 represented by this idealized setup are those methods that do not directly alter land or ocean
504 properties and thereby introduce additional effects on climate or atmospheric CO₂, such as
505 direct air capture with geological storage. In contrast, afforestation, for example, alters
506 vegetation distribution and thereby shifts the distribution of ecosystems with different turnover
507 times and induces additional biogeophysical effects. Such effects are not intended to be
508 captured by **esm-flat10-cdr**. The net-zero variant, **esm-flat10-nz**, follows the same pathway as
509 **esm-flat10-cdr** until year 150, after which emissions are held at zero. Finally, the **esm-flat10-rev**
510 experiment imposes abrupt/step transitions: emissions follow **esm-flat10-zec** until year 200 and
511 then abruptly switch to -10 Pg C yr⁻¹ for an additional 100 years. As such the comparison of



512 **esm-flat10-zec** and **esm-flat10-rev** allows a cleaner assessment of any asymmetry between the
513 response to positive and negative emissions.

514 Together, these experiments allow assessment of whether the climate-carbon system responds
515 symmetrically to increasing and decreasing emissions, or whether it exhibits hysteresis and path
516 dependence. They also enable evaluation of the sensitivity of carbon-cycle and temperature
517 responses to gradual versus abrupt transitions to net zero and net-negative emissions. Results
518 from the **esm-flat10**, **esm-flat10-zec**, and **esm-flat10-cdr** experiments have been evaluated for
519 participating models in Sanderson et al. (2025), demonstrating their feasibility and scientific
520 value for this framework. The **esm-flat10-nz** (which is mentioned in Sanderson et al. (2025)) and
521 **esm-flat10-rev** variants extend this approach to further isolate pathway dependence (gradual
522 versus abrupt) to zero and negative emissions.

523 The flat10 reversibility experiments are complementary to simulations proposed in the Tipping
524 Points Modelling Intercomparison Project (TIPMIP; Jones et al. (2025)), whose Tier 1 ESM
525 protocol is likewise emissions-driven and initialized from pre-industrial, forcing the system
526 through positive, zero, and negative emissions to probe zero-emissions commitment,
527 negative-emission efficacy, and reversibility. The difference is what each design holds common
528 across models. flat10 fixes the emission rate at 10 Pg C/yr, so cumulative emissions are identical
529 across the ensemble and the temperature-versus-time slope gives TCRE directly; TIPMIP scales
530 each model's emissions to its TCRE to impose a common warming rate of 2°C per century,
531 better suited to locating where in warming space tipping elements cross their thresholds. The
532 two coincide only for a model whose TCRE is near 2°C per 1000 Pg C, so for most models these
533 are distinct runs and neither substitutes for the other; we do not ask groups to repeat TIPMIP
534 simulations under the C4MIP banner, or the converse. We do ask that the conservation
535 diagnostics identified in Section 5 of this paper be reported on the flat10 reversibility runs, and
536 we encourage aligning the zero- and negative-emission diagnostics across both activities. For
537 AR7, C4MIP objective is to supply the carbon-cycle reversibility metrics
538 (positive-versus-negative asymmetry, ZEC, and TCRE under net-negative emissions), while



539 TIPMIP's objective is the assessment of biophysical threshold behaviour and irreversibility in the
540 context of tipping elements.

541

542 **3.5 Pulse experiment**

543 In addition to emissions-driven **esm-flat10** variants described in the previous sections, C4MIP
544 also proposes the **esm-pi-pulse-500** experiment, another emissions-driven experiment
545 designed to characterize the response of the coupled carbon-climate system to a well-defined
546 perturbation. Pulse experiments allow quantification of impulse-response functions that
547 describe how the resulting perturbation in $[\text{CO}_2]$ decays following a discrete pulse of emission.
548 The last comprehensive quantification of impulse-response functions was performed by Joos et
549 al. (2013) using results from ESMs of varying complexity for a pulse of 100 Pg C emitted in both
550 pre-industrial and present-day atmospheres (background $[\text{CO}_2]$ of 389 ppm for present-day,
551 corresponding approximately to year 2010–2015 conditions). Joos et al. (2013) also analyzed
552 model responses for a pulse of 5000 Pg C in the pre-industrial atmosphere.

553 Pulse experiments provide valuable information about the effective lifetime of CO_2 in the
554 coupled carbon-climate system and the characteristic timescales of carbon uptake associated by
555 different reservoirs. The resulting impulse-response functions provide a convenient framework
556 for the development and calibration of reduced-complexity carbon-cycle emulators and
557 integrated assessment models (IAMs), which rely on impulse-response formulations to
558 represent the evolution of atmospheric CO_2 and associated climate responses (Hooss et al.,
559 2001; Good et al., 2011). Repeating a pulse experiment within C4MIP provides an ideal
560 opportunity to reassess the impulse-response of newer generation ESMs and update the
561 widely-used function from earlier model generations.

562 Given the variability in response to smaller pulses, arising from internal climate variability in
563 comprehensive ESMs, and to avoid the need for multiple ensemble members we adopt a
564 relatively large pulse size of 500 Pg C. We note that a perturbation of this magnitude is
565 sufficiently large that nonlinear carbon-cycle and climate responses may contribute to the



566 simulated evolution of atmospheric CO₂. As a result, this experiment may not be viewed as a
567 means of deriving a small-perturbation linear impulse-response function, but as a large-pulse
568 sensitivity experiment that provides information on the behaviour of the coupled
569 carbon-climate system under a substantial carbon perturbation. This experiment therefore
570 serves both as an opportunity to reassess pulse-response characteristics in newer-generation
571 ESMs and as a means of evaluating the extent to which impulse-response formulations derived
572 from earlier model generations remain applicable under larger perturbations.

573

574 **3.6 Carbon budgets and evaluation of carbon-cycle components**

575 In addition to the idealized experiments considered above, C4MIP also plans to use and analyze
576 other CMIP7 results from non-idealized simulations that include the full set of historical forcings
577 and future scenario pathways. These analyses will primarily draw on simulations performed as
578 part of the CMIP7 DECK, including the historical simulation (**hist**), its emissions-driven
579 counterpart (**esm-hist**), and future scenario simulations as part of the ScenarioMIP. Together
580 these simulations provide an opportunity to evaluate the behaviour of the models' coupled
581 climate-carbon cycle system under realistic forcing pathways, for both concentration- and
582 emissions-driven variants, and to compare model results directly with observation-based
583 datasets.

584 Analyses of these simulations are expected to span a broad range of topics including, but not
585 limited to: evaluation of differences and consistencies between concentration-driven and
586 emissions-driven simulations (e.g., Hajima et al., 2025); changes in the amplitude of the
587 seasonal CO₂ cycle (H. D. Graven et al., 2013) and the interhemispheric CO₂ gradient over the
588 historical period (e.g., Zhao & Zeng, 2014); evaluation of land and ocean fluxes and pools and
589 components such as gross primary productivity, respiration, and soil carbon (e.g., Anav et al.,
590 2013; Collier et al., 2018; Todd-Brown et al., 2013); comparison of model-diagnosed compatible
591 emissions with observation-based anthropogenic emissions inventories (e.g., C. Jones et al.,
592 2013); assessment of the magnitude and variability of the land and ocean carbon sinks (e.g.,
593 Koven et al., 2015); evaluation of the behaviour of the airborne fraction of cumulative



emissions; investigation of the role of climate variability modes such as the El Niño–Southern Oscillation (ENSO) in modulating global and regional land-atmosphere and ocean-atmosphere CO₂ fluxes (e.g., C. D. Jones et al., 2001; Rödenbeck et al., 2018); and the role of plant physiological responses to rising CO₂ as a driver of regional changes in precipitation, drought stress, and runoff (Fowler et al., 2019; Kooperman et al., 2018; Swann et al., 2016). Evaluation against emergent constraints can also be applied to these simulations, such as the strength of interannual variability of CO₂ fluxes (Cox et al., 2013) and the seasonal cycle of atmospheric CO₂ (Wenzel et al., 2016)

Compared to idealized experiments, experiments over the historical period and for future scenarios allow the evaluation of C cycle responses (including pools and fluxes) under realistic forcing pathways that include land-use change, aerosols, and other non-CO₂ forcings, and allow direct comparison with observation-based datasets. These simulations provide a link between process-based understanding achieved from idealized experiments and evaluation of C cycle components against observation-based constraints under realistic forcings. Since future climate scenarios in CMIP7 are intended to be performed in emissions-driven mode (Van Vuuren et al., 2026) in addition to concentration-driven mode, the process-based understanding gained from idealized C4MIP experiments, together with the evaluation of carbon-cycle components against observations, will help interpret and explain the carbon-cycle responses simulated under realistic future forcing pathways.

The scope and diversity of these potential analyses depend strongly on community engagement. While the C4MIP co-chairs and members of its Scientific Steering Committee coordinate the experimental design and lead a set of core analyses, many of the studies referenced in this section from previous CMIP phases were also conducted by researchers from the broader climate modelling community. This distributed approach to be followed again in the upcoming phase is an integral part of C4MIP and has enabled a wide range of investigations of the coupled carbon-climate system across successive CMIP phases.



620 4. Experiment protocol, the case for BGC runs, and more ensemble members

621 Table 1 summarizes all experiments proposed under the C4MIP umbrella for CMIP7 and
622 separately identifies those included in the AFT and those proposed for participation beyond
623 AFT. The experiment duration and total simulation years are also listed separately for AFT and
624 post-AFT participation to provide an indication of the associated computational burden. The
625 table also identifies concentration (c) and emissions (e) driven runs.



