



Long-Term Climate Change Commitment and Reversibility: An EMIC Intercomparison

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(Manuscript received 30 July 2012, in final form 5 February 2013)

ABSTRACT

This paper summarizes the results of an intercomparison project with Earth System Models of Intermediate Complexity (EMICs) undertaken in support of the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5). The focus is on long-term climate projections designed to 1) quantify the climate change commitment of different radiative forcing trajectories and 2) explore the extent to which climate change is reversible on human time scales. All commitment simulations follow the four representative concentration pathways (RCPs) and their extensions to year 2300. Most EMICs simulate substantial surface air temperature and thermocline sea level rise commitment following stabilization of the atmospheric composition at year-2300 levels. The meridional overturning circulation (MOC) is weakened temporarily and recovers to near-preindustrial values in most models for RCPs 2.6–6.0. The MOC weakening is more persistent for RCP8.5. Elimination of anthropogenic CO₂ emissions after 2300 results in slowly decreasing atmospheric CO₂ concentrations. At year 3000 atmospheric CO₂ is still at more than half its year-2300 level in all EMICs for RCPs 4.5–8.5. Surface air temperature remains constant or decreases slightly and thermocline sea level rise continues for centuries after elimination of CO₂ emissions in all EMICs. Restoration of atmospheric CO₂ from RCP to preindustrial levels over 100–1000 years requires large artificial removal of CO₂ from the atmosphere and does not result in the simultaneous return to preindustrial climate conditions, as surface air temperature and sea level response exhibit a substantial time lag relative to atmospheric CO₂.

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DOI: 10.1175/JCLI-D-12-00584.1

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1. Introduction

This paper summarizes the results of a model intercomparison project undertaken in support of the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC). Fifteen groups running Earth System Models of Intermediate Complexity (EMICs) participated in the intercomparison. Coordinated experiments include simulations of the climate of the past millennium and simulations of long-term future climate change, in addition to a set of idealized experiments. This paper discusses the future climate projections (performed by 12 modeling groups), while the idealized and last-millennium simulations are the focus of a separate paper (Eby et al. 2013). The goals of the future climate simulations are 1) to quantify the long-term climate change commitment in response to different radiative forcing trajectories and 2) to explore the extent to which climate change is reversible if atmospheric CO₂ is left to evolve freely or is artificially restored to pre-industrial levels.

Climate change commitment refers to the climate changes that are to be expected in the future in response to past human activities. The concept of commitment is tied to the thermal inertia of the climate system (Hansen et al. 1985), which causes the effects of greenhouse gas emissions to be felt beyond the duration of those emissions. Climate change commitment is a useful metric for climate science and policy, as it quantifies the minimum climate change humanity faces and represents a benchmark against which to measure the effect of future emissions. Most studies consider the “warming commitment,” but here we use the broader term “climate change commitment” to include other aspects of climate change such as sea level rise (Wigley 2005).

Different forms of climate change commitment have been discussed in the literature. The most prominent is the “constant composition” commitment, which refers to the climate changes that are to be expected after stabilization of the chemical composition of the atmosphere, and hence the radiative forcing, at a specified level (Wigley 2005; Meehl et al. 2005; Hare and Meinshausen 2006). This commitment was highlighted in the IPCC Fourth Assessment Report (AR4) and has been estimated at between 0.3° and 0.9°C for the period 2090–99 relative to 1980–99 if the atmospheric composition is stabilized at year 2000 levels (Meehl et al. 2007).

Another type of commitment, which has received greater attention more recently, is the “zero emission” commitment, which is the warming that is to be expected after complete elimination of emissions (Hare and Meinshausen 2006; Matthews and Caldeira 2008; Plattner et al. 2008; Eby et al. 2009; Lowe et al. 2009; Frölicher and

Joos 2010; Solomon et al. 2010; Gillett et al. 2011; Zickfeld et al. 2012; Matthews and Zickfeld 2012). Most studies have explored the climate response to elimination of CO₂ emissions only. These studies have shown that instantaneous elimination of CO₂ emissions results in approximately constant global mean temperature for several centuries after emissions cease. When emissions of non-CO₂ greenhouse gases and aerosols also cease (Hare and Meinshausen 2006; Solomon et al. 2010; Frölicher and Joos 2010; Armour and Roe 2011; Matthews and Zickfeld 2012), the climate warms for about a decade and then gradually cools. The initial warming is due to the fast elimination of the negative radiative forcing associated with aerosols, which have a short atmospheric residence time. Greenhouse gases, on the other hand, have a longer atmospheric lifetime and their concentration and associated radiative forcing decline gradually after elimination of emissions. After about a century, the response is largely dominated by the long-lived CO₂ and global mean temperature converges to that obtained under elimination of CO₂ emissions alone. Matthews and Weaver (2010) argue that the zero emission commitment is a more useful measure of climate change commitment because it does not convolute the physical response of the climate system to past emissions with the response to future emissions that are needed to maintain the atmospheric CO₂ concentration at stable levels, as for the constant composition commitment.

Another form of climate change commitment is the “constant emissions” commitment, which refers to the climate changes to be expected in response to constant anthropogenic emissions (Wigley 2005; Hare and Meinshausen 2006). This type of commitment is less prominently discussed in the literature. A study with a simple climate model [the Model for the Assessment of Greenhouse Gas-Induced Climate Change (MAGICC)] estimates the constant emissions commitment at 1.4°–2.7°C by 2100 (above preindustrial) assuming constant year-2005 emissions (Hare and Meinshausen 2006).

The second set of experiments that is part of this model intercomparison is aimed at exploring the extent to which the climate system can revert to “safe” levels, should climate change impacts turn out to be “dangerous.” Insight gained from zero emission commitment simulations suggests that because of the long residence time of CO₂ in the atmosphere (Archer and Brovkin 2008; Eby et al. 2009) and the large thermal reservoir of the ocean, complete elimination of emissions can at best lead to stable or slowly decreasing temperatures. If permafrost carbon feedbacks are considered, elimination of emissions could lead to a continuing increase in temperature (MacDougall et al. 2012). Therefore, restoring temperature to lower levels in a time frame meaningful to

human societies can only be accomplished with “negative emissions” (i.e., net removal of carbon dioxide from the atmosphere). Such negative emissions can be achieved, for instance, by biomass energy in combination with capture and geological storage of the emitted CO₂ (BECS; Azar et al. 2006), or by CO₂ “scrubbers” that remove the CO₂ directly from the atmosphere (Keith et al. 2006).

Few studies to date have explored the response of the climate system to scenarios with negative emissions or “overshoot” scenarios (Yoshida et al. 2005; Tsutsui et al. 2007; Nusbaumer and Matsumoto 2008; Zickfeld et al. 2012). Most of these studies use idealized scenarios, such as atmospheric CO₂ increasing gradually to 2 or 4 times the preindustrial level and then decreasing at a similar rate (Held et al. 2010; Boucher et al. 2012). These studies suggest that because of the long time scales of components of the climate system, global mean temperature, precipitation, ocean heat content, and other quantities lag the forcing and revert to the target level only slowly. The residual change (i.e., the difference between the target and the actual level) increases with the level of peak forcing (Held et al. 2010; Boucher et al. 2012). The idealized scenarios used in these papers, which entail large and abrupt decreases in atmospheric CO₂, imply levels of negative emissions that are likely beyond known technological capabilities (McGlashan et al. 2012). The set of scenarios used for phase 5 of the Coupled Model Intercomparison Project (CMIP5; Taylor et al. 2012) includes one scenario with moderate negative emissions that is based on plausible technological and economic assumptions [representative concentration pathway (RCP) 2.6; Moss et al. (2010)].

In this paper, we analyze multicentury constant composition, zero emission, and constant emissions commitment simulations with EMICs under a range of radiative forcing scenarios. In addition, we investigate the EMICs’ response to a set of reversibility scenarios, whereby atmospheric CO₂ is artificially restored to preindustrial levels, or is left to evolve freely after a millennium of constant radiative forcing. Finally, we explore the cumulative CO₂ emissions that are compatible with climate stabilization targets using inverse simulations with two EMICs.

The paper is organized as follows. In section 2 we briefly introduce the EMICs that participated in the model intercomparison and describe the experimental setup. In section 3 the results of the model simulations are presented and discussed with reference to the literature. The section starts with a discussion of the ability of EMICs to simulate the climate of the twentieth century, continues with a description of the results of the climate change commitment and reversibility simulations, and ends with a discussion of cumulative emissions compatible

with long-term climate targets. Section 4 presents a summary and conclusions.

2. Methods

a. Participating models

This study includes results from 12 EMICs, eight of which are coupled climate–carbon cycle models. The models are the University of Bern 3D Earth system model with Lund–Potsdam–Jena dynamic global vegetation (Bern3D-LPJ; Ritz et al. 2011; Stocker et al. 2011), versions 2.4 and 3 α of the Potsdam Institute Climate and Biosphere Model (CLIMBER-2.4, CLIMBER-3 α ; Petoukhov et al. 2000; Montoya et al. 2005), version 1.0 of the Danish Center for Earth System Science (DCESS) Earth system model (Shaffer et al. 2008), release 2.2.7 of the Grid Enabled Integrated Earth system model (GENIE) adapted with an implementation of land use change (Holden et al. 2013), the A. M. Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences, climate model (IAP RAS CM; Eliseev and Mokhov 2011), version 2.2 of the Massachusetts Institute of Technology’s Integrated Global System Model (IGSM2.2; Sokolov et al. 2005), version 1.2 of the Loch–Vecode–Ecbilt–Clio–Agism Model (LOVECLIM 1.2; Goosse et al. 2010), version 1.0 of the Minnesota Earth System Model for Ocean biogeochemistry (MESMO 1.0; Matsumoto et al. 2008), the Model for Interdisciplinary Research on Climate (MIROC)-lite-LCM (loosely coupled model; Tachiiri et al. 2010), version 2.0 of the University of Maryland (UMD) Coupled Atmosphere–Biosphere–Ocean model (Zeng et al. 2004), and version 2.9 of the University of Victoria Earth System Climate Model (UVic ESCM 2.9; Weaver et al. 2001; Eby et al. 2009). The characteristics of each model are briefly described in the EMIC intercomparison companion paper (Eby et al. 2013).

A common trait of these models is that they are simplified; that is, they include processes in a more parameterized form and have generally lower resolution compared to atmosphere–ocean general circulation models (AOGCMs) and complex Earth system models (ESMs). The group of EMICs, however, is very heterogeneous, ranging from zonally averaged (Petoukhov et al. 2000) or mixed layer ocean models (Sokolov et al. 2005) coupled to statistical–dynamical models of the atmosphere to low-resolution 3D ocean general circulation models coupled to simplified dynamical models of the atmosphere (Goosse et al. 2010). Eight out of the 12 models include an interactive carbon cycle (Bern3D-LPJ, DCESS, GENIE, IGSM2.2, MESMO, MIROC-lite-LCM, UMD, and UVic). Of these, several models calculate land use emissions internally (Bern3D-LPJ,

DCESS, GENIE, IGSM 2.2, MIROC-lite-LCM, and UVic) and/or represent seafloor sediment processes, including deep water carbonate sedimentation (Bern3D-LPJ, DCESS, GENIE, and UVic).

b. Experimental design

Most models were spun up with year-850 forcing. The models were then integrated from 850 to 2005 using known natural (orbital, volcanic, and solar) and anthropogenic (greenhouse gas, aerosol, and land cover change) forcing, following phase three of the Paleoclimate Modelling Intercomparison Project (PMIP3)/CMIP5 protocol. Details on the implementation of these forcings in individual EMICs is provided in the appendix of the EMIC intercomparison companion paper (Eby et al. 2013). Note that in this paper we only consider the 1850–2005 portion of the last millennium simulation (henceforth referred to as the “historical” or HIST simulation). The full simulation is discussed in detail in Eby et al. (2013). The MIROC-lite-LCM model was spun up with year-1850 forcing and integrated from 1850 to 2005.

Starting from the end point of the historical simulation, models were integrated with CO₂ concentration and non-CO₂ greenhouse gas forcing specified according to four RCPs (from 2006 to 2100) and their extensions (to 2300) (Meinshausen et al. 2011). Aerosol forcing (direct effect) and land cover change followed RCP specifications until 2100 and were held constant thereafter. Natural forcings were specified as follows: orbital forcing was held fixed at year-2005 levels, solar irradiance was set to repeat the last solar cycle (1996–2008), and volcanic forcing was set to zero. The atmospheric CO₂ concentration of the four RCPs (RCP2.6, RCP4.5, RCP6.0, and RCP8.5) and their extensions is shown in Fig. 1.

From year 2301 to 3000 a set of climate change commitment simulations was performed for all four RCPs. In the constant composition (CCO) commitment simulations, atmospheric CO₂ concentration and the forcing from non-CO₂ greenhouse gases were held constant at year-2300 levels. Other forcings were held fixed at the level specified for the RCP simulations. A slightly different simulation protocol was followed for the MIROC-lite-LCM, with constant solar forcing after 2300 (no solar cycle). EMICs with a carbon cycle diagnosed the CO₂ emissions compatible with the specified CO₂ concentration trajectories.

The commitment runs described in the following were performed with climate–carbon cycle models only. In a second set of simulations, which we designate as the preindustrial CO₂ emission (PIEM-CO₂) commitment experiments, the “anthropogenic CO₂ perturbation”—defined as the difference in implied CO₂ emissions

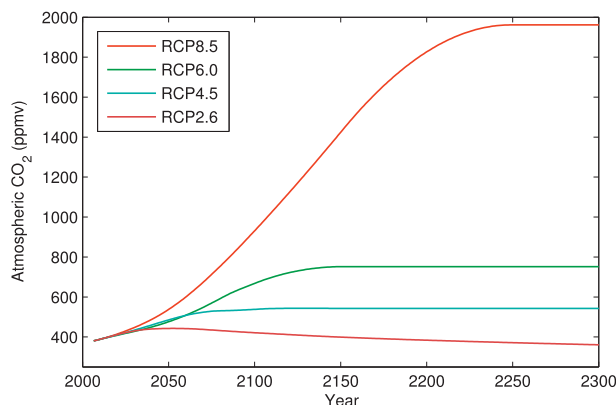


FIG. 1. Time evolution of atmospheric CO₂ between 2006 and 2300 for the four RCPs and their extensions (RCP database version 2.0; <http://tntcat.iiasa.ac.at:8787/RcpDb/>).

between the last decade of the RCP simulations (2290–2300) and the decade 1840–50 of the historical simulation—was set to zero starting in 2300, while the radiative forcing from non-CO₂ greenhouse gases was held fixed at year-2300 levels. Other forcings were held fixed at the level specified for the RCP simulations. For the GENIE model, CO₂ emissions were set to zero after 2300. It should be noted that in most models, setting the anthropogenic perturbation to zero did not result in zero emissions exactly. The reason is that the 1840–50 land–atmosphere and ocean–atmosphere CO₂ fluxes in response to forcing are not exactly consistent with the specified atmospheric CO₂. Diagnosed emissions are negative in all models (except UMD), implying a flux of CO₂ from the land and ocean to the atmosphere. Processes responsible for the excess emissions could be the warming recovery after volcanic eruption, or land use change.

In the preindustrial emission (PIEM) simulations, CO₂ emissions after 2300 were specified as in the PIEM-CO₂ simulation, but the radiative forcing from non-CO₂ greenhouse gases was set to 1840–50 average levels. Other forcings were held fixed at the level specified for the RCP simulations.

In the constant emission (CEM) commitment simulations, implied CO₂ emissions over the last decade of the RCP integrations (years 2290–2300) were diagnosed, and held fixed at this value from year 2300 onward. Radiative forcing from non-CO₂ greenhouse gases was held constant at year-2300 levels and other forcings were held fixed at the level specified for the RCP simulations.

