

Carbon Dioxide Emission Pathways Avoiding Dangerous Ocean Impacts

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ABSTRACT

Anthropogenic emissions of greenhouse gases could lead to undesirable effects on oceans in coming centuries. Drawing on recommendations published by the German Advisory Council on Global Change, levels of unacceptable global marine change (so-called guardrails) are defined in terms of global mean temperature, sea level rise, and ocean acidification. A global-mean climate model [the Aggregated Carbon Cycle, Atmospheric Chemistry and Climate Model (ACC2)] is coupled with an economic module [taken from the Dynamic Integrated Climate–Economy Model (DICE)] to conduct a cost-effectiveness analysis to derive CO₂ emission pathways that both minimize abatement costs and are compatible with these guardrails. Additionally, the “tolerable windows approach” is used to calculate a range of CO₂ emissions paths that obey the guardrails as well as a restriction on mitigation rate. Prospects of meeting the global mean temperature change guardrail (2° and 0.2°C decade^{−1} relative to preindustrial) depend strongly on assumed values for climate sensitivity: at climate sensitivities >3°C the guardrail cannot be attained under any CO₂ emissions reduction strategy without mitigation of non-CO₂ greenhouse gases. The ocean acidification guardrail (0.2 unit pH decline relative to preindustrial) is less restrictive than the absolute temperature guardrail at climate sensitivities >2.5°C but becomes more constraining at lower climate sensitivities. The sea level rise and rate of rise guardrails (1 m and 5 cm decade^{−1}) are substantially less stringent for ice sheet sensitivities derived in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report, but they may already be committed to violation if ice sheet sensitivities consistent with semiempirical sea level rise projections are assumed.

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1. Introduction

As the body of knowledge grows regarding the possible worsening effects of an increasingly altered climate state, so too do concerns over how to avoid the most drastic outcomes. Intergovernmental collaboration on this topic was proclaimed by Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC), which calls for the avoidance of “dangerous

anthropogenic interference with the climate system” (UNFCCC 1992). Clearly any definition of “dangerous anthropogenic interference” (DAI) involves a value judgment as perceptions of danger vary among individuals and social groups (Dessai et al. 2004). Such value judgments are ideally excluded from scientific analysis, so quantitative studies often address Article 2 obliquely, such as via risk or vulnerability assessments [e.g., “reasons for concern,” “concepts of danger,” or “key vulnerabilities,” terms used respectively in Smith et al. (2001); ECF (2004), and Schneider et al. 2007], and leave to policymakers the task of determining what is acceptable. In an alternative approach, thresholds for DAI are defined based on expert judgments of systemic physical, ecological, or societal tolerances (e.g., Parry et al. 2001; O’Neill and Oppenheimer 2002; Barnett and Adger 2003; Corfee-Morlot and Höhne 2003; Graßl et al. 2003; Oppenheimer and Alley 2004; Hansen 2005; Keller et al. 2005; Schubert et al. 2006; Harvey 2007; Funk et al. 2008). Despite varied approaches and perspectives, general consensus suggests that common definitions of danger include singular events with irreversible and widespread consequences that have been referred to as “tipping points” in the recent literature (Lenton et al. 2007; e.g., collapse of the thermohaline circulation, disintegration of one or both polar ice sheets) and lasting conditions with broad ecological and economic impacts (e.g., widespread and frequent coral reef bleaching, rapid sea level rise, increased frequency of extreme weather). The European Union has settled upon a precautionary 2°C target for avoiding the most dangerous impacts, a target that is now supported by numerous scientific and environmental groups and most nations on Earth (e.g., Graßl et al. 2003; Bali Declaration 2007; Union of Concerned Scientists 2007; Greenpeace 2008; Copenhagen Accord 2009).

What avoiding DAI implies in terms of greenhouse gas (GHG) emissions can be explored through the use of integrated assessment models including relevant social and environmental aspects. A number of climatic thresholds (e.g., global mean temperature, thermohaline circulation stability) have been used to calculate least-cost emissions pathways (e.g., Keller et al. 2000; Mastrandrea and Schneider 2004; Keller et al. 2005; Bruckner and Zickfeld 2009; McInerney and Keller 2008). Emissions corridors compatible with such thresholds can also be calculated using the “tolerable windows approach” (TWA; Bruckner et al. 1999; Petschel-Held et al. 1999). Corridors define a solution space for emissions pathways that satisfy prescribed constraints or “guardrails.” Emissions corridors constrained simultaneously by environmental and economic considerations have been calculated by Petschel-Held et al. (1999) and Kriegler and Bruckner

(2004) for global mean temperature guardrails, by Toth et al. (2003) for degree of ecological transformation, and by Zickfeld and Bruckner (2003, 2008) and Bruckner and Zickfeld (2009) for thermohaline circulation stability.

Because of their societal importance, climatic thresholds other than global mean temperature and thermohaline circulation merit examination using the above approaches. Sea level rise threatens a growing proportion of the world population as coastal cities expand; a 40-cm rise in mean sea level by the 2080s could flood 100 million people per year for even low emission Special Report on Emissions (SRES) scenarios (Nakicenovic et al. 2000), assuming no additional flood defenses are put in place (Nicholls et al. 2007). Globally ocean pH has decreased 0.1 units from the average acidity in 1750 (Orr et al. 2005), with a continuing decline expected to have detrimental consequences for marine life that has evolved in a slightly alkaline and relatively stable chemical environment. A decrease in seawater pH lowers the saturation state for carbonate minerals such as calcite and aragonite. This affects the stability and production rates of carbonate minerals, which are the building blocks of coral reefs and form the shells and skeletons of other marine calcifying organisms. Coral reefs contain 25% of marine species (Buddemeier et al. 2004) and supply 2%–5% of the annual global fisheries harvest (Fischlin et al. 2007), mostly in developing nations (Pauly et al. 2005). Using ocean acidity as a threshold for allowable carbon emissions was recently suggested to be critical but utterly lacking (Zeebe et al. 2008). Because ocean acidification is largely dependent on carbon dioxide (with minimal dependence on temperature), application of an ocean acidification threshold is essentially equivalent to setting a CO₂ concentration target.

Cost-effective pathways and emissions corridors are derived here using a set of indicators for undesirable climate changes (global mean temperature change, sea level rise, and ocean acidification) to constrain future CO₂ emissions pathways.

These so-called guardrails were published by the German Advisory Council on Global Change (WBGU; Schubert et al. 2006) and are to be interpreted as recommended boundaries on acceptable levels of anthropogenic alteration of the Earth system, for the purpose of giving decision makers quantitative guidelines for avoiding DAI. The set of guardrails is as follows (in the following referred to as “WBGU guardrails”):

- Climate protection: The global mean rise in near-surface air temperature must be limited to a maximum of 2°C relative to the preindustrial value while also limiting the rate of temperature change to a maximum of 0.2°C decade^{−1} (originally proposed in Graßl et al. 2003).

- Sea level rise: Absolute sea level rise should not exceed 1 m in the long term (implied to be steady state in the document), and the rate should remain below 5 cm decade⁻¹ at all times.
- Ocean acidification: The pH of near-surface water should not drop more than 0.2 units below the pre-industrial average value in any larger ocean region (nor in the global mean).

The absolute guardrails reflect both human and environmental limits of intolerable change, while the rate guardrails reflect the maximum estimated rates of human and environmental adaptive capacity. The WBGU report (Schubert et al. 2006) also recommends a protection of 20%–30% of the area of marine ecosystems and mentions the risk of triggering the release of methane hydrate under global warming, but these issues are not addressed in this study. The WBGU guardrails are used as constraints in a coupled climate–economy model to calculate least-cost emissions pathways and emissions corridors.

