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Probabilistic Regional Impacts from Model patterns and Emissions (PRIME)

WIEMIP will use the PRIME[1] workflow to generate data for both the idealized 1pctCO_2 and for the Overshoot Scenario runs. PRIME combines the FaIR simple climate model with a pattern scaling algorithm to allow rapid generation of gridded climatic data from emissions scenarios, bypassing the computational requirements of a fully coupled ESM. PRIME has been shown to produce reliable results for a range of CMIP6 emissions scenarios (SSP1-2.6, SSP5-3.4-OS, SSP5-8.5) for an ensemble of ESMs. PRIME has limitations due to its mostly linear parameterization, including the inability to capture global “tipping points” and the assumption that a change in emissions (either positive or negative) results in a change in climate that retains the same directionality as the parameterization. However, the ability to rapidly reproduce, and evaluate, CMIP6 runs as well as the limited computational requirement makes PRIME a key part of the WIEMIP workflow.

Meteorology data are generated with PRIME using the same protocol for each simulation type (i.e., 1pctCO_2 and Overshoot Scenarios): the 50th percentile of the parameterized temperature response from FaIR and three GCM patterns: UKESM1-0-LL, IPSL-CM6A-LR, and GFDL-ESM4. PRIME anomalies are then applied to a CRUJRA climatology. A stable CRUJRA climatology is also supplied for spinning up models. The 50th percentile of FaIR was chosen to give a median temperature response to emissions under literature-constrained TCR and ECS values and the chosen GCM patterns represent a range of future responses.

[1] Mathison et al., 2025

1pctCO2 simulation protocol to diagnose feedback factors (gamma, beta)

The 1pctCO_2 simulations increase CO_2 concentration at a rate of 1% per year from a pre-industrial (280 ppm - note this differs slightly from TRENDY and CMIP PI CO_2 concentrations) state. Details follow the C4MIP protocol and are described here with slight modification. Under the 1pctCO_2 framework, CO_2 doubles after 70 years and quadruples after 140 years. The WIEMIP protocol involves running the same set of simulations used for C4MIP[2] analysis, but in land-only mode. There are four required 1pctCO_2 simulations - SPIN, CTRL, BGC, COU - which should ideally be repeated for multiple factorial runs (i.e., turning key processes such as fire on and off) to quantify the impact of different processes on TCRE. All 1pctCO_2 runs will start in 1850 and end in 2000 (150 years, **without leap days**, with the additional ten years to help with averaging periods) with the exception of the spin-up run (which should be run for as long as necessary to spin up the model). We ask groups to run at the highest temporal and spatial resolution possible for their model (e.g., 6-hourly and 0.5°) to enable greater standardization across models. Models are required to fix land use in 1850 and disable wood harvest for the SPIN, CTRL, BGC, and COU runs. Other drivers (nitrogen deposition, population, lightning, etc) should be set to pre-industrial levels (1850) for the duration of the 1pct runs. The nitrogen deposition dataset is provided in Appendix 2.

Gamma, while expressed in units of “Pg C K-1” defined as changes in global mean temperature, is sensitive to global patterns of temperature, precipitation, and other meteorological change. The same land model, therefore, may give different estimates of gamma if driven with different GCM pattern data. WIEMIP will provide PRIME data generated with three GCM patterns (UKESM1-0-LL, IPSL-CM6A-LR, and GFDL-ESM4) to sample and quantify the change in gamma between different GCM patterns. However, we ask that modelers prioritize using the **UKESM** dataset for the 1pctCO_2 runs (see section “Optional ensembles of varying climate patterns” below for information on the other two GCM patterns) and focus their efforts on the factorial runs.

1) Spin-up (SPIN)

[2] https://gmd.copernicus.org/articles/9/2853/2016/

CO_2 concentration should be set to 280ppm. Land use should be held constant at 1850 using the most recent version of the LUH2 dataset (https://zenodo.org/records/15557904) with wood harvest disabled.