Experiment	c- or e-driven	Assessment Fast Track (AFT) or not	Tier/ Priority	Duration (AFT)	Duration (post-AFT)	Time period	Purpose and comments
esm-flat10	e	Fast track	0	150 yrs	150 x 4 = 600 years	1850-1999	Primary TCRE diagnostic experiment
flat10-bgc	c	Post FT	1		150 yrs	1850-1999	Quantification of β , γ and comparison to 1pctCO2 runs.
flat10-rad	c	Post FT	1		150 yrs	1850-1999	Concentration-driven with CO2 from emissions-driven coupled esm-flat10 experiment.
esm-flat10-zec	e	Fast track	0	220 yrs	220 x 4 = 880 yrs	1950-2169	Primary ZEC diagnostic experiment, branching from corresponding esm-flat10 ensemble member in year 100.
flat10-zec-bgc	c	Post FT	1		220 yrs	1950-2169	Concentration-driven with CO2 from emissions-driven esm-flat10-zec experiment.
	c		2		220 x 4 = 880 yrs	1950-2169	Additional ensembles for flat10-zec-bgc proposed as Tier 2.
esm-flat10-cdr	e	Fast track	0	220 yrs	220 x 4 = 880 yrs	1950-2169	TCRE under negative emissions, role of ZEC in reversibility, branching from year 100 in corresponding flat10 ensemble member.
flat10-cdr-bgc	c	Post FT	1		220 yrs	1950-2169	Concentration-driven with CO2 from emissions-driven esm-flat10-cdr experiment.
			2		220 x 4 = 880 yrs	1950-2169	Additional ensembles for flat10-cdr-bgc proposed as Tier 2.
esm-flat10-nz	e	Post FT	1		170 x 4 = 680 yrs	2000-2169	Comparison against standard ZEC after linear rampdown in emissions instead of abrupt cessation. Branches from esm-flat10-cdr in the year 150.
esm-flat10-rev	e	Post FT	1		120 x 4 = 480 yrs	2050-2169	TCRE under negative emissions, branched from esm-flat10-zec in the year 200.
flat10-rev-bgc	c	Post FT	2		120 yrs	2050-2149	Concentration-driven with CO2 from emissions-driven esm-flat10-rev experiment.
1pctCO2	c	Fast track	0	150 yrs		1850-1999	Part of the DECK
1pctCO2-bgc	c	Fast track	0	150 yrs		1850-1999	Usual feedbacks β , γ for backward compatibility with CMIP5 and CMIP6
1pctCO2-rad	c	Fast track	0	150 yrs		1850-1999	
hist-co2	c	Post FT	1		172 yrs	1850-2021	
hist-co2-bgc	c	Post FT	2		172 yrs	1850-2021	
2xCO2	c	Fast track	0	300 yrs		1850-2149	Part of Assessment Fast Track for CFMIP
2xCO2-bgc	c	Post FT	1		300 yrs	1850-2149	For intrinsic feedback analyses
2xCO2-rad	c	Post FT	1		300 yrs	1850-2149	
esm-pi-pulse-500	e	Post FT	1		500 yrs	1850-2349	Quantification of impulse-response function for a large pulse. The first 500 years are requested as Tier 1, and the following 500 years as Tier 2.
esm-pi-pulse-500	e	Post FT	2		500 yrs	2350-2849	
esm-pi-pulse-500-bgc	e	Post FT	1		500 yrs	1850-2349	
esm-pi-pulse-500-bgc	e	Post FT	2		500 yrs	2350-2850	
TOTAL years				890 yrs	6204 yrs 3804 yrs (without additional ensembles)		

Table 1: C4MIP experiments included in the Assessment Fast Track (AFT, blue rows) and those proposed for participation beyond AFT (tan rows). Experiment duration and total simulation years are listed separately for AFT and post-AFT experiments.



629 The primary additional computational cost arises from the request for an additional four
630 ensemble members for the **esm-flat10**, **esm-flat10-zec**, **esm-flat10-nz**, **esm-flat10-rev** and
631 **esm-flat10-cdr** experiments. However, these experiments are efficiently branched such that
632 the first 100 years of simulation are common to all experiments, the 'nz' and 'cdr' variants are
633 common until year 150, and the 'zec' and 'rev' experiments are common until year 200. The
634 ZEC signal exhibits substantial variability in comprehensive Earth System Models (MacDougall et
635 al., 2020) because once CO₂ emissions cease the response of the coupled carbon–climate
636 system is largely influenced by internal climate variability rather than the continuing external
637 forcing. As a result, estimating ZEC becomes a signal-to-noise ratio problem (Borowiak et al.,
638 2024). The requested four additional ensemble members are therefore intended to improve the
639 signal-to-noise ratio and provide a more robust estimate of ZEC.

640 The response of the coupled carbon-climate system in the **esm-flat10-cdr** experiment also
641 exhibits variability (Sanderson et al., 2025) and the system also exhibits potential hysteresis for
642 a range of variables. As a result, the trajectory of recovery can differ across realizations due to
643 internal climate variability, and additional ensemble members are aimed at providing a more
644 robust characterization of the system response.

645 Feedback from the C4MIP community indicated strong interest in corresponding BGC
646 simulation for most experiments. Together with the fully coupled simulations, their
647 biogeochemically-only coupled variants allow the carbon-cycle response to changes in
648 atmospheric CO₂ to be separated from the response driven by the associated climate change,
649 and many analyses rely on this comparison (Chimuka et al., 2023). For this reason,
650 corresponding BGC simulations have been requested for several experiments. In contrast to
651 fully-coupled simulations, additional ensemble members for BGC variants of emissions-driven
652 ZEC and CDR experiments (**flat10-zec-bgc** and **flat10-cdr-bgc**) are considered a lower priority, as
653 the primary motivation for ensembles arises from the need to better quantify the role of
654 internal climate variability on surface-atmosphere CO₂ exchange in the fully coupled
655 experiments.



As with previous phases of CMIP, all C4MIP experiments are initialized from corresponding **piControl** and **esm-piControl** experiments and all non-CO₂ forcings including land cover, concentration of non-CO₂ GHGs, and emissions of aerosols are kept at their pre-industrial 1850 level.

4.1. Experiment protocol for concentration-driven simulations and their BGC/RAD versions

The protocol for concentration-driven experiments remains the same as in CMIP6 (C. D. Jones et al., 2016). Depending on the experiment type and model configuration - radiatively coupled (RAD), biogeochemically coupled (BGC), or fully coupled (COU) - the specified changing CO₂ concentration is used for relevant model components (for radiation in RAD runs, for land and ocean biogeochemistry in BGC runs, and for both radiation and biogeochemistry components in COU runs) or else the CO₂ is specified to remain at its pre-industrial 1850 level. In all cases, the same CO₂ concentration is specified uniformly throughout the atmosphere (both geographically and across all vertical atmospheric levels). The concentration follows the prescribed scenario, with annual CO₂ values interpolated to the model time step where possible. In the flat10 concentration-driven variants the prescribed CO₂ comes from the emissions-driven **esm-flat10** experiment. The concentration-driven experiments where all simulations use prescribed concentrations include **1pctCO2**, **2xCO2**, **hist-co2** and their corresponding BGC and/or RAD versions as indicated in Table 1.

4.2. Experiment protocol for emissions-driven simulations and their BGC/RAD versions

Following Sanderson et al. (2025), the flat10 variants of the emissions-driven experiments use spatially homogeneous CO₂ emissions. For a global emission rate of 10 Pg C/yr, and using the Earth's surface area of 510,064,471 km² (510.06 million km²; obtained using Climate Data Operators, CDO), and 365 days in a year, this yields a spatially uniform emission flux applied across a model's all grid cells. The resulting emissions per unit area and per unit time are 6.2168×10^{-10} kg C/m²s or equivalently 22.7949×10^{-10} kg CO₂/m²s. Modelling groups should verify this



683 calculation using the Earth's surface area represented in their model, as the total area may
684 differ slightly between models, and should also confirm whether their model uses 360, 365, or
685 365.25 days per year when converting the annual emission rate to a per-second flux. The linear
686 decrease to zero emissions in the **esm-flat10-zec** experiment, followed by a further decrease to
687 -10 Pg C/yr in the **esm-flat10-cdr** experiment, is implemented by applying the corresponding
688 time-varying changes to this globally uniform emission flux.

689

690 In the context of the flat10 experiments, the corresponding BGC and RAD versions are proposed
691 to be performed in concentration-driven mode using the simulated globally averaged CO_2
692 concentration from the emissions-driven COU **esm-flat10** simulation. The objective is to
693 estimate the β and γ feedback metrics from the flat10 experiments and compare them with
694 those derived from the traditional **1pctCO2** experiments. More broadly, the bigger context is to
695 assess whether the flat10 experiment framework can be used to estimate these feedback
696 metrics in future phases of C4MIP, potentially reducing or eliminating the need for dedicated
697 BGC and RAD versions of the **1pctCO2** experiment.

698

699 Using the CO_2 trajectory from the emissions-driven COU **esm-flat10** simulation ensures that the
700 BGC and RAD versions experience the same atmospheric CO_2 trajectory, while retaining the
701 traditional C4MIP framework for calculating the β and γ feedback metrics. This approach also
702 avoids the large differences in CO_2 concentration and temperature that arise when the BGC and
703 RAD versions of **esm-flat10** are instead performed as emissions-driven simulations. For
704 example, when an emissions-driven version of the flat10 experiment is run in BGC mode, the
705 simulated CO_2 concentration is expected to be somewhat lower than in the fully coupled (COU)
706 mode. This occurs because, in the absence of temperature increases associated with higher
707 CO_2 , the land and ocean biogeochemical components take up more carbon than in the COU
708 simulation. In contrast, when the same emissions-driven experiment is run in RAD mode, the
709 land and ocean biogeochemistry components do not respond to the increase in $[\text{CO}_2]$, and all
710 emitted carbon remains in the atmosphere. At the same time, both land and ocean respond to
711 the higher temperatures they experience in the RAD configuration by releasing additional



carbon. As a result, the simulated increase in CO₂, and the associated temperature change, in the RAD version of an emissions-driven run can be more than twice that seen in the COU or BGC versions. These large differences in CO₂ concentration and temperature between the RAD, BGC, and COU simulations can lead to differences in the derived values of the feedback metrics, compared to the case where COU, RAD, and BGC simulations experience the same CO₂ trajectory.

For the last two CMIP phases, C4MIP has used the concentration-driven **1pctCO2** experiment to quantify the β and γ feedback metrics (Arora et al., 2013b, 2020). While performing the BGC and RAD versions of the flat10 emissions-driven experiment (**esm-flat10**) in concentration-driven mode (identified as **flat10-bgc** and **flat10-rad** in Table 1) avoids the large [CO₂] differences between the COU, BGC, and RAD versions and makes them more consistent with previous C4MIP phases (Arora et al., 2013b, 2020), the flat10 approach is different in two ways compared to the traditional C4MIP approach. First, although the same [CO₂] is used for COU, BGC, and RAD experiments for a given ESM, the [CO₂] will be different across different ESMs depending on their response to emissions. Second, in contrast to the traditional C4MIP approach where all COU, BGC, and RAD versions of **1pctCO2** experiment were concentration-driven, in the new flat10 approach **esm-flat10** is an emissions-driven experiment and **flat10-bgc** and **flat10-rad** are concentration-driven experiments. This introduces inconsistency which we raised earlier in the context of how ZEC was estimated using CMIP6 experiments. In the emissions-driven COU **esm-flat10** experiment, atmospheric CO₂ is represented as a fully interactive three-dimensional field with spatial gradients and a seasonal cycle. In contrast, the concentration-driven BGC and RAD versions prescribe a globally uniform CO₂ concentration that is applied everywhere geographically and across all vertical levels of the atmosphere.