2. Methods

A globally averaged climate–carbon cycle model, the Aggregated Carbon Cycle, Atmospheric Chemistry and Climate Model (ACC2 3.1; Tanaka et al. 2007; Tanaka 2008), is coupled with a simple model of the world economy, based on the economic module in the Dynamic Integrated Climate–Economy Model (DICE; Nordhaus 1992, 1994; Nordhaus and Boyer 2000; Nordhaus 2008), in order to assess the social mitigation burden associated with time-dependent emissions mitigation efforts. The sea level component of ACC2 is modified to improve the representation of thermal expansion and the sea level rise contribution from ice caps and small glaciers, and to reflect new estimates of the mass balance sensitivity of the Greenland and Antarctic ice sheets. A detailed description of the modifications made to the thermal expansion and sea level rise calculations in ACC2 can be found in the appendix. The DICE version used is DICE-2007, which is described in Nordhaus (2008).

a. Model ACC2

The model ACC2 (Tanaka 2008) describes major physical and biogeochemical processes in the Earth system on a global-annual-mean level.¹ ACC2 is a descendant of the Integrated Assessment of Climate Protection Strategies (ICLIPS) Climate Model (ICM)

(Bruckner et al. 2003) and has been used for several applications (e.g., Tanaka et al. 2009a,b; Tanaka and Raddatz 2011). Ocean and land CO₂ uptake are described by two separate four-reservoir box models tuned to the respective impulse response functions, which are the measured temporal response of a state variable calculated from the perturbation of the control run of a more complex model (Hooss et al. 2001; Joos et al. 1996). Parameterizations of atmospheric chemistry involve direct radiative forcing agents (CO₂, CH₄, N₂O, SF₆, 29 species of halocarbons, tropospheric and stratospheric O₃, and stratospheric water vapor) and indirect radiative forcing agents (OH, NO_x, CO, and VOC) (Joos et al. 2001). The radiative forcing due to aerosols is represented by the following three types: the direct effect of sulfate aerosols, the direct effect of carbonaceous aerosols (black carbon and organic carbon), and the indirect effect of all aerosols. The sum of the individual radiative forcing terms is the total radiative forcing, which is used by an energy balance model, the Diffusion Ocean Energy Balance Climate Model (DOECLIM; Krieglner 2005) to calculate surface air temperature. DOECLIM comprises essentially two boxes: 1) land coupled with the troposphere over land and 2) ocean coupled with the troposphere over ocean. Coupled to the ocean box is a heat diffusion model that describes heat transfer to the deep ocean, which is described in greater detail in Tanaka et al. (2007, section 2.3) and also in the appendix. Changes in large-scale ocean circulation due to temperature change are not modeled. The temperature feedback to ocean CO₂ uptake is provided with the equilibrium constants for marine carbonate species that are given as functions of the seawater temperature (Millero 1995; Millero et al. 2006). A detailed description of the inorganic carbon ocean module can be found in Tanaka (2008, ch. 2.1.2) and Tanaka et al. (2009b); briefly, it contains a four-layer box model where the first layer is in equilibrium with the atmosphere and the second through fourth layers represent the total anthropogenic contribution to ocean inorganic carbon inventory. A detailed description of the pH calculation can be found in the appendix. The temperature feedback to the land CO₂ uptake is modeled with a Q10 parameter, which indicates how much the rate of soil respiration increases with a temperature increase of 10°C.

1) PARAMETER ESTIMATION

In the model ACC2, the values of uncertain parameters are estimated against geophysical observational data between the years 1750 and 2005. Such parameter estimates are used in the simulations from year 2005 onward so that assumptions on uncertain parameters are consistent from the past to the future. In the original

¹ ACC2 model code is freely available upon request from K. Tanaka.

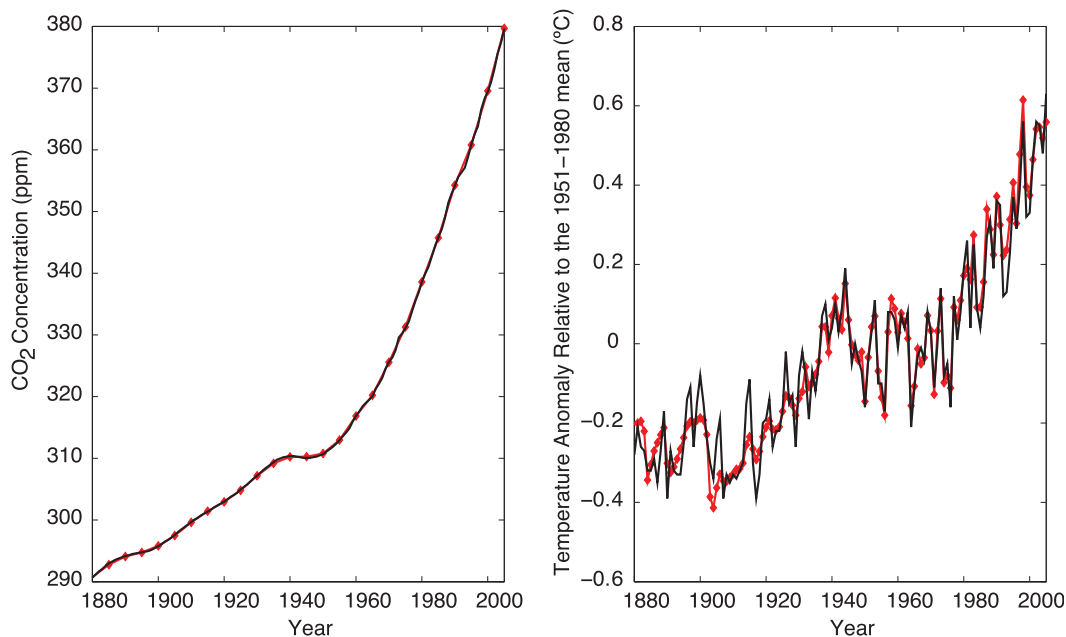


FIG. 1. (left) ACC2 model inversion atmospheric CO_2 concentration and (right) global mean temperature. Model output (red lines) is compared with historical reconstructions (black lines). CO_2 concentration observations are a combination of Antarctic ice core reconstructions (1880–1968; Etheridge et al. 1996) and direct atmospheric observations (1969–2005; Keeling et al. 2009). Global mean temperature reconstructions include both land and ocean measurements and are shown as a 20-yr running mean relative to the 1951–80 average (Hansen et al. 2010).

ACC2 3.1, the spinup mode ran from 1750 to 2000. The model is updated with an additional 5 yr of data. Examples of uncertain parameters are preindustrial land and ocean CO_2 uptake, and the beta factor (parameterization for CO_2 fertilization). Climate sensitivity (defined herein as the equilibrium global temperature change resulting from a doubling of atmospheric CO_2 concentration from the preindustrial value) is prescribed in each spinup mode integration for consistency with each future mode integration. Data include atmospheric concentrations of CO_2 , CH_4 , and N_2O , and global-mean surface air temperature change each year [from 1750 to 2005; for the lists of parameters and data for 1750–2000, see Tables 3.1 and 3.2 of Tanaka (2008)]. In the ACC2 inversion approach, a best estimate of uncertain parameters is obtained by minimizing the cost function that consists of the sum of the squared deviations of parameters and data from their a priori values weighted by their uncertainty. From the perspective of the inverse estimation theory (Tarantola 2005), underlying assumptions that should be explicitly noted here are 1) Gaussian error assumptions and 2) independent error assumptions (Tanaka et al. 2009b). For more detailed discussion related to the assumptions, see Tanaka (2008, ch. 3). Of the three major uncertainties in the climate system (climate sensitivity, aerosol forcing, and ocean diffusivity), climate sensitivity is prescribed while aerosol

forcing is simultaneously computed against historical observations (Tanaka and Raddatz 2011). The ocean diffusivity is assumed to be $0.55 \text{ cm}^2 \text{ s}^{-1}$ (Tanaka et al. 2007, section 3.4).

The inverse parameter estimation does a reasonable job of reproducing key climate time series. Figure 1 shows global CO_2 concentration and global mean temperature from 1880 to 2005, overlaid with Antarctic ice core CO_2 measurements (1880–1968; Etheridge et al. 1996), CO_2 flask measurements (1969–2005; Keeling et al. 2009), and global mean temperature reconstructions (Hansen et al. 2010). Additional comparisons of ACC2 inversion results with historical data can be found in Tanaka et al. (2009a,b).