Other forcing – nitrogen deposition, n fertilization, lightning, population, etc – should be set to pre-industrial levels (1850) and kept constant during the spin-up. Fire can be enabled or disabled depending on your setup.

The spin-up climate data should be drawn from the provided stable climate dataset, which is temporally downscaled CRUJRA data (i.e., from daily to 6 hourly).

Any acceleration techniques which model groups may use are acceptable – such as spinning up parts of the system in isolation or techniques which accelerate equilibration times for slowly evolving components.

No specific output is required to be submitted, but model groups should check long-term stability of the model state, with careful focus on aspects – such as soil moisture, carbon stores or vegetation fractions – which may exhibit long-term inertia and therefore may drift. Model groups should use their discretion what is an acceptable residual drift which may be unavoidable in some of these components. Following C4MIP, a land carbon drift of <10Pg per century is recommended.

2) (Pre-industrial) Control run (CTRL)

The control run is a continuation from the spin-up and used to quantify any residual drifts or trends in model output (analogous to TRENDY S0). It should use the same forcing (fixed CO_2, other GHGs, fixed land-use, recycled 20-year climate, fixed nitrogen deposition) as the spin-up. **Please use the provided stable climate dataset for the duration of the control run.** Models should output variables for the control run as detailed below in the variable request. The control run should extend at least as long as the 1% simulations (150 years).

3) 1% Biogeochemically coupled (BGC)

This run uses the same climate data as for the control run (i.e., the provided **stable climate** dataset), but now the CO_2 concentrations provided to the model will increase following the 1% pathway. **The location of the CO_2 values is in the Appendix.** This design is similar to the TRENDY "S1" simulations of CO_2-only (though without transient N deposition). This run, and the 1%-COU run below – should begin from the same point ("start dump") as the control run above (i.e., immediately following final SPIN year), so that the CTRL run and the BGC (and COU) 1% runs are run over a parallel period of time. Land use, nitrogen deposition, etc, should be kept constant at the same year used in spinup (1850).

4.a) 1% Fully coupled simulation (COU)

This simulation is analogous to TRENDY S2 runs, where both atmospheric CO_2 and climate change over time while land use is kept constant at year 1850 (i.e., same as

SPIN). **Use the provided 1pctCO_2 dynamic climate dataset for the full duration of the COU run.** No other forcings than CO_2 and climate should be varied - so keep land use, nitrogen deposition, etc fixed at preindustrial values as in the CTRL run.

4.b) Optional 1% radiatively coupled simulation (RAD)

This simulation is part of the standard suite of 1pctCO_2 simulations in C4MIP and is driven with the **1pctCO_2 dynamic climate dataset** and **constant** pre-industrial (280ppm) CO_2 concentrations. Groups with capacity should prioritize factorial simulations (See Sect. 5) over the RAD simulation. Land use and other drivers should be fixed in 1850 as in the other 1pctCO_2 simulations. WIEMIP plans to derive gamma based on the difference between COU and BGC, so the RAD simulation is not essential.

5) Factorial runs and process selection

The above set of experiments 2, 3, 4a should be repeated for as many as possible factorial runs with individual processes turned on/off. A new spin-up may or may not be required – groups should check if their model is already in long-term steady state when a process is turned on/off. For example turning on fire is likely to change the initial state and a new spin-up would be required, but turning off dynamic vegetation may not – the simulation can proceed from the same start point but with no subsequent changes in PFT fractions. **A control run is still required even if a new spin-up is not**.
To ensure comparability between systems with and without processes, we ask that groups undertaking process-based factorials re-tune their model to match baseline ("baseline" refers to your model with all key processes enabled) stocks and fluxes. For example, a run without prognostic fire enabled may require higher mortality scalars, as fire increases overall mortality. The priority of factorial runs is still an open discussion in WIEMIP meetings, but we would like to prioritize on/off fire, on/off interactive nitrogen, and on/off permafrost before others.

