

LongRunMIP - motivation and design for a large collection of millennial-length AO-GCM simulations

Article

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1 **LongRunMIP – motivation and design for a large collection of**
2 **millennial-length AO-GCM simulations**

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ABSTRACT

62 We present a model intercomparison project, LongRunMIP, the first collec-
63 tion of millennial-length (1000+ year) simulations of complex coupled cli-
64 mate models with a representation of ocean, atmosphere, sea ice, and land
65 surface, and their interactions. Standard model simulations are generally only
66 a few hundred years long. However, modeling the long-term equilibration
67 in response to radiative forcing perturbation is important for understanding
68 many climate phenomena, such as the evolution of ocean circulation, time-
69 and temperature-dependent feedbacks, and the differentiation of forced signal
70 and internal variability. The aim of LongRunMIP is to facilitate research into
71 these questions by serving as an archive for simulations that capture as much
72 of this equilibration as possible. The only requirement to participate in Lon-
73 gRunMIP is to contribute a simulation with elevated, constant CO₂ forcing
74 that lasts at least 1000 years. LongRunMIP is a MIP of opportunity in that
75 the simulations were mostly performed prior to the conception of the archive
76 without an agreed-upon set of experiments. For most models, the archive
77 contains a preindustrial control simulation and simulations with an idealized
78 (typically abrupt) CO₂ forcing. We collect 2D surface and top-of-atmosphere
79 fields, and 3D ocean temperature and salinity fields. Here, we document the
80 collection of simulations and discuss initial results, including the evolution of
81 surface and deep ocean temperature and cloud radiative effects. As of sum-
82 mer 2019, the collection includes 50 simulations of 15 models by 10 modeling
83 centers. The data of LongRunMIP are publicly available. We encourage sub-
84 mission of more simulations in the future.

85 (Capsule Summary) LongRunMIP is the first collection of millennial-length simulations of com-
86 plex coupled climate models and enables investigations of how these models equilibrate in re-
87 sponse to radiative perturbations.

88 1. Motivation and objectives

89 Millennial-length climate simulations are necessary to understand the equilibrium states that oc-
90 cur in response to external forcings, as well as the relationship between transient and equilibrated
91 behavior. Unforced millennial-length simulations are useful as well, as they allow us to consider
92 long-term internal variability and to analyze shorter-term variability with increased statistical cer-
93 tainty. Reasons to study these long time scales include:

- 94 • To better understand long-term climate dynamics. Outstanding issues include the time scales
95 of ocean circulation response (e.g., Jansen et al. 2018; Rind et al. 2018), continental drying
96 trends (e.g., Sniderman et al. 2019), or sea level rise (e.g., Bilbao et al. 2015; Rugenstein et al.
97 2016c).
- 98 • To help predict the impacts of 20th and 21st century emissions on century timescales, such as
99 ice sheet stability, deep ocean warming, or polar amplification (e.g., Frölicher and Joos 2010;
100 Clark et al. 2016; Mauritsen and Pincus 2017), which are rarely explicitly simulated using a
101 fully-coupled climate model.
- 102 • To more accurately estimate Equilibrium Climate Sensitivity (ECS), which is the equilibrium
103 response of the surface air temperature to a doubling of CO₂ due to the “fast” feedbacks water
104 vapor, lapse rate, clouds, and sea ice but excluding Earth system feedbacks such as changes
105 in the carbon cycle, ice sheets, or vegetation. While ECS has long been a focus of scientific

106 inquiry, substantial uncertainty remains as to its value (e.g., Charney et al. 1979; Knutti et al.
107 2017).

- 108 • To understand the relationship between the transient response of the climate and its equilibra-
109 tion. Since radiative feedbacks can depend on the evolution of the spatial pattern of warming
110 (e.g., Senior and Mitchell 2000; Winton et al. 2010; Armour et al. 2013; Andrews et al. 2015;
111 Andrews and Webb 2018) and on the background temperature (e.g., Colman and McAvaney
112 2009; Caballero and Huber 2013; Block and Mauritsen 2013; Meraner et al. 2013; Bloch-
113 Johnson et al. 2015), a constant effective sensitivity of the climate is an inadequate assump-
114 tion. Several methods have been proposed to predict the equilibrium response from transient
115 simulations given a changing global feedback (Held et al. 2010; Winton et al. 2010; Armour
116 et al. 2013; Geoffroy et al. 2013b,a; Frölicher et al. 2014; Proistosescu and Huybers 2017;
117 Saint-Martin et al. 2019), but only fully equilibrated climate model simulations can serve to
118 test how well these methods predict equilibrium conditions.
- 119 • To test theories for the relationship between feedbacks at different time-scales (Gregory et al.
120 2015, 2016; Zhou et al. 2016; Rugenstein et al. 2016a; Armour 2017; Proistosescu and Huy-
121 bers 2017; Ceppi and Gregory 2017; Andrews and Webb 2018; Andrews et al. 2018), and
122 to quantify the influence of slow, centennial-scale modes on the temperature evolution of the
123 last century (Armour 2017; Proistosescu and Huybers 2017).
- 124 • To understand the relevance, time scales, and magnitude of the energy imbalances and drifts
125 exhibited by climate models (e.g., Hobbs et al. 2016), with the potential application of de-
126 creasing the spin-up time needed to run these models.
- 127 • To understand the relationship between the forced response and internal variability. This re-
128 lationship is currently studied using the time frame of one or two centuries, which is not

129 enough to robustly quantify the internal variability under consideration (e.g., Maher et al.
130 2018; Lutsko and Takahashi 2018; Bloch-Johnson et al. in revision), **millennial time scales**
131 **with varying forcings** (e.g., Köhler et al. 2017; Khon et al. 2018; Rehfeld et al. 2018) or by
132 using expensive large ensemble simulations **on decadal to centennial time scales** (e.g., Deser
133 **et al. 2012; Maher et al. 2019; Rodgers et al. 2015**). Millennial long simulations allow us to
134 differentiate the transient response from the equilibrated forced response, even for quantities
135 with large internal variability, such as precipitation, droughts, or the El Niño-Southern Os-
136 cillation (ENSO), **and also the significance of a change in internal variability in a transient**
137 **simulation relative to the control simulation** (e.g., Brown et al. 2017).

- 138 • To compare climate model responses and paleo proxies, e.g. of surface or deep ocean temper-
139 atures or hydrological conditions on land in order to provide an independent way of testing
140 climate models (Gebbie and Huybers 2019; Burls and Fedorov 2017; Scheff et al. 2017).

141 With LongRunMIP, we aim to advance knowledge in the above mentioned areas, fill a gap in the
142 CMIP protocols (Taylor et al. 2011; Eyring et al. 2016), and collect published data in one location
143 for easy public access.

144 **The goals of LongRunMIP are**

- 145 a) to continuously gather existing millennial-length simulations (both published and unpub-
146 lished)
- 147 b) to standardize the collected data (e.g., using the same units and sign conventions)
- 148 c) to make the data publicly available and easily accessible
- 149 d) to foster an interdisciplinary community of users working on millennial-length problems,
150 with experts on oceanography, atmospheric dynamics, energy balance modeling, ice sheet
151 modeling, and paleoclimatology

152 **The objectives of this paper** are to

- 153 a) motivate the data collection strategy (Section 2)
- 154 b) specify the requirements for LongRunMIP contributors (Section 2 and b)
- 155 c) give an overview of currently submitted simulations and models (Section 2a, b, and Table 1)
- 156 d) give a sample of some initial analysis on these simulations (Section 3)
- 157 e) show how LongRunMIP relates to the existing literature on millennial-length simulations
158 (Section 4a)
- 159 f) discuss the limitations and opportunities of LongRunMIP (Section 4b and c).