2) ICE MASS BALANCE SENSITIVITY

Ice mass balance sensitivities of the Antarctic and Greenland ice sheets are parameters in ACC2 and are adjustable. Meehl et al. (2007, p. 817) give sensitivities for the Greenland ice sheet (GIS) as $0.11 \pm 0.09 \text{ mm yr}^{-1} \text{ } ^\circ\text{C}^{-1}$ and for the Antarctic ice sheet (AIS) as $-0.29 \pm 0.18 \text{ mm yr}^{-1} \text{ } ^\circ\text{C}^{-1}$. These sensitivities are based on a global warming of 3°C relative to the preindustrial temperature and are interpreted as the rate of sea level rise (in millimeters per year) occurring for every additional degree of warming. A negative value corresponds to a negative contribution to

sea level, or net growth of the ice sheet. Aside from different parameter values for ice mass balance, ACC2 treats both ice sheets identically so it is useful to think of the combined GIS and AIS sensitivities as a “total” ice sheet sensitivity. The Meehl et al. (2007, p. 817) total sensitivity used for base runs is therefore $-0.18 \text{ mm yr}^{-1} \text{ }^{\circ}\text{C}^{-1}$.

Using this total sensitivity in ACC2 gives sea level rise projections at the low end of the Intergovernmental Panel on Climate Change (IPCC) range (see the 90% confidence interval for sea level rise components for 2090–99 relative to 1980–99 in Fig. 2), but these results ignore the physical processes contributing to ice sheet dynamics (Alley et al. 2005) and assume that the Antarctic contribution remains negative. Because ice sheet sensitivity is poorly constrained, a comparative analysis is performed with respect to this quantity. Recent publications using a semiempirical approach to sea level rise estimation (e.g., Vermeer and Rahmstorf 2009; Grinsted et al. 2010; Jevrejeva et al. 2010) project substantially higher sea level rise by 2100 than Meehl et al. (2007). To reproduce these studies, which do not distinguish between the individual sea level rise contributors, total ice sheet sensitivity in ACC2 is tuned to attain a sea level rise central estimate of the “Moberg” 5%–95% confidence interval in Grinsted et al. (2010), which requires the use of a $4.11 \text{ mm yr}^{-1} \text{ }^{\circ}\text{C}^{-1}$ total ice sheet sensitivity. Such a strong sensitivity implies rapid deterioration of both the Greenland and Antarctic ice sheets, with annual total ice sheet contributions to sea level rise in 2100 about 3 times ACC2 estimates for 2012.

b. Model DICE

The economic model used is the globally aggregated Dynamic Integrated Climate–Economy Model (DICE-2007; Nordhaus 2008). It is selected from a number of other economic models because it is computationally efficient, written in Generic Algebraic Modeling System (GAMS), and has a history of use in similar integrated assessments (e.g., Keller et al. 2000; Mastrandrea and Schneider 2004; Schneider and Mastrandrea 2005; Bruckner and Zickfeld 2009; McInerney and Keller 2008; McInerney et al. 2012). Briefly, DICE is a Ramsey-type optimal growth model that contains endogenous variables that represent the fundamental elements of the long-term economic development process—the investment and capital accumulation cycle.

A Cobb–Douglas production function describes the transformation of the factor inputs, capital $K(t)$ and labor $L(t)$, into a product $Q(t)$ (often simply called “output”) net of mitigation spending, under consideration of exogenous technological change $A(t)$:

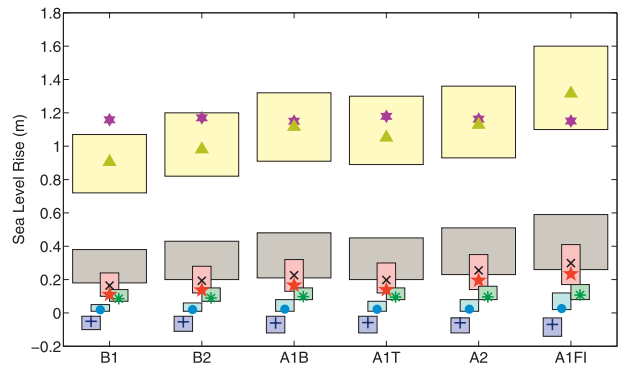


FIG. 2. Mean sea level rise between years 2090 and 2099 relative to the 1990–99 mean, broken down by contributor. This plot is a recreation of Fig. 10.33 in Meehl et al. (2007), where IPCC 90% confidence intervals for the time period 2090–99 relative to 1980–99 are denoted by boxes, and markers represent ACC2 model output averaged in a similar fashion. Total sea level rise is denoted by the gray box (black x), thermal expansion by pink (red star), glaciers by green (green star), and the Greenland Ice Sheet by light blue (blue dot). The Antarctic contribution is modeled using both the IPCC-recommended ice mass balance sensitivity (dark blue plus signs) and one tuned to Grinsted et al. (2010). The 90% confidence intervals for total sea level rise from Table 2 in Grinsted et al. (2010) are denoted by yellow boxes, with the value obtained by tuning the total ice sheet sensitivity in ACC2 shown as yellow triangles. Committed sea level rise at year 2010 using Eq. (7) is denoted by the purple star.

$$Q(t) = \Omega(t)A(t)K(t)^{\gamma}L(t)^{1-\gamma}. \quad (1)$$

Here γ denotes the elasticity of output with respect to capital and is assumed equal to 0.3, and $\Omega(t)$ is applied to reduce economic output where mitigation costs occur.

Industrial CO_2 emissions, $E(t)$, are calculated as the product of a prescribed carbon-intensity factor, $\sigma(t)$, and output, modified by an emissions control level $\mu(t)$:

$$E(t) = [1 - \mu(t)]\sigma(t)Q(t). \quad (2)$$

Here $\mu(t) = 0$ corresponds to the reference case without emissions control, referred to as “business as usual” (BAU). Carbon dioxide emissions $E(t)$ provide the link between DICE and ACC2. Note that negative emissions (i.e., net carbon sequestration from the atmosphere) that would allow the emissions control level $\mu(t)$ to exceed 100% are not permitted in this study. Allowing for carbon sequestration at a level that could alter globally aggregated emissions would be speculative given present technology.

The percentage abatement cost (with respect to the premitigation output) $\Omega(t)$ is modeled by a power law

$$\Omega(t) = 1 - b_1\mu(t)^{b_2}, \quad (3)$$

with calibration parameters b_1 and b_2 . Note that in contrast to the original DICE formulation, climate

change damages are not taken into account. This implies that cost-effective pathways do not include damage costs to the economy, except for those associated with the applied guardrails.²

In the original version of DICE, a globally aggregated intertemporal social welfare function W is maximized in order to derive optimal climate change abatement. W is modeled according to

$$W = \int_t U[C(t), L(t)](1 + q)^{-t}, \quad (4)$$

$$U[C(t), L(t)] = L(t)[c(t)^{1-\alpha}/(1-\alpha)], \quad (5)$$

where $c(t)$ is *per capita* consumption [derived from $C(t)$], $L(t)$ is labor, q is a social rate of time preference factor, and α is the elasticity of the marginal utility of consumption. The pure rate of social time preference is set to 1.5% yr^{-1} , and the elasticity of the marginal utility of consumption is set to 2 in order to achieve a real return on capital of 5.5% yr^{-1} over the first five decades of the simulations (Nordhaus 2008).