Table 1: WIEMIP factorial table

The table below represents a theoretical model's process factorial and interaction runs. Rows indicate processes represented (wetlands are not represented in the example model), and columns represent the factorial set up. In addition, there are two interaction runs aimed at quantifying the interaction between permafrost-fire (**i**) and fire-nitrogen (**ii**).

Table: Theoretical Model's Process Factorials (for illustrative purposes only!)

	Example Model Name	Factorial runs							Interaction runs	
Process	**"Main" or "baseline" run**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**i**	**ii**
Permafrost	Y	N	Y	Y	Y	Y	Y	Y	N	N
Wetlands	N	N	N	N	N	N	N	N	N	N
Fire	Y	Y	N	Y	Y	Y	Y	Y	N	Y
Dynamic Vegetation	Y	Y	Y	N	Y	Y	Y	Y	Y	Y
Interactive Nitrogen	Y	Y	Y	Y	N	Y	Y	Y	Y	N
BVOC	Y	Y	Y	Y	Y	N	Y	Y	Y	Y
Inland Waters	Y	Y	Y	Y	Y	Y	N	Y	Y	Y

6) Nitrogen cycle (BGC-ndep and COU-ndep)

Models with an interactive nitrogen cycle are also requested to run with transient nitrogen deposition to examine the impacts of nitrogen on the carbon cycle. We request that modeling teams with the capability re-run the **BGC** and **COU** simulations. Nitrogen deposition should be prescribed using standard C4MIP[3] drivers, presented in Appendix 2. N deposition follows a scaled 1% increase using SSP5-85, matching 2100 N deposition values when the 1pctCO_2 CO_2 concentration reaches the 2100 concentration in SSP5-85. The BGC-ndep and COU-ndep protocol follows exactly the **BGC** and **COU** simulations but with transient nitrogen deposition instead of preindustrial. The nitrogen deposition dataset is sourced from ESGF.

[3] https://gmd.copernicus.org/articles/9/2853/2016/

7) Optional ensembles of varying climate patterns

The difference between the COU and the BGC runs is used to measure the sensitivity of the carbon cycle to changing climate (gamma_land). While gamma is expressed in units of “PgC K^{-1}” defined as changes in global mean temperature, we know that it is also sensitive to the patterns of temperature, precipitation and other climate variable changes. The same land model may give different gamma values if different GCM climate data are used. Ensembles of simulations which sample and quantify this are useful and experiment 7 is a repeat of 3 and 4a but using alternative GCMs (IPSL-CM6A-LR and GFDL-ESM4). We request that process decomposition is prioritised over sampling more than one GCM pattern if total number of runs are constrained.

Computing β_{land} and γ_{land}

WIEMIP will compute β_{land} and γ_{land} using the results of the 1pctCO_2 runs. β_{land} is defined as

$$\beta_{land} = \Delta C_{land} / \Delta CO_2.$$

At 2x PI CO_2 (year 70 in the 1pctCO_2 simulation) the sum of the land carbon (i.e., vegC+litterC+soilC, and so forth) from the BGC run(s) will be computed and differenced with the sum of pre-industrial land carbon to computeΔC_{land}. The 2xCO_2 level is of primary interest for TCRE.

γ_{land} is computed as follows:

$$\gamma_{land} = (\Delta C_{land,\,COU} - \Delta C_{land,\,BGC}) / \Delta tas_{COU},$$

Where COU and BGC represent the coupled and biogeochemically coupled simulations and Δtas_{COU} is the change in global temperature. All differences will be computed at 70 years of simulation (2xCO_2).

Time averaging of variables will be applied to anything that has year to year variability, such as temperature and fluxes. For stocks, we will take snapshots at year 70. Temperature will be derived from the provided forcing data.

Gamma and beta will be calculated for tropics (30S-30N) and extratropics (regions outside tropics).