160 **2. Experimental design and data collection strategy**

161 LongRunMIP is the first and largest compilation of millennial-length simulations of complex cli-
162 mate models to date, where a “complex climate model” is understood to include an atmospheric,
163 sea ice, land, and full depth ocean component, i.e. Atmosphere-Ocean General Circulation Mod-
164 els (AO-GCMs) with a dynamic atmosphere and ocean, as opposed to Models of Intermediate
165 Complexity (EMICs), which are often used to study millennial-length questions in climate science
166 (e.g., Zickfeld et al. 2013; Levermann et al. 2013). These model simulations include the “fast”
167 feedbacks, such as changes in water vapor, lapse rate, sea ice, and clouds (Charney et al. 1979),
168 but no “slow” feedbacks, such as changes in the ice-sheets. **Vegetation is treated differently in the**
169 **models (see Section 2b).** In Section 4 we discuss the implications and limitations of **our** approach.
170 Our goal is to collect as many simulations from as many independent models as possible, while
171 keeping the archive and data sharing manageable. Consequently, we keep our requirements for
172 contributions low.

173 *a. Simulations and variables*

174 A step-increase in atmospheric CO₂ concentrations (in the following called “step-forcing”) is
175 one of the simplest experiments for studying a model’s response to forcing and is used as a bench-
176 mark simulation in CMIP3, CMIP5, and CMIP6 (Meehl et al. 2007; Taylor et al. 2011; Eyring
177 et al. 2016). More realistic, gradual forcing scenarios have been shown to be representable by the
178 step-forcing scenarios and exhibit feedbacks that correlate with those computed from step-forcing
179 simulations (Good et al. 2013, 2015; Geoffroy and Saint-Martin 2014; Colman and Hanson 2016).
180 The CMIP3 protocol required a step-forcing of *doubling* atmospheric CO₂ (here referred to as
181 *abrupt2x*) above pre-industrial levels in a slab (i.e. non-dynamical) ocean, which for decades has
182 been used to define ECS (e.g., Charney et al. 1979; Boer and Yu 2003c; Danabasoglu and Gent
183 2009). The integration time scale of these model setups are a couple of decades. However, a
184 *quadrupling* of CO₂ (here referred to as *abrupt4x*) above pre-industrial levels has a better ratio of
185 forced signal to internal variability. Because the forced response was assumed to scale linearly
186 with increased forcing, the CMIP5 protocol requested an abrupt quadrupling of CO₂, now in a
187 fully coupled model with a dynamical ocean, requiring longer integration time scales. The CMIP6
188 protocol again requests abrupt CO₂ quadrupling experiments, but encourages also the submission
189 of abrupt CO₂ doublings, to study the relation between different forcing levels (Eyring et al. 2016;
190 Good et al. 2016). CMIP5 and 6 protocols require the submission of 150 years of model output.
191 A representative response of surface temperature anomalies and top of the atmosphere (TOA) ra-
192 diative imbalance to an *abrupt4x* scenario is shown in Fig. 1. All anomalies mentioned in this
193 paper are computed as the difference of the experiment from the average of the control simulation.
194 After the 150 years of CMIP protocol length (blue shading) and after 1000 years (the minimum
195 contribution to LongRunMIP, light red shading), the surface temperature response of the exem-

196 plary model shown here has reached 75 % and 88 % of its final value respectively, while the TOA
197 radiation has equilibrated 85 % and 93 % of the forcing respectively (7.6 W m^{-2} for this model).
198 Thus, the final equilibration is a CPU-intensive exercise; the model shown here needs 4000 years
199 to balance the final 0.5 W m^{-2} (dark red shading).

200 The set of variables we collect is motivated by the interest of the LongRunMIP contributors and
201 organizers in ECS, temperature and time dependent feedbacks, and deep ocean warming. Table
202 1 lists the variable names, units, and temporal and spatial resolution of the requested variables.
203 The naming and sign conventions follow the CMIP5 protocol¹. Given the large amount of data
204 involved, we have kept our requested variable list low to allow as many groups as possible to
205 participate. For the same reason, we do not request the data to be “CMORized”², i.e. written in
206 conformance with the CMIP standards. However, we do homogenize signs, variable long names,
207 and units, and also provide a regridded version of the fields, as well as global means.

208 *b. Minimal, optimal, and current contributions*

209 The *minimal requirement* to contribute to LongRunMIP are annual fields of a single simulation
210 of any CO_2 forcing scenario that has at least 1000 years of constant forcing, along with a control
211 simulation of any length. The complexity of the model should be CMIP5-class and include dy-
212 namic atmosphere, ocean, and sea ice components. An *optimal contribution* comprises monthly
213 fields of fully equilibrated *abrupt2x*, *4x*, and *8x* simulations and a control simulation of several
214 millennia.

215 Table 2 lists the model characteristics of the *current* contributions. Because the archive is assem-
216 bled from experiments initiated independently for research purposes by multiple modeling groups,
217 there is no pre-defined protocol like for the CMIP simulations. The models are diverse in origin

¹http://cmip-pcmdi.llnl.gov/cmip5/data_description.html

²<https://pcmdi.llnl.gov/CMIP6/Guide/dataUsers.html>

218 and sample the CMIP5 range of models well (see discussion on model genealogy in Knutti 2010).
219 Table 2 lists references for each model and publications using (parts of) the model output. Most
220 of the current contributions to LongRunMIP are extensions of CMIP5 simulations, sometimes
221 with updated model versions, while one model is an extension of a CMIP3 and another model an
222 extension of a CMIP6 contributions (CCSM3 and CNRM-CM6-1 respectively).

223 Many of our current contributions fall short of the optimal expectation for equilibrium, because
224 even several millennia are insufficient for the deep ocean to equilibrate (see discussion around
225 Fig. 4). However, a few millennia appear to be enough for the surface temperature and TOA
226 radiative imbalance to reach a new steady state in most models (see Section 3), and many questions
227 can be adequately addressed with the current contributions. Our approach is to be inclusive, and
228 to leave it to the user to determine the degree of equilibration needed for their research and to
229 develop criteria for model selection.

230 Most contributions are step-forcing simulations, generally to 2x or 4x pre-industrial CO₂ con-
231 centrations (in Fig. 2 abrupt2x in colored in yellow, abrupt4x in orange, abrupt8x in dark red;
232 abrupt2.4x and abrupt4.8x in dark and light pink). There are currently three exceptions: 1) some
233 model simulations have gradual increases in CO₂ at 1% per year until doubled or quadrupled con-
234 centrations are reached, after which the concentration is kept constant (1pct2x and 1pct4x, light
235 and medium red in Fig. 2). 2) One model simulates the 1850-2010 period, after which CO₂ in-
236 creases either piecewise linearly for 90 years until reaching 2.4x pre-industrial values (CCSM3II).
237 3) Finally, one model simulates the historical period and then the CMIP5 extended representative
238 concentration pathway 8.5 (including CH₄, N₂O, CFC11, and CFC12 in addition to CO₂) until
239 year 2300 after which all forcing agents are kept constant (RCP8.5+, violet in Fig. 2) For the
240 models that did not contribute a a millennial-long step-forcing simulation, we collect short (typ-
241 ically 150 year) step-forcing simulations, generally from the CMIP5 archive. These simulations

242 can be used to estimate the effective climate sensitivity and to relate transient and equilibrium
243 responses. They are not mentioned in Table 2 and Fig. 2.

244 Most contributors were able to submit all requested variables. Some models only stored annual
245 output, while for a few models the entire model output (including many more variables than listed
246 in Table 1) is available. In principle, but with considerable effort, additional variables not listed in
247 Table 1 could be requested from some or all contributors.

248 Some models are outliers in some sense. For example, the simulation *abrupt4x* of FAMOUS
249 warms anomalously strong (Fig. 2 and 7) due to a shortwave cloud effect which is positive through-
250 out the simulation and longwave clear-sky effect, which increases anomalously strongly (not
251 shown, see Rugenstein et al. (2019)). In principle though, such extreme behavior could represent
252 possible characteristics of the real world (e.g., Bloch-Johnson et al. 2015; Schneider et al. 2019).
253 Another atypical model is EC-Earth-PISM, which is the only model with an interactive Greenland
254 ice sheet. This additional component and its historical and RCP8.5+ forcing scenario makes it
255 harder to compare the simulation to other models and attribute changes to one forcing component.
256 This model also does not equilibrate but finally produces a negative TOA imbalance, which prob-
257 ably would increase if the simulation was integrated further. We encourage similar “problematic”
258 submissions, since our focus is on understanding model behavior and the large range of model
259 responses (discussed in Section 3).