In addition to the commitment simulations, a set of reversibility runs (RE) was also performed by several EMIC groups. These simulations start from the year-3000 model configuration of the CCO experiments and extend to the year 4000. In the first experiment (REa),

TABLE 1. Model experiments.

| Expt | Simulation | Timeframe | CO ₂ forcing | Non-CO ₂ greenhouse gas forcing | No. of models |
|----------------------|--|-----------|---|--|---------------|
| HIST | Historical | 1850–2005 | CMIP5 concentration | CMIP5 forcing | 12 |
| RCP | Representative concentration pathways and extensions | 2006–2300 | CMIP5 concentration | CMIP5 forcing | 12 |
| CCO | Constant composition commitment | 2301–3000 | Constant year-2300 concentration | Constant year-2300 forcing | 12 |
| PIEM-CO ₂ | Preindustrial CO ₂ emission commitment | 2301–3000 | Constant 1840–50 emissions | Constant year-2300 forcing | 7 |
| PIEM | Preindustrial emission commitment | 2301–3000 | Constant 1840–50 emissions | Constant 1840–50 forcing | 7 |
| CEM | Constant emission commitment | 2301–3000 | Constant 2290–2300 emissions | Constant year-2300 forcing | 7 |
| REa | Reversibility a | 3001–4000 | Linear decrease in concentration over 100 yr | Constant year-2300 forcing | 11 |
| REb | Reversibility b | 3001–4000 | Linear decrease in concentration over 1000 yr | Constant year-2300 forcing | 11 |
| REc | Reversibility c | 3001–4000 | Zero emissions | Constant year-2300 forcing | 7 |
| TTR | Temperature tracking | 2005–2500 | Diagnosed | Linear decrease to zero by 2300 | 2 |

atmospheric CO₂ decreases linearly to the preindustrial level over 100 yr, while non-CO₂ forcings are held fixed at year-3000 levels. Forcing specifications are similar in the second experiment (REb), except that CO₂ is prescribed to decrease to preindustrial levels over a period of 1000 yr. In the third experiment (REc), atmospheric CO₂ is allowed to evolve freely (zero CO₂ emissions) and non-CO₂ forcings are again held fixed at year-3000 levels. The REc experiments with freely evolving atmospheric CO₂ were performed by EMICs with an interactive carbon cycle only.

Finally, a set of simulations was carried out whereby a temperature stabilization trajectory was specified, and the cumulative emissions consistent with that temperature trajectory were calculated, following the inverse modeling approach described in Zickfeld et al. (2009). Four temperature tracking (TTR) simulations were performed, with global mean surface air temperatures stabilizing at 1.5°, 2°, 3°, and 4°C warming relative to preindustrial. The simulations started from the end of the historical simulation and were integrated to year 2500. Natural forcings were specified as in the RCP simulations. Land use change was held constant at the year-2005 pattern, whereas non-CO₂ greenhouse gas and aerosol forcing linearly decreased from year-2005 values to zero by 2300. All model simulations are summarized in Table 1.

3. Results and discussion

a. Historical simulation

The performance of EMICs over the historical period is discussed in detail in Eby et al. (2013). Here, we briefly summarize the main findings to allow the reader to put the EMICs' future projections and their uncertainty ranges into perspective.

Over the twentieth century EMICs simulate a model ensemble mean warming of 0.78°C (range: 0.4°–1.2°C), compared to the observed warming of 0.73°C (Morice et al. 2013) over the same period (Table 2). Five models stay mostly within the observational uncertainty envelope for this period, five tend to overestimate the observed warming, and two tend to underestimate it (see Fig. 1b of Eby et al. 2013). The spread in the models is a result of different climate sensitivities and differences in the specification of radiative forcing, particularly from land use change and tropospheric aerosols (Eby et al. 2013).

EMICs simulate a model-mean rate of ocean thermal expansion for 1955–2010 of 0.9 mm yr⁻¹ compared to the observations-based estimate of 0.54 mm yr⁻¹ for the upper 0–2000 m of the world ocean (Levitus et al. 2012). Most EMICs overestimate the observed rate of thermal expansion. The observed trend is for the upper 0–2000 m of the ocean only, whereas the modeled estimates are for the entire ocean, but the contribution of the deep ocean to the thermal expansion trend [0.11 mm yr⁻¹ for 1992–2005; Purkey and Johnson (2010)] is unlikely to explain the entire difference. Ocean thermal expansion is determined by both the models' heat uptake efficacy and climate sensitivity, which differ largely between models (see Table 2 of Eby et al. 2013).

The atmospheric CO₂ concentration was specified in the historical simulation and EMICs with an interactive carbon cycle were used to diagnose the CO₂ emissions compatible with the specified CO₂ concentrations. The average EMIC carbon cycle response for the 1990s is within the uncertainty range of observed values (Denman et al. 2007), except for diagnosed emissions, which are slightly underestimated (Table 2). Ocean fluxes simulated

TABLE 2. Changes in climate and carbon cycle variables from EMIC historical simulations and observations. Shown are the warming over the twentieth century (ΔT), the rate of thermosteric sea level rise averaged over 1971–2010 (SLR_{th}), the carbon fluxes averaged over 1990–99, and cumulative fluxes from 1800 to 1994. Here $Land_{LUC}$ are land-use change fluxes from simulations with land-use forcing only (see Eby et al. 2013); $Land_{RES}$ is the residual land flux, which is derived as the difference between the land flux from the historical simulation with all forcings and $Land_{LUC}$. Carbon fluxes are positive when directed into the atmosphere. Observation-based estimates are from Morice et al. (2013) for the twentieth-century warming, Levitus et al. (2012) for 1955–2010 thermal expansion for the 0–2000-m layer of the World Ocean, Denman et al. (2007, their Table 7.1) for the 1990s carbon fluxes, and Sabine et al. (2004) for the cumulative carbon fluxes.

| Model | ΔT ($^{\circ}C$) | SLR_{th} ($mm\ yr^{-1}$) | 1990s carbon fluxes ($PgC\ yr^{-1}$) | | | | Cumulative fluxes 1800–1994 (PgC) | | |
|-------------------------|----------------------------|---------------------------------|--|-------------------|-------------------|------------|---------------------------------------|------------------|------------------|
| | | | $Land_{LUC}$ | $Land_{RES}$ | Ocean | Emissions | Land | Ocean | Emissions |
| Bern3D-LPJ | 0.57 | 0.60 | 0.7 | −0.8 | −1.8 | 5.2 | 108 | −104 | 167 |
| CLIMBER-2 | 0.91 | 1.38 | — | — | — | — | — | — | — |
| CLIMBER-3 | 0.91 | 1.29 | — | — | — | — | — | — | — |
| DCESS | 0.84 | 0.89 | 0.3 | −0.9 | −1.8 | 5.7 | 4 | −102 | 260 |
| GENIE | 1.00 | 0.85 | 0.5 | −1.4 | −2.1 | 6.1 | 21 | −114 | 251 |
| IAP RAS CM | 0.80 | — | — | — | — | — | — | — | — |
| IGSM | 0.70 | 0.43 | 0.3 | −0.7 | −2.2 | 5.9 | 43 | −122 | 237 |
| LOVECLIM | 0.38 | 0.51 | — | — | — | — | — | — | — |
| MESMO | 1.15 | 0.95 | — | −0.6 | −1.9 | 5.9 | −28 | −102 | 305 |
| MIROC-lite-LCM | 0.70 | 0.69 | — | −0.1 ^a | −1.6 | 5.4 | 108 ^b | −86 ^b | 140 ^b |
| UMD | 0.79 | 1.33 | — | −0.6 | −2.4 | 6.2 | −51 | −136 | 344 |
| UVic | 0.75 | 1.18 | 1.3 | −1.2 | −2.0 | 5.2 | 24 | −112 | 244 |
| EMIC mean ^c | 0.78 ^d | 0.92 | 0.6 | −1.0 | −1.9 ^d | 5.6 | 40 | −111 | 233 |
| EMIC range ^c | 0.38 to 1.15 | 0.43 to 1.38 | 0.3 to 1.3 | −1.4 to −0.7 | −2.2 to −1.6 | 5.2 to 6.1 | 4 to 108 | −122 to −102 | 156 to 258 |
| Observed | 0.73 | 0.54 | 1.6 | −2.6 | −2.2 | 6.4 | 39 | −118 | 244 |
| Uncertainty | | 0.49 to 0.59 | 0.5 to 2.7 | −4.3 to −0.9 | −2.6 to −1.8 | 6.0 to 6.8 | 11 to 67 | −137 to −99 | 224 to 264 |

^a Land use change fluxes could not be diagnosed for this model because of the lack of a historical simulation with land use change forcing only.

^b Cumulative fluxes for this model are for 1851–1994.

^c The MESMO and UMD models were excluded from the EMIC mean and range for the carbon cycle variables because they did not simulate land use change fluxes. Only the total land flux is reported for these models. The MIROC-lite-LCM model was excluded from the EMIC mean and range for the 1800–1994 cumulative fluxes because no carbon flux data were available prior to 1851.

^d These values differ slightly from those reported in Eby et al. (2013) because of a different subset of EMICs included in the calculation.

by all but one EMIC are within the uncertainty range of observed values. Although the EMIC average land fluxes fall within the large range of uncertainty, several models underestimate both the land use change flux and the residual land flux (i.e., the total land–atmosphere flux minus the land use change flux).

The EMICs' cumulative carbon fluxes from 1800 to 1994 are compared to estimates from Sabine et al. (2004). Again, all models estimate total ocean uptake within the uncertainty range of observed values (Table 2). Land uptake differs substantially between models, with only half of the models' simulated fluxes falling within the estimated uncertainty range. EMICs whose land flux agrees well with observation also simulate 1800–1994 cumulative emissions within the observed range. Overall, the twentieth-century climate and carbon cycle response simulated by EMICs agrees reasonably well with observations, which supports the use of EMICs to project long-term climate change and to complement more complex AOGCMs and ESMs.

b. Constant composition commitment

Figure 2 shows the time evolution of physical climate variables for the constant composition commitment simulations. At the multicentury time scale considered in this study, the warming depends strongly on the forcing scenario, being highest in RCP8.5 and lowest in the low-emission RCP2.6 scenario. Following the radiative forcing the model ensemble mean temperature under the RCP2.6 scenario peaks at year 2070 and declines until reaching a minimum in 2300, after which it slowly increases again. Global mean temperature under RCP2.6 peaks at 1.0 $^{\circ}C$ relative to 1986–2005 in the ensemble mean (model range: 0.6 $^{\circ}$ –1.4 $^{\circ}C$) and decreases to 0.6 $^{\circ}C$ (0.2 $^{\circ}$ –1.1 $^{\circ}C$) at 2300. Assuming an observed warming of 0.7 $^{\circ}C$ between 1850 and 2005, the ensemble mean peak and year-2300 warming are 1.7 $^{\circ}$ and 1.3 $^{\circ}C$ above preindustrial, respectively. In a few models, however, peak warming exceeds 2.0 $^{\circ}C$ relative to preindustrial (Fig. 3).

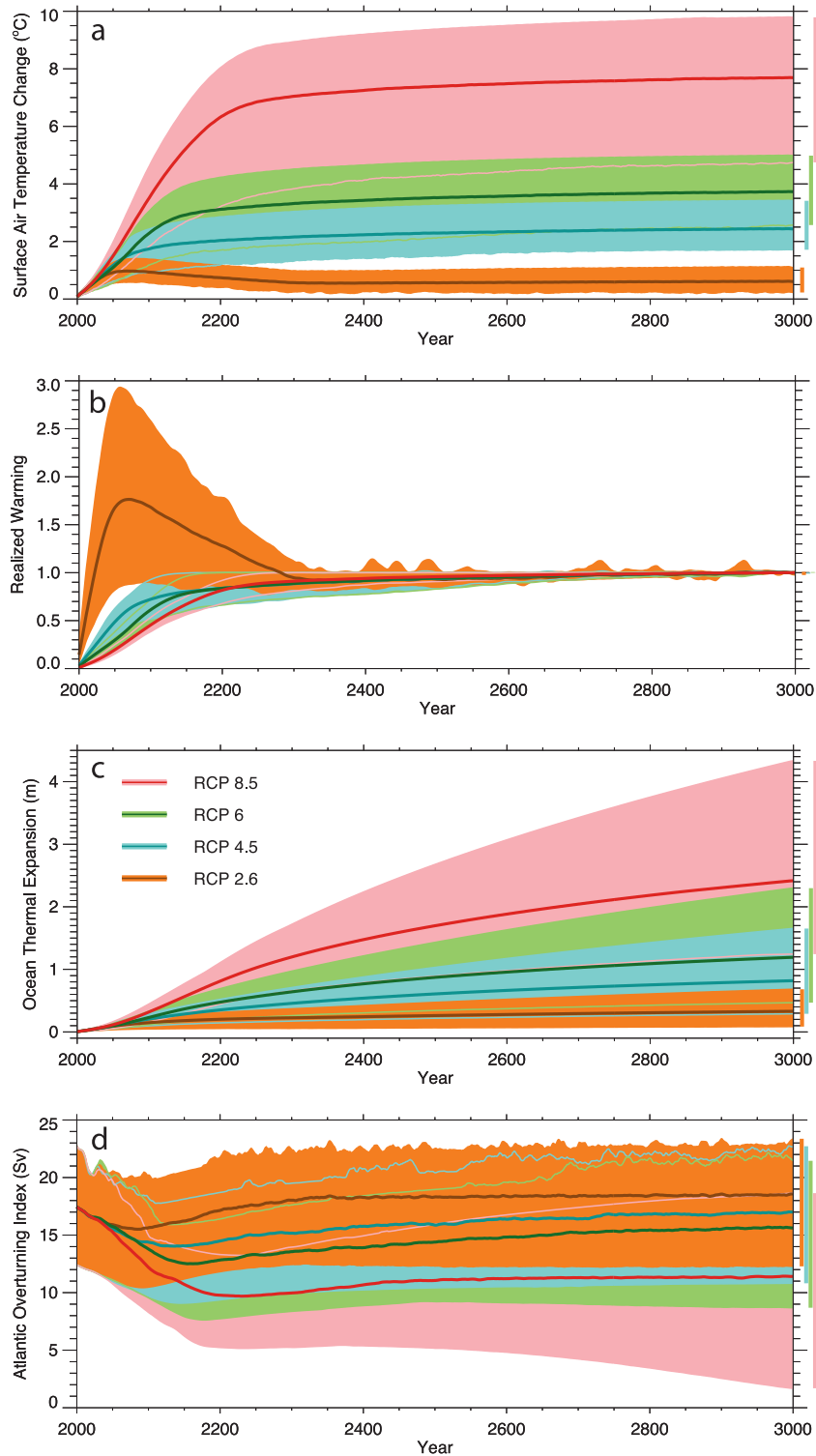


FIG. 2. Time evolution of physical climate variables for the CCO commitment simulations under the four RCP scenarios: (a) surface air temperature change, (b) the fraction of realized warming (calculated as the ratio of warming at any time to the warming averaged over 2981–3000), (c) ocean thermal expansion, and (d) the Atlantic overturning index, defined as the maximum value of the overturning streamfunction in the North Atlantic. Anomalies are relative to 1986–2005. Shown are the model ensemble averages (thick solid lines), the ranges spanned by all models (shaded domains, delimited by thin solid lines), and the range in the year 3000 (vertical bars on right side). Data were smoothed using a 10-yr moving average.