735

A concentration-driven simulation effectively “sees” higher CO₂ over the northern hemisphere during summer than an emissions-driven simulation because the seasonal cycle in atmospheric CO₂ is absent. Since most of the global land area is located in the northern hemisphere, a concentration-driven version of an emissions-driven experiment, using the same simulated global mean CO₂ from the emissions-driven run, will therefore tend to simulate slightly higher



land carbon uptake than its emissions-driven counterpart. This bias is expected to be small relative to the overall perturbation because the response of photosynthesis to CO₂ is nonlinear, and the expected amplitude of the annual CO₂ cycle in the **esm-flat10** experiment (~7–15 ppm) is small compared to the much larger background concentration on which it is superimposed. It is also worth noting that current ESMs do not explicitly simulate within-canopy CO₂ concentrations. Photosynthesis in ESMs responds to the atmospheric CO₂ concentration in the lowest model layer, rather than to the much larger diurnal CO₂ variations (than the seasonal variations) that occur within canopies. Consequently, these unresolved CO₂ variations do not influence the comparison between emissions- and concentration-driven simulations.

Despite these inconsistencies and differences from the traditional C4MIP approach to calculate β and γ , feedback from the C4MIP community indicates that concentration-driven **flat10-bgc** and **flat10-rad** remain the preferred and *pragmatic* approach for estimating the feedback metrics.

4.3. Experiment protocol for the 500 Pg C pulse experiment

The **esm-pi-pulse-500** experiment is initialized from pre-industrial conditions and integrated for 1000 years to characterize the long-term response of the coupled carbon–climate system to a discrete carbon perturbation. Given the computational cost of this long simulation, the first 500 years are requested as Tier 1, with the remaining 500 years designated as Tier 2. Although somewhat model-dependent, the 500 Pg C pulse can be 1) implemented by modifying the atmosphere restart file at the start of a pre-industrial simulation, with the only change being an increase in the atmospheric CO₂ field corresponding to an added 500 Pg C (equivalent to a 235.84 ppm rise above the pre-industrial background), or 2) by emitting the entire 500 Pg C pulse over the first day or first time step of the simulation. Regardless of the method of implementation, the objective is to ensure that the entire perturbation is introduced in a very short time at the start of the simulation so that the subsequent 1000-year length of the experiment captures the decay of the atmospheric CO₂ increase and the long-timescale response of the land and ocean carbon reservoirs.



770

771 **5. Conservation of C and N fluxes, and equilibrium criteria**

772 The C4MIP protocol paper for CMIP6 (C. D. Jones et al., 2016) included a dedicated section
773 describing the land and ocean carbon-cycle variables required to track the total amount of
774 carbon in the Earth system and explicitly verify carbon conservation. Although the overall
775 structure of the CMIP7 data request has changed compared to CMIP6, the primary variables
776 required for carbon conservation remain largely unchanged. However, several additional
777 variables have been introduced in the CMIP7 data request that also need to be considered
778 when assessing conservation. Conservation of carbon (and, where applicable, nitrogen) is a
779 fundamental requirement for evaluating Earth system models. Failure to conserve these
780 quantities makes it difficult to determine whether simulated carbon pools and fluxes are
781 physically consistent, complicates interpretation of model results, and limits confidence in their
782 inclusion in multi-model analyses. Here we suggest some basic checks to verify conservation
783 for the land and ocean carbon cycle components. Models for which conservation cannot be
784 demonstrated using the requested variables are planned to be identified so that, if included in
785 multi-model analyses, their results can be interpreted with appropriate caution. This should not
786 be interpreted as an assessment of the care taken by individual modelling groups or as an
787 indication that a model does not conserve carbon internally. Rather, as models incorporate
788 increasingly complex processes, it becomes more difficult to track all associated pools and
789 fluxes in a standardized data request, and individual terms can inadvertently be omitted,
790 misreported, or become difficult to reconstruct from the reported variables. This also provides
791 modelling groups with an opportunity to explain the reasons for any apparent non-conservation
792 (e.g., a missed pool or a flux which can then be included in subsequent analyses), identify
793 missing or unavailable variables, and, where appropriate, present alternative conservation
794 equations specific to their model formulation. As Earth system models continue to evolve and
795 incorporate new carbon-cycle processes, it has become increasingly challenging for a
796 standardized CMIP data request to anticipate and fully represent all carbon pools and fluxes
797 across all modelling systems. Continued documentation of model-specific processes and



conservation relationships by modelling groups is therefore essential for the community to refine and expand conservation diagnostics so that they remain applicable to the widest possible range of models.

5.1. Land

The following conservation checks are suggested for the land carbon cycle.

The total land carbon store (**cLand**) should equal the sum of its individual components (carbon in vegetation, soil, litter, land-use change product pool, and geological storage) both per unit area (kg C/m^2) and over all land (Pg C):

$$\text{cLand} = \text{cVeg} + \text{cSoil} + \text{cLitter} + \text{cProduct} + \text{cGeologicStorage} \quad (8)$$

This equality should hold exactly. Not all models include every carbon pool (e.g., **cGeologicStorage**, which is a new CMIP7 variable to represent carbon stored in geologic reservoirs as a result of prognostic carbon dioxide removal methods utilizing biosphere-derived carbon, such as BECCS), but all pools represented by a given model should be reported and included in the conservation equation.

For fluxes, a few basic checks are encouraged. For example,

$$\text{gpp} = \text{npp} + \text{ra} \quad (9)$$

where **gpp** is the gross primary productivity, **npp** is the net primary productivity, and **ra** is the autotrophic respiration. Similar to equation (8), equation (9) holds both per unit area ($\text{kg C m}^{-2} \text{ s}^{-1}$) and over all land (Pg C/yr):

In addition,

$$\text{netAtmosLandCO2Flux} = \text{gpp} - \text{ra} - \text{rh} - \text{fFire} - \text{fHarvestToAtmos} - \text{fDeforestToAtmos} - \text{fProductDecomp} \quad (10)$$



where **fFire** are fire emissions from both natural and anthropogenic fires but exclude land-use change related fires, **fHarvestToAtmos** and **fDeforestToAtmos** are direct harvest and land-use/deforestation related carbon losses to the atmosphere. **fDeforestToAtmos** in most models represents deforestation-related fires. The exact form of the equation will depend on the processes represented by individual models. For example, if models include herbivory related grazing loss, CO₂ flux from decomposition of carbon in river, and additional non-CO₂ carbon losses, such as methane emissions (e.g., from wetlands or fire), and carbon monoxide, black carbon, organic carbon emissions from fire, emissions of volatile organic compounds, and/or carbon gain/losses through other processes, additional terms will be required in Equation (10). In such cases, modelling groups are encouraged to document these processes and provide the corresponding conservation equation for their model. Our intent here is not to put together a comprehensive list of all possible processes that models may represent but to highlight the potential for lack of conservation using standardized CMIP data request.

While **netAtmosLandCO2Flux** (kg C m⁻² s⁻¹ at the grid cell level, and Pg C/yr at the global scale) accounts for vertical fluxes at each grid cell, lateral fluxes such as **fCLandToOcean** (that represents loss of carbon through leaching) and through trade of agricultural or forestry products that do not contribute to **nbp** must be accounted for through equation (11). At each grid cell and at the global level land carbon fluxes should satisfy

$$nbp = netAtmosLandCO2Flux - fCLandToOcean \quad (11)$$

where **nbp** is the global net biome productivity, defined as the net carbon flux into the land (i.e., causing the tendency or change in land carbon stock over time). For models that do not explicitly simulate lateral carbon export from land to the ocean, **fCLandToOcean**, also a new CMIP7 variable, is zero and **nbp** and **netAtmosLandCO2Flux** are identical. It may therefore be sufficient to submit only one of these variables when lateral carbon transport is absent. Similar to **nbp** and **netAtmosLandCO2Flux**, **fCLandToOcean** is a land realm variable (all have units of kg C m⁻² s⁻¹ at the grid cell level). Equation (11) should hold exactly provided that all carbon losses are represented by the reported variables.



849

850 Finally, cumulative net biome production should equal the simulated change in total land
 851 carbon:

$$852 \quad \int nbp dt = \Delta cLand \quad (12)$$

853 Equation (12) links the cumulative net carbon flux to the simulated change in the total land
 854 carbon pool. Unlike the previous conservation checks, this relationship may not hold exactly
 855 because fluxes and carbon pools are both provided as averages over a reporting interval (e.g.,
 856 monthly means for CMIP) according to the CMIP7 Data Request. For equation (12) to hold
 857 exactly, fluxes must be time-averaged and values of pools should be instantaneous at the end
 858 of the reporting period. Small differences may therefore arise when comparing the time integral
 859 of fluxes with changes in provided carbon pools. A small tolerance (for example, $\pm 1\%$) is
 860 therefore appropriate when evaluating this conservation relationship.

861 5.2. Ocean

862 Neither CMIP6 or CMIP7 data request includes a total ocean carbon variable (referred to here
 863 as **cOcean**) in units of kg C/m³ or mol C/m³ or if vertically integrated over the ocean depth in
 864 units of kg C/m² analogous to **cLand** (kg C/m²). As an example, it is possible to calculate **cOcean**
 865 using mole concentration (mol C/m³) of dissolved inorganic carbon (**dissic**), zooplankton (**zooc**),
 866 dissolved organic carbon (**dissoc**), detrital organic carbon (**detoc**), and phytoplankton (**phyc**)
 867 variables:

$$868 \quad cOcean (mol C/m^3) = dissic + dissoc + zooc + phyc + detoc \quad (13a)$$

869 and then use **cOcean** to calculate total global ocean carbon

$$870 \quad Total\ Ocean\ C\ (Pg\ C) = \frac{12.011}{10^{15}} \sum_{i,j,k} cOcean_{i,j,k} V_{i,j,k} \quad (13b)$$

871 where, i, j, k refer to the latitude, longitude, and depth indices, and V is the volume of a given
 872 ocean grid cell in m³.