260 In nine models, the vegetation is fixed to pre-industrial conditions (ECHAM5, CCSM3,
261 CCSM3II, HadCM3L, FAMOUS, MIROC32, ECEARTH, GISSE2R, CNRMCM61), while the
262 other seven models have dynamic vegetation schemes (MPIESM11, MPIESM12, CESM104,
263 HadGEM2, GFDLESM2M, GFDLCM3, IPSLCM5A).

264 3. Sample of model output

265 *a. Imbalances in the control simulation and drift*

266 In principle, the TOA radiative imbalance should be zero in a control simulation. Most models
267 contributing to LongRunMIP do not loose or gain energy (Fig. 3). However, some models that are
268 equilibrated in the sense that they show no substantial drift, still have a constant energy leakage.
269 For CMIP5 models, imbalances of the same order of magnitude (and larger) have been shown to be
270 uncorrelated with the forced response (Hobbs et al. 2016). If computing atmospheric anomalies,
271 we suggest **users** to take the difference of each time step to the time-averaged control simulation
272 imbalance, except for CCSM3II and GFDL-CM3 for which the difference to a polynomial fit to
273 the control simulation time series seems appropriate (see Fig. 3).

274 The deep ocean (defined here as **depth level around 2 km**) has an astonishingly small drift in
275 the global average in most models (Fig. 4, lowest panel). While the surface ocean time scales
276 closely follows the global mean surface air temperature anomaly, the deep ocean takes centuries
277 to equilibrate. Panel a and b of Fig. 4 display the surface and deep ocean temperature anomalies,
278 computed as the difference of the forced and control simulations, while the lowest panel shows the
279 absolute temperatures of the deep ocean in the control simulations to indicate the model spread in
280 the base state. Previous work on long-term trends in deep ocean temperature and salinity shows
281 that these trends **may** reflect ongoing changes in stratification and the strength and depth of the
282 Atlantic Meridional Overturning Circulation (AMOC; e.g., Stouffer and Manabe 2003; Rugenstein
283 et al. 2016a; Marzocchi and Jansen 2017; Jansen et al. 2018). Even if the energy flux imbalance
284 at the TOA or the ocean surface are close to a new steady state this does not necessarily indicate
285 that the deep ocean is equilibrated as well (Zhang et al. 2013; Hobbs et al. 2016; Marzocchi and
286 Jansen 2017). Reaching deep ocean equilibration may not be necessary for studies concerned with

287 surface properties only. However, for interpretation of paleo proxies and comparison with model
288 simulations, distinguishing between the transient and equilibrium response in the intermediate or
289 deep ocean is necessary (Zhang et al. 2013; Marzocchi and Jansen 2017; Rind et al. 2018; Jansen
290 et al. 2018).

291 *b. Evolution of surface temperature and cloud radiative effect*

292 The evolution of large scale surface air temperature patterns on decadal to millennial time scales
293 (Fig. 5) are robust among models and different forcing levels. The simulations show a strong land-
294 sea warming contrast on short time scales and little warming over the Southern Ocean on decadal
295 to centennial time scales (e.g., Manabe et al. 1991; Gregory 2000; Joshi and Gregory 2008; Geoff-
296 froy and Saint-Martin 2014; Armour et al. 2016). A warming pattern reminiscent of the positive
297 phase of ENSO and the Interdecadal Pacific Oscillation occurs throughout the Pacific basin (**panel**
298 **b**; Held et al. 2010; Song and Zhang 2014; Andrews et al. 2015; Luo et al. 2017) but decays on
299 centennial to millennial time scales (**panel c and d**), with a large model spread in time scales (**not**
300 **shown**). As it approaches equilibrium, the temperature pattern becomes more homogeneous, the
301 land-sea warming contrast reduces (e.g., Held et al. 2010; Geoffroy and Saint-Martin 2014), and
302 the Southern Hemisphere high latitudes keep warming beyond year 1000. As in previous studies,
303 the AMOC first declines (Gregory et al. 2005; Zhu et al. 2014; Kostov et al. 2014; Trossman et al.
304 2016) and then recovers (Stouffer and Manabe 2003; Li et al. 2013; Zickfeld et al. 2013; Rugen-
305 stein et al. 2016a; Rind et al. 2018), resulting in a delayed warming in the North Atlantic. **Panel**
306 **a, b, and e correspond to the blue shading in Fig. 1, and are known from CMIP5 simulations (e.g.,**
307 **Andrews et al. 2015), while panel c, d, f, and g highlight that the simulations still warm substan-**
308 **tially on centennial to millennial time scales, mainly in areas with more sensitive – i.e. positive**
309 **or small negative – feedbacks (Rugenstein et al. 2019). Normalizing the zonal-mean temperature**

310 anomaly by the global mean warming reveals the relative **zonal-mean** warming (Fig. 6). Arctic am-
311 plification begins very early in the simulations and warming throughout the Southern Hemisphere
312 is lower than the global average in almost all models for the first centuries. Between year 100 and
313 1000 the Southern Hemisphere warms more than the Northern Hemisphere in all latitudes pole-
314 ward from 30°, in some regions by more than 4 K. Antarctic warming slowly increases, but is still
315 substantially less than Arctic amplification (e.g., Salzmann 2017). In a couple of models, the am-
316 plitude of Antarctic and Arctic amplification is the same after 4000 years of model integration time
317 (GISSE2R and ECHAM5; Li et al. 2013), while in other models the Antarctic amplification stays
318 substantially smaller and still increasing after a couple of thousand years. LongRunMIP shows
319 that there is no reduction in model spread in the polar regions through time and that although all
320 models follow a similar large scale pattern evolution (Fig. 5), the local response time scales, e.g.
321 in the North Atlantic, Southern Ocean, or equatorial Pacific differ by hundreds to thousands years.

322 While the large scale temperature response is rather robust between models and simulations,
323 the cloud radiative effect (CRE) differs strongly in magnitude and time evolution, both between
324 models and between forcing levels for the same model (Fig 7). We show the shortwave CRE –
325 computed as the difference between “all sky” and “clear sky” shortwave radiative fluxes (e.g.,
326 **Ramanathan et al. 1989; Ceppi et al. 2017**) – as a function of surface air temperature anomaly.
327 The models disagree in the overall sign, as expected from CMIP5 models on shorter time scales
328 (e.g., Vial et al. 2013; Caldwell et al. 2015), but can even change sign within a single simulation
329 (e.g., ECEARTH or CESM *abrupt8x*). The strength of variation in time within one simulation
330 can depend strongly on the forcing level (e.g. MIROC32 *1pct2x* vs. *1pct4x*) and the time scales
331 of change differ between the models (e.g. IPSLCM5R vs. MPIESM12 *abrupt4x*). For some
332 simulations, cloud response barely changes with temperature, contributing negligibly to the overall
333 feedback (e.g. MPIESM12 *abrupt16x*, CESM104 *abrupt4x*, and MIROC32 *1pct2x*).