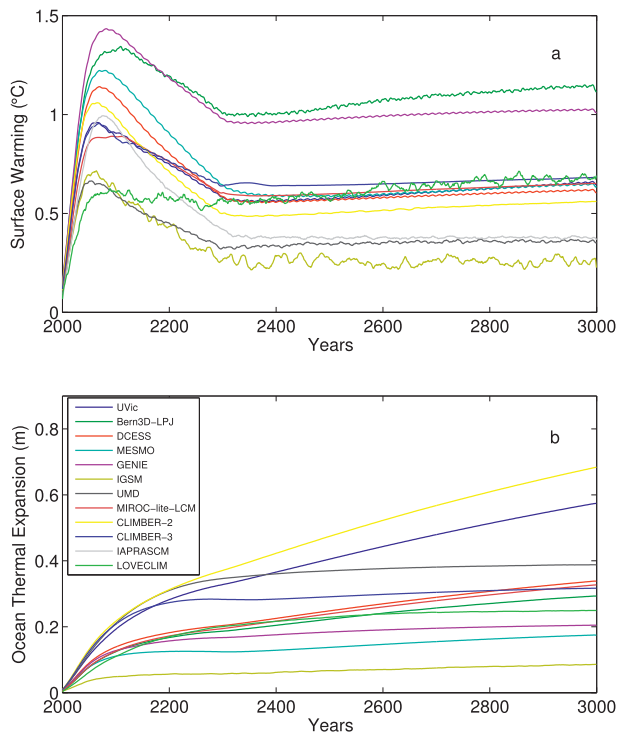


FIG. 3. RCP2.6 CCO commitment simulations: (a) surface air temperature change and (b) ocean thermal expansion. Anomalies are relative to 1986–2005. Data in (a) were smoothed using a 10-yr moving average.

Under the other RCP scenarios (RCP4.5, RCP6.0, and RCP8.5) the global temperature increases rapidly until the time of stabilization of the forcing, and more slowly thereafter. By 2300, global warming approaches 2.2°C under RCP4.5, 3.3°C under RCP6.0, and 7.0°C under RCP8.5 in the ensemble mean (relative to 1986–2005). The ensemble means and model ranges are generally consistent with those simulated by AOGCMs and ESMs contributing to the CMIP5 (Table 3).

Most EMICs simulate a considerable warming commitment following stabilization of radiative forcing at year-2300 levels. The continuing albeit slower warming after stabilization is a well-known feature of climate models and is associated with the large thermal inertia of the ocean (Hansen et al. 1985). IPCC AR4 models estimated the additional warming after stabilization of the atmospheric composition at year-2000 levels at 0.6°C for the period 2090–99 relative to 1980–99 (Meehl et al. 2007), or 0.3°C relative to 2000. A year-2000 constant composition commitment simulation is not part of this EMIC intercomparison, so direct comparison with IPCC AR4 results are not possible. However, the EMIC mean warming of 0.5°C between 2100 (the time of stabilization of the forcing) and 2300 for the RCP4.5 constant

composition simulation is consistent with the IPCC AR4 estimate. The additional warming between 2300 and 3000 is 0.3°, 0.5°, and 0.8°C in the ensemble mean for RCPs 4.5, 6.0, and 8.5, respectively, indicating a slight increase with radiative forcing. Another measure of constant composition commitment is the fraction of realized warming (Solomon et al. 2009), which is here estimated as the ratio of warming at a given time to the warming averaged over the last two decades of the simulation (2981–3000) (Fig. 2). At the time of stabilization of radiative forcing, the fraction of realized warming is about 70%–90% in the ensemble mean for RCPs 4.5, 6.0, and 8.5.

Sea level rise due to thermal expansion (thermosteric sea level rise) continues for centuries after stabilization of radiative forcing in all scenarios because of the long response time scale of the deep ocean. Despite the peaking and declining radiative forcing under RCP2.6, the rate of thermosteric sea level rise is positive throughout the duration of the simulation in all models (Fig. 3). Thermal expansion simulated by EMICs for the four RCPs and selected time periods is given in Table 3. The model mean thermal expansion by 2100 agrees very well with that simulated by CMIP5 models (Yin 2012).

The thermosteric sea level rise commitment after stabilization of radiative forcing is substantial under RCPs 4.5, 6.0, and 8.5 and at year 3000 amounts to 1.5–3 times the thermosteric sea level rise at the time of forcing stabilization. Note that none of the EMICs include sea level rise resulting from melting of land-based glaciers and ice sheets. Consideration of these contributions would lead to substantially higher sea level rise estimates, but the exact value is highly uncertain because of incomplete understanding of glacier and ice sheet dynamics.

The Atlantic meridional overturning circulation (MOC) weakens under all scenarios (Fig. 2). Under RCPs 2.6, 4.5, and 6.0 the weakening is temporary, and the circulation recovers to within 80% of the preindustrial strength at the end of the simulation in most models. Under RCP8.5 the weakening is more persistent, and the model ensemble-mean MOC recovers to 60% of the preindustrial strength at 3000. Under this scenario the MOC response varies considerably among models; while in some models the circulation recovers to near preindustrial values, it is close to a complete collapse in the Bern3D-LPJ EMIC.

Comparison of constant composition commitment estimates with those from an earlier EMIC intercomparison (Plattner et al. 2008) is hampered by the use of different scenarios [Special Report on Emissions Scenarios (SRES) as opposed to RCPs] and sets of models used. However, given the similarity of the SRES B1 stabilization scenario and RCP4.5 (in both scenarios atmospheric CO₂ stabilizes at 550 ppmv), we attempted a comparison of the warming and thermal expansion commitment for

TABLE 3. Global mean warming and thermal expansion relative to the 1986–2005 reference period for selected time periods and four RCPs. CMIP5 surface air temperature anomalies (Knutti and Sedláček 2013) and thermal expansion (Yin 2012) are shown for comparison. Listed are the model ensemble mean and the minimum and maximum values from the model distribution in parentheses. CMIP5 thermal expansion values are relative to 2006. EMIC year 2981–3000 values are from the CCO simulations.

| Scenario | 2081–2100 | | 2281–2300 | | 2981–3000 |
|----------|-----------------------|-------------------|-------------------|-------------------|-------------------|
| | EMIC | CMIP5 | EMIC | CMIP5 | EMIC |
| | Warming (°C) | | | | |
| RCP2.6 | 1.0 (0.6, 1.4) | 1.0 (0.0, 2.0) | 0.6 (0.3, 1.0) | — | 0.6 (0.3, 1.1) |
| RCP4.5 | 1.7 (0.9, 2.4) | 1.8 (1.0, 2.8) | 2.2 (1.3, 3.0) | — | 2.5 (1.7, 3.5) |
| RCP6.0 | 2.1 (1.1, 2.8) | 2.3 (1.5, 3.2) | 3.3 (1.9, 4.5) | — | 3.8 (2.6, 5.0) |
| RCP8.5 | 3.1 (1.6, 4.1) | 3.7 (2.5, 5.0) | 7.0 (3.8, 8.9) | — | 7.8 (4.7, 9.8) |
| | Thermal expansion (m) | | | | |
| RCP2.6 | 0.14 (0.05, 0.20) | 0.13 (0.10, 0.18) | 0.22 (0.06, 0.37) | 0.21 (0.14, 0.27) | 0.33 (0.09, 0.68) |
| RCP4.5 | 0.18 (0.09, 0.26) | 0.18 (0.14, 0.22) | 0.45 (0.17, 0.69) | 0.52 (0.37, 0.63) | 0.82 (0.29, 1.64) |
| RCP6.0 | 0.20 (0.10, 0.29) | — | 0.62 (0.26, 0.95) | — | 1.20 (0.47, 2.29) |
| RCP8.5 | 0.27 (0.13, 0.38) | 0.28 (0.22, 0.37) | 1.17 (0.64, 1.66) | 1.19 (0.95, 1.45) | 2.48 (1.24, 4.31) |

these two scenarios. The additional warming between years 2100 and 3000 is larger in Plattner et al. (2008) than in this study (0.6°–1.6°C for SRES B1 versus 0.1°–1.2°C for RCP4.5), but with a similar intermodel range (~1.0°C). Thermal expansion commitment is similar in the two studies, with the range simulated in this study encompassing the range of Plattner et al. (2008) (0.3–1.1 m for SRES B1 versus 0.2–1.4 m for RCP4.5). Differences in warming and thermal expansion commitment may be as a result of the different sets of models used in the two intercomparisons, but also to differences in non-CO₂ forcing between scenarios.

EMICs with an interactive carbon cycle were used to diagnose the CO₂ emissions compatible with the CO₂ concentration pathways specified under the constant composition commitment simulations. Diagnosed CO₂ emissions are estimated by closing the global-mean carbon budget of the atmosphere and are determined by the atmosphere–land and atmosphere–ocean CO₂ fluxes. Figure 4 shows CO₂ emissions and changes in carbon inventories since 1850 simulated by eight EMICs for scenario RCP2.6. CO₂ emissions peak around 2020 and decline steeply thereafter. Since the rate of atmospheric CO₂ decrease exceeds the rate of CO₂ uptake by carbon sinks, diagnosed emissions become negative in all models. Minimum emissions range from –1.5 to –0.5 PgC yr^{–1}. After stabilization of atmospheric CO₂, emissions settle at a slightly positive value (equal to the rate of CO₂ uptake by carbon sinks). Cumulative CO₂ emissions since 1850 vary substantially among models despite identical prescribed atmospheric CO₂ and range from 300 to 830 PgC at 2300 and from 380 to 1040 PgC at year 3000. The airborne fraction of cumulative emissions decreases from 45%–70% at the time of peak atmospheric CO₂ (year 2050) to 15%–42% at the end of the simulation.

Accumulated land carbon uptake is negative at the year 2000 in all models that simulate land use change (LUC) emissions interactively on the basis of land cover changes (all EMICs except MESMO and UMD). The reason is that CO₂ emissions resulting from land use exceed net CO₂ uptake by vegetation during most of the historical period (Eby et al. 2013). Between 2000 and the year of peak atmospheric CO₂, the terrestrial biosphere acts as a sink of CO₂ in most models (except in Bern3D-LPJ and UVic). Between the CO₂ peak and the time of CO₂ stabilization, the terrestrial biosphere becomes a source of CO₂ in all models. The range in land carbon uptake under the RCP2.6 scenario is spanned by the UMD model at the upper end, which has a small land uptake sensitivity to CO₂ (β_L) but also a small sensitivity to temperature (γ_L) (Eby et al. 2013) and does not simulate LUC emissions, and the Bern3D-LPJ and UVic models at the lower end (both models have large land uptake sensitivities to CO₂ but also medium to large sensitivities to temperature and do simulate LUC emissions). The fraction of cumulative emissions taken up by the land (land uptake fraction) decreases between 2100 and 2300 and remains approximately constant thereafter.

The ocean takes up carbon from the atmosphere throughout the duration of the RCP 2.6 constant composition simulation in all models. Ocean carbon uptake slows after the peak in atmospheric CO₂ and accelerates again after CO₂ is stabilized. Accumulated ocean carbon uptake is larger than accumulated land carbon uptake at all times in all models. The range in ocean carbon uptake is spanned by the UMD model at the upper end [highest ocean carbon uptake sensitivity to CO₂ (γ_O); Eby et al. 2013] and the UVic model (low carbon uptake sensitivity to CO₂). The ocean uptake fraction increases continuously between the time of peak CO₂ and 2300, and remains approximately constant thereafter.

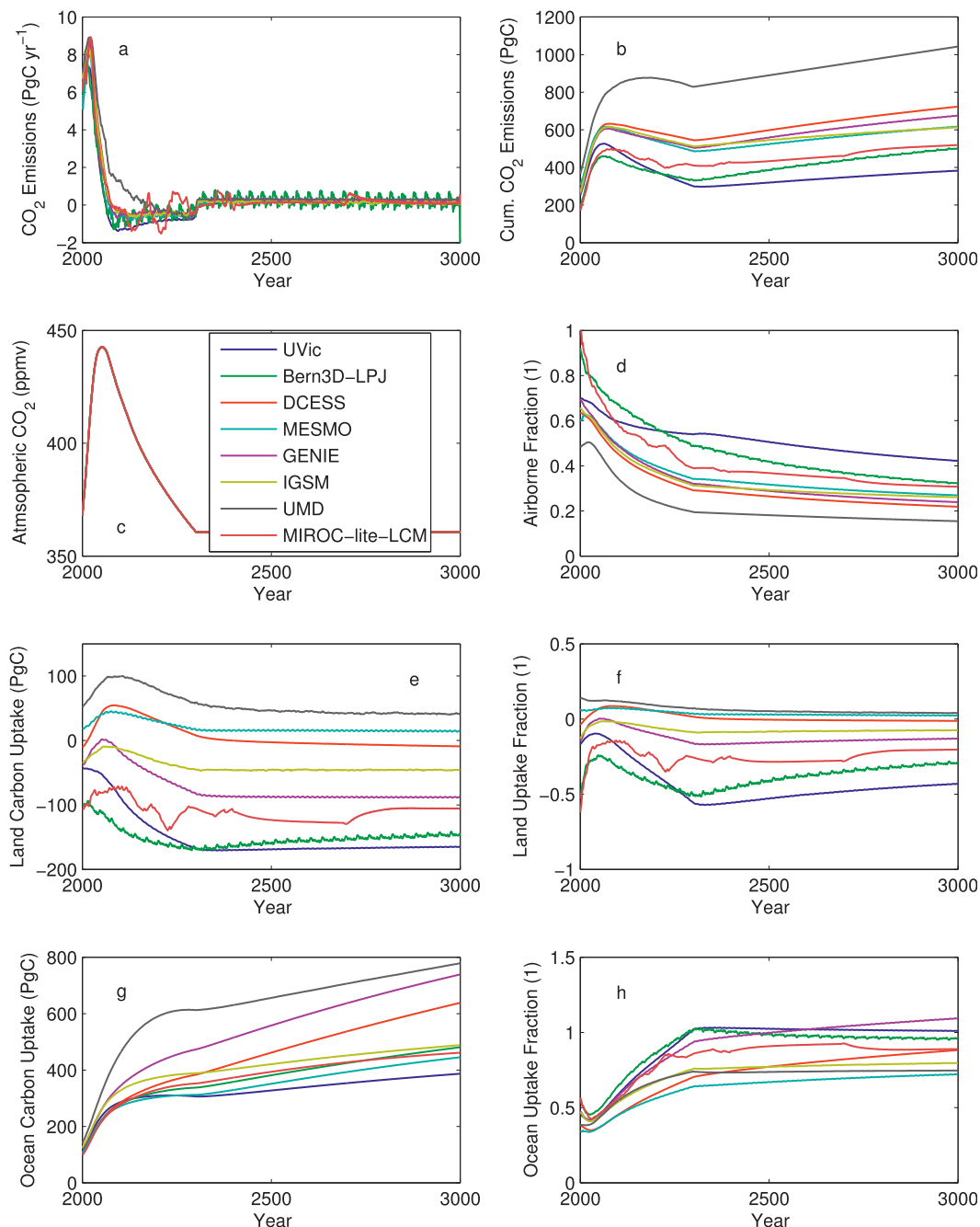


FIG. 4. Changes in carbon inventories in RCP2.6 CCO commitment simulations for eight EMICs with an interactive carbon cycle: (a) CO_2 emissions, (b) cumulative CO_2 emissions since 1850, (c) atmospheric CO_2 concentration, (d) airborne fraction of cumulative emissions, (e) land uptake since 1850, (f) fraction of cumulative emissions taken up by land, (g) ocean uptake since 1850, and (h) fraction of cumulative emissions taken up by ocean. Note that for individual models the ocean uptake fraction can be >1 , if the land uptake fraction is <0 . Data in (a) were smoothed using a 10-yr moving average.