873

874 Similarly, data requests for both CMIP6 and CMIP7 also do not include a single flux variable that
 875 allows the calculation of the change in **cOcean** at each grid cell. This flux (referred to here as
 876 ocean net flux, **netOceanCO2Flux**), analogous to **netAtmosLandCO2Flux**, can be reconstructed
 877 using existing flux terms of the data request as follows, where $fgco2_{mol}$ is the atmosphere to
 878 ocean CO₂ flux in molar units (mol C m⁻² s⁻¹) and calculated as (1000/12.011).**fgco2**, where
 879 **fgco2** is represented in units of kg C m⁻² s⁻¹; **icfriver** and **ocfriver** are inorganic and organic
 880 carbon fluxes, respectively, from rivers (mol C m⁻² s⁻¹); **fric** and **froc** are downward inorganic
 881 and organic carbon flux at ocean bottom (mol C m⁻² s⁻¹). **expcob** the downward flux of
 882 particulate organic carbon reaching the ocean bottom (mol C m⁻² s⁻¹) is an equivalent term to
 883 **froc**.

884

$$885 \text{netOceanCO2Flux (mol C m}^{-2}\text{s}^{-1}\text{)} = fgco2_{mol} + icfriver + ocfriver - fric - froc \text{ (or expcob)}$$

886 (14a)

887 and then use **netOceanCO2Flux** to calculate total global net CO₂ flux leaving or entering the
 888 ocean

$$889 \text{Global netOceanCO2Flux (Pg C)} = \frac{12.011 \times 365.25 \times 24 \times 3600}{10^{15}} \sum_{i,j} (\text{netOceanCO2Flux})_{i,j} A_{o(i,j)}$$

890 (14b)

891 where $A_{o(i,j)}$ is the area of ocean grid cells.

892 Once *Total Ocean C* and *Global netOceanCO2Flux* have been calculated, conservation can
 893 be evaluated in a manner analogous to that for the land carbon cycle globally (equation 12)
 894 where the ocean transport/advection terms are ignored since their global sum is equal to zero.
 895 If equation (15) is used at the grid cell level (using **cOcean** and **netOceanCO2Flux**) then, unlike
 896 land, a transport/advection term must be included that quantifies the volume of C
 897 entering/leaving each ocean grid cell.



$$\int Global netOceanCO2Flux dt = \Delta Total Ocean C \quad (15)$$

As for the land carbon cycle, this relationship may not hold exactly because of the time averaging process applied to the fluxes and carbon pools. The same tolerance ($\pm 1\%$) suggested for Equation (12) is therefore recommended when evaluating equation (15).

5.3. Atmosphere

Similar to **cOcean**, neither the CMIP6 nor the CMIP7 data request includes a variable for the atmospheric carbon inventory ($kg C/m^3$), or if vertically integrated in units of $kg C/m^2$, referred to here as **cAtmos** analogous to **cLand** ($kg C/m^2$). However, it can be calculated from the three-dimensional atmospheric CO_2 mass mixing ratio (kg/kg) field (the variable **co23D** in CMIP7 data request) as

$$cAtmos_{i,j,k} (kg C/m^3) = \frac{12.011}{44.001} (co23D \cdot \rho_{air})_{i,j,k} \quad (16a)$$

where $\rho_{air} = \frac{P}{R_d T_K}$ is the air density in (kg/m^3), P is the pressure (Pa), T_K is temperature in Kelvin, R_d is the gas constant ($287 J/(kg K)$), and where, i, j, k refer to the latitude, longitude, and atmospheric level indices. **cAtmos** can then be used calculate total atmospheric carbon burden

$$Total atmospheric C burden (Pg C) = \frac{1}{10^{15}} \sum_{i,j,k} (cAtmos)_{i,j,k} V_{i,j,k} \quad (16b)$$

where, $V_{i,j,k}$ is the volume of air (m^3) in each atmospheric grid cell (i, j, k).

The CMIP7 data request includes a variable representing the net rate of carbon accumulation in the atmosphere. This quantity (referred to here as **netAtmosCO2Flux** and referred to as **fco2all** in the CMIP7 data request) can be reconstructed from the reported carbon fluxes, for example, as



920

921 $\text{netAtmosCO2Flux} = \text{fco2fos} + [\text{prescribed LUC emissions if any}] - \text{netAtmosLandCO2flux} - \text{fgco2}$
 922 (17)

923

924 where **fco2fos** is the fossil-fuel CO₂ emissions. There is no equivalent CMIP7 variable for
 925 prescribed land-use change (LUC) emissions, but this term is needed for models that do not
 926 simulate LUC interactively. Integrating

$$927 \quad \text{Global netAtmosCO2Flux (Pg C)} = \frac{1}{10^{15}} \sum_{i,j} (\text{netAtmosCO2Flux})_{i,j} A_{a(i,j)} \quad (18)$$

928 Once *Total atmospheric C burden* and *Global netAtmosCO2Flux* have been calculated,
 929 atmospheric carbon conservation can be evaluated using

$$930 \quad \int \text{Global netAtmosCO2Flux} \, dt = \Delta \text{Total atmospheric C burden} \quad (19)$$

931 for the whole globe where the atmospheric transport/advection terms are ignored since their
 932 global sum is equal to zero. If equation (19) is used at the grid cell level (using **cAtmos** and
 933 **netAtmosCO2Flux**) then, unlike land, a transport/advection term must be included that
 934 quantifies the volume of C entering/leaving each atmospheric column above a grid cell. As for
 935 the land and ocean carbon budgets, this relationship may not hold exactly and a small tolerance
 936 ($\pm 1\%$) is therefore appropriate when evaluating this conservation relationship.

937 In cases where the conservation relationships given by Equations (12) and (15) for the land and
 938 ocean carbon budgets, respectively, are not satisfied, we recommend using changes in carbon
 939 pools to infer the corresponding net fluxes. Experience from modelling groups suggests that,
 940 when conservation errors occur, carbon pools are generally more reliable than the reported
 941 fluxes. Given the complexity of ESMs, it is not uncommon for fluxes associated with certain
 942 processes to be omitted from the provided output, resulting in apparent non-conservation.



943 5.4. Equilibrium criteria

944 Analysis of carbon exchange between ESM components becomes challenging when a model
945 exhibits significant drift in its pre-industrial control simulation. Following Jones et al. (2016), we
946 define an acceptably small drift in a properly spun-up model as one in which the land, ocean,
947 and atmospheric carbon stores each vary by less than 10 Pg C per century (i.e., a long-term
948 average drift of ≤ 0.1 Pg C yr⁻¹). This is broadly equivalent to an atmospheric CO₂ drift of less
949 than about 5 ppm/century. We suggest that a drift smaller than this value is highly desirable but
950 this value is a guideline. Exceeding this drift in the control run may preclude a model from being
951 included in a C4MIP analysis, but we would expect that decision to be made for models
952 individually. For example, a large ocean drift in a concentration-driven experiment may not
953 preclude analysis of land carbon fluxes and vice-versa. We also stress that being within these
954 drifts is a minimum but not necessarily sufficient quality condition. Regional patterns and drifts
955 of stores and fluxes will also be assessed and depending on the analysis may preclude inclusion
956 of a given model's results.

957 6. Carbon isotopes

958 Carbon isotopes ($\delta^{13}\text{C}$ and $\Delta^{14}\text{C}$) were introduced as part of C4MIP in CMIP6 (C. D. Jones et al.,
959 2016) and the CMIP7 data request also includes carbon isotopes variables. Carbon isotopes
960 provide powerful tools for evaluation and understanding of various carbon cycle and climate
961 processes, including ecohydrological coupling (e.g., Peters et al., 2018), terrestrial productivity
962 (e.g., H. D. Graven et al., 2024), and oceanic gas exchange and circulation (e.g., Claret et al.,
963 2021; Pookkandy et al., 2023). Modelling groups are requested to report output for carbon
964 isotopes in carbon pools and fluxes for historical and future simulations. The protocols for
965 carbon isotopes in CMIP7 are the same as in CMIP6 (C. D. Jones et al., 2016); see also Orr et al.
966 (2017) for more information on implementation of carbon isotopes in ocean models.
967 Atmospheric forcing data for $\delta^{13}\text{C}$ and $\Delta^{14}\text{C}$ in atmospheric CO₂ from Graven et al. (2017) has
968 been revised and updated for 1700–2023 and is available at input4mips
969 (<https://esgf-node.ornl.gov/search/input4mips/>, variable names delta13co2 and delta14co2,
970 version ImperialCollege-3-0). Atmospheric $\delta^{13}\text{C}$ in CO₂ is provided as an annual global average



and atmospheric $\Delta^{14}\text{C}$ in CO_2 is provided annually for 4 zonal bands: $90^\circ\text{--}30^\circ\text{S}$, $30^\circ\text{--}0^\circ\text{S}$, $0^\circ\text{--}30^\circ\text{N}$, and $30^\circ\text{--}90^\circ\text{N}$. Atmospheric forcing data for future scenarios will soon be available at input4mips.

7. Summary

This paper presents the experimental design and protocol for C4MIP for CMIP7. The protocol builds on previous C4MIP contributions to CMIP while extending the scientific scope of the project to address emerging carbon-cycle questions and policy-relevant metrics. The proposed experiments have been developed through extensive community discussion and attempt to balance scientific ambition with the computational burden placed on participating modelling centres.

C4MIP has in the past relied primarily on concentration-driven experiments to quantify climate-carbon feedbacks. In CMIP7, these simulations remain an important component of C4MIP, but are complemented by a broader suite of emissions-driven experiments that provide a physically consistent framework for investigating carbon-cycle behaviour and estimating policy-relevant metrics such as TCRE and ZEC. To maintain backward compatibility with previous C4MIP phases, we retain the BGC and RAD versions of the **1pctCO2** experiment. The newly proposed emissions-driven experiments of the flat10 family now form an important component of the C4MIP contribution to CMIP7. These experiments not only provide an emissions-driven framework for estimating TCRE and ZEC, but also address the role of negative emissions and the question of reversibility in the context of the coupled carbon-climate system. The proposed BGC and RAD versions of the **2xCO2** experiment, with its instantaneous increase in atmospheric CO_2 , will be particularly relevant for the analysis of the scenario independence of new feedback metrics, complementing the corresponding **1pctCO2** experiments, in which CO_2 increases gradually. The proposed 500 Pg C pulse experiment will help reassess impulse-response characteristics in newer-generation ESMs and evaluate the extent to which impulse-response formulations derived from earlier model generations remain applicable to larger perturbations. Finally, although the additional ensemble members requested for the **esm-flat10-zec** experiment are categorized as Tier 2, we hope that modelling groups are able to perform these



999 simulations, as this will help quantify the uncertainty in ZEC arising from internal climate
1000 variability.