334 **4. Discussion and Outlook**

335 *a. Published millennial-length simulations*

336 Models of intermediate complexity are the most common tools used to study century to millen-
337 nium time scales in the climate system (e.g., Zickfeld et al. 2013; Eby et al. 2013; Levermann et al.
338 2013; Rugenstein et al. 2016c; Jansen et al. 2018). However, they usually have a poorly resolved
339 atmosphere and little or no representation of cloud processes. In contrast, the publications in Table
340 3 feature millennium-length AO-GCM simulations. Asterisks mark contributions to LongRunMIP.
341 These papers provide a solid body of work on millennial-length climate simulations, but rarely use
342 the same forcing levels and simulation length and focus on different aspects of the climate sys-
343 tem. Three papers compare model formulation and processes of two AO-GCMs each (Frölicher
344 et al. 2014; Paynter et al. 2018; Krasting et al. 2018), but otherwise models have not been sys-
345 tematically compared against each other. Fig. 4 and 7 show that AO-GCMs can strongly differ in
346 their behavior. Spatial patterns of e.g., precipitation and surface heat fluxes also vary strongly be-
347 tween models and between different forcing scenarios for the same model (not shown), suggesting
348 that some mechanisms and processes discussed in the published literature are not generalizable
349 across models. For example, there is disagreement about which regions are thought to dominate
350 the changing feedback parameter (Senior and Mitchell 2000; Andrews et al. 2015; Meraner et al.
351 2013; Caballero and Huber 2013) or whether or not, and on which time scales, the AMOC recovers
352 from its initial reduction (Voss and Mikolajewicz 2001; Stouffer and Manabe 2003; Li et al. 2013;
353 Rind et al. 2018; Thomas and Fedorov 2019). Paleo climate simulations are often several thou-
354 sand years long, however, they usually include boundary conditions such as ice sheets or changing
355 continental configurations, which differ from the ones used here. However, paleo climate studies
356 often discuss equilibration time scales and deep ocean temperature trends relevant to the types

357 of models included in LongRunMIP (e.g., Brandefelt and Otto-Bliesner 2009; Zhang et al. 2013;
358 Klockmann et al. 2016; Marzocchi and Jansen 2017; Gottschalk et al. 2019).

359 *b. Limitations*

360 LongRunMIP analyses are currently limited mainly by the collected *variables* (Table 1). In-
361 cluding cloud fields and 3D atmospheric temperature and humidity fields, **for example**, would
362 allow users to study atmospheric dynamics and radiative feedbacks in more detail. The *differ-*
363 *ent forcing scenarios* of model contributions to LongRunMIP are both a strength and weakness.
364 Minimal requirements **have** encouraged a large number of contributions so far. However, study-
365 ing a single forcing scenario requires model selection or scaling between different forcing levels.
366 *Slab ocean simulations*, which replace a model’s dynamical ocean with a much shallower non-
367 dynamical mixed-layer, are a computationally cheap tool to compare fast and slow time scales and
368 the relevance of surface warming patterns (Boer and Yu 2003c; Danabasoglu and Gent 2009; Li
369 et al. 2013). We hope to receive submissions of these simulations in the future, to allow analysis of
370 their utility. Century to millennial-time scales in the real world include more processes and *Earth*
371 *System Feedbacks* than are included in LongRunMIP simulations, such as the carbon cycle, vege-
372 tation feedbacks, forcing agents other than CO₂ (such as other greenhouse gases or aerosols), ice
373 sheets, glacial rebound effects, changes to continental configuration, and orbital variation. Further,
374 the real climate system is never in equilibrium or steady state, because the forcing continuously
375 changes (e.g., Köhler et al. 2017). These Earth system feedbacks and additional forcings must be
376 taken into account when comparing the LongRunMIP models with paleo proxies or when project-
377 ing or predicting changes in future centuries or millennia.

378 *c. Summary and expected impact*

379 LongRunMIP is the first archive of millennial-length simulations of complex climate models,
380 featuring 50 simulations of 15 models by 10 modeling centers under various forcing scenarios (Ta-
381 ble 2). The archive provides an unprecedented opportunity to study the equilibrium response of a
382 large number of models to forcing. The variables included allow study of a range of phenomena
383 associated with the atmosphere, ocean, land, and sea ice (Table 1), and we expect LongRunMIP to
384 contribute to current discussions laid out in Section 1. This includes ocean heat uptake, sea level
385 rise, ocean circulation response to warming, large scale modes of variability, sea ice reduction,
386 polar amplification, precipitation variability, atmospheric dynamics, **long-term memory in time**
387 **series**, spatial warming patterns, ocean - atmosphere interactions, model spin-up techniques, the
388 relation of internal variability and forced response under different forcing levels, committed cli-
389 mate response, and the relation of time and state dependence of fast feedbacks and Earth System
390 Feedbacks and processes.

391 LongRunMIP is a MIP of opportunity, without an agreed upon protocol, and is a result of the
392 willingness of individual research groups to provide model output from simulations often con-
393 ducted over years of real-world time. As a result, the experiments are not standardized, but most
394 models provided a millennial-length simulation that begins with an abrupt quadrupling of CO₂
395 concentration. In addition to collecting simulations, we provide output with standardized formats
396 and variable names, and include versions regridded to a common grid, as well as global averages.

397 LongRunMIP builds upon a body of pioneering studies that looked at the behavior of models be-
398 yond the centennial scale (Table 3), LongRunMIP allows this sort of analysis to be applied across
399 a diverse group of models that exhibit strikingly different behavior (Fig. 7), and hopefully encour-

400 age others to look beyond the limitations and assumptions normally imposed by computational
401 constraints, to directly study the equilibration of the fully coupled atmosphere-ocean system.

402 *Data access and sharing*

403 LongRunMIP currently consists of 15 TB of data and available for download at
404 <https://data.iac.ethz.ch/longrunmip/>. Fields shown in this paper can be accessed on
405 <https://data.iac.ethz.ch/longrunmip/BAMS/>.

406 See www.longrunmip.org for more details on available variables, contact information, sample
407 figures and videos, and links to join a discussion community. We will be collecting more
408 simulations over the next couple of years.

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808

809 **LIST OF TABLES**

810 **Table 1.** Description of collected variables. 2D means spatial resolution of latitude and
811 longitude, except for *msfmyz* where it means latitude and depth. 3D means lat-
812 itude, longitude, and depth. *msfmyz* is the sum of the eularian, eddybolus, and
813 submeso component. For *so* and *thetao* there are also February and September
814 values available for most models. 39

815 **Table 2.** Overview of models and contributed simulations. The resolution of atmosphere
816 and ocean is given in # of grid points per latitude x longitude, and latitude x
817 longitude x depth, respectively. Models are referred to by their shortnames
818 throughout the manuscript. **Section 2b** describes the forcing levels. References
819 in the last **column** describe the models and simulations. Some simulations are
820 published in their full length, some simulations contributed to LongRunMIP are
821 the extensions of simulations discussed in the references, and some simulations
822 are unpublished. 40

823 **Table 3.** Published millennial-length simulations 41

824 TABLE 1. Description of collected variables. 2D means spatial resolution of latitude and longitude, except for
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826 eularian, eddybolus, and submeso component. For *so* and *thetao* there are also February and September values
827 available for most models.

Shortname	Longname	Unit	Resolution
hfls	Surface Upward Latent Heat Flux	W m^{-2}	monthly, 2D
hfss	Surface Upward Sensible Heat Flux	W m^{-2}	monthly, 2D
pr	Precipitation on atmospheric grid	$\text{kg m}^{-2} \text{s}^{-1}$	monthly, 2D
psl	Sea Level Pressure	Pa	monthly, 2D
rlds	Surface Downwelling Longwave Radiation	W m^{-2}	monthly, 2D
rlus	Surface Upwelling Longwave Radiation	W m^{-2}	monthly, 2D
rlut	TOA Outgoing Longwave Radiation	W m^{-2}	monthly, 2D
rlutes	TOA Outgoing Clear-Sky Longwave Radiation	W m^{-2}	monthly, 2D
rsds	Surface Downwelling Shortwave Radiation	W m^{-2}	monthly, 2D
rsdt	TOA Incident Shortwave Radiation	W m^{-2}	monthly, 2D
rsus	Surface Upwelling Shortwave Radiation	W m^{-2}	monthly, 2D
rsut	TOA Outgoing Shortwave Radiation	W m^{-2}	monthly, 2D
rsutes	TOA Outgoing Clear-Sky Shortwave Radiation	W m^{-2}	monthly, 2D
tas	Near-Surface Air Temperature	K	monthly, 2D
ts	Atmospheric surface temperature	K	monthly, 2D
sic	Sea Ice Area Fraction	%	monthly, 2D
msftmyz	Meridional Overturning Circulation	$\text{m}^3 \text{s}^{-1}$	annual, 2D
tos	Sea surface temperature	K	annual, 2D
sos	Sea surface salinity	psu	annual, 2D
wfo	Net water flux into sea water	$\text{kg m}^{-2} \text{s}^{-1}$	annual, 2D
evs	Water evaporation	$\text{kg m}^{-2} \text{s}^{-1}$	annual, 2D
pr_ocn	Precipitation (rain and snow) on ocean grid	$\text{kg m}^{-2} \text{s}^{-1}$	annual, 2D
tauuo	Surface downward wind stress in x direction	N m^{-2}	annual, 2D
tauvo	Surface downward wind stress in y direction	N m^{-2}	annual, 2D
so	Sea Water Salinity	psu	annual, 3D
thetao	Sea Water Potential Temperature	K	annual, 3D