Figure 5 displays changes in carbon inventories in the year 3000 for constant composition commitment simulations under all four RCPs. Diagnosed cumulative CO_2 emissions increase approximately linearly with

atmospheric CO_2 for RCPs 2.6–6.0, but the increase becomes less than linear at higher radiative forcing in most models. The spread in cumulative emissions diagnosed by models also increases with higher atmospheric CO_2 , with

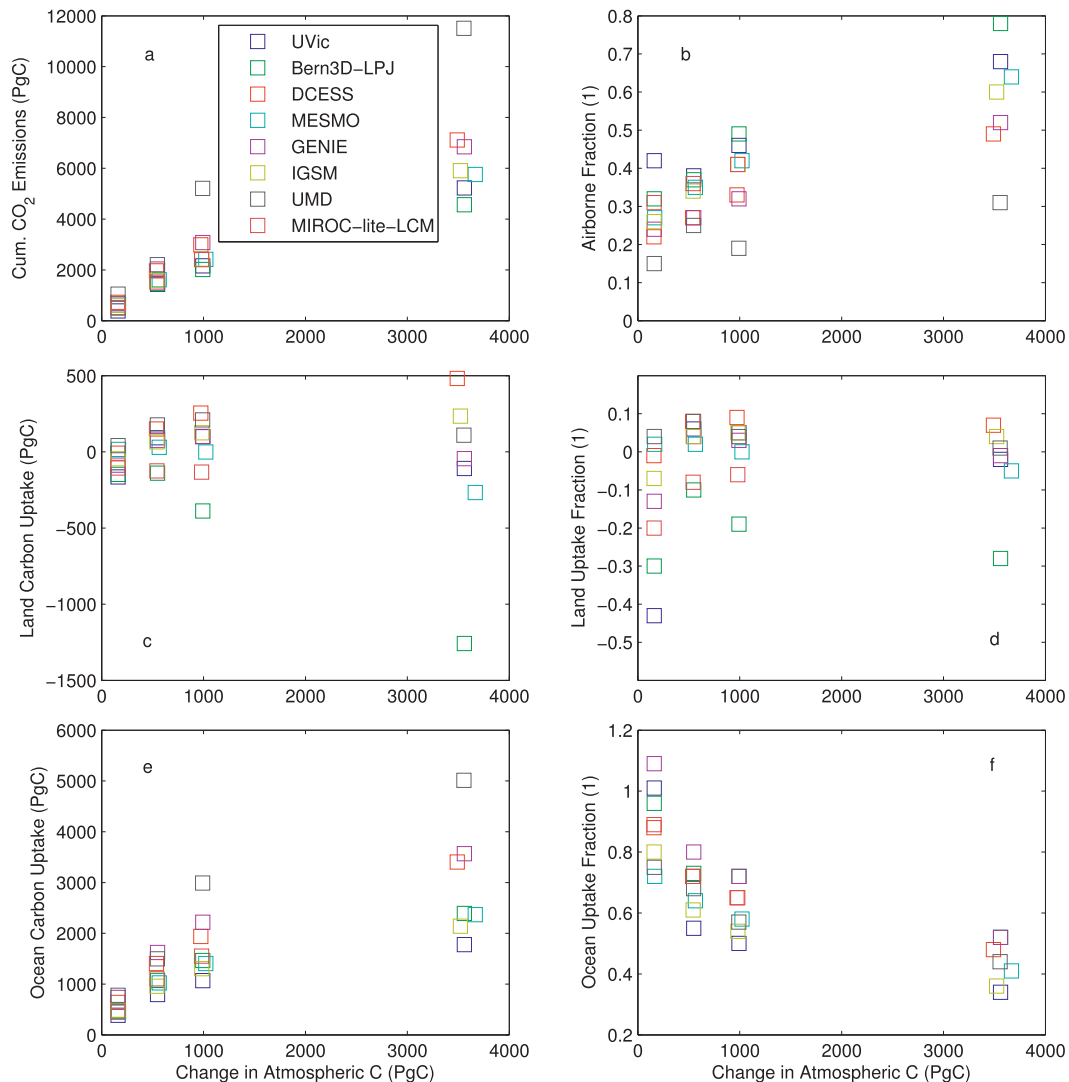


FIG. 5. Changes in carbon inventories by the year 3000 as a function of the change in atmospheric carbon between 1850 and 3000 for RCPs 2.6–8.5: (a) cumulative carbon emissions since 1850, (b) airborne fraction of cumulative emissions, (c) land carbon uptake since 1850, (d) land uptake fraction, (e) ocean carbon uptake since 1850, and (f) ocean uptake fraction.

a range as large as 4500–11 500 PgC for RCP8.5. Cumulative emissions at the upper end of this range are close to estimates of the carbon bound in the total fossil fuel resource base [9500–15 600 PgC; Johansson et al. (2012)].

The airborne fraction increases with increasing atmospheric CO₂, from a model ensemble mean of 0.27 for RCP2.6 to 0.57 for RCP8.5. The increase in airborne fraction with CO₂ is mostly a result of the decreasing ocean uptake fraction. Ocean carbon uptake is largely driven by atmospheric CO₂, with the lowest cumulative uptake occurring in RCP2.6 and the largest in RCP8.5. The ocean uptake fraction decreases significantly with higher CO₂ in all models, from an ensemble mean value of 0.89 in RCP2.6 to 0.44 in RCP8.5. The decrease in

ocean uptake fraction is due to nonlinear ocean carbonate chemistry and stronger climate–carbon cycle feedbacks at higher atmospheric CO₂ (Friedlingstein et al. 2006; Plattner et al. 2008).

The results for land carbon uptake are more complex, as they vary significantly across models and scenarios. In RCPs 4.5 and 6.0, the terrestrial biosphere takes up carbon between 2000 and the year of CO₂ stabilization in all models (not shown). In RCP8.5, the terrestrial biosphere initially takes up CO₂ but becomes a CO₂ source after about a century in most models. The Bern3D-LPJ exhibits negligible land uptake even in the first 100 yr of the RCP8.5 simulation. After CO₂ stabilization, the land response ranges from strong emissions (Bern3D-LPJ) to

weak uptake (UVic) under all RCPs (not shown). RCP differences in land carbon uptake during the twenty-first century result from different strengths of carbon cycle feedbacks, but also from differences in land cover change. For instance, RCPs 4.5 and 6.0 include reforestation, while RCPs 2.6 and 8.5 assume substantial deforestation.

The behavior of land carbon uptake at 3000 as a function of atmospheric CO₂ varies strongly across models: while some EMICs simulate an increase in land uptake with increasing CO₂ (e.g., DCESS), others simulate a strong decrease (Bern3D-LPJ; Fig. 5c). Bern3D-LPJ has the highest sensitivity of land carbon uptake to temperature (Eby et al. 2013), as it includes a representation of carbon release from permafrost soils and peatlands. The land uptake fraction increases from RCP2.6 to RCP4.5 in most models, and remains approximately constant or decreases from RCP4.5 to RCP8.5 (the ensemble mean land uptake fraction remains approximately constant across RCPs). The low land uptake fraction under RCP2.6 in some models may be due to relatively large LUC emissions (Arora et al. 2011).

Our results differ from those of a previous EMIC intercomparison (Plattner et al. 2008), which found that the fractional distribution of excess carbon among the atmosphere, ocean, and terrestrial biosphere remained approximately constant across scenarios. That study, however, considered a much narrower range in atmospheric CO₂ changes (~700–1000 PgC).

c. Preindustrial CO₂ emission commitment

Preindustrial CO₂ emission commitment (PIEM-CO₂) is investigated by setting the anthropogenic CO₂ emission perturbation to zero after 2300 and letting the atmospheric CO₂ concentration evolve freely. Non-CO₂ radiative forcing is held constant at year-2300 levels. These simulations were performed by EMICs with an interactive carbon cycle only. As discussed in section 2b, setting the anthropogenic perturbation to zero does not result in zero emissions exactly: decadal-mean CO₂ emissions after 2300 range from -0.5 to 0.5 PgC yr⁻¹ for all RCPs (Fig. 6). CO₂ emissions are ≤0 in all models, except for the UMD model. The long-term effect of these annual emissions is evident in Fig. 7 for the RCP2.6 PIEM-CO₂ commitment simulation, with cumulative emissions declining between 2300 and 3000 (with exception of the UMD model, for which cumulative emissions increase). Note that despite the slightly different model setup, the PIEM-CO₂ commitment simulations are comparable to the zero-CO₂-emission commitment simulations discussed in the literature.

As CO₂ emissions nearly cease, atmospheric CO₂ declines as the ocean and land continue to absorb carbon

from the atmosphere (Fig. 6). The efficacy of carbon uptake differs between models and so does the rate of decline of atmospheric CO₂. By the year 3000, atmospheric CO₂ is still far away from a new equilibrium because of the long time scales of CO₂ removal from the atmosphere (Eby et al. 2009). By 3000, the ensemble mean atmospheric CO₂ is 330 ppmv in RCP2.6, 440 ppmv in RCP4.5, 590 ppmv in RCP6.0, and 1560 ppmv in RCP8.5. Note that the upper boundary of the atmospheric CO₂ range spanned by models increases after 2300. The upper limit is set by the UMD model, which has slightly positive CO₂ emissions. Atmospheric CO₂ at 3000 in RCPs 4.5–8.5 is still at a high fraction (≥0.5) of the peak atmospheric CO₂ in all models (Fig. 8). These results are consistent with previous studies (Montenegro et al. 2007; Archer and Brovkin 2008; Plattner et al. 2008; Eby et al. 2009; Solomon et al. 2009; Archer et al. 2009), which showed that a significant fraction of CO₂ remains airborne after several hundred years, and that this fraction increases with higher CO₂ concentrations (or emissions).

Despite decreasing radiative forcing after 2300 in most models, global mean temperature decreases only slightly in RCPs 4.5–6.0 between 2300 and 3000 and remains approximately constant in RCP8.5 (Table 4). This near constancy of global mean temperature after elimination of anthropogenic CO₂ emissions is known from earlier studies with EMICs and complex ESMs (Matthews and Caldeira 2008; Plattner et al. 2008; Eby et al. 2009; Solomon et al. 2009; Lowe et al. 2009; Frölicher and Joos 2010; Gillett et al. 2011; Zickfeld et al. 2012) and results from the cancellation of two opposing effects: the delayed warming due to ocean thermal inertia and the decrease in radiative forcing associated with declining atmospheric CO₂ levels in conjunction with the logarithmic dependence of forcing on atmospheric CO₂ (Eby et al. 2009; Solomon et al. 2010). At 3000, the fraction of warming that persists relative to that in the year 2300 (the year the anthropogenic perturbation is set to zero, which approximately corresponds to the year of peak warming) is 0.85, 0.89, and 0.99 in the ensemble mean for RCPs 4.5, 6.0, and 8.5 respectively (Fig. 8). These values are consistent with those from Eby et al. (2009), who found that 80%–100% of the warming anomaly persists 700 years after emissions were eliminated, with the fraction increasing with the amount of cumulative emissions.

In contrast to global mean temperature, sea level rise due to thermal expansion continues after elimination of anthropogenic CO₂ emissions in RCPs 4.5–8.5. The sea level rise between 2300 and 3000 is substantial in these scenarios (Table 4) and comparable to the sea level rise between 1850 and 2300. While sea level rise in some EMICs levels off toward the end of the simulation, it continues to rise in others. This is consistent with the

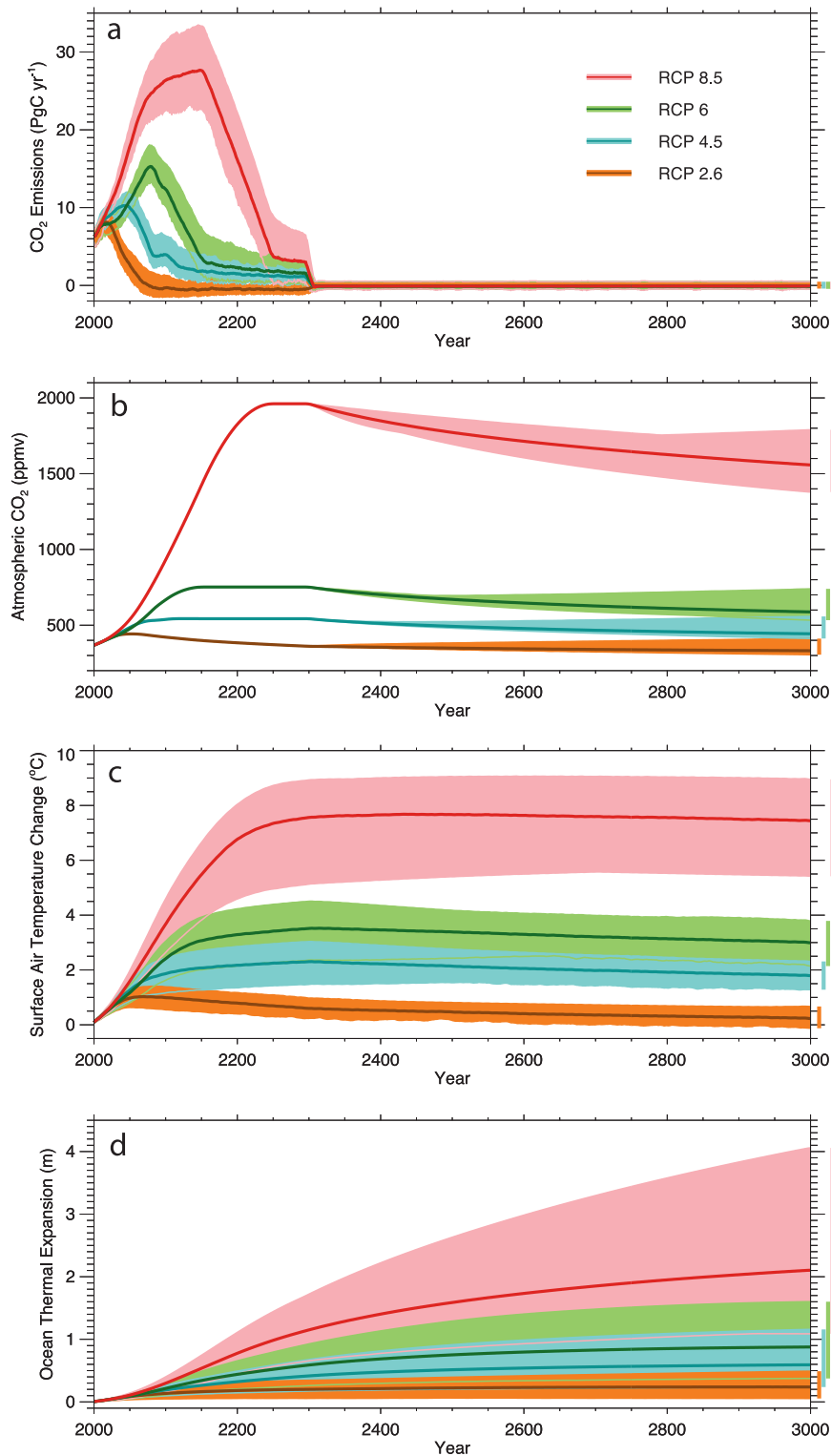


FIG. 6. Time evolution of climate variables for the PIEM-CO₂ commitment simulations under four RCP scenarios: (a) diagnosed cumulative CO₂ emissions since 1850, (b) atmospheric CO₂, (c) surface air temperature change, and (d) ocean thermal expansion. Anomalies are relative to 1986–2005. Shown are the model ensemble averages (thick solid lines), the ranges spanned by all models (shaded domains, delimited by thin solid lines), and the range in the year 3000 (vertical bars on right side). Data were smoothed using a 10-yr moving average.