Here, either 1) constrained optimal mitigation strategies that obey prescribed environmental guardrails or 2) emissions corridors representing the set of all emissions paths that do not violate elected environmental guardrails and, simultaneously, a constraint on acceptable mitigation rates are derived. In the first case (cost-effectiveness analysis), W will be maximized subject to the prescribed guardrails (in the absence of climate damages, W is effectively an abatement cost function).³ In the second case (tolerable windows analysis), W is a diagnostic variable used to compute welfare relative to the reference case without emissions control (BAU). Note that in contrast to traditional cost/benefit analysis and the original formulation of Nordhaus, the welfare function defined in this paper only takes into account welfare losses due to mitigation measures. As long as the pathway stays within the selected guardrails, welfare losses due to remaining climate damages are neglected.

c. Coupled ACC2–DICE

ACC2 contains a 255-yr spinup mode (1750–2005) that utilizes an inversion approach to estimate uncertain

parameters and calculate starting points for the year 2005. ACC2 is run in standalone mode for the spinup before being coupled to the mitigation cost-related economic relationships of the DICE model for the future runs (2005–2195). DICE operates with 10-yr time steps, and ACC2 uses an annual iteration, so CO_2 emissions from sequential iterations in DICE are linearly interpolated into annual values for coupling. ACC2–DICE is run to year 2195 in order to avoid end point effects in the time series of interest (2005–2100) and to partially account for inertia in the climate system. Energy-related CO_2 emissions are calculated in DICE, while CO_2 emissions from land-use change and emissions of non- CO_2 GHGs and pollutants are prescribed to follow IPCC SRES scenario A1B (Nakicenovic et al. 2000) until 2100. Afterward these emissions are held constant at year 2100 levels. It is assumed that emissions of SO_2 are coupled to energy-related CO_2 emissions, considering that SO_2 emissions originate mainly from the burning of fossil fuels. A desulfurization rate of 1.5% yr^{-1} is prescribed to account for implementation of low-sulfur alternatives, a rate below the 2% yr^{-1} judged to be unsustainable over the long term by Alcamo and Kreileman (1996). Zickfeld and Bruckner (2008) performed a sensitivity study of emissions corridors with respect to the desulfurization rate and found that reduced allowable CO_2 emissions correspond with higher desulfurization rates, owing to the faster reduction of the aerosol cooling effect.

d. Model application schemes

1) COST-EFFECTIVENESS ANALYSIS

The objective of cost-effectiveness analysis is to calculate CO_2 emissions pathways that minimize abatement costs while obeying prescribed constraints (WBGU guardrails on global marine change, in this case). To achieve this goal, welfare is used as the objective function. Least-cost⁴ emissions paths are calculated from a start year of 2005 but constrained with WBGU guardrails from 2011 onward.

Note that in contrast to traditional cost/benefit analysis, within the cost-effectiveness framework the cost of emissions reduction and the damages caused by climate change are not traded off. In the cost-effectiveness framework, higher climate sensitivities imply lower cost-effective emission trajectories. For sufficiently high climate sensitivities, it might not be possible to stay below the temperature limit.

² Alternatively, the calculation presented here could be viewed as replacing the standard DICE quasi-quadratic damage functions with step functions that are zero within the guardrails and very high everywhere else.

³ In a strict sense, instead of minimizing pure mitigation costs, the approach minimizes the welfare implication (losses) of mitigation measures.

⁴ “Least-cost” is used here in a broad sense, referring to constrained welfare maximization.

2) TOLERABLE WINDOWS APPROACH

Cost-effectiveness analysis provides emissions pathways that minimize the costs of mitigation while respecting climate change guardrails. From an environmental standpoint one might rather seek to minimize climate change subject to mitigation cost constraints. The tolerable windows approach (Bruckner et al. 1999; Petschel-Held et al. 1999) is a compromise between these two different approaches as it places constraints on both environmental impacts and mitigation costs.⁵ The TWA provides a bundle of emissions paths (an “emissions corridor”) respecting both climate change guardrails and an economic constraint.

The upper (lower) bound of the emissions corridor is calculated by maximizing (minimizing) CO₂ emissions every 10 yr, and aggregating the maxima (minima) of the resulting paths into boundaries (Fig. 8). Stepping outside of or even following the boundaries of the emissions corridor violates either economic or environmental guardrails. The converse is not necessarily true; not all conceivable pathways within the corridor are admissible.

Emissions corridors that comply with the WBGU guardrails described earlier are computed here. In addition, a socioeconomic constraint is imposed to satisfy expectations about the socioeconomically acceptable pace of emissions reductions [see also Bruckner and Zickfeld (2009), and references therein].

The emissions control level $\mu(t)$ is not allowed to increase faster than some prescribed value:

$$0 \leq \dot{\mu}(t) \leq \dot{\mu}_{\max}, \quad (6)$$

where $\dot{\mu}_{\max}$ is set to 1.33% yr⁻¹ in this analysis. This upper value of $\dot{\mu}_{\max}$ is based on the observed emissions reductions in Germany over the 1990s (i.e., in the years after reunification), where it is assumed that all of the reductions are due to active mitigation in order to establish an extreme case of intentional reductions (Bruckner and Zickfeld 2009). Furthermore, in order to avoid artificial oscillations in the emissions control level, $\mu(t)$ is not allowed to decline.

⁵ In a nutshell, the TWA can be described as follows: on the basis of a set of prescribed constraints (guardrails) that exclude intolerable climate change impacts and unacceptable mitigation measures, the admissible range of future emissions paths is sought by investigating the dynamic relationships linking the causes and effects of global climate change (Bruckner et al. 2003).

3. Results

a. Least-cost emissions paths

1) GLOBAL MEAN TEMPERATURE GUARDRAILS

The WBGU-recommended limits on global mean temperature (2°C absolute, 0.2°C decade⁻¹) prove highly constraining over the range of climate sensitivities examined (2° to 4.5°C per CO₂ doubling, suggested by the IPCC as the “likely” range; Meehl et al. 2007). For climate sensitivities equal or greater than 2°C, a maximum rate of temperature change of 0.2°C decade⁻¹ is not attainable because of rapid temperature increases in the first 15 years of the twenty-first century (Fig. 3, top middle panel). The temperature change rate guardrail is influenced more in these early years by non-CO₂ GHG species, rendering CO₂ mitigation ineffective for respecting temperature rate thresholds over the near term. While the rate of temperature rise can be restrained below the guardrail in latter decades for the higher climate sensitivities, this rate guardrail is omitted in the rest of the analysis.

Using a 2°C guardrail without a rate constraint reveals a large dependence of the emissions pathway on the equilibrium climate sensitivity used in the model. Figure 3 shows least-cost pathways for the 2°C absolute temperature change guardrail using climate sensitivities of 2°, 2.5°, and 3°C, where a half degree of climate sensitivity necessitates an additional 2–3 GtC yr⁻¹ emission reduction by 2020, with differences increasing over the run. For these pathways, non-CO₂ GHGs and CO₂ emissions from land use change are prescribed following the IPCC SRES scenario A1B (Nakicenovic et al. 2000). Of the climate sensitivities in the range 2° to 4.5°C, only 2°, 2.5°, and 3°C produced least-cost pathways that were able to respect the prescribed maximum temperature. According to this analysis, should the global climate sensitivity be greater than 3°C, it would be impossible to prevent global temperature rising beyond 2°C over the model run without emissions reduction strategies for non-CO₂ GHGs. IPCC (Meehl et al. 2007) gives a most likely sensitivity value of about 3°C, which suggests that respecting the 2°C guardrail may prove challenging if CO₂ emissions alone are mitigated. Certainly any CO₂ emission pathway that does respect the WBGU global temperature limit must depart substantially from the DICE business-as-usual pathway within the next 5 to 10 yr (shown as a thin dotted line in Fig. 3). For a climate sensitivity of 3°C, emissions would have to be reduced by 60% (relative to BAU) by 2015 in order to respect the absolute temperature guardrail.