828 TABLE 2. Overview of models and contributed simulations. The resolution of atmosphere and ocean is given
829 in # of grid points per latitude x longitude, and latitude x longitude x depth, respectively. Models are referred
830 to by their shortnames throughout the manuscript. Section 2b describes the forcing levels. References in the
831 last column describe the models and simulations. Some simulations are published in their full length, some
832 simulations contributed to LongRunMIP are the extensions of simulations discussed in the references, and some
833 simulations are unpublished.

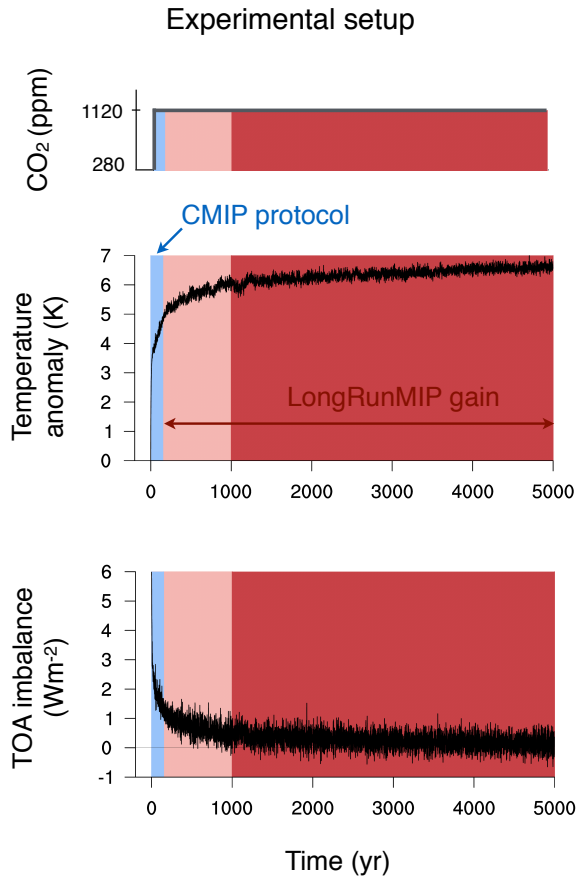
Model (shortname)	Forcing level shortname	Length (yrs)	Atmosphere resolution	Ocean resolution	Control sim (yrs)	Model and simulation documentation
CCSM3 CCSM3	abrupt2x abrupt4x abrupt8x	3000 2120 1450	48 x 96	100 x 116 x 25	1530	Yeager et al. (2006) Danabasoglu and Gent (2009)
CCSM3 CCSM3II	abrupt2.4 abrupt4.8 lin2.4	3701 3132 3990	48 x 96	100 x 116 x 25	3805	Yeager et al. (2006) Castruccio et al. (2014)
CESM 1.0.4 CESM104	abrupt2x abrupt4x abrupt8x	2500 5900 5100	96 x 144	384 x 20 x 60	1320	Gent et al. (2011) Danabasoglu et al. (2012) Rugenstein et al. (2016c)
CNRM-CM6-1 CNRMCM61	abrupt2x abrupt4x	750 1850	128 x 256	180 x 360 x 75	2000	Voltaire et al. (2019) Saint-Martin et al. (2019)
EC-Earth-PISM ECEARTH	historical RCP8.5+	1270	160 x 320	292 x 362 x 42	508	Hazeleger et al. (2012) Svendsen et al. (2015)
ECHAM5/MPIOM ECHAM5	abrupt4x 1pct4x	1000 6080	48 x 96	101 x 120 x 40	100	Jungclauss et al. (2006) Li et al. (2013)
FAMOUS FAMOUS	abrupt2x abrupt4x	3000 3000	37 x 48	73 x 96 x 20	3000	Smith et al. (2008)
GFDL-CM3 GFDLCM3	1pct2x	5000	90 x 144	200 x 360 x 50	5200	Donner et al. (2011) Paynter et al. (2018)
GFDL-ESM2M GFDLESM2M	1pct2x	4500	90 x 144	200 x 360 x 50	1340	Dunne et al. (2012) Paynter et al. (2018)
GISS-E2-R GISSE2R	abrupt4x 1pct4x	5000 5000	90 x 144	180 x 288 x 32	5225	Schmidt et al. (2014); Miller et al. (2014); Nazarenko et al. (2015) Rind et al. (2018)
HadCM3L HadCM3L	abrupt2x abrupt4x abrupt6x abrupt8x	1000 1000 1000 1000	73 x 96	73 x 96 x 20	1000	Cox et al. (2000) Cao et al. (2016)
HadGEM2-ES HadGEM2	abrupt4x	1328	145 x 192	216 x 360 x 40	239	Collins et al. (2011) Andrews et al. (2015)
IPSL-CM5A-LR IPSLCM5ALR	abrupt4x	1000	96 x 96	149 x 182 x 31	1000	Dufresne et al. (2013)
MIROC 3.2 MIROC32	1pct2x 1pct4x	2000 2000	64 x 128	192 x 256 x 44	681	Hasumi and Emori (2004) Yamamoto et al. (2015); Yoshimori et al. (2016)
MPIESM-1.2 MPIESM12	abrupt2x abrupt4x abrupt8x abrupt16x	1000 1000 1000 1000	96 x 192	220 x 256 x 40	1237	Mauritsen et al. (2018) Rohrschneider et al. (2019)
MPIESM-1.1 MPIESM11	abrupt4x	4459	96 x 192	220 x 256 x 40	2000	Mauritsen et al. (2018)