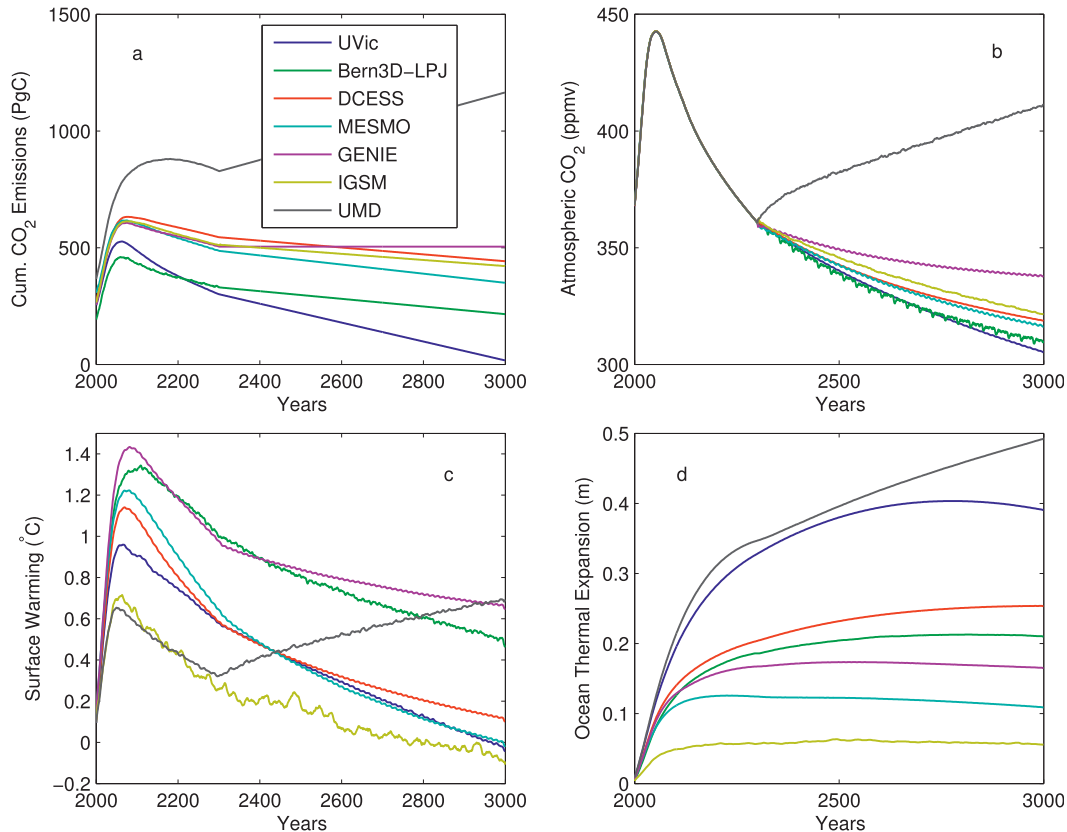


FIG. 7. RCP2.6 PIEM- CO_2 commitment simulations: (a) cumulative CO_2 emissions since 1850, (b) atmospheric CO_2 , (c) surface air temperature change, and (d) ocean thermal expansion. Anomalies in (c) and (d) are relative to 1986–2005. Data in (c) were smoothed using a 10-yr moving average. Note that the response of the UMD model differs from that of other models resulting from slightly positive CO_2 emissions after year 2300.

results of a previous EMIC intercomparison (Plattner et al. 2008). In zero-emission commitment simulations with a complex ESM, Gillett et al. (2011) found thermosteric sea level to still rise 900 years after cessation of emissions. Given that surface air temperature remains elevated for centuries to millennia and intermediate-depth temperature in the high-latitude Southern Ocean continues to warm, potentially leading to a collapse of the West Antarctic Ice Sheet (Gillett et al. 2011), thermal expansion on these time scales is likely to be compounded by large sea level contributions from disintegrating ice sheets.

Both global mean warming and sea level rise behave differently in RCP2.6 than in the higher scenarios (Fig. 7). Because of the strong decline in atmospheric CO_2 and, accordingly, radiative forcing already before 2300, the warming and sea level rise commitment after 2300 are lower in this scenario. Global mean temperature continues to decrease between 2300 and 3000 and sea level stabilizes or even starts to slightly drop in some models (except for the UMD model, for which atmospheric CO_2 increases after 2300).

An interesting question in view of the comparability of results from different studies is whether the preindustrial (or zero) CO_2 emission commitment is dependent on the time CO_2 emissions cease. We address this question by comparing the temperature and thermal expansion commitment in PIEM- CO_2 simulations with those in the reversibility simulations (REc) with constant year-2300 radiative forcing to the year 3000 and zero CO_2 emissions thereafter. If CO_2 emissions cease earlier (e.g., in 2300 as opposed to 3000), the system is further away from equilibrium with the stabilized radiative forcing, the fraction of realized warming is smaller (Fig. 2b), and one would expect a larger temperature and thermal expansion commitment. One complicating factor in our comparison is that the PIEM- CO_2 simulations entail slightly negative (as opposed to zero) emissions in most models, leading to a more rapid decline in atmospheric CO_2 and hence radiative forcing after cessation of emissions. The model average decrease in surface air temperature after emissions cease is lower in the REc than in the PIEM- CO_2 simulations (-0.2°C versus -0.5°C for RCPs 4.5 and 6.0),

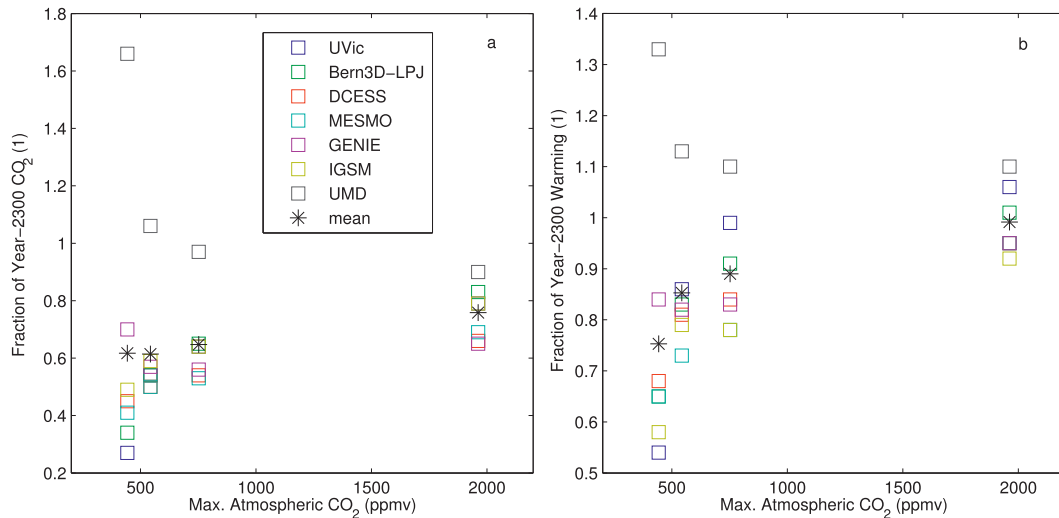


FIG. 8. PIEM- CO_2 simulations for RCPs 2.6–8.5. (a) Atmospheric CO_2 in year 3000 as a fraction of atmospheric CO_2 in year 2300 (corresponding to peak atmospheric CO_2 in RCPs 4.5–8.5). (b) Warming in year 3000 as a fraction of warming in year 2300 (corresponding approximately to peak warming in RCPs 4.5–8.5). Results are shown as a function of the peak atmospheric CO_2 concentration in each RCP, which is the same for all models.

which we attribute to the slower decline in radiative forcing in the REc simulations. On the other hand, the thermal expansion commitment is larger in the PIEM- CO_2 simulations (0.3 m versus 0.1 m in the REc simulation for RCP6.0), consistent with the smaller fraction of realized warming at the time emissions cease. These results indicate that the temperature commitment is determined largely by the radiative forcing after emissions cease, whereas the thermal expansion commitment is determined by the radiative forcing before emissions cease, consistent with the longer response time scale of the deep ocean.

d. Preindustrial emission commitment

The PIEM simulations are similar to the PIEM- CO_2 simulations described in the previous paragraph, except that non- CO_2 radiative forcing is abruptly set to zero in the year 2300. Note that this is different from setting emissions

of non- CO_2 gases to zero because the finite atmospheric lifetime of these gases would lead to a gradual decline in their concentration and associated radiative forcing (except for aerosols, which have a very short atmospheric residence time). Similar to the PIEM- CO_2 runs, atmospheric CO_2 declines after 2300 under all RCPs (Fig. 9). The rate of decrease is slightly larger than in the PIEM- CO_2 simulations as a result of the greater efficiency of the carbon sinks in a slightly cooler climate (i.e., a reduced climate–carbon cycle feedback). The surface temperature decreases abruptly around 2300 and more gradually thereafter, with a rate similar to that in the PIEM- CO_2 simulations. Accordingly, the warming commitment after 2300 is more negative than in the PIEM- CO_2 runs (Table 4). Note that the temperature response in the simulations described here is different from that projected in simulations where all anthropogenic emissions are set to zero (Hare and Meinshausen 2006; Armour and Roe

TABLE 4. Projected global mean warming and thermocline sea level rise between 2300 and 3000 in CEM, CCO, PIEM- CO_2 , and PIEM commitment simulations. Given are model ensemble means and model ranges in parentheses.

| Scenario | CEM | CCO | PIEM- CO_2 | PIEM |
|---|---------------------|-------------------|---------------------|---------------------|
| Warming commitment ($^{\circ}\text{C}$) | | | | |
| RCP2.6 | −0.8 (−1.0, −0.4) | 0.0 (−0.1, 0.1) | −0.4 (−0.7, 0.4) | −0.8 (−1.2, 0.4) |
| RCP4.5 | 0.8 (0.5, 1.3) | 0.3 (0.0, 0.6) | −0.5 (−1.0, 0.3) | −1.2 (−1.8, 0.3) |
| RCP6.0 | 1.1 (0.7, 1.4) | 0.4 (0.0, 0.9) | −0.5 (−1.2, 0.4) | −1.2 (−2.0, 0.4) |
| RCP8.5 | 1.3 (0.7, 1.7) | 0.7 (0.0, 1.2) | −0.1 (−0.7, 0.6) | −1.3 (−2.3, 0.6) |
| Thermal expansion commitment (m) | | | | |
| RCP2.6 | −0.04 (−0.10, 0.02) | 0.11 (0.03, 0.32) | 0.04 (−0.02, 0.15) | −0.03 (−0.09, 0.15) |
| RCP4.5 | 0.40 (0.16, 0.83) | 0.38 (0.12, 0.95) | 0.18 (0.02, 0.49) | 0.08 (−0.08, 0.34) |
| RCP6.0 | 0.60 (0.24, 1.19) | 0.57 (0.20, 1.34) | 0.29 (0.04, 0.69) | 0.16 (−0.07, 0.47) |
| RCP8.5 | 1.30 (0.41, 2.84) | 1.31 (0.38, 2.64) | 0.97 (0.22, 2.37) | 0.66 (0.03, 1.69) |

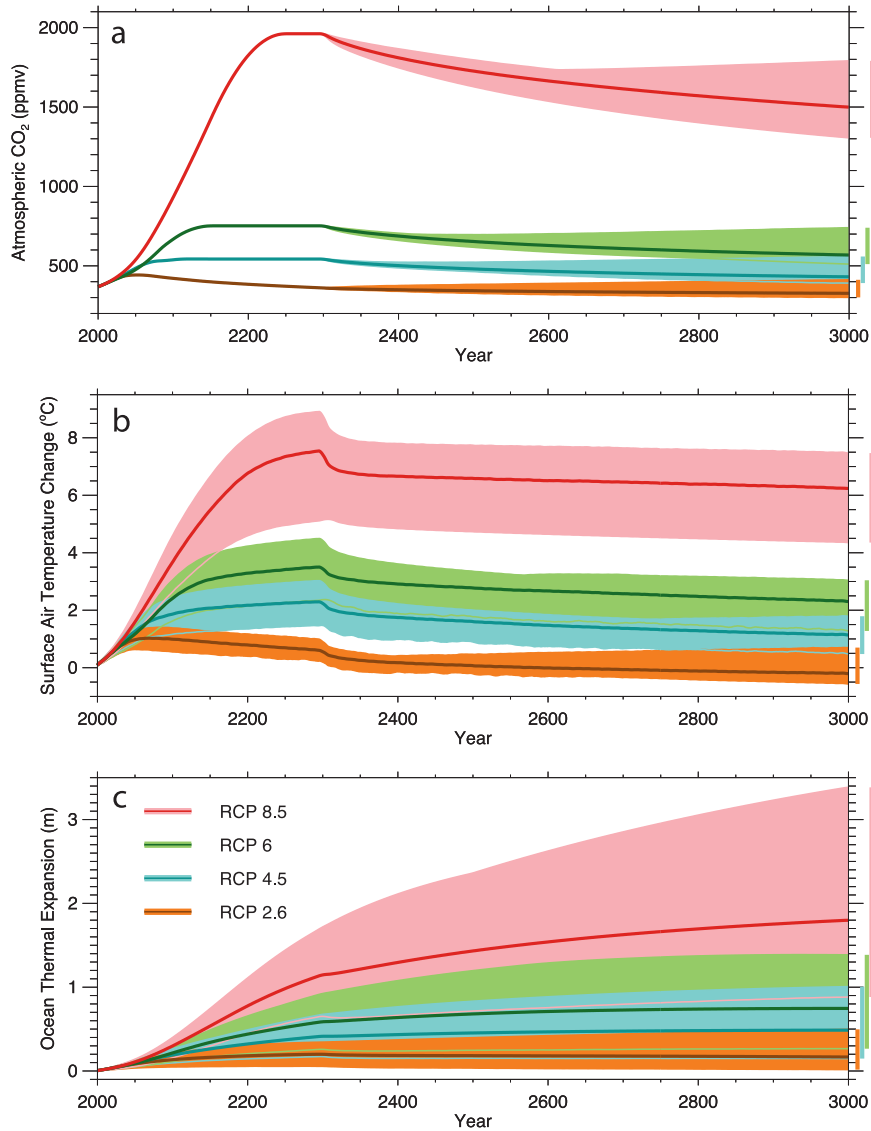


FIG. 9. Time evolution of climate variables for the PIEM commitment simulations under four RCP scenarios: (a) atmospheric CO_2 , (b) surface air temperature change, and (c) ocean thermal expansion. Anomalies are relative to 1986–2005. Shown are the model ensemble averages (thick solid lines), the ranges spanned by all models (shaded domains, delimited by thin solid lines), and the range in the year 3000 (vertical bars on right side). Data were smoothed using a 10-yr moving average.

2011; Matthews and Zickfeld 2012). In those simulations, temperature increases temporarily after elimination of emissions due to the removal of the negative radiative forcing from aerosols (Hare and Meinshausen 2006; Armour and Roe 2011; Matthews and Zickfeld 2012). In the RCPs used in the present study, the year-2300 non- CO_2 radiative forcing is dominated by the positive forcing from non- CO_2 greenhouse gases such that a removal of this forcing leads to a sudden cooling. The sea level rise commitment in PIEM simulations is smaller than in

PIEM- CO_2 simulations (Table 4), consistent with the more rapid decline in radiative forcing.

e. Constant emission commitment

The CEM commitment simulations differ from the simulations described previously in that CO_2 emissions are held constant at significant positive values after 2300 in RCPs 4.5–8.5 (range of 0.8–6.4 PgC yr^{-1} ; Fig. 10). Since only a fraction of these CO_2 emissions is taken up by carbon sinks, atmospheric CO_2 increases again after

2300 (as opposed to remaining constant or decreasing as in the other commitment simulations). As a result, surface air temperature continues to increase, with a significant positive warming commitment after 2300 (Table 4). Thermosteric sea level also continues to rise after 2300, with the sea level rise between 2300 and 3000 being several factors larger than that realized by 2300 (Table 4).