1001 In developing the conservation framework presented in Section 5 and through subsequent
1002 discussions among the C4MIP co-chairs and SSC members, it has become clear that assessing
1003 carbon conservation is likely to be more challenging for CMIP7 than for CMIP6. This reflects not
1004 a lack of carbon conservation within models, but rather the increasing difficulty of capturing all
1005 model processes in the standardized CMIP data request as Earth system models become more
1006 complex and incorporate new carbon-cycle processes. Although we identify the primary
1007 variables in the CMIP7 data request needed to assess conservation, Section 5 illustrates that
1008 assessing conservation from the available requested variables, particularly for the ocean carbon
1009 cycle, can require combining several quantities and is therefore not always straightforward. We
1010 hope that vertically integrated **cOcean** and **cAtmos**, analogous to **cLand**, and **netOceanCO2Flux**,
1011 analogous to **netAtmosLandCO2Flux**, will become part of the standard CMIP data request. In
1012 the same spirit, **fco2all** might more appropriately be referred to as **netAtmosCO2Flux**. The
1013 challenge related to assessing conservation from available CMIP6 quantities has also been
1014 highlighted by Tang et al. (2025). We envision a C4MIP-led community paper in the future in
1015 which the land and ocean carbon-cycle leads from participating modelling groups document
1016 conservation diagnostics, identify sources of non-conservation, and describe how newly
1017 introduced processes are represented in their respective models. Such an effort would improve
1018 the interpretation of CMIP7 simulations and help inform future data requests and experimental
1019 protocols, whether for a future CMIP phase or other community model intercomparison
1020 projects. In terms of requested simulations, C4MIP requires 890 model years for the
1021 Assessment Fast Track, increasing to 3,804 model years for the complete experiment suite and
1022 to 6,204 model years when all requested ensemble members are included.

1023 The experiments proposed here provide a common framework for investigating carbon-climate
1024 interactions across a range of forcing pathways. As in previous CMIP phases, the value of C4MIP
1025 will ultimately depend on broad community participation, and the experiments described here
1026 are expected to support a diverse range of analyses extending well beyond the core objectives
1027 of the project. While maintaining continuity with previous CMIP phases, C4MIP has evolved



1028 from a project focused primarily on quantifying climate-carbon feedbacks to one that addresses
1029 a broader set of scientific questions related to the behaviour of the coupled carbon-climate
1030 system under a range of emissions pathways.

1031

1032 **Author contribution**

1033 VKA developed the initial structure of the manuscript based on discussions within the C4MIP
1034 Scientific Steering Committee (SSC), with input from CDJ and TI, the two other C4MIP co-chairs,
1035 and wrote a substantial portion of the manuscript. Significant scientific input, feedback,
1036 suggestions, and corrections were provided by CDJ, PF, GLT-M, BS, and CK across various
1037 sections of the manuscript. MK and AR provided assistance with the ocean carbon conservation
1038 equations. The remaining co-authors are members of the C4MIP SSC and contributed edits to
1039 various sections of the manuscript. Their contributions to the scientific discussions within the
1040 C4MIP SSC meetings also helped shape the overall direction of the manuscript.

1041

1042 **Code and data availability**

1043 No new analyses are presented in this C4MIP protocol paper. Consequently, no new data or
1044 code are generated or required to reproduce the results presented here. Figure 1, which
1045 illustrates the concentration- and emissions-driven scenarios, is based on previously published
1046 data.

1047

1048 **Acknowledgements**

1049 Guilherme L. Torres Mendonça was supported by research grant no. 2023/04579-5 from the
1050 São Paulo Research Foundation (FAPESP). Victor Brovkin acknowledges support by the
1051 European Research Council project Q-Arctic (grant no. 951288) and funding by the Deutsche
1052 Forschungsgemeinschaft for project 390683824 'CLICCS - Climate, Climatic Change, and Society'.
1053 JP was supported by the German Federal Ministry of Research, Technology and Space (BMFT),
1054 project "CDRSynTra2" (No. 01LS2501A) and by Schmidt Sciences, LLC, under the project
1055 CLARiTy. Pierre Friedlingstein was supported by the Schmidt Sciences, LLC, under the project



1056 CALIPSO. CDK, FMH, and JTR acknowledge support from the Reducing Uncertainties in
1057 Biogeochemical Interactions through Synthesis and Computation Science Focus Area (RUBISCO
1058 SFA), which is sponsored by the Biological and Environmental Research (BER) program in the US
1059 Department of Energy Office of Science. Lawrence Berkeley National Laboratory is managed by
1060 the University of California for the US Department of Energy under Contract No.
1061 DE-AC02-05CH11231. Oak Ridge National Laboratory is managed by UT-Battelle, LLC, for the US
1062 Department of Energy under Contract No. DEAC05-00OR2272.

1063

1064

1065

1066



1067 References

- 1068 Adloff, M., Reick, C. H., & Claussen, M. (2018). Earth system model simulations show different
 1069 feedback strengths of the terrestrial carbon cycle under glacial and interglacial
 1070 conditions. *Earth System Dynamics*, 9(2), 413–425.
 1071 <https://doi.org/10.5194/esd-9-413-2018>
- 1072 Allen, M. R., Frame, D. J., Huntingford, C., Jones, C. D., Lowe, J. A., Meinshausen, M., &
 1073 Meinshausen, N. (2009). Warming caused by cumulative carbon emissions towards the
 1074 trillionth tonne. *Nature*, 458(7242), 1163–1166. <https://doi.org/10.1038/nature08019>
- 1075 Anav, A., Friedlingstein, P., Kidston, M., Bopp, L., Ciais, P., Cox, P., Jones, C., Jung, M., Myneni, R.,
 1076 & Zhu, Z. (2013). Evaluating the Land and Ocean Components of the Global Carbon Cycle
 1077 in the CMIP5 Earth System Models. *Journal of Climate*, 26(18), 6801–6843.
 1078 <https://doi.org/10.1175/JCLI-D-12-00417.1>
- 1079 Arias, P. A., Bellouin, N., Coppola, E., Jones, R. G., Krinner, G., Marotzke, J., Naik, V., Palmer, M.
 1080 D., Plattner, G.-K., Rogelj, J., Rojas, M., Sillmann, J., Storelvmo, T., Thorne, P. W., Trewin,
 1081 B., Achuta Rao, K., Adhikary, B., Allan, R. P., Armour, K., ... Zickfeld, K. (2021). Technical
 1082 summary. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N.
 1083 Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R.
 1084 Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (Eds.), *Climate*
 1085 *Change 2021: The physical science basis. Contribution of working group I to the Sixth*
 1086 *Assessment Report of the Intergovernmental Panel on Climate Change* (p. 33–144).
 1087 Cambridge University Press. <https://doi.org/10.1017/9781009157896.002>



- 1088 Arora, V. K., Boer, G. J., Friedlingstein, P., Eby, M., Jones, C. D., Christian, J. R., Bonan, G., Bopp,
 1089 L., Brovkin, V., Cadule, P., Hajima, T., Ilyina, T., Lindsay, K., Tjiputra, J. F., & Wu, T. (2013a).
 1090 Carbon–Concentration and Carbon–Climate Feedbacks in CMIP5 Earth System Models.
 1091 *Journal of Climate*, 26(15), 5289–5314. <https://doi.org/10.1175/JCLI-D-12-00494.1>
- 1092 Arora, V. K., Boer, G. J., Friedlingstein, P., Eby, M., Jones, C. D., Christian, J. R., Bonan, G., Bopp,
 1093 L., Brovkin, V., Cadule, P., Hajima, T., Ilyina, T., Lindsay, K., Tjiputra, J. F., & Wu, T. (2013b).
 1094 Carbon–concentration and carbon–climate feedbacks in CMIP5 earth system models.
 1095 *Journal of Climate*, 26(15), 5289–5314. <https://doi.org/10.1175/JCLI-D-12-00494.1>
- 1096 Arora, V. K., Katavouta, A., Williams, R. G., Jones, C. D., Brovkin, V., Friedlingstein, P., Schwinger,
 1097 J., Bopp, L., Boucher, O., Cadule, P., Chamberlain, M. A., Christian, J. R., Delire, C., Fisher,
 1098 R. A., Hajima, T., Ilyina, T., Joetzjer, E., Kawamiya, M., Koven, C. D., ... Ziehn, T. (2020).
 1099 Carbon–concentration and carbon–climate feedbacks in CMIP6 models and their
 1100 comparison to CMIP5 models. *Biogeosciences*, 17(16), 4173–4222.
 1101 <https://doi.org/10.5194/bg-17-4173-2020>
- 1102 Asaadi, A., Schwinger, J., Lee, H., Tjiputra, J., Arora, V., Séférián, R., Liddicoat, S., Hajima, T.,
 1103 Santana-Falcón, Y., & Jones, C. D. (2024). Carbon cycle feedbacks in an idealized
 1104 simulation and a scenario simulation of negative emissions in CMIP6 Earth system
 1105 models. *Biogeosciences*, 21(2), 411–435. <https://doi.org/10.5194/bg-21-411-2024>
- 1106 Boer, G. J., & Arora, V. (2010). Geographic Aspects of Temperature and Concentration Feedbacks
 1107 in the Carbon Budget. *Journal of Climate*, 23(3), 775–784.
 1108 <https://doi.org/10.1175/2009JCLI3161.1>



- 1109 Borowiak, A., King, A. D., Brown, J. R., Jones, C. D., Ziehn, T., Meinshausen, M., & Cassidy, L.
 1110 (2024). Projected Global Temperature Changes After Net Zero Are Small But Significant.
 1111 *Geophysical Research Letters*, 51(8), e2024GL108654.
 1112 <https://doi.org/10.1029/2024GL108654>
- 1113 Chimuka, V. R., Nzotungicimpaye, C.-M., & Zickfeld, K. (2023). Quantifying land carbon cycle
 1114 feedbacks under negative CO₂ emissions. *Biogeosciences*, 20(12), 2283–2299.
 1115 <https://doi.org/10.5194/bg-20-2283-2023>
- 1116 Claret, M., Sonnerup, R. E., & Quay, P. D. (2021). A Next Generation Ocean Carbon Isotope
 1117 Model for Climate Studies I: Steady State Controls on Ocean ¹³C. *Global Biogeochemical*
 1118 *Cycles*, 35(4), e2020GB006757. <https://doi.org/10.1029/2020GB006757>
- 1119 Collier, N., Hoffman, F. M., Lawrence, D. M., Keppel-Aleks, G., Koven, C. D., Riley, W. J., Mu, M.,
 1120 & Randerson, J. T. (2018). The International Land Model Benchmarking (ILAMB) System:
 1121 Design, Theory, and Implementation. *Journal of Advances in Modeling Earth Systems*,
 1122 10(11), 2731–2754. <https://doi.org/10.1029/2018MS001354>
- 1123 Covey, C., AchutaRao, K. M., Cubasch, U., Jones, P., Lambert, S. J., Mann, M. E., Phillips, T. J., &
 1124 Taylor, K. E. (2003). An overview of results from the Coupled Model Intercomparison
 1125 Project. *Global and Planetary Change*, 37(1), 103–133.
 1126 [https://doi.org/10.1016/S0921-8181\(02\)00193-5](https://doi.org/10.1016/S0921-8181(02)00193-5)
- 1127 Cox, P. M., Pearson, D., Booth, B. B., Friedlingstein, P., Huntingford, C., Jones, C. D., & Luke, C. M.
 1128 (2013). Sensitivity of tropical carbon to climate change constrained by carbon dioxide
 1129 variability. *Nature*, 494(7437), 341–344. <https://doi.org/10.1038/nature11882>