TABLE 3. Published millennial-length simulations

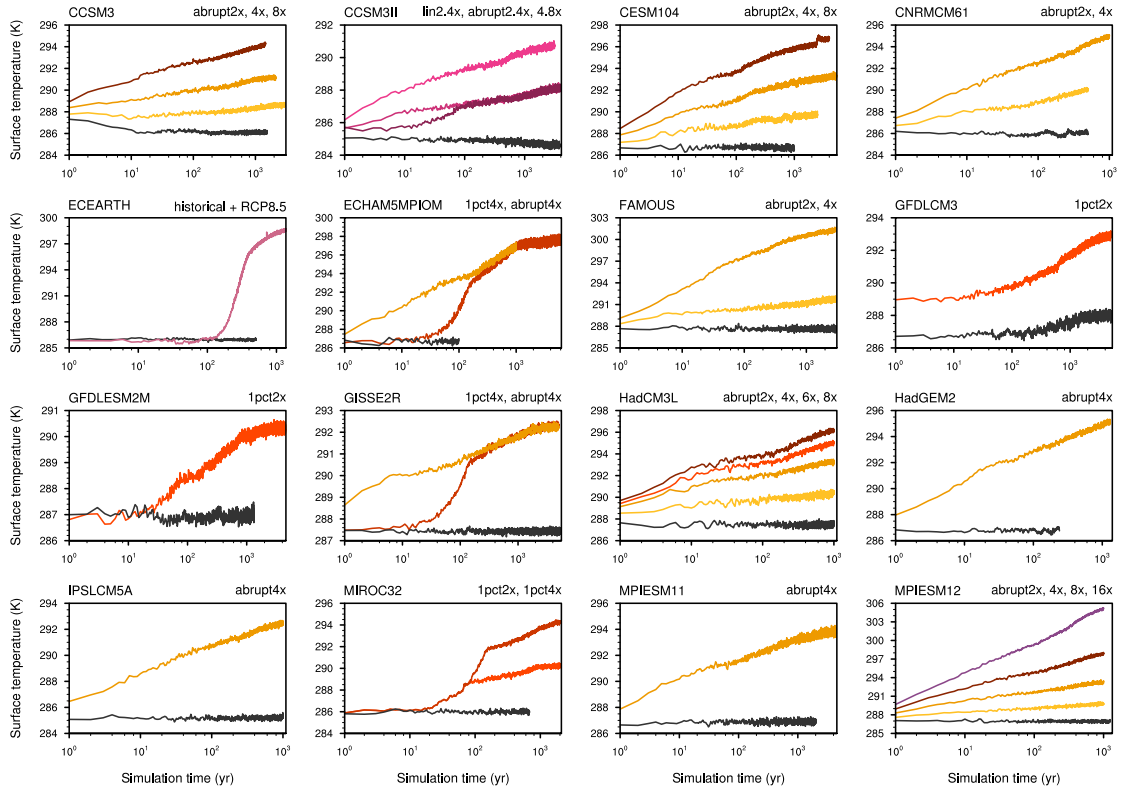
Paper	Model	Forcing level	Length (yr)	Content/scientific comment
Senior and Mitchell (2000)	HadCM2	2xCO ₂	≈ 800	Included flux adjustments; effective climate sensitivity increases due to SW CRE due to changes in the inter-hemispheric temperature gradient
Bi et al. (2001)	CSIRO	3xCO ₂	≈ 1000	Cessation and recovery of Antarctic Bottom Water and North Atlantic Deep Water formation
Voss and Mikolajewicz (2001)	ECHAM3	2x and 4xCO ₂	850	Adjustment time scales, committed warming, ocean thermohaline circulation
Stouffer and Manabe (1999, GFDL 2003)	GFDL	0.5x, 2x, 4xCO ₂	and 4000	Thermohaline circulation and paleo-oceanographic implications
Boer and Yu (2003b,a,c)	CCCma	2050 and forcing	2100 1000	Radiative feedbacks and surface warming; effective climate sensitivity decreases with time; slab versus fully coupled models
Gregory et al. (2004)	HadCM3	2xCO ₂	≈ 1000	TOA radiative imbalance and surface temperature are not linearly related; after 1000 yr the model is still 0.7 W m ⁻² away from equilibrium
* Danabasoglu and Gent (2009)	CCSM3	2x, 4x, and 8xCO ₂	3000	Comparing slab and fully coupled models; determining ECS; Jonko et al. (2013) analyzed the contributions of different feedbacks to doublings of CO ₂
Gillett et al. (2011)	CanESM1	21st century	≈ 1000	Impact of reduced emissions
* Li et al. (2013)	ECHAM5/MPI-OM	2xCO ₂	≈ 6000	Comparing slab and fully coupled models; determining ECS; adjustment time scales of surface warming patterns, ocean heat uptake, and sea level rise
Frölicher et al. (2014); Frölicher and Paynter (2015)	GFDL-ESM2M, CSM1	4xCO ₂ pulse	1000	Climate impact of CO ₂ emission stoppage; evolving feedbacks; ECS; transient climate response to cumulative carbon emissions
* Andrews et al. (2015)	HadGEM2-ES	4xCO ₂	≈ 1300	Non-constancy of feedbacks; variations of TOA components cancel each other on the century to millennial time scale
* Yamamoto et al. (2015); Yoshimori et al. (2016)	MIROC3.2	2x and 4xCO ₂	2000	Deep ocean ventilation overall increases oxygenation after a transient decrease; review article on ocean heat uptake in coupled models and energy balance models
* Cao et al. (2016)	HadCM3L	2x, 4x, 6x, 8xCO ₂	1000	Comparing CO ₂ to other forcing agents and geo-engineering scenarios
* Rugenstein et al. (2016b,a)	CESM104	2x, 4x, 8xCO ₂	≈ 1300	Dependence of global and regional radiative feedback evolution on surface heat flux patterns; forcing adjustment
* Paynter et al. (2018)	GFDL-ESM2M, CM3	GFDL- 2xCO ₂	≈ 5000	Evolution of global and regional radiative feedbacks and the role of atmospheric vertical velocity fields and inversion strengths
* Rind et al. (2018)	GISS-E2-R	4xCO ₂	≈ 2000	AMOC reduction and recovery on North Atlantic surface flux conditions
Krasting et al. (2018)	GFDL-ESM2Mb, GFDL-ESM2G	4xCO ₂	5000	Ocean heat uptake, model formulation of diapycnal diffusivity and ocean vertical coordinates

LIST OF FIGURES

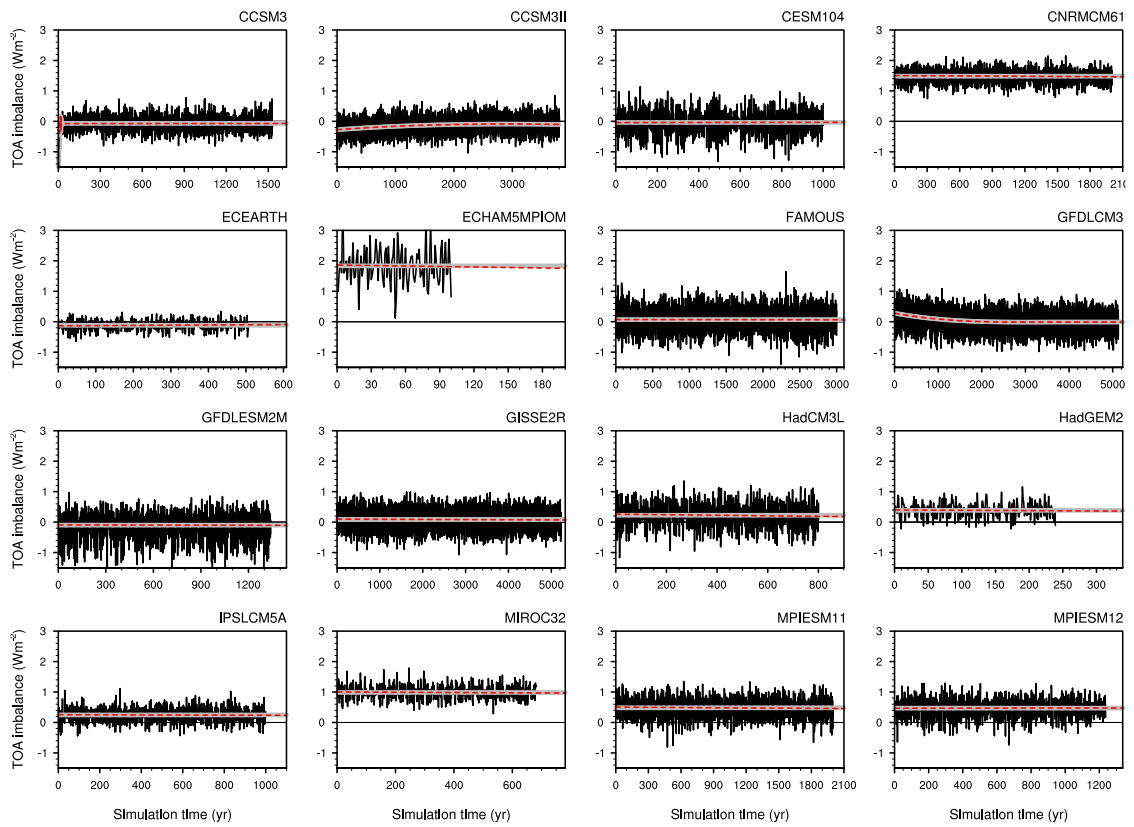
834		
835	Fig. 1.	Global and annual mean surface air temperature (<i>tas</i> in Table 1) anomaly and top of the
836		atmosphere (TOA) radiative imbalance (computed as $rsdt - rlut - rsut$, see Table 1) to a step-
837		forcing of quadrupling CO ₂ as simulated by the CESM104 model. For the Coupled Model
838		Intercomparison Project Phase 5 and 6, this simulation is part of the standard protocol, but
839		only 150 simulated years are requested (blue shading). We collect simulations that extended
840		this experiment for at least 850 years (light red shading), ideally until they are equilibrated
841		(end of dark red shading). 43
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844		tration is doubled, quadrupled, sextupled, octupliated, as a step-forcing branched off the
845		control simulation. <i>1pct2x</i> and <i>1pct4x</i> means the CO ₂ concentration is linearly increased
846		1 % per year until the concentration is doubled or quadrupled, respectively. The simula-
847		tions of ECEARTH and CCSM3II are described in Section b. Note the different axis ranges
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858		the time scale in c) is shorter than in a) and b) 46
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863		and g, due to the length of these contributions. See Table 2 for details of the length of each
864		simulation. 47
865	Fig. 6.	Time evolution of the zonal mean surface air temperature response normalized by the global
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867		relative to the globally mean warming (a-d). Panel e-g show the differences (note the differ-
868		ence scale) . Panel a, b, e, and f contain only <i>abrupt4x</i> simulations, while panel c, d, and g
869		also contain the <i>1pct2x</i> and <i>RCP8.5+</i> simulations with integration lengths above 4000 years.
870		Table 2 lists all simulations and model long names. 48
871	Fig. 7.	Simulated shortwave cloud radiative effects SW CRE for different levels of global surface
872		air temperature changes. Each point is a ten-year running average. Note the different axes
873		labels, which cover a large range in TOA imbalance and surface temperature. Table 2 lists
874		all simulations and model long names. 49