The climate response in the RCP2.6 CEM simulation is very different from that under the higher RCPs: CO₂ emissions in the year 2300 are slightly negative in all models (from -0.7 to -0.2 PgC yr⁻¹), and holding emissions fixed at these values results in a continuing decrease in atmospheric CO₂. Accordingly, global mean temperature continues to decrease, and sea level starts to fall between 2300 and 3000 in all models. The ensemble mean warming and sea level rise commitments are slightly more negative than to those in the RCP2.6 PIEM commitment simulations (Table 4).

f. Climate change reversibility

To explore under which conditions the climate system can revert to its preindustrial state, a set of “reversibility” simulations was carried out. These simulations were started from the year-3000 state of the CCO simulations. Two simulations were performed with atmospheric CO₂ decreasing linearly to zero (ramp) over a period of 100–1000 yr, respectively. These scenarios are highly idealized and are used for illustrative purpose only. Since the atmospheric CO₂ changes are externally prescribed, these simulations give insight into the reversibility of the physical climate system. A third simulation, in which atmospheric CO₂ is allowed to evolve freely after emissions are set to zero, is aimed at exploring the reversibility of changes in the coupled climate–carbon cycle system. It should be noted that non-CO₂ forcing after year 3000 is held fixed at slightly positive values and therefore the total forcing after ramp down of atmospheric CO₂ to preindustrial levels is different from zero.

With atmospheric CO₂ decreasing to preindustrial levels over a period of 100 yr, surface air temperature decreases rapidly at first (during the CO₂ ramp-down phase) and more slowly thereafter (Fig. 11). At the year 4000 surface air temperature is still higher than under 1851–60 conditions (Table 5). This remaining warming 900 years after atmospheric CO₂ returned to preindustrial levels can be explained by the thermal inertia of the climate system, which plays out both during periods of warming and cooling, and the (small) residual positive radiative forcing from non-CO₂ sources.

The thermosteric sea level rise trend is also reversed with decreasing atmospheric CO₂. Rates of sea level fall, however, are slower than rates of cooling, and sea level is significantly higher than under preindustrial conditions

at year 4000 (Table 5). The thermohaline circulation exhibits a rapid strengthening in the ensemble mean during the CO₂ decrease phase, with the overturning first overshooting and then slowly converging to preindustrial values. Note that under RCP8.5 the thermohaline circulation is close to collapse in the Bern3D-LPJ model, but recovers after the ramp down of atmospheric CO₂.

In the simulations with a slower decrease of atmospheric CO₂ (over 1000 yr), surface air temperature also starts to drop after the year 3000, but the cooling is more gradual than in the 100-yr ramp-down experiment (Fig. 12). Also, the rate of cooling is lower during the first 500 years of the ramp down than during the last 500 years. This nonlinear response can again be explained with the thermal inertia of the climate system: despite 700 years of constant forcing (from 2300 to 3000) the climate system is still equilibrating with that forcing, and the associated warming commitment acts to offset the cooling because of decreasing CO₂ levels during the first few hundred years of the CO₂ ramp-down phase. Surface air temperature at 4000 is warmer than in the simulations with a 100-yr ramp down, particularly for the higher RCPs (Table 5).

In contrast to temperature, thermosteric sea level continues to rise for several centuries after CO₂ starts to decrease. For instance, ensemble mean sea level does not peak until the year 3200 under RCP6.0 and 3300 under RCP8.5. Year-4000 sea level rise is about twice as high in these simulations as in the 100-yr ramp-down experiments (Table 5). The thermohaline circulation recovers slowly at first and more rapidly toward the end of the CO₂ decrease phase. Under RCPs 4.5–8.5 the ensemble-mean overturning at year 4000 exceeds the preindustrial value. Individual models deviate substantially from the ensemble-mean behavior. For instance, overturning in the Bern3D-LPJ model does not recover under declining CO₂ levels, but collapses completely around the year 3500.

In the third reversibility experiment, atmospheric CO₂ is allowed to evolve freely after the year 3000 (under zero CO₂ emissions). This simulation was performed by a subset of EMICs with an interactive carbon cycle only. It is similar to the PIEM-CO₂ simulation, except that a 700-yr CO₂ stabilization phase precedes the free-evolving-CO₂ phase (and emissions are exactly zero as opposed to slightly negative in the PIEM-CO₂ experiments). Following the cessation of CO₂ emissions, atmospheric CO₂ declines because of CO₂ uptake by marine and terrestrial carbon sinks (Fig. 13). As discussed earlier for the PIEM-CO₂ experiments, surface air temperature remains approximately constant after elimination of CO₂ emissions, while sea level continues to rise. Compared to the reversibility experiments with CO₂ ramp down, surface air

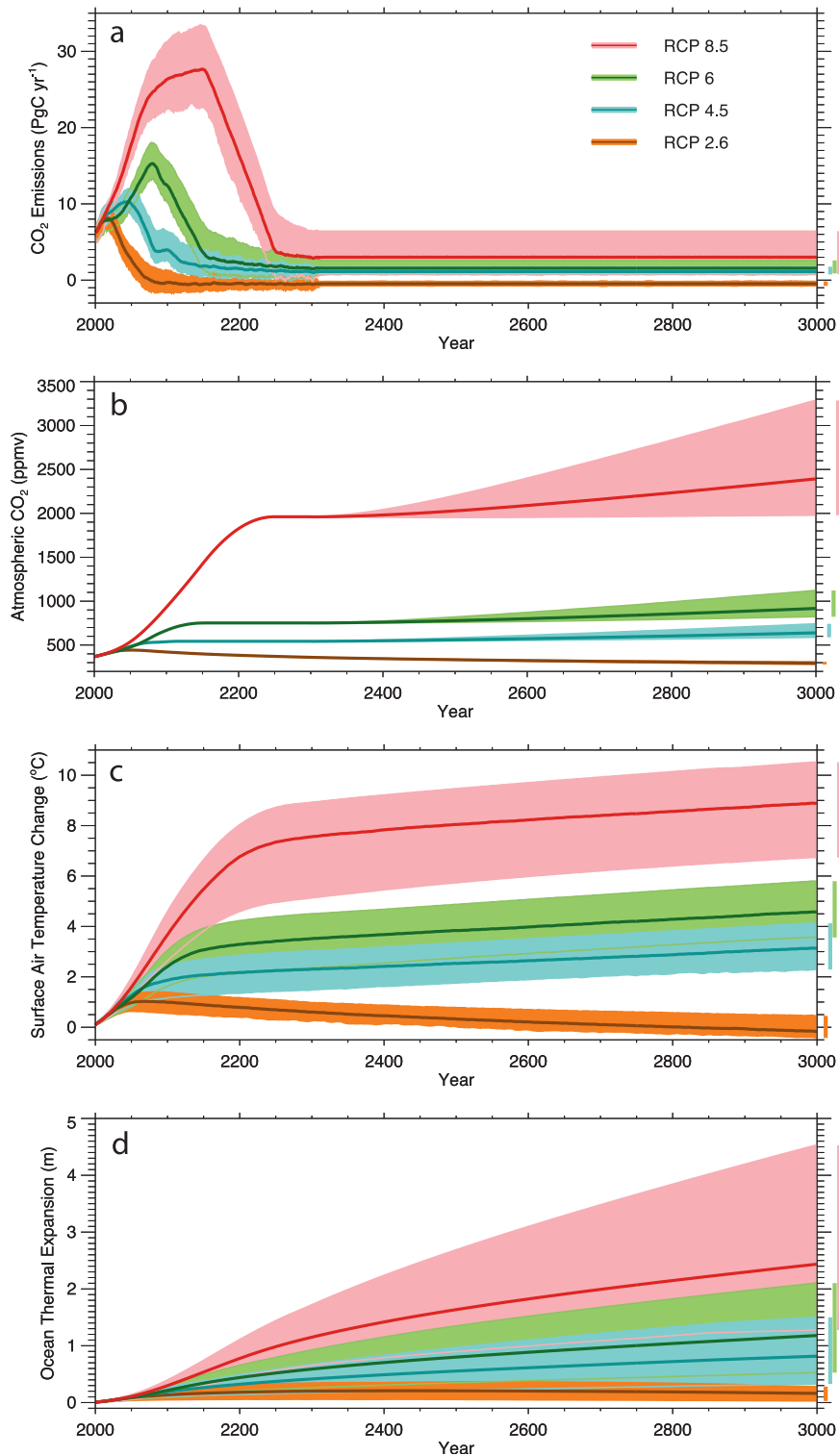


FIG. 10. Time evolution of climate variables for the CEM commitment simulations under four RCP scenarios: (a) diagnosed CO₂ emissions, (b) atmospheric CO₂, (c) surface air temperature change, and (d) ocean thermal expansion. Anomalies in (c) and (d) are relative to 1986–2005. Shown are the model ensemble averages (thick solid lines), the ranges spanned by all models (shaded domains, delimited by thin solid lines), and the range in the year 3000 (vertical bars on right side). Data were smoothed using a 10-yr moving average.

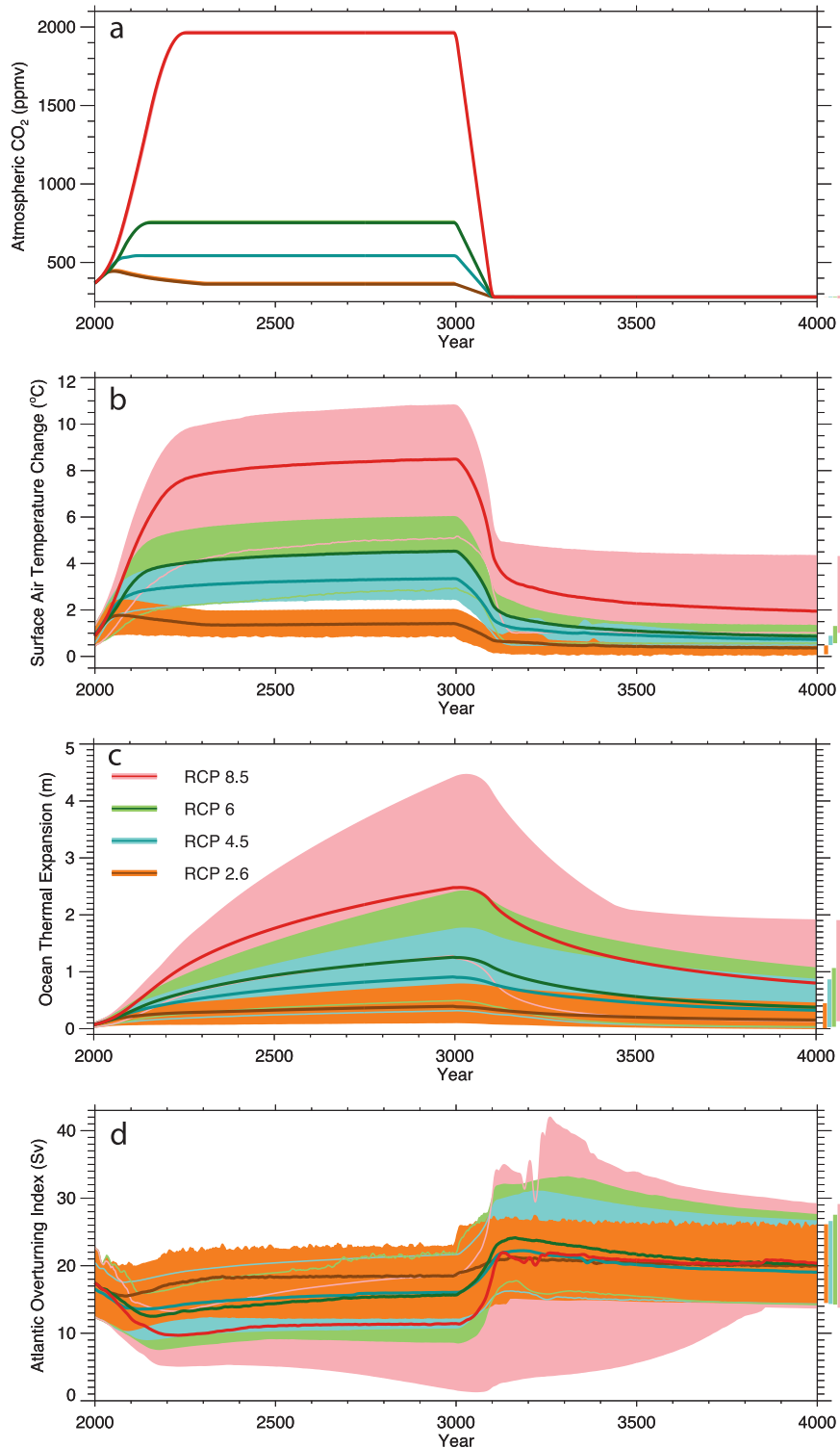


FIG. 11. Time evolution of climate variables for REa simulations with atmospheric CO₂ after year 3000 decreasing to preindustrial levels over 100 yr: (a) atmospheric CO₂, (b) surface air temperature change, (c) ocean thermal expansion, and (d) Atlantic overturning index (maximum of the overturning streamfunction in the North Atlantic). Anomalies in (b) and (c) are relative to preindustrial (1851–60). Shown are the model ensemble averages (thick solid lines), the ranges spanned by all models (shaded domains, delimited by thin solid lines), and the range in the year 3000 (vertical bars on side). Data were smoothed using a 10-yr moving average.

TABLE 5. Warming and thermosteric sea level in 3991–4000 relative to 1851–60 for climate reversibility simulations with a 100-yr ramp down of atmospheric CO₂ after the year 3000 (REa), a 1000-yr ramp down of atmospheric CO₂ (REb), and freely evolving CO₂ (REc). Given are model ensemble means and model ranges in parentheses.

| Scenario | REa | REb | REc |
|----------|----------------|-----------------------|----------------|
| | | Warming (°C) | |
| RCP2.6 | 0.4 (0.1,0.5) | 0.5 (0.1,0.7) | 1.3 (0.7,1.8) |
| RCP4.5 | 0.7 (0.5,0.9) | 1.1 (0.6,1.4) | 3.2 (2.2,4.0) |
| RCP6.0 | 0.9 (0.6,1.3) | 1.4 (0.7,1.9) | 4.5 (3.4,5.3) |
| RCP8.5 | 2.0 (1.1,4.3) | 3.1 (1.5,4.6) | 8.9 (6.7,10.2) |
| | | Thermal expansion (m) | |
| RCP2.6 | 0.2 (0.05,0.4) | 0.3 (0.1,0.7) | 0.4 (0.1,0.8) |
| RCP4.5 | 0.3 (0.1,0.9) | 0.5 (0.2,1.5) | 0.8 (0.4,1.6) |
| RCP6.0 | 0.4 (0.1,1.1) | 0.8 (0.3,2.0) | 1.2 (0.6,2.4) |
| RCP8.5 | 0.8 (0.2,1.9) | 1.9 (0.5,3.5) | 2.9 (1.3,6.3) |

temperature and sea level rise at 4000 are much higher in the free-evolving-CO₂ case (Table 5). Similarly to surface air temperature, the thermohaline circulation remains approximately constant after emissions cease. An exception is again the overturning in the Bern3D-LPJ model, which collapses completely by the year 3200.