The cooling role of aerosols is highlighted by the difference in the global mean temperature pathways of the

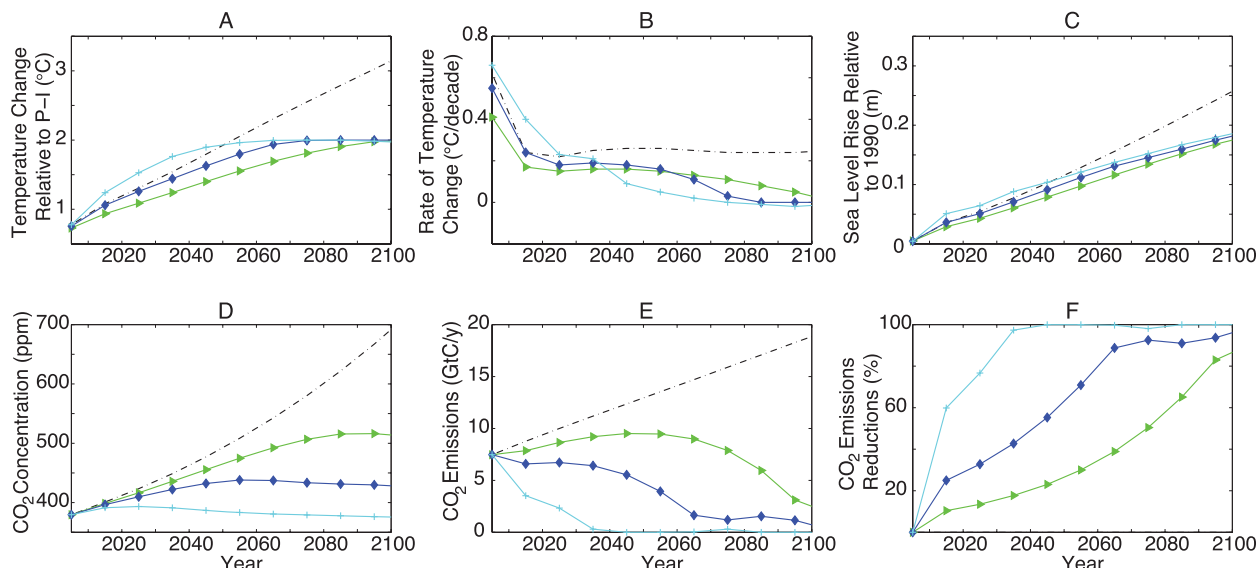


FIG. 3. Cost-effective pathways for the WBGU absolute temperature guardrail (2.0°C), using various equilibrium climate sensitivities. All runs use prescribed emissions of non-CO₂ GHGs following the SRES A1B scenario. Shown are (a) the change in global mean temperature relative to the preindustrial equilibrium, (b) the rate of global mean temperature change, (c) the change in global mean sea level relative to the level at 1990, (d) atmospheric CO₂ concentration, (e) annual global CO₂ emissions, and (f) the requisite reductions in global CO₂ emissions relative to the BAU case. Colors denote climate sensitivities of 2.0°C (green triangle), 2.5°C (blue diamond), and 3°C (cyan plus sign). The business-as-usual [BAU; $\mu(t) = 0$] path is denoted by a dotted black line. No feasible emissions paths exist for climate sensitivities above 3°C.

3°C climate sensitivity cost-effective and BAU configurations in Fig. 3a. The application of a desulfurization rate tied to CO₂ emissions reductions in the cost-effective pathways yields a larger temperature change prior to 2050 than what results in the BAU scenario, and it increases the rate of temperature change over the first 30 yr despite the higher annual CO₂ emissions in the BAU case.

Increasing CO₂ emissions reductions over time in the pathways illustrated in Fig. 3 are a result of the high rate of return on capital in the DICE model. DICE uses an estimated market-derived pure rate of time preference of 1.5% yr⁻¹, although not all analyses use this market rate [e.g., Stern (2007) used a rate of 0.1% yr⁻¹]. A sensitivity analysis with respect to positive time preference rates between 0.1 and 4.5% yr⁻¹ has been conducted and found to have little influence on cost-effective CO₂ emission pathways (less than 1 GtC yr⁻¹ between the end members). Low sensitivity in this analysis to the time preference rate is due to the strong temperature constraint: relaxing the temperature guardrail yields greater sensitivity to the time preference rate. Note that in the cost-effectiveness framework, the rate of change of the emission control level [Eq. (6)] is not taken into account.

Assumptions regarding emissions of non-CO₂ GHGs have a large effect on least-cost CO₂ pathways for the

WBGU temperature guardrail. Figure 4 shows resultant pathways using A1B non-CO₂ GHG emissions plus two hypothetical non-CO₂ GHG emissions reductions scenarios, using a climate sensitivity of 3.0°C. In the first hypothetical scenario, all non-CO₂ GHG emissions are set to zero starting in year 2012 (red line in Fig. 4). CO₂ emissions are sustainable at a significantly higher level (4–10 GtC yr⁻¹) than under non-CO₂ GHG emissions evolving according to the A1B scenario (Fig. 4, blue line) if non-CO₂ GHG emissions are eliminated. In the second hypothetical scenario, non-CO₂ GHG emissions are linearly reduced from A1B levels at 2011 to zero at 2100 (shown as the green line in Fig. 4). These higher CO₂ emissions pathways in the hypothetical emissions scenarios resemble the 2.0°C climate sensitivity pathway in Fig. 3 (green path).

2) SEA LEVEL RISE GUARDRAILS

Cost-effective emissions pathways compatible with the WBGU-recommended sea level rise guardrails (1 m absolute, 5 cm decade⁻¹) follow BAU emissions paths if the IPCC total ice mass balance sensitivity (−0.18 mm yr⁻¹ °C⁻¹) is used and no sea level rise commitment beyond the year 2200 is considered. If a total ice mass balance sensitivity of 4.11 mm yr⁻¹ °C⁻¹ is applied to adjust ACC2 sea level response to the range projected by recent semiempirical sea level models

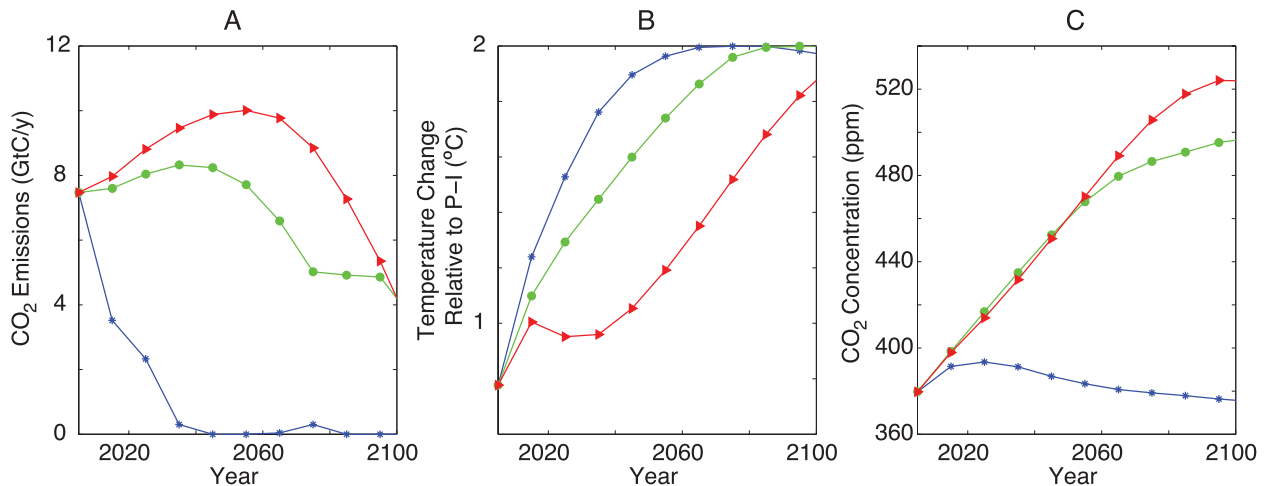


FIG. 4. Cost-effective pathways for the 2°C temperature guardrail using two hypothetical scenarios for non-CO₂ GHG emissions [zero emissions starting year 2012 (red triangles) and a linear decrease from 2011 emissions to zero at 2100 (green circles)]. A climate sensitivity of 3°C is assumed. The pathway for non-CO₂ GHGs following SRES scenario A1B (blue stars) is shown for comparison. Shown are (a) annual global CO₂ emissions, (b) the change in global mean temperature relative to the preindustrial equilibrium, and (c) atmospheric CO₂ concentration.