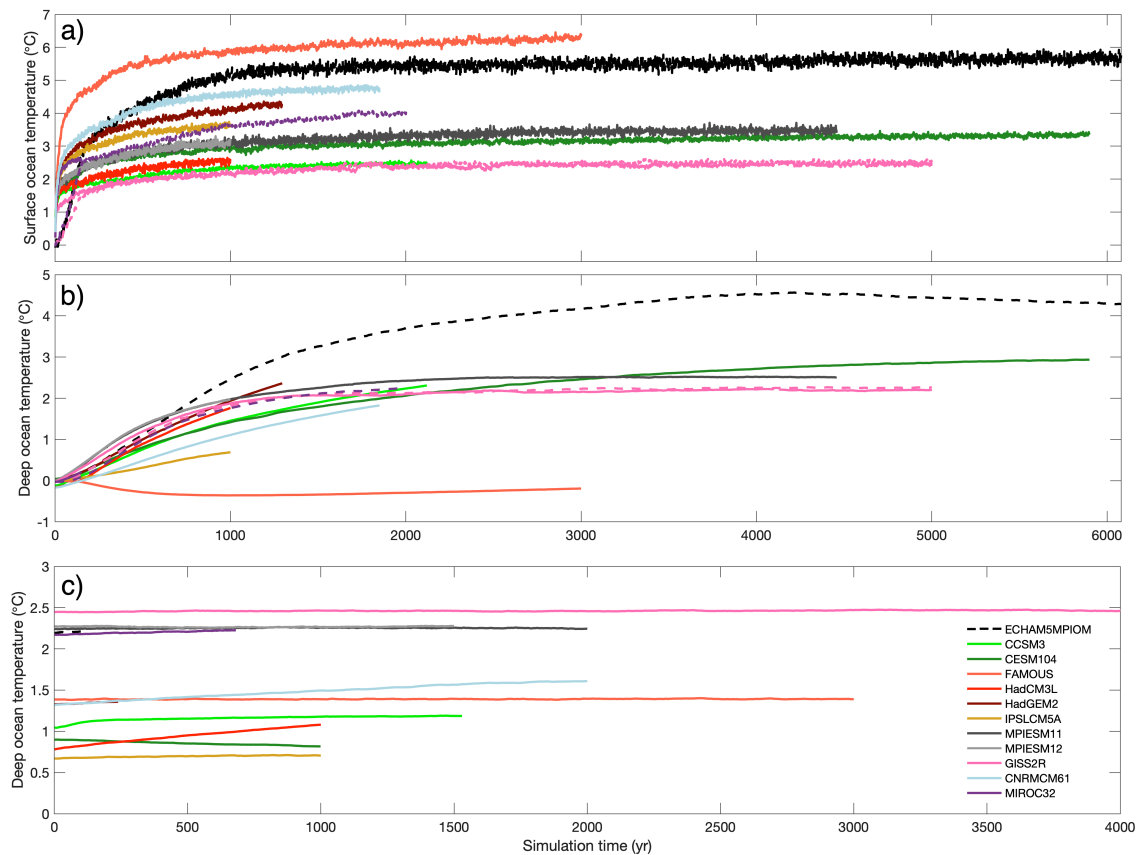
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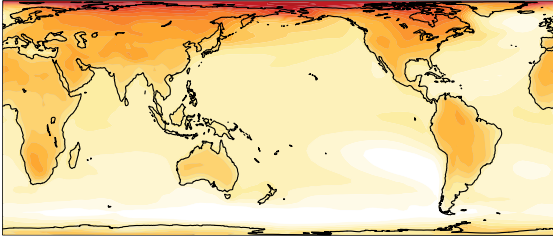


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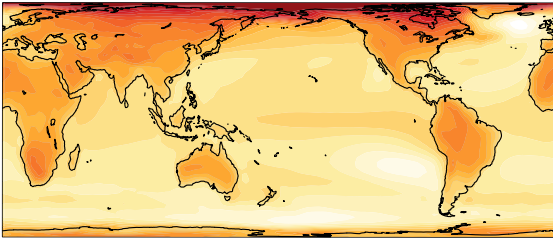


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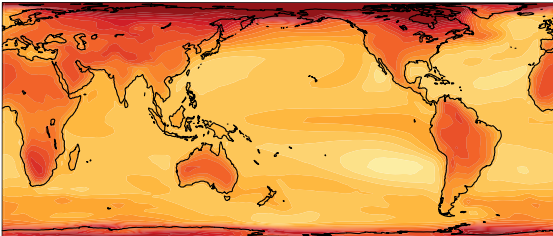
a) Temperature anomaly year 15-25



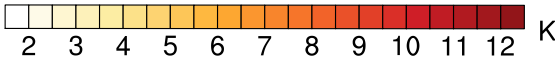
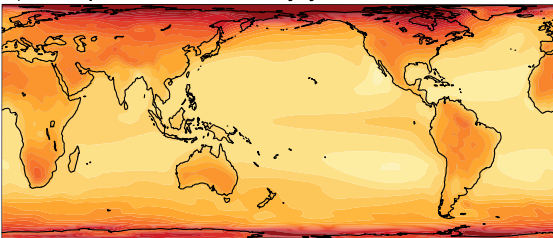
b) Temperature anomaly year 80-120