EMICs with an interactive carbon cycle were used to diagnose the CO₂ emissions compatible with the CO₂ concentration trajectories for the two reversibility experiments with CO₂ ramp down (Fig. 14). The abrupt decrease of atmospheric CO₂ in the two experiments (Figs. 11a, 12a) requires emissions to become negative to close the CO₂ budget. Emissions are much more negative in the experiments with a fast (100 yr) ramp down than in those with a slower (1000 yr) ramp down, particularly under the higher RCPs. For each experiment, the larger the rate of atmospheric CO₂ decline, the more negative the diagnosed CO₂ emissions.

Negative emissions imply that the prescribed rate of atmospheric CO₂ decline exceeds the uptake capacity of the marine and terrestrial carbon sinks. In the 100-yr ramp-down experiments, terrestrial carbon inventories decline strongly during the CO₂ decrease phase, and remain relatively stable thereafter in all models (Fig. 15). At year 4000, terrestrial carbon inventories are smaller than at preindustrial. The likely reason is the lag of surface air temperature relative to atmospheric CO₂, such that the terrestrial biosphere is subject to higher temperatures despite a return to preindustrial CO₂ conditions. Ocean carbon inventories also decline during the CO₂ ramp-down phase, although more gradually, and continue to decline until the end of the simulation in all models. At year 4000, ocean carbon inventories are higher than at preindustrial in most models.

In the 1000-yr ramp-down experiment, the decline in land carbon inventories in response to declining CO₂

levels is more gradual and continues for the duration of the ramp down (not shown). Ocean carbon inventories, on the other hand, continue to increase after the decline in atmospheric CO₂ in several models (exceptions are the UVic and UMD models). By year 3500, ocean carbon turns around and starts to decrease in all models. Continuing ocean carbon uptake at the beginning of the ramp-down phase offsets the carbon release from the terrestrial biosphere at first, such that diagnosed CO₂ emissions are only slightly negative. Diagnosed emissions become increasingly more negative toward the end of the ramp down as both ocean and land release CO₂ into the atmosphere (Fig. 14b).

g. Cumulative emissions compatible with temperature targets

A last set of simulations was performed with the UVic and Bern3D-LPJ EMICs to explore the cumulative emissions compatible with long-term temperature targets. These simulations used an inverse modeling approach, whereby CO₂ emissions compatible with prescribed temperature trajectories were diagnosed (Zickfeld et al. 2009). Figure 16 displays the diagnosed cumulative emissions for temperature trajectories stabilizing at 1.5°, 2°, 3°, and 4°C for the UVic and Bern3D-LPJ EMICs. The temperature trajectories prescribed to the two models are slightly different until the time of temperature stabilization (Fig. 16a). This does not affect the comparability of results, however, since we discuss the cumulative emissions since preindustrial, and the climate response centuries after elimination of emissions is independent of the emission trajectory (Eby et al. 2009; Zickfeld et al. 2009, 2012). Model mean allowable cumulative emissions are 770, 1000, 1460, and 1950 PgC for temperature targets of 1.5°, 2°, 3°, and 4°C, respectively. These estimates are slightly lower than the allowable cumulative emissions estimated with an earlier version of the UVic model (Zickfeld et al. 2009). The estimate for the 2°C target coincides with the value of 1000 PgC from Allen et al. (2009), and is somewhat higher than the value calculated by Meinshausen et al. (2009), who assumed stronger forcing from non-CO₂ gases.

Allowable cumulative emissions at 2500 are slightly higher in the Bern3D-LPJ than in the UVic model for the lower temperature targets (1.5°–2°C), whereas they are lower for the highest temperature target (4°C). Allowable emissions consistent with temperature targets depend on both the physical and biogeochemical model response. For instance, the higher the climate sensitivity and/or the stronger the (positive) climate–carbon cycle feedback, the lower the amount of cumulative emissions consistent with a specified temperature target (Zickfeld et al. 2009). Both EMICs have a relatively high climate sensitivity and

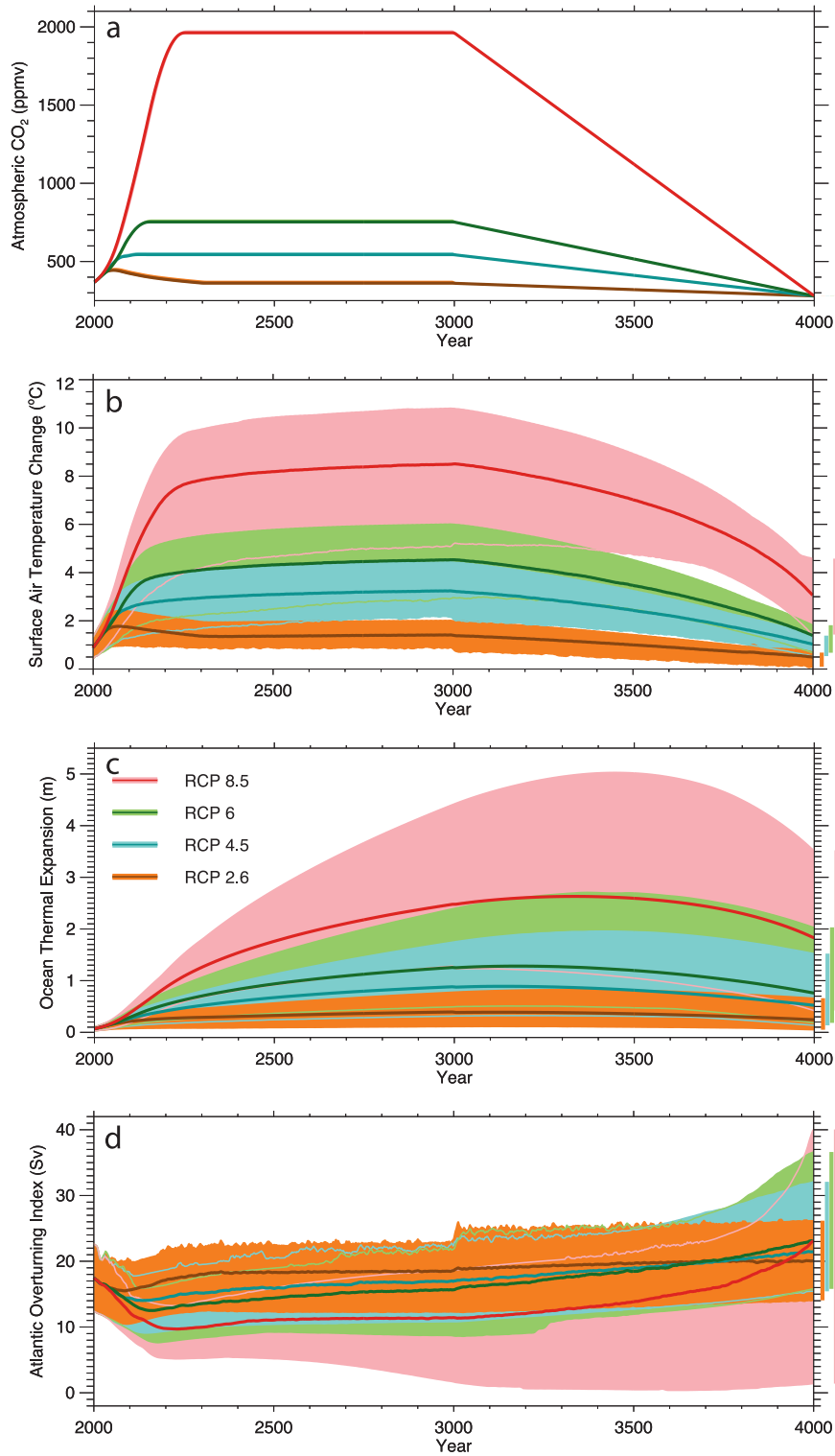


FIG. 12. As in Fig. 11, but for REb simulations with atmospheric CO₂ after year 3000 decreasing to preindustrial levels over 1000 yr.

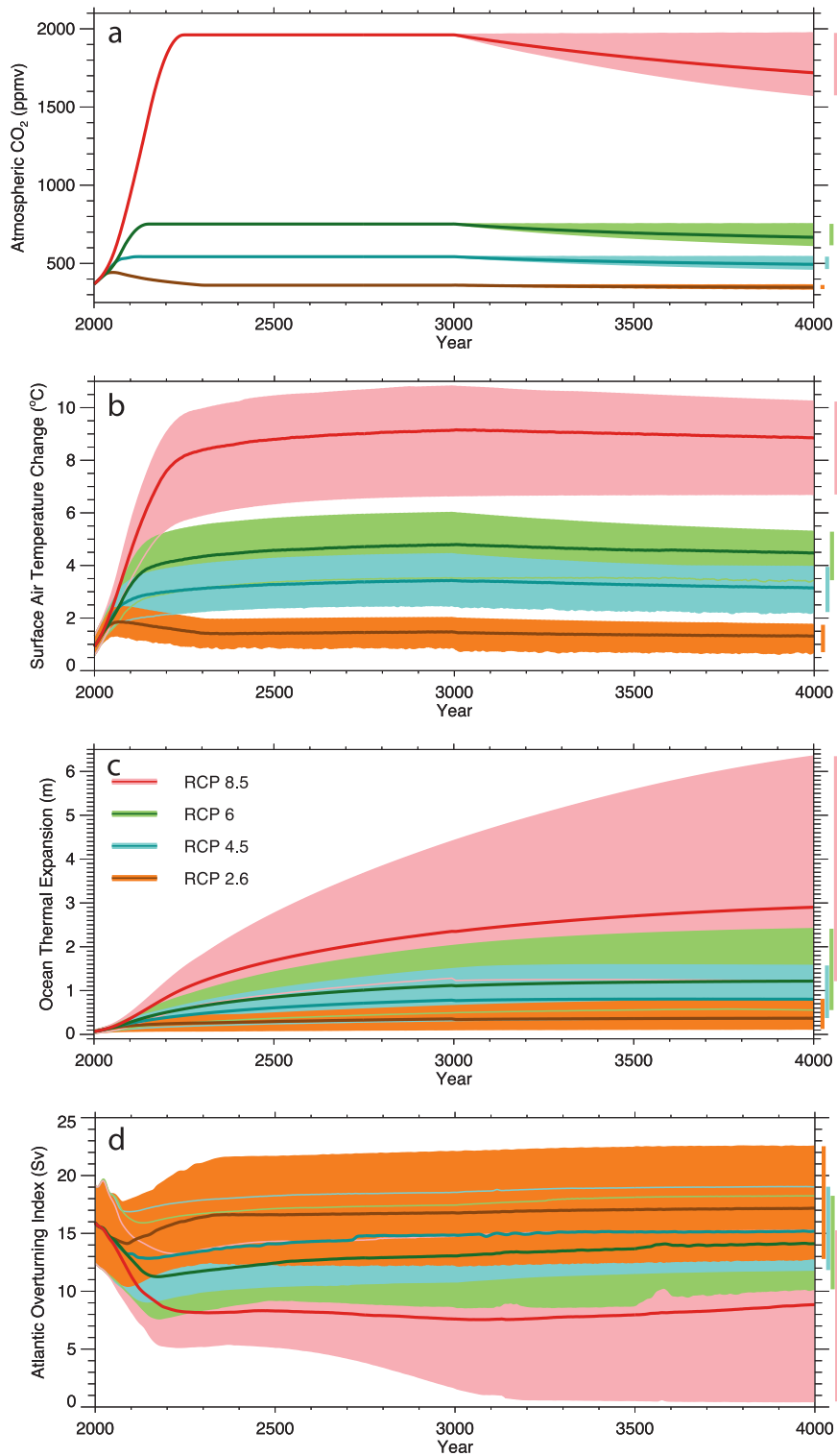


FIG. 13. As in Fig. 11, but for REc simulations with atmospheric CO₂ after year 3000 evolving freely (zero emissions). These experiments were performed by EMICs with an interactive carbon cycle only.

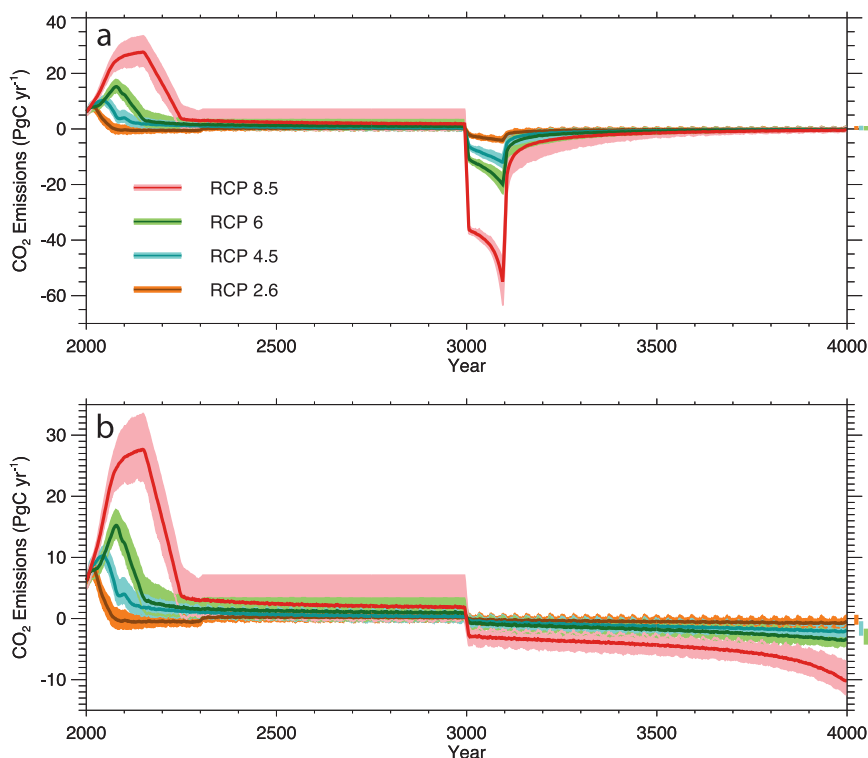


FIG. 14. Diagnosed CO_2 emissions for reversibility simulations with atmospheric CO_2 after year 3000 decreasing to preindustrial levels over (a) 100 and (b) 1000 yr. Results are shown for seven EMICs with an interactive carbon cycle. Shown are the model ensemble averages (thick solid lines), the ranges spanned by all models (shaded domains, delimited by thin solid lines), and the range in the year 3000 (vertical bars on right-side). Note the different vertical scales in (a) and (b).

a high total carbon uptake sensitivity to temperature, but also a high total carbon uptake sensitivity to CO_2 (see Tables 2 and 4 of Eby et al. 2013). The relative ordering of these sensitivities between the two models is time and scenario dependent (e.g., the equilibrium climate sensitivity is higher in UVic than Bern3D-LPJ at $2 \times \text{CO}_2$, but lower at $4 \times \text{CO}_2$), which may explain the change in ordering of allowable emissions with the level of temperature stabilization.