- 1130 Dunne, J. P., Hewitt, H. T., Arblaster, J. M., Bonou, F., Boucher, O., Cavazos, T., Dingley, B., Durack,
 1131 P. J., Hassler, B., Juckes, M., Miyakawa, T., Mizielinski, M., Naik, V., Nicholls, Z., O'Rourke,
 1132 E., Pincus, R., Sanderson, B. M., Simpson, I. R., & Taylor, K. E. (2025). An evolving
 1133 Coupled Model Intercomparison Project phase 7 (CMIP7) and Fast Track in support of
 1134 future climate assessment. *Geoscientific Model Development*, 18(19), 6671–6700.
 1135 <https://doi.org/10.5194/gmd-18-6671-2025>
- 1136 Enting, I., & Clisby, N. (2019). Estimates of climatic influence on the carbon cycle. *Earth System*
 1137 *Dynamics Discussions*, 2019, 1–21. <https://doi.org/10.5194/esd-2019-41>
- 1138 Enting, I. G. (2022). Response function analysis of carbon dioxide and climate using the
 1139 Padé-Laplace technique. *AIMS Geosciences*, 8(3), 346–365.
 1140 <https://doi.org/10.3934/geosci.2022020>
- 1141 Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016).
 1142 Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental
 1143 design and organization. *Geoscientific Model Development*, 9(5), 1937–1958.
 1144 <https://doi.org/10.5194/gmd-9-1937-2016>
- 1145 Forster, P., Smith, C. J., Walsh, T., Lamb, W. F., Lamboll, R., Hauser, M., Ribes, A., Rosen, D.,
 1146 Gillett, N., Palmer, M. D., Rogelj, J., von Schuckmann, K., Seneviratne, S. I., Trewin, B.,
 1147 Zhang, X., Allen, M., Andrew, R., Birt, A., Borger, A., ... Zhai, P. (2023). Indicators of Global
 1148 Climate Change 2022: Annual update of large-scale indicators of the state of the climate
 1149 system and human influence. *Earth System Science Data*, 15(6), 2295–2327.
 1150 <https://doi.org/10.5194/essd-15-2295-2023>



- 1151 Forster, P., Smith, C., Walsh, T., Lamb, W. F., Lamboll, R., Hall, B., Hauser, M., Ribes, A., Rosen, D.,
 1152 Gillett, N. P., Palmer, M. D., Rogelj, J., von Schuckmann, K., Trewin, B., Allen, M., Andrew,
 1153 R., Betts, R. A., Borger, A., Boyer, T., ... Zhai, P. (2024). Indicators of Global Climate
 1154 Change 2023: Annual update of key indicators of the state of the climate system and
 1155 human influence. *Earth System Science Data*, 16(6), 2625–2658.
 1156 <https://doi.org/10.5194/essd-16-2625-2024>
- 1157 Forster, P., Storelvmo, T., Armour, K., Collins, W., Dufresne, J.-L., Frame, D., Lunt, D. J., Mauritsen,
 1158 T., Palmer, M. D., Watanabe, M., Wild, M., & Zhang, H. (2021). The Earth's Energy
 1159 Budget, Climate Feedbacks, and Climate Sensitivity. In V. Masson-Delmotte, P. Zhai, A.
 1160 Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M.
 1161 Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R.
 1162 Yu, & B. Zhou (Eds.), *Climate Change 2021: The Physical Science Basis. Contribution of*
 1163 *Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on*
 1164 *Climate Change* (pp. 923–1054). Cambridge University Press.
 1165 <https://www.ipcc.ch/report/ar6/wg1/chapter/chapter-7/>, doi:
 1166 10.1017/9781009157896.009
- 1167 Fowler, M. D., Kooperman, G. J., Randerson, J. T., & Pritchard, M. S. (2019). The effect of plant
 1168 physiological responses to rising CO₂ on global streamflow. *Nature Climate Change*,
 1169 9(11), 873–879. <https://doi.org/10.1038/s41558-019-0602-x>
- 1170 Friedlingstein, P., Cox, P., Betts, R., Bopp, L., von Bloh, W., Brovkin, V., Cadule, P., Doney, S., Eby,
 1171 M., Fung, I., Bala, G., John, J., Jones, C., Joos, F., Kato, T., Kawamiya, M., Knorr, W.,
 1172 Lindsay, K., Matthews, H. D., ... Zeng, N. (2006). Climate–Carbon Cycle Feedback Analysis:



- 1173 Results from the C4MIP Model Intercomparison. *Journal of Climate*, 19(14), 3337–3353.
- 1174 <https://doi.org/10.1175/JCLI3800.1>
- 1175 Friedlingstein, P., Dufresne, J.-L., Cox, P. M., & Rayner, P. (2003). How positive is the feedback
 1176 between climate change and the carbon cycle? *Tellus B: Chemical and Physical*
 1177 *Meteorology*. <https://doi.org/10.3402/tellusb.v55i2.16765>
- 1178 Friedlingstein, P., O’Sullivan, M., Jones, M. W., Andrew, R. M., Bakker, D. C. E., Hauck, J.,
 1179 Landschützer, P., Le Quéré, C., Li, H., Luijkx, I. T., Peters, G. P., Peters, W., Pongratz, J.,
 1180 Schwingshackl, C., Sitch, S., Canadell, J. G., Ciais, P., Aas, K., Alin, S. R., ... Zeng, J. (2026).
 1181 Global Carbon Budget 2025. *Earth System Science Data*, 18(5), 3211–3288.
 1182 <https://doi.org/10.5194/essd-18-3211-2026>
- 1183 Gillett, N. P., Arora, V. K., Matthews, D., & Allen, M. R. (2013). Constraining the Ratio of Global
 1184 Warming to Cumulative CO₂ Emissions Using CMIP5 Simulations. *Journal of Climate*,
 1185 26(18), 6844–6858. <https://doi.org/10.1175/JCLI-D-12-00476.1>
- 1186 Good, P., Gregory, J. M., & Lowe, J. A. (2011). A step-response simple climate model to
 1187 reconstruct and interpret AOGCM projections. *Geophysical Research Letters*, 38(1).
 1188 <https://doi.org/10.1029/2010GL045208>
- 1189 Graven, H., Allison, C. E., Etheridge, D. M., Hammer, S., Keeling, R. F., Levin, I., Meijer, H. A. J.,
 1190 Rubino, M., Tans, P. P., Trudinger, C. M., Vaughn, B. H., & White, J. W. C. (2017). Compiled
 1191 records of carbon isotopes in atmospheric CO₂ for historical simulations in CMIP6.
 1192 *Geoscientific Model Development*, 10(12), 4405–4417.
 1193 <https://doi.org/10.5194/gmd-10-4405-2017>



- 1194 Graven, H. D., Keeling, R. F., Piper, S. C., Patra, P. K., Stephens, B. B., Wofsy, S. C., Welp, L. R.,
 1195 Sweeney, C., Tans, P. P., Kelley, J. J., Daube, B. C., Kort, E. A., Santoni, G. W., & Bent, J. D.
 1196 (2013). Enhanced Seasonal Exchange of CO₂ by Northern Ecosystems Since 1960.
 1197 *Science*, 341(6150), 1085–1089. <https://doi.org/10.1126/science.1239207>
- 1198 Graven, H. D., Warren, H., Gibbs, H. K., Khatiwala, S., Koven, C., Lester, J., Levin, I., Spawn-Lee, S.
 1199 A., & Wieder, W. (2024). Bomb radiocarbon evidence for strong global carbon uptake
 1200 and turnover in terrestrial vegetation. *Science*, 384(6702), 1335–1339.
 1201 <https://doi.org/10.1126/science.adl4443>
- 1202 Gregory, J. M., Jones, C. D., Cadule, P., & Friedlingstein, P. (2009). Quantifying Carbon Cycle
 1203 Feedbacks. *Journal of Climate*, 22(19), 5232–5250.
 1204 <https://doi.org/10.1175/2009JCLI2949.1>
- 1205 Hajima, T., Kawamiya, M., Ito, A., Tachiiri, K., Jones, C. D., Arora, V., Brovkin, V., Séférian, R.,
 1206 Liddicoat, S., Friedlingstein, P., & Shevliakova, E. (2025). Consistency of global carbon
 1207 budget between concentration- and emission-driven historical experiments simulated by
 1208 CMIP6 Earth system models and suggestions for improved simulation of CO₂
 1209 concentration. *Biogeosciences*, 22(5), 1447–1473.
 1210 <https://doi.org/10.5194/bg-22-1447-2025>
- 1211 Hansen, J., Lacis, A., Rind, D., Russell, G., Stone, P., Fung, I., Ruedy, R., & Lerner, J. (1984).
 1212 Climate Sensitivity: Analysis of Feedback Mechanisms. In *Climate Processes and Climate*
 1213 *Sensitivity* (pp. 130–163). American Geophysical Union (AGU).
 1214 <https://doi.org/10.1029/GM029p0130>