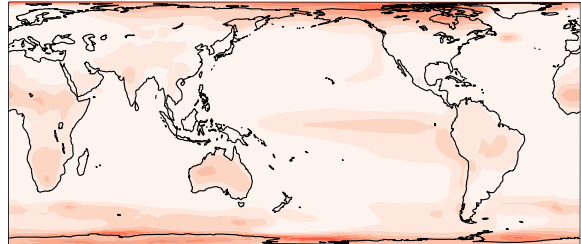
c) Temperature anomaly year 900-1000



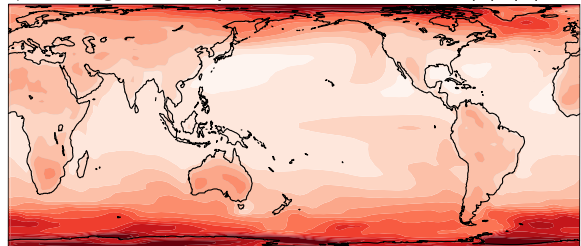
d) Temperature anomaly year 4000-4200



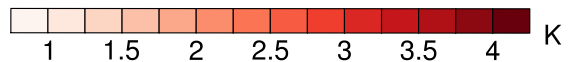
e) Change in temperature anomalies (b)-(a)



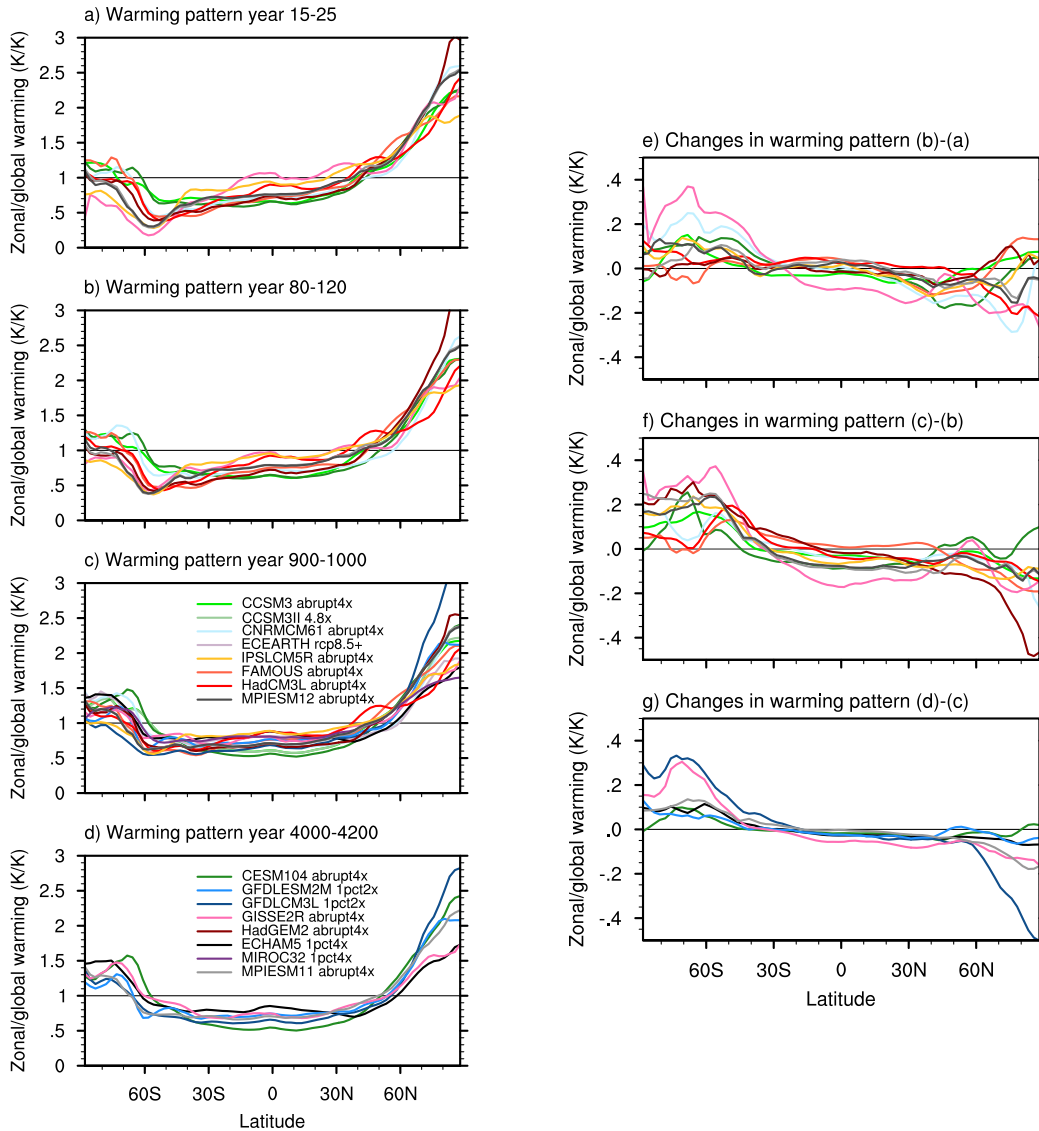
f) Change in temperature anomalies (c)-(b)



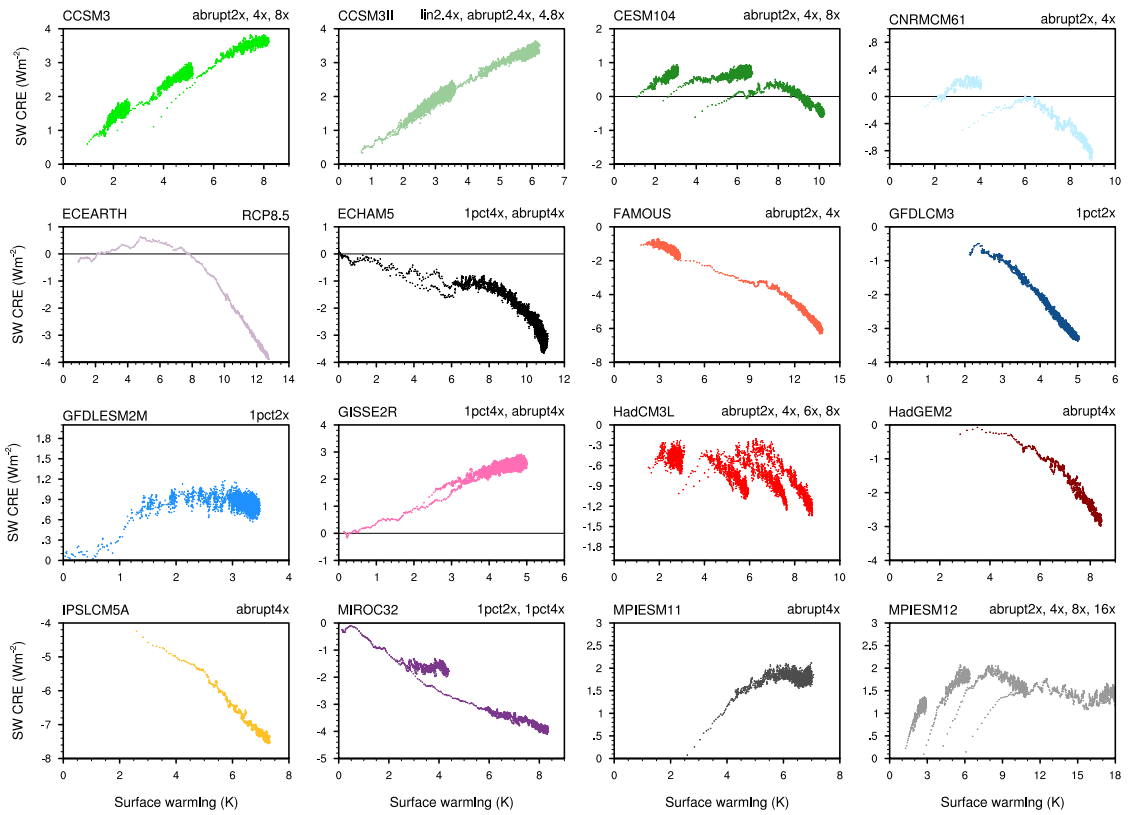
g) Change in temperature anomalies (d)-(c)



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904 FIG. 7. Simulated shortwave cloud radiative effects **SW CRE** for different levels of global surface air tem-
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