Matthews et al. (2009) proposed the climate-carbon response (CCR), defined as the ratio of temperature change to cumulative carbon emissions, as a metric for the combined physical and biogeochemical response of the climate system to CO_2 emissions. CCR has been suggested to be relatively insensitive to the emissions scenario and approximately constant over time. Eby et al. (2013) calculated the CCR for eight EMICs with an interactive carbon cycle from an idealized $4 \times \text{CO}_2$ experiment with a 1% CO_2 increase per year and noted that the CCR in the EMICs varies appreciably with time. At the time of CO_2 doubling, the CCR ranges from 1.4 to $2.5^\circ\text{C EgC}^{-1}$ [note that these numbers differ from those in Table 4 of

Eby et al. (2013), which are taken at the time of CO_2 quadrupling]. The models' CCR can be inverted to compute the range of cumulative emissions consistent with temperature targets. Ensemble mean allowable cumulative emissions are 830, 1100, 1650, and 2200 PgC for temperature targets of 1.5° , 2° , 3° , and 4°C , respectively (Fig. 17). Since the CCR was computed for cumulative emissions of about 1000 PgC , CCR-based allowable emission estimates for temperature targets of 1.5° – 2°C are likely more accurate than those for the higher temperature targets. While the cumulative emissions estimated from the temperature tracking experiments and the CCR are very similar for the Bern3D-LPJ model, particularly for lower temperature targets, the CCR-derived estimates are considerably higher for the UVic model. The difference in the UVic model's allowable emissions estimates for the low temperature targets could be explained by a net positive radiative forcing from non- CO_2 sources in the temperature tracking simulations (not present in the idealized $4 \times \text{CO}_2$ simulation from which the CCR was derived), which reduces the amount of allowable CO_2 emissions. Because of differences in forcing

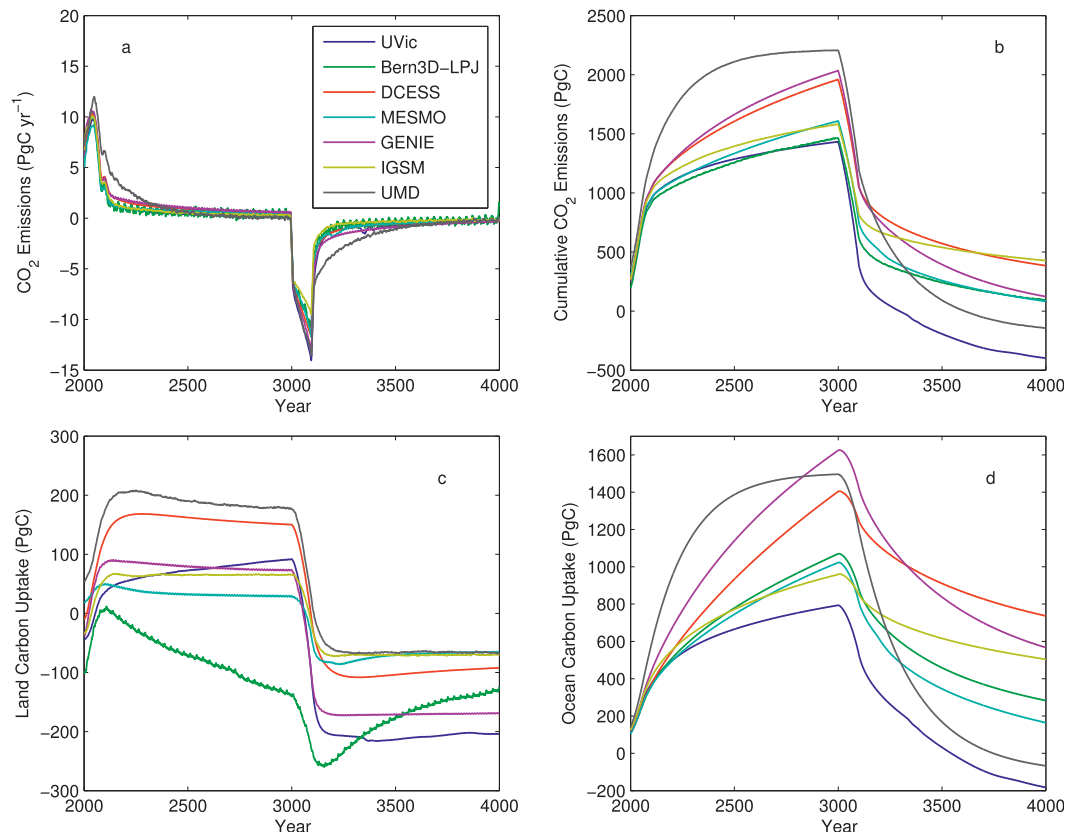


FIG. 15. Changes in carbon inventories for the RCP4.5 REa simulation with atmospheric CO_2 after year 3000 decreasing to preindustrial levels over 100 yr: (a) CO_2 emissions, (b) cumulative CO_2 emissions since 1850, (c) land uptake since 1850, and (d) ocean uptake since 1850. Data in (a) were smoothed using a 10-yr moving average.

implementation, the non- CO_2 radiative forcing imbalance seems not to be present in the Bern3D-LPJ temperature tracking runs, such that the two allowable emissions estimates are very similar for low temperature targets. For higher targets, the discrepancy between the CCR-based and temperature-tracking-derived estimates is likely a result of the time and scenario dependence of CCR.

4. Summary and conclusions

We presented results from long-term climate projections with 12 EMICs. The first set of projections contains climate change commitment simulations to the year 3000. Three different types of climate commitment are considered: 1) constant composition, 2) preindustrial emission, and 3) constant emission commitments. All commitment simulations follow common CO_2 concentration trajectories until the year 2300: the four RCP scenarios (2.6, 4.5, 6.0, and 8.5) and their extensions. Climate projections to 2300 are consistent with results from AOGCMs, confirming that EMICs are well suited to complement simulations with more complex models. Simulated ensemble-mean surface air temperatures

exceed the 2°C target set by the Copenhagen Accord in all scenarios, except for the low-emissions RCP2.6 scenario. Under this scenario, the model ensemble mean temperature peaks at 1.7°C relative to preindustrial, and returns to 1.3°C by 2300. The spread between models, however, is considerable, and peak warming in a few models exceeds the 2°C target.

EMICs simulate substantial surface air temperature and thermosteric sea level rise commitment following stabilization of the atmospheric composition at year-2300 levels for RCPs 4.5, 6.0, and 8.5. For these scenarios, the thermosteric sea level rise between years 2300 and 3000 amounts to several times the sea level rise by the time of radiative forcing stabilization. Sea level rise due to thermal expansion still continues at the year 3000 under all scenarios considered. The Atlantic meridional overturning circulation is weakened temporarily under RCPs 2.6–6.0 and recovers to within 80% of the preindustrial value several centuries after forcing stabilization. The MOC weakening is more persistent for RCP8.5, with one model close to a complete collapse in the year 3000.

EMICs with an interactive carbon cycle are used to diagnose the CO_2 emissions compatible with the CO_2

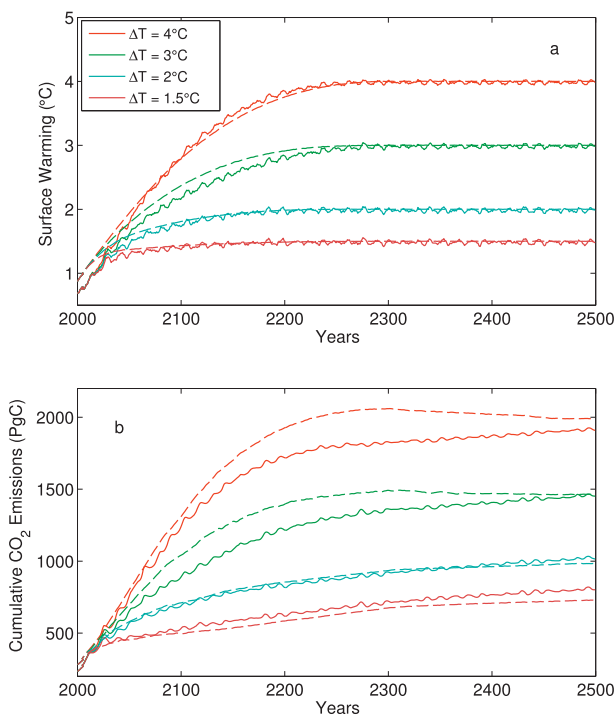


FIG. 16. Cumulative CO₂ emissions compatible with a set of long-term temperature targets (1.5°–4°C) for temperature tracking experiments with two EMICs: UVic (dashed) and Bern3D-LPJ (solid). (a) Surface air temperature change relative to preindustrial (1800 for UVic and 850 for Bern3D-LPJ). (b) Cumulative CO₂ emissions since preindustrial.

concentration pathways specified for the constant composition commitment simulations. Diagnosed cumulative emissions between 1850 and 3000 increase approximately linearly with atmospheric CO₂ for RCPs 2.6–6.0, but the increase becomes less than linear at higher radiative forcing. The year-3000 airborne fraction of cumulative emissions increases with increasing atmospheric CO₂. The increasing airborne fraction is due largely to a decrease in the ocean uptake fraction with higher radiative forcing. The model ensemble mean land uptake fraction is rather constant across RCP scenarios, but the CO₂ dependence varies strongly between models.

Elimination of anthropogenic CO₂ emissions after 2300 and constant year-2300 non-CO₂ radiative forcing result in slowly decreasing atmospheric CO₂ concentrations. At year 3000 atmospheric CO₂ is still at more than half the year-2300 level in all EMICs for RCPs 4.5–8.5, with the fraction increasing with RCP scenario. Surface air temperature remains nearly constant or decreases slightly in all EMICs, with 85%–99% of the maximum warming still persisting in the year 3000 for RCPs 4.5–8.5. Sea level rise due to thermal expansion continues after elimination of CO₂ emissions in RCPs 4.5–8.5 and is comparable to the sea level rise between 1850 and 2300. At 3000, 700 years

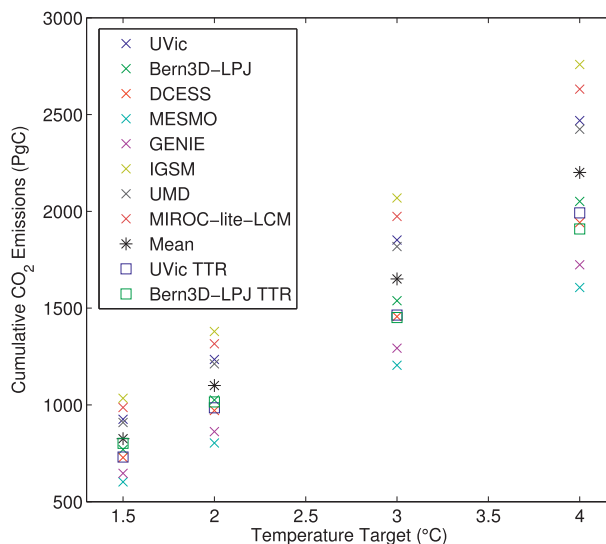


FIG. 17. Cumulative CO₂ emissions compatible with a set of long-term temperature targets (1.5°–4°C) for EMICs with an interactive carbon cycle. Allowable cumulative emissions are derived from the models' CCR. Also shown are the year-2500 cumulative emissions derived from TTR experiments with the UVic and Bern3D-LPJ EMICs (square symbols).

after anthropogenic CO₂ emissions are zeroed, sea level is still rising in several EMICs. If radiative forcing from non-CO₂ forcing agents is eliminated simultaneously with CO₂ emissions, temperature and thermosteric sea level decline slightly faster than in the simulations with elimination of CO₂ emissions alone, but still remain substantially higher in the year 3000 compared to preindustrial.

The largest warming and thermosteric sea level rise commitment are simulated for the case with CO₂ emissions held fixed at year-2300 levels and constant year-2300 non-CO₂ radiative forcing. In response to increasing atmospheric CO₂ levels after 2300, surface air temperature and sea level continue to rise, with a substantial post-2300 commitment.

The climate change commitment associated with the low emissions scenario RCP2.6 differs from that of the higher RCPs. Because of the decline in atmospheric CO₂ and radiative forcing already before 2300, the warming and thermosteric sea level rise commitment after 2300 are lower in this scenario. The difference is largest for the constant emissions commitment simulations, since year-2300 emissions are negative (as opposed to positive in the other scenarios). Accordingly, atmospheric CO₂ decreases after 2300, surface air temperature continues to cool, and sea level starts to fall.

Results of the climate change commitment simulations differ widely between EMICs, both in the physical and biogeochemical response. The difference in the response

of the terrestrial carbon cycle to atmospheric CO₂ and climate is particularly large. Compared to an earlier EMIC intercomparison (Plattner et al. 2008), the range of carbon cycle responses appears to have even widened. This may be explained by the larger number of coupled climate–carbon cycle models included in the present model intercomparison and the increase in model complexity since the Plattner et al. (2008) study. Most EMICs now include interactive representation of land use change emissions. One model includes representation of carbon release from permafrost and peatlands, while another includes nitrogen limitation. On the ocean side, several models now include representation of sediment processes. The large model spread suggests that continued efforts are needed to better understand the processes driving the response of land and ocean uptake to CO₂ and climate, and to better represent these processes in models.

If CO₂ emissions cease, and it is left to the natural carbon sinks to take up excess CO₂, atmospheric CO₂ declines only slowly, and climate change is largely irreversible on centennial to millennial time scales, as discussed above in the context of the preindustrial emission commitment simulations. Two additional experiments were carried out by EMICs to explore the reversibility of the climate system in response to an artificial “ramp down” of atmospheric CO₂ to preindustrial levels (over 100–1000 yr). Because of the large thermal inertia of the ocean, surface air temperature and thermohaline sea level exhibit a substantial time lag relative to atmospheric CO₂. Even 900 years after CO₂ is restored to preindustrial levels, surface air temperature and particularly sea level are still considerably higher than under 1851–60 conditions. The thermohaline circulation strengthens rapidly during the CO₂ decrease phase, first overshooting and then slowly converging to the preindustrial value. If atmospheric CO₂ is returned to preindustrial levels more slowly (over 1000 yr), surface air temperature also cools more slowly, and sea level continues to rise for several centuries before starting to fall. The model ensemble mean thermohaline circulation recovers slowly at first and more rapidly toward the end of the CO₂ decrease phase. The ramp down of CO₂ to preindustrial levels over 100–1000 yr requires large negative emissions (i.e., net removal of CO₂ from the atmosphere), which are likely unrealistic with technologies currently available to capture CO₂ from the atmosphere (McGlashan et al. 2012).

In summary, results from the commitment and reversibility simulations suggest that it is very difficult to revert from a given level of warming on time scales relevant to human activities, even after complete elimination of emissions. Reversing global warming may be desirable if climate change exceeds adaptive capacities of

natural and human systems. Our results suggest that significant negative emissions have the potential to reverse global warming but whether CO₂ capture technology is feasible at the necessary scale is debatable.

Using an inverse modeling approach, two EMICs (Bern3D-LPJ and UVic) estimated the cumulative CO₂ emissions (CO₂ budget) compatible with long-term global mean temperature stabilization targets. Cumulative emissions between preindustrial and the year 2500 are similar between the two models and amount to a mean value of 1000 PgC for 2°C. A somewhat higher model ensemble mean estimate is derived based on the climate–carbon response (CCR; Matthews et al. 2009) computed for EMICs with an interactive carbon cycle. As cumulative CO₂ emissions from fossil fuels and land use up to today amount to about 500 PgC, the remaining CO₂ budget consistent with the 2°C target is about 500 PgC, assuming that the radiative forcing of non-CO₂ greenhouse gases continues to be compensated by negative aerosol forcing, as has been approximately the case in the past. The results of this model intercomparison therefore support the conclusions from previous studies that it is still possible in theory to meet the 2°C target, but leeway is getting tight, particularly in the face of socioeconomic and technological inertia.

Acknowledgments. KZ and AJW acknowledge support from the National Science and Engineering Research Council (NSERC) Discovery Grant Program. AJW acknowledges support from NSERC’s G8 Research Councils Initiative on Multilateral Research Funding Program. AVE and IIM were supported by the President of Russia Grant 5467.2012.5, by the Russian Foundation for Basic Research, and by the programs of the Russian Academy of Sciences. EC, TF, HG, and GPB acknowledge support from the Belgian Federal Science Policy Office. FJ, RS, and MS acknowledge support by the Swiss National Science Foundation and by the European Project CARBOCHANGE (Grant 264879), which received funding from the European Commission’s Seventh Framework Programme (FP7/2007–2013). PBH and NRE acknowledge support from EU FP7 Grant ERMITAGE 265170.

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