- 1215 Hoffman, F. M., Hassler, B., Swaminathan, R., Lewis, J., Andela, B., Collier, N., Hegedűs, D., Lee,
 1216 J., Pascoe, C., Pflüger, M., Stockhause, M., Ullrich, P., Xu, M., Bock, L., Chun, F., Gier, B. K.,
 1217 Kelley, D. I., Lauer, A., Lenhardt, J., ... Dunne, J. P. (2026). Rapid Evaluation Framework for
 1218 the CMIP7 Assessment Fast Track. *Geoscientific Model Development*, 19(15), 7415–7455.
 1219 <https://doi.org/10.5194/gmd-19-7415-2026>
- 1220 Hooss, G., Voss, R., Hasselmann, K., Maier-Reimer, E., & Joos, F. (2001). A nonlinear impulse
 1221 response model of the coupled carbon cycle-climate system (NICCS). *Climate Dynamics*,
 1222 18(3), 189–202. <https://doi.org/10.1007/s003820100170>
- 1223 Jeevanjee, N., Paynter, D. J., Dunne, J. P., Sentman, L. T., & Krasting, J. P. (2026). On the Utility of
 1224 the Transient Climate Response. *Geophysical Research Letters*, 53(8), e2025GL121354.
 1225 <https://doi.org/10.1029/2025GL121354>
- 1226 Jones, ., Bossert, I., Dennis, D. P., Jeffery, H., Jones, C. D., Koenigk, T., Loriani, S., Sanderson, B.,
 1227 Séférian, R., Wyser, K., Yang, S., Abe, M., Bathiany, S., Braconnot, P., Brovkin, V., Burger, F.
 1228 A., Cadule, P., Castruccio, F. S., Danabasoglu, G., ... Ziehn, T. (2025). The TIPMIP Earth
 1229 system model experiment protocol: Phase 1. *EGUsphere*, 2025, 1–45.
 1230 <https://doi.org/10.5194/egusphere-2025-3604>
- 1231 Jones, C. D., Arora, V., Friedlingstein, P., Bopp, L., Brovkin, V., Dunne, J., Graven, H., Hoffman, F.,
 1232 Ilyina, T., John, J. G., Jung, M., Kawamiya, M., Koven, C., Pongratz, J., Raddatz, T.,
 1233 Randerson, J. T., & Zaehle, S. (2016). C4MIP – The Coupled Climate–Carbon Cycle Model
 1234 Intercomparison Project: Experimental protocol for CMIP6. *Geoscientific Model*
 1235 *Development*, 9(8), 2853–2880. <https://doi.org/10.5194/gmd-9-2853-2016>



- 1236 Jones, C. D., Collins, M., Cox, P. M., & Spall, S. A. (2001). The Carbon Cycle Response to ENSO: A
 1237 Coupled Climate–Carbon Cycle Model Study. *Journal of Climate*, 14(21), 4113–4129.
 1238 [https://doi.org/10.1175/1520-0442\(2001\)014<4113:TCCRTE>2.0.CO;2](https://doi.org/10.1175/1520-0442(2001)014<4113:TCCRTE>2.0.CO;2)
- 1239 Jones, C. D., & Friedlingstein, P. (2020). Quantifying process-level uncertainty contributions to
 1240 TCRE and Carbon Budgets for meeting Paris Agreement climate targets. *Environmental*
 1241 *Research Letters*. <http://iopscience.iop.org/10.1088/1748-9326/ab858a>
- 1242 Jones, C. D., Frölicher, T. L., Koven, C., MacDougall, A. H., Matthews, H. D., Zickfeld, K., Rogelj, J.,
 1243 Tokarska, K. B., Gillett, N. P., Ilyina, T., Meinshausen, M., Mengis, N., Séférian, R., Eby, M.,
 1244 & Burger, F. A. (2019). The Zero Emissions Commitment Model Intercomparison Project
 1245 (ZECMIP) contribution to C4MIP: quantifying committed climate changes following zero
 1246 carbon emissions. *Geoscientific Model Development*, 12(10), 4375–4385.
 1247 <https://doi.org/10.5194/gmd-12-4375-2019>
- 1248 Jones, C., Robertson, E., Arora, V., Friedlingstein, P., Shevliakova, E., Bopp, L., Brovkin, V., Hajima,
 1249 T., Kato, E., Kawamiya, M., Liddicoat, S., Lindsay, K., Reick, C. H., Roelandt, C.,
 1250 Segschneider, J., & Tjiputra, J. (2013). Twenty-First-Century Compatible CO₂ Emissions
 1251 and Airborne Fraction Simulated by CMIP5 Earth System Models under Four
 1252 Representative Concentration Pathways. *Journal of Climate*, 26(13), 4398–4413.
 1253 <https://doi.org/10.1175/JCLI-D-12-00554.1>
- 1254 Joos, F., Roth, R., Fuglestad, J. S., Peters, G. P., Enting, I. G., von Bloh, W., Brovkin, V., Burke, E.
 1255 J., Eby, M., Edwards, N. R., Friedrich, T., Frölicher, T. L., Halloran, P. R., Holden, P. B.,
 1256 Jones, C., Kleinen, T., Mackenzie, F. T., Matsumoto, K., Meinshausen, M., ... Weaver, A. J.
 1257 (2013). Carbon dioxide and climate impulse response functions for the computation of



- 1258 greenhouse gas metrics: A multi-model analysis. *Atmospheric Chemistry and Physics*,
 1259 13(5), 2793–2825. <https://doi.org/10.5194/acp-13-2793-2013>
- 1260 Keeling, C. D., & Piper, S. C. (2001). *Exchanges of Atmospheric CO₂ and ¹³CO₂ with the Terrestrial*
 1261 *Biosphere and Oceans from 1978 to 2000. IV. Critical Overview* [Technical Report].
 1262 Scripps Institution of Oceanography, University of California, San Diego.
 1263 <https://escholarship.org/uc/item/7zk4f1dj>
- 1264 Kooperman, G. J., Chen, Y., Hoffman, F. M., Koven, C. D., Lindsay, K., Pritchard, M. S., Swann, A.
 1265 L. S., & Randerson, J. T. (2018). Forest response to rising CO₂ drives zonally asymmetric
 1266 rainfall change over tropical land. *Nature Climate Change*, 8(5), 434–440.
 1267 <https://doi.org/10.1038/s41558-018-0144-7>
- 1268 Koven, C. D., Chambers, J. Q., Georgiou, K., Knox, R., Negron-Juarez, R., Riley, W. J., Arora, V. K.,
 1269 Brovkin, V., Friedlingstein, P., & Jones, C. D. (2015). Controls on terrestrial carbon
 1270 feedbacks by productivity versus turnover in the CMIP5 Earth System Models.
 1271 *Biogeosciences*, 12(17), 5211–5228. <https://doi.org/10.5194/bg-12-5211-2015>
- 1272 Lin, X., Rogers, B. M., Sweeney, C., Chevallier, F., Arshinov, M., Dlugokencky, E., Machida, T.,
 1273 Sasakawa, M., Tans, P., & Keppel-Aleks, G. (2020). Siberian and temperate ecosystems
 1274 shape Northern Hemisphere atmospheric CO₂ seasonal amplification. *Proceedings of the*
 1275 *National Academy of Sciences*, 117(35), 21079–21087.
 1276 <https://doi.org/10.1073/pnas.1914135117>
- 1277 MacDougall, A. H., Frölicher, T. L., Jones, C. D., Rogelj, J., Matthews, H. D., Zickfeld, K., Arora, V.
 1278 K., Barrett, N. J., Brovkin, V., Burger, F. A., Eby, M., Eliseev, A. V., Hajima, T., Holden, P. B.,
 1279 Jeltsch-Thömmes, A., Koven, C., Mengis, N., Menviel, L., Michou, M., ... Ziehn, T. (2020).



- 1280 Is there warming in the pipeline? A multi-model analysis of the Zero Emissions
 1281 Commitment from \chemCO_2. *Biogeosciences*, 17(11), 2987–3016.
 1282 <https://doi.org/10.5194/bg-17-2987-2020>
- 1283 Matthews, H. D., Gillett, N. P., Stott, P. A., & Zickfeld, K. (2009). The proportionality of global
 1284 warming to cumulative carbon emissions. *Nature*, 459(7248), 829–832.
 1285 <https://doi.org/10.1038/nature08047>
- 1286 Meehl, G. A., Boer, G. J., Covey, C., Latif, M., & Stouffer, R. J. (1997). Intercomparison makes for a
 1287 better climate model. *Eos, Transactions American Geophysical Union*, 78(41), 445–451.
 1288 <https://doi.org/10.1029/97EO00276>
- 1289 Meehl, G. A., Covey, C., McAvaney, B., Latif, M., & Stouffer, R. J. (2005). Overview of the Coupled
 1290 Model Intercomparison Project. *Bulletin of the American Meteorological Society*, 86(1),
 1291 89–94. <https://doi.org/10.1175/BAMS-86-1-89>
- 1292 Meehl, G. A., Stocker, T. F., Collins, W. D., Friedlingstein, P., Gaye, A. T., Gregory, J. M., Kitoh, A.,
 1293 Knutti, R., Murphy, J. M., Noda, A., Raper, S. C. B., Watterson, I. G., Weaver, A. J., & Zhao,
 1294 Z.-C. (2007). Global Climate Projections. In S. Solomon, D. Qin, M. Manning, Z. Chen, M.
 1295 Marquis, K. B. Averyt, M. Tignor, & H. L. Miller (Eds.), *Climate Change 2007: The Physical*
 1296 *Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the*
 1297 *Intergovernmental Panel on Climate Change*. Cambridge University Press.
 1298 <https://www.ipcc.ch/report/ar4/wg1/global-climate-projections/>
- 1299 National Research Council. (1979). *Carbon Dioxide and Climate: A Scientific Assessment*. The
 1300 National Academies Press. <https://doi.org/10.17226/12181>



- 1301 Orr, J. C., Najjar, R. G., Aumont, O., Bopp, L., Bullister, J. L., Danabasoglu, G., Doney, S. C., Dunne,
 1302 J. P., Dutay, J.-C., Graven, H., Griffies, S. M., John, J. G., Joos, F., Levin, I., Lindsay, K.,
 1303 Matear, R. J., McKinley, G. A., Mouchet, A., Oschlies, A., ... Yool, A. (2017).
 1304 Biogeochemical protocols and diagnostics for the CMIP6 Ocean Model Intercomparison
 1305 Project (OMIP). *Geoscientific Model Development*, 10(6), 2169–2199.
 1306 <https://doi.org/10.5194/gmd-10-2169-2017>
- 1307 Peters, W., van der Velde, I. R., van Schaik, E., Miller, J. B., Ciais, P., Duarte, H. F., van der
 1308 Laan-Luijkx, I. T., van der Molen, M. K., Scholze, M., Schaefer, K., Vidale, P. L., Verhoef, A.,
 1309 Wårlind, D., Zhu, D., Tans, P. P., Vaughn, B., & White, J. W. C. (2018). Increased water-use
 1310 efficiency and reduced CO₂ uptake by plants during droughts at a continental scale.
 1311 *Nature Geoscience*, 11(10), 744–748. <https://doi.org/10.1038/s41561-018-0212-7>
- 1312 Pookkandy, B., Graven, H., & Martin, A. (2023). Contemporary oceanic radiocarbon response to
 1313 ocean circulation changes. *Climate Dynamics*, 61(7), 3223–3235.
 1314 <https://doi.org/10.1007/s00382-023-06737-3>
- 1315 Randerson, J. T., Lindsay, K., Munoz, E., Fu, W., Moore, J. K., Hoffman, F. M., Mahowald, N. M., &
 1316 Doney, S. C. (2015). Multicentury changes in ocean and land contributions to the
 1317 climate-carbon feedback. *Global Biogeochemical Cycles*, 29(6), 744–759.
 1318 <https://doi.org/10.1002/2014GB005079>
- 1319 Reick, C. H., & Torres Mendonça, G. L. (2025). On the foundation of the α – β – γ approach to
 1320 carbon–climate feedbacks. *EGUsphere Preprint for Earth System Dynamics*.
 1321 <https://hdl.handle.net/21.11116/0000-0011-F3E7-6>