(Grinsted et al. 2010), then neither the absolute sea level nor the rate guardrail can be attained over the range of climate sensitivities examined. In ACC2, a maximum total ice mass balance sensitivity of $1.6 \text{ mm yr}^{-1} \text{ }^{\circ}\text{C}^{-1}$ is allowed when using IPCC SRES scenario A1B and a climate sensitivity of 3°C to achieve compliance with WBGU sea level guardrails. Figure 5 shows a range of emissions pathways using total ice mass balance sensitivities that start with the control value ($-0.18 \text{ mm yr}^{-1} \text{ }^{\circ}\text{C}^{-1}$) and incrementally increase to where compliance with both rate and absolute WBGU guardrails is no longer possible.

3) OCEAN ACIDIFICATION GUARDRAIL

Figure 6 illustrates the effect of imposing the WBGU pH guardrail (maximum drop of 0.2 units relative to preindustrial levels) on least-cost emissions pathways. Meeting the pH guardrail requires stabilization of atmospheric CO₂ concentrations at 462 ppm. CO₂ stabilization, in turn, entails CO₂ emissions that decline continuously until a stable level is reached ($1.5\text{--}2.5 \text{ GtC yr}^{-1}$, depending on climate sensitivity), at which time anthropogenic CO₂ emissions approximately equal uptake by natural carbon sinks. Small differences in allowable emissions between climate sensitivities arise from climate-carbon cycle feedbacks, which become stronger with increasing temperature. Similarly, the role of non-CO₂ GHGs in determining optimal emissions pathways in ACC2 is minor (not shown). Respecting the pH guardrail requires significant departure of CO₂ emissions from the BAU pathway. Reductions in CO₂ emissions relative to BAU must begin immediately, with $15\%\text{--}20\% \text{ yr}^{-1}$

before 2015, and increase rapidly midcentury to $86\%\text{--}93\%$ by 2100. As with the temperature guardrail analysis, the increasing mitigation with time is a result of the positive social rate of time preference used in DICE.

For climate sensitivities greater than 2.5°C, global mean temperature rise for the pH-constrained pathway exceeds the WBGU-recommended 2°C guardrail by the

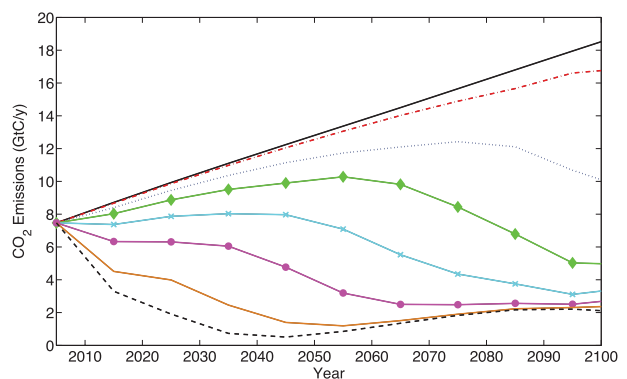


FIG. 5. Cost-effective CO₂ emissions pathways using several ice mass balance sensitivities selected to show the general solution space within which pathways exist that comply with WBGU sea level rise rate and absolute guardrails. Total ice mass balance sensitivities range from IPCC-recommended ($-0.18 \text{ mm yr}^{-1} \text{ }^{\circ}\text{C}^{-1}$, black solid line) to $1.6 \text{ mm yr}^{-1} \text{ }^{\circ}\text{C}^{-1}$ (black dashed line), the highest total sensitivity that also respects the WBGU guardrails (rate and absolute). Pathways for 0.5 (red dash-dotted), 0.7 (blue dotted), 0.9 (green diamond), 1.1 (cyan x), 1.3 (magenta circle), and $1.5 \text{ mm yr}^{-1} \text{ }^{\circ}\text{C}^{-1}$ (orange solid) are also shown for comparison. All non-CO₂ GHGs follow the A1B scenario and climate sensitivity is held at 3°C.

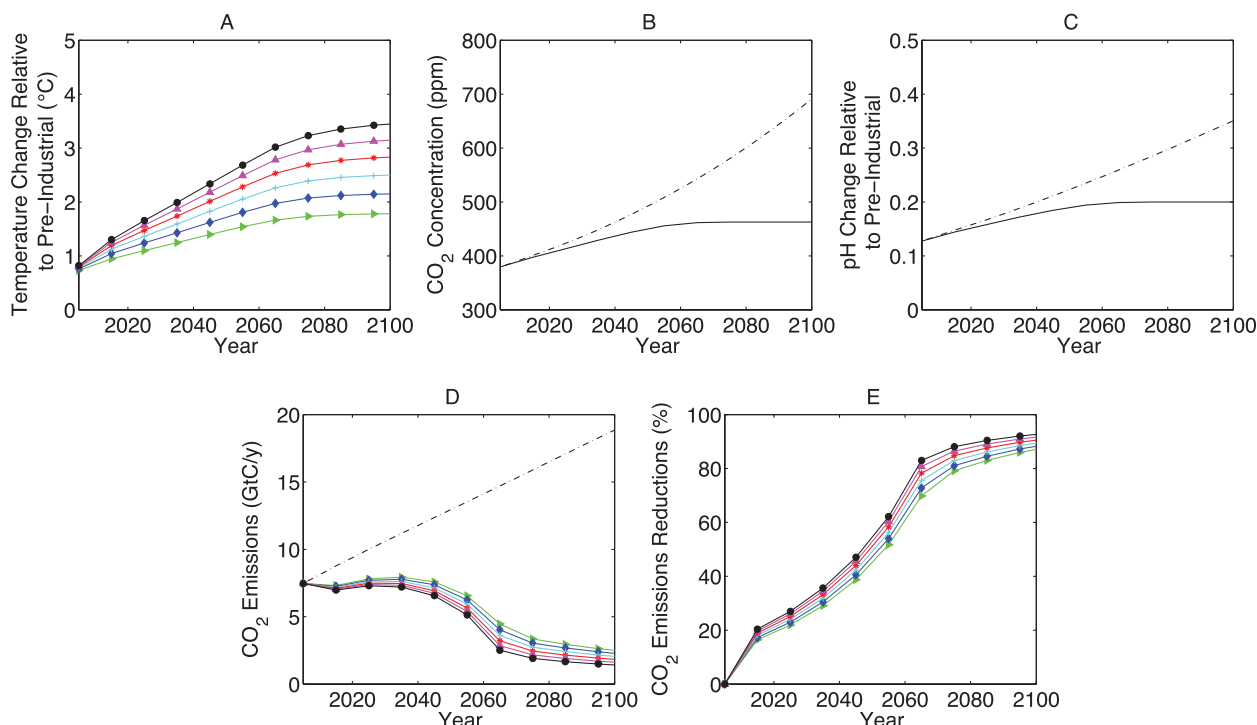


FIG. 6. Cost-effective pathways for the ocean acidification guardrail. Pathways for different equilibrium climate sensitivities are denoted by colors: 2.0°C (green triangle), 2.5°C (blue diamond), 3.0°C (cyan plus sign), 3.5°C (red star), 4.0°C (magenta triangle), and 4.5°C (black circle). The BAU emission pathway is shown as a dash-dotted line. Shown are (a) the change in global mean temperature relative to the preindustrial equilibrium, (b) atmospheric CO₂ concentration, (c) the change in pH relative to the preindustrial value, (d) annual global CO₂ emissions, and (e) the requisite reductions in global CO₂ emissions relative to the BAU case.

middle of the century. However, if climate sensitivity is lower than about 2.5°C, larger CO₂ emissions reductions are required in order to meet the pH guardrail than to meet the temperature guardrail (Fig. 7). This suggests that enforcement of a 2°C temperature guardrail by the international community would guard against unacceptable ocean acidification, unless climate sensitivity turns out to be at the lower end of the IPCC range. Note that this does not necessarily mean that bleaching of coral reefs is prevented by observing the WBGU temperature guardrails. A warming of 1°C could cause severe bleaching (O'Neill and Oppenheimer 2002). Several other factors come into play in determining the state of coral reef ecosystems.

b. Emissions corridors respecting WBGU guardrails

Figure 8 displays the emissions corridor for the WBGU ocean acidification guardrail with non-CO₂ emissions following SRES scenario A1B, using a climate sensitivity of 3°C. The BAU path exceeds the upper boundary of the corridor displayed in Fig. 8 around the year 2016, implying that, under BAU conditions, the ocean acidification guardrail would be violated after 2016. The lower bound of the corridor is determined by the maximum admissible emissions control rate ($\dot{\mu}_{\max}$).

It is important to bear in mind that in accordance with the concept of the tolerable windows approach, the emissions corridor imposes necessary but not sufficient conditions on the admissibility of emissions pathways.

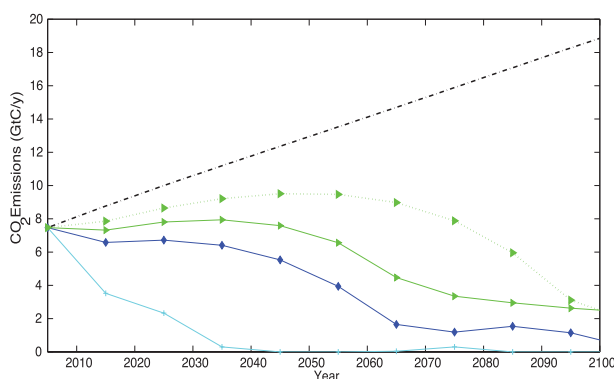


FIG. 7. Cost-effective pathways complying with combined WBGU temperature and pH guardrails. Pathways for different equilibrium climate sensitivities are denoted by colors: 2.0°C (green triangle), 2.5°C (blue diamond), and 3.0°C (cyan plus sign). For comparison, the dashed green line with a green triangle marker denotes the 2°C climate sensitivity pathway respecting the WBGU temperature guardrail only and the black dashed line represents the BAU emission pathway.

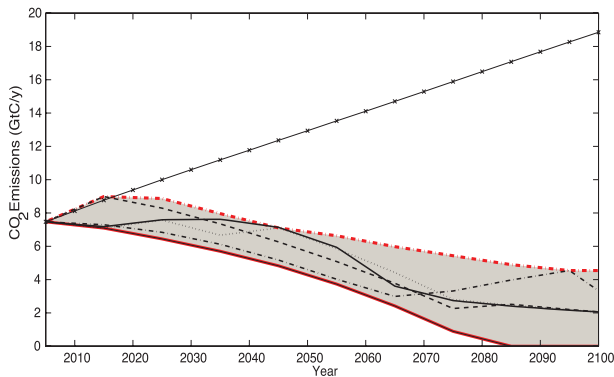


FIG. 8. Emissions corridor for the WBGU ocean acidification guardrail with non-CO₂ emissions following SRES scenario A1B using a climate sensitivity of 3°C. Red lines denote the boundary between acceptable and unacceptable domains (lower bound: solid line; upper bound: dashed line). Black broken lines illustrate the algorithm used for the calculation of the upper corridor boundary. These lines maximize CO₂ emissions in year 2015 (dashed), 2045 (dotted), and 2095 (dash-dotted). The solid black line denotes the cost-effective emissions pathway under the same constraints and parameter settings. The BAU pathway is represented by the thin cross-hatched line.

This implies that all emissions paths crossing the corridor boundaries violate at least one guardrail, but not all emissions paths within the corridor are necessarily admissible. For instance, the upper corridor boundary is not an admissible pathway because it comprises the maximum emissions points of multiple emissions pathways, each of which must satisfy constraints over the entire time horizon. As illustrated in Fig. 8, emissions pathways along the upper corridor boundary are associated with steep emissions reductions after the peak. This is consistent with the idea that meeting climate stabilization targets depends upon cumulative emissions (e.g., Matthews et al. 2009; Zickfeld et al. 2009).

It is noteworthy that applying the 2°C temperature guardrail alone or in combination with the pH guardrail yields infeasible solutions for climate sensitivities larger than 2.5°C under standard constraints on the emission reduction rate ($\dot{\mu} \leq 1.33\% \text{ yr}^{-1}$). This implies that it is not possible to meet the environmental and economic guardrails at the same time. To obtain a feasible solution for the combined pH and temperature guardrails, the constraint on the maximum admissible emissions control rate $\dot{\mu}_{\text{max}}$ needs to be relaxed to $1.38\% \text{ yr}^{-1}$ for a climate sensitivity of 2.5°C. For a climate sensitivity of 3°C, $\dot{\mu}_{\text{max}}$ must be increased substantially, to $4.5\% \text{ yr}^{-1}$.

4. Discussion

In the analysis of least-cost CO₂ emissions pathways that respect WBGU guardrails, it is found that for

climate sensitivities greater than 2.5°C, the pH guardrail is less constraining than the global mean temperature limits ($0.2^\circ\text{C decade}^{-1}$, 2°C total). At lower climate sensitivities ($<2.5^\circ\text{C}$), the pH guardrail (drop of 0.2 units) becomes more binding than the global mean temperature target. Sea level targets are the most restrictive of the three and may already be impossible to achieve depending upon ice sheet and overall climate sensitivity.

a. Global mean temperature

For climate sensitivities within the IPCC likely range (a 67% probability of 2° to 4.5°C), emissions pathways are required to deviate immediately and substantially from business as usual in order to respect the temperature guardrail of 2°C . The rate guardrail of $0.2^\circ\text{C decade}^{-1}$ for all runs in the first decade and the absolute temperature guardrail for runs using climate sensitivities greater than 3°C prove too restrictive without regulation of greenhouse gases other than CO₂. Friedlingstein et al. (2011) similarly showed that near-term departure from BAU is required to respect a 2°C guardrail, with immediate and complete elimination of CO₂ emissions in 2111 avoiding guardrail violation, but a 1% per annum CO₂ emissions decrease crossing the guardrail, if a climate sensitivity of 3°C is assumed and only CO₂ emissions are considered. Ramanathan and Feng (2008) estimate that a warming commitment of 2.4°C was reached in 2005 if future GHG concentrations had been fixed at 2005 levels, also implying that substantial departure from BAU is required to respect a 2°C guardrail. Including non-CO₂ greenhouse gas mitigation in our analysis reduces necessary CO₂ mitigation by as much as 10 GtC yr^{-1} in the middle of the 21st century for a scenario with complete elimination of non-CO₂ greenhouse gas emissions after 2012. A recent analysis of published CO₂ emissions pathways found that no positive cumulative industrial CO₂ emissions pathway was “very likely” (a greater than 90% probability) to respect the 2°C temperature guardrail, and any negative cumulative industrial CO₂ emissions pathway must peak between 2010 and 2015 (Rogelj et al. 2011), consistent with the above results requiring immediate and substantial emissions reductions.

ACC2/DICE cost-effective pathways respecting the temperature guardrail settle on CO₂-equivalent concentrations between about 500 and 700 ppm by 2100 for climate sensitivities between 2° and 3°C , higher than the Hare and Meinshausen (2006) 90% confidence interval estimate for a climate sensitivity of 2.8°C (somewhere between 350 and 440 ppm CO₂-equivalent concentration for a temperature change of 2°C). A CO₂-equivalent concentration target of 400 ppm (considered likely to respect the 2°C temperature guardrail) by 2100 has been shown to correspond to a CO₂ emissions pathway

peaking at about 9 GtC yr^{-1} in 2015 and reaching zero between 2070 and 2075 for a suite of integrated assessment models, although these studies allowed for negative emissions (Edenhofer et al. 2010; van Vuuren and Riahi 2011).

Recent studies have emphasized the importance of cumulative emissions in determining peak global temperature. The best estimates of cumulative CO_2 emissions compatible with the 2°C target range from 590 to 1008 GtC, depending on carbon cycle assumptions, the time period examined, and the treatment of non- CO_2 GHGs (Allen et al. 2009; Matthews et al. 2009; Zickfeld et al. 2009). Optimal cumulative carbon emissions in ACC2/DICE that obey the 2°C guardrail vary across model configurations but fall between 105 and 813 GtC over the 2005 to 2100 period.

b. Global mean sea level

Alternative measures of unacceptable climate change based on sea level rise indicators require less abatement than temperature guardrails, if ice mass balance sensitivity estimates for the Antarctic and Greenland ice sheets published in the latest IPCC report (Meehl et al. 2007) prove correct. Semiempirical estimates of sea level response to warming published since Meehl et al. (2007) (e.g., Vermeer and Rahmstorf 2009; Grinsted et al. 2010; Jevrejeva et al. 2010) all indicate that the Meehl et al. (2007) ice response estimates are likely too low; WBGU sea level guardrails may in fact be the most restrictive. With ice sheet sensitivity in ACC2 tuned to a Grinsted et al. (2010) estimate, the WBGU guardrails cannot be attained across the range of climate sensitivities considered ($2^\circ\text{--}4.5^\circ\text{C}$). The maximum total ice sheet mass balance sensitivity that respects WBGU sea level rise guardrails is $1.6 \text{ mm yr}^{-1} \text{ }^\circ\text{C}^{-1}$. Furthermore, cumulative CO_2 emissions that correspond with this maximum total allowable ice sheet mass balance sensitivity (713 GtC) lie within the range of cumulative emissions found that respect the WBGU temperature guardrail.

c. Sea level commitment

Lacking in the above analysis of sea level response is any treatment of sea level rise commitment, or the difference between the transient and equilibrium sea level (S_{eq}) for any given change in global mean temperature (T). A simple linearized relationship based on Holocene–Anthropocene temperature and sea level change is found in Grinsted et al. (2010) [Eq. (7)] and has been adapted to ACC2, where equilibrium is assumed at the preindustrial start (b is zero):

$$S_{\text{eq}} = aT + b. \quad (7)$$

The coefficient for sea level corresponding to a given temperature change (a) is given a value of $1.29 \text{ m }^\circ\text{C}^{-1}$ based on the Moberg estimate in Grinsted et al. (2010). Because this is an equilibrium formula it does not use the more complex ocean thermal diffusion model regularly employed in ACC2. This linear relationship is assumed to be tightly constrained to the period for which it was tuned, so its application is limited to noting that the sea level commitment for all SRES scenarios in year 2100 already exceeds the WBGU absolute guardrail of 1-m rise (relative to the 1990–99 mean; Fig. 2).

d. Ocean acidification

Of pressing concern is ocean acidification, which is likely to violate global mean guardrails early this century, provided no emission management steps are taken. In this model, complying with the WBGU pH guardrail (maximum drop of 0.2 units relative to preindustrial levels) requires stabilization of the atmospheric CO_2 concentration at 460 ppm, broadly consistent with the results of Cao et al. (2007). Recent work, however, by Cao and Caldeira (2008) shows that stabilization at 450 ppm can result in larger pH declines regionally, with 11% of the global ocean experiencing acidification exceeding the WBGU guardrail. Also consistent with the Cao et al. (2007) study, it is found that at a given CO_2 concentration the degree of ocean acidification is relatively independent of temperature change (climate sensitivity) because change in mean pH is mostly a function of CO_2 concentration. The relative stringency of the pH versus the absolute temperature guardrail, however, is dependent on the climate sensitivity, as the allowable CO_2 concentration corresponding with the 2°C target increases (decreases) at lower (higher) climate sensitivities.

The independence of a pH guardrail from both non- CO_2 GHG emissions and climate sensitivity makes it effectively a CO_2 concentration guardrail, and the least uncertain of the WBGU guardrails. Previous work has shown global minimum pH to be dependent both on the year of peak CO_2 emissions and on the rate of postpeak emission decline (Bernie et al. 2010). The Bernie et al. (2010) study found that a rough doubling of current ocean acidification (approximately the WBGU guardrail) would occur with a peak in emissions in 2016 and a 5% annual emission reduction thereafter. This is a more generous emissions trajectory than what is found in this cost-effectiveness analysis, which requires immediate 15%–20% annual reductions in emissions coupled with 86%–93% annual reductions over the long term.

e. General discussion

General findings regarding the cost-effectiveness analysis include the importance of non- CO_2 GHGs in shaping

optimal emissions pathways, which suggests regulation of a suite of GHGs to be necessary given the difficulty already faced with meeting temperature and sea level rate and absolute guardrails. This is corroborated by Toth et al. (2003), Ramanathan and Feng (2008), Zickfeld and Bruckner (2008), Gillett and Matthews (2010), Solomon et al. (2010), and Tanaka et al. (2010), and is particularly true should climate sensitivity prove to be at the higher end of the IPCC range (Meehl et al. 2007). Reducing emissions of non-CO₂ GHGs would increase optimal CO₂ emission pathways over the next century, significantly so if strong reductions occur.

Declarations by the Group of Eight (G8) in recent years for a nonbinding commitment to a 50% reduction in global CO₂ emissions (relative to some unspecified year) by 2050 are insufficient for respecting WBGU guardrails for any climate sensitivity above 2.5°C according to this analysis. The Stern report (Stern 2007) concludes that CO₂-equivalent concentrations should not exceed 550 ppm if the risks of the worst climate change impacts are to be reduced. In this modeling framework, stabilizing CO₂-equivalent concentration at this level could violate all WBGU guardrails, depending upon the climate and ice sheet mass balance sensitivities.

The emission cuts required to respect WBGU guardrails also respect thresholds safeguarding the stability of the thermohaline circulation. Keller et al. (2000) found that stabilizing CO₂ concentrations between 700 to 840 ppm by 2100 would prevent a thermohaline circulation collapse. CO₂ concentrations admissible under the WBGU guardrails stabilize at between 370 and 500 ppm (roughly 500 to 700 ppm factoring in all GHGs as CO₂ equivalent) in ACC2/DICE, which would maintain a safe margin. McInerney and Keller (2008), however, point out that the probability of crossing climate thresholds can never be eliminated, given current parameter uncertainty. Currently unrecognized climatic feedbacks, or actual forcing sensitivities higher than model estimates, could lead to unanticipated violation of WBGU guardrails. Furthermore, welfare or abatement optimizing methods may give less robust mitigation strategies with respect to avoiding dangerous climate thresholds than those that balance uncertainty against worst-case losses in utility (McInerney et al. 2012).

f. Tolerable emissions corridors

The tolerable windows approach addresses a criticism of cost-effectiveness analysis in that instead of providing one stringent pathway that might be difficult to follow precisely or difficult to negotiate, it calculates a tolerable emissions corridor. This analysis of the WBGU guardrail for temperature suggests that attaining both economic and environmental guardrails is feasible only for

climate sensitivities $\leq 2.5^\circ\text{C}$, if non-CO₂ GHGs are not also mitigated. This infeasible result for the temperature guardrail using higher climate sensitivities highlights the quickly diminishing options. Earlier work by Kriegler and Bruckner (2004) examined a 2°C temperature guardrail for a climate sensitivity of 3.5°C using similar methods and found a feasible corridor peaking at 10 GtC yr⁻¹. Emissions corridors complying with the pH guardrail alone are feasible solutions in this analysis. These corridors would simultaneously safeguard against thermohaline circulation collapse, which requires the upper corridor bound to peak between 20 and 90 GtC yr⁻¹ (depending on the value of hydrological sensitivity) for a 3.5°C climate sensitivity (Zickfeld and Bruckner 2008).

g. Sensitivity of economic parameters

There are several contentious assumptions and parameters within the DICE model, most notably the market-derived social rate of time preference factor (q) [see discussions in Nordhaus (2008) and Stern (2007)]. A sensitivity study is conducted with regard to both the social rate of time preference and abatement cost function parameters in the DICE model, and cost-effective CO₂ emissions pathways are found to be insensitive (less than 1 GtC yr⁻¹) to parameter choice owing to the dominance of the temperature and pH guardrails in determining optimal pathways and corridors. Emissions corridors, however, are sensitive to the mitigation constraint ($\dot{\mu}_{\max} \leq 1.33\% \text{ yr}^{-1}$). Relaxing the constraint on the maximum rate of emissions reductions affects only the lower corridor boundary, consistent with the results of Bruckner and Zickfeld (2009). Tolerable maximum levels of mitigation are, however, open political questions and this analysis foreshadows a looming choice between respecting either tolerable economic or tolerable climate