- 1322 Rödenbeck, C., Zaehle, S., Keeling, R., & Heimann, M. (2018). How does the terrestrial carbon
 1323 exchange respond to inter-annual climatic variations? A quantification based on
 1324 atmospheric CO₂ data. *Biogeosciences*, 15(8), 2481–2498.
 1325 <https://doi.org/10.5194/bg-15-2481-2018>
- 1326 Rogelj, J., Forster, P. M., Kriegler, E., Smith, C. J., & Séférian, R. (2019). Estimating and tracking
 1327 the remaining carbon budget for stringent climate targets. *Nature*, 571(7765), 335–342.
 1328 <https://doi.org/10.1038/s41586-019-1368-z>
- 1329 Rubino, M., Etheridge, D. M., Trudinger, C. M., Allison, C. E., Rayner, P. J., Enting, I., Mulvaney, R.,
 1330 Steele, L. P., Langenfelds, R. L., Sturges, W. T., Curran, M. A. J., & Smith, A. M. (2016). Low
 1331 atmospheric CO₂ levels during the Little Ice Age due to cooling-induced terrestrial
 1332 uptake. *Nature Geoscience*, 9(9), 691–694. <https://doi.org/10.1038/ngeo2769>
- 1333 Sanderson, B. M., Brovkin, V., Fisher, R. A., Hohn, D., Ilyina, T., Jones, C. D., Koenigk, T., Koven, C.,
 1334 Li, H., Lawrence, D. M., Lawrence, P., Liddicoat, S., MacDougall, A. H., Mengis, N.,
 1335 Nicholls, Z., O'Rourke, E., Romanou, A., Sandstad, M., Schwinger, J., ... Ziehn, T. (2025).
 1336 flat10MIP: an emissions-driven experiment to diagnose the climate response to positive,
 1337 zero and negative CO₂ emissions. *Geoscientific Model Development*, 18(17), 5699–5724.
 1338 <https://doi.org/10.5194/gmd-18-5699-2025>
- 1339 Schwinger, J., Tjiputra, J. F., Heinze, C., Bopp, L., Christian, J. R., Gehlen, M., Ilyina, T., Jones, C.
 1340 D., Salas-Mélia, D., Segschneider, J., Séférian, R., & Totterdell, I. (2014). Nonlinearity of
 1341 Ocean Carbon Cycle Feedbacks in CMIP5 Earth System Models. *Journal of Climate*,
 1342 27(11), 3869–3888. <https://doi.org/10.1175/JCLI-D-13-00452.1>



- 1343 Stouffer, R. J., Eyring, V., Meehl, G. A., Bony, S., Senior, C., Stevens, B., & Taylor, K. E. (2017).
 1344 CMIP5 Scientific Gaps and Recommendations for CMIP6. *Bulletin of the American*
 1345 *Meteorological Society*, 98(1), 95–105. <https://doi.org/10.1175/BAMS-D-15-00013.1>
 1346 Swann, A. L. S., Hoffman, F. M., Koven, C. D., & Randerson, J. T. (2016). Plant responses to
 1347 increasing CO₂ reduce estimates of climate impacts on drought severity. *Proceedings of*
 1348 *the National Academy of Sciences*, 113(36), 10019–10024.
 1349 <https://doi.org/10.1073/pnas.1604581113>
 1350 Tachiiri, K. (2020). Relationship between physical and biogeochemical parameters and the
 1351 scenario dependence of the transient climate response to cumulative carbon emissions.
 1352 *Progress in Earth and Planetary Science*, 7(1), 74.
 1353 <https://doi.org/10.1186/s40645-020-00392-6>
 1354 Tang, G., Nicholls, Z., Jones, C., Gasser, T., Norton, A., Ziehn, T., Romero-Prieto, A., &
 1355 Meinshausen, M. (2025). Investigating carbon and nitrogen conservation in reported
 1356 CMIP6 Earth system model data. *Geoscientific Model Development*, 18(7), 2111–2136.
 1357 <https://doi.org/10.5194/gmd-18-2111-2025>
 1358 Taylor, K. E., Stouffer, R. J., & Meehl, G. A. (2012). An Overview of CMIP5 and the Experiment
 1359 Design. *Bulletin of the American Meteorological Society*, 93(4), 485–498.
 1360 <https://doi.org/10.1175/BAMS-D-11-00094.1>
 1361 Todd-Brown, K. E. O., Randerson, J. T., Post, W. M., Hoffman, F. M., Tarnocai, C., Schuur, E. A. G.,
 1362 & Allison, S. D. (2013). *Causes of variation in soil carbon simulations from CMIP5 Earth*
 1363 *system models and comparison with observations*. 10(3), 1717–1736.
 1364 <https://doi.org/10.5194/bg-10-1717-2013>



- 1365 Torres Mendonça, G. L., Pongratz, J., & Reick, C. H. (2021). Identification of linear response
 1366 functions from arbitrary perturbation experiments in the presence of noise – Part 2:
 1367 Application to the land carbon cycle in the MPI Earth System Model. *Nonlinear Processes*
 1368 *in Geophysics*, 28(4), 533–564. <https://doi.org/10.5194/npg-28-533-2021>
- 1369 Torres Mendonça, G. L., Pongratz, J., & Reick, C. H. (2024). Timescale dependence of airborne
 1370 fraction and underlying climate–carbon-cycle feedbacks for weak perturbations in
 1371 CMIP5 models. *Biogeosciences*, 21(7), 1923–1960.
 1372 <https://doi.org/10.5194/bg-21-1923-2024>
- 1373 Van Vuuren, D. P., O’Neill, B. C., Tebaldi, C., Sanderson, B. M., Chini, L. P., Friedlingstein, P.,
 1374 Hasegawa, T., Riahi, K., Govindasamy, B., Bauer, N., Eyring, V., Fall, C. M. N., Frieler, K.,
 1375 Gidden, M. J., Gohar, L. K., Högnér, A., Jones, A. D., Kikstra, J., King, A., ... Ziehn, T. (2026).
 1376 The Scenario Model Intercomparison Project for CMIP7 (ScenarioMIP-CMIP7).
 1377 *Geoscientific Model Development*, 19(7), 2627–2656.
 1378 <https://doi.org/10.5194/gmd-19-2627-2026>
- 1379 Varney, R. M., Friedlingstein, P., Chadburn, S. E., Burke, E. J., & Cox, P. M. (2024). Soil
 1380 carbon-concentration and carbon-climate feedbacks in CMIP6 Earth system models.
 1381 *Biogeosciences*, 21(11), 2759–2776. <https://doi.org/10.5194/bg-21-2759-2024>
- 1382 Wang, W., Ciais, P., Nemani, R. R., Canadell, J. G., Piao, S., Sitch, S., White, M. A., Hashimoto, H.,
 1383 Milesi, C., & Myneni, R. B. (2013). Variations in atmospheric CO₂ growth rates coupled
 1384 with tropical temperature. *Proceedings of the National Academy of Sciences*, 110(32),
 1385 13061–13066. <https://doi.org/10.1073/pnas.1219683110>



- 1386 Wenzel, S., Cox, P. M., Eyring, V., & Friedlingstein, P. (2016). Projected land photosynthesis
 1387 constrained by changes in the seasonal cycle of atmospheric CO₂. *Nature*, 538(7626),
 1388 499–501. <https://doi.org/10.1038/nature19772>
- 1389 Williams, R. G., Goodwin, P., Ceppi, P., Jones, C. D., & MacDougall, A. H. (2025a). A normalised
 1390 framework for the Zero Emissions Commitment. *Biogeosciences*, 22(22), 7167–7186.
 1391 <https://doi.org/10.5194/bg-22-7167-2025>
- 1392 Williams, R. G., Goodwin, P., Ceppi, P., Jones, C. D., & MacDougall, A. H. (2025b). A normalised
 1393 framework for the Zero Emissions Commitment. *Biogeosciences*, 22(22), 7167–7186.
 1394 <https://doi.org/10.5194/bg-22-7167-2025>
- 1395 Zarakas, C. M., Swann, A. L. S., Laguë, M. M., Armour, K. C., & Randerson, J. T. (2020). Plant
 1396 Physiology Increases the Magnitude and Spread of the Transient Climate Response to
 1397 CO₂ in CMIP6 Earth System Models. *Journal of Climate*, 33(19), 8561–8578.
 1398 <https://doi.org/10.1175/JCLI-D-20-0078.1>
- 1399 Zhao, F., & Zeng, N. (2014). Continued increase in atmospheric CO₂ seasonal amplitude in the
 1400 21st century projected by the CMIP5 Earth system models. *Earth System Dynamics*, 5(2),
 1401 423–439. <https://doi.org/10.5194/esd-5-423-2014>
- 1402 Zickfeld, K., Azevedo, D., Mathesius, S., & Matthews, H. D. (2021). Asymmetry in the
 1403 climate–carbon cycle response to positive and negative CO₂ emissions. *Nature Climate*
 1404 *Change*, 11(7), 613–617. <https://doi.org/10.1038/s41558-021-01061-2>
- 1405 Zickfeld, K., Eby, M., Matthews, H. D., Schmittner, A., & Weaver, A. J. (2011). Nonlinearity of
 1406 Carbon Cycle Feedbacks. *Journal of Climate*, 24(16), 4255–4275.
 1407 <https://doi.org/10.1175/2011JCLI3898.1>



1408 Zickfeld, K., MacDougall, A. H., & Matthews, H. D. (2016). On the proportionality between global
1409 temperature change and cumulative CO₂ emissions during periods of net negative CO₂
1410 emissions. *Environmental Research Letters*, 11(5), 055006.
1411 <https://doi.org/10.1088/1748-9326/11/5/055006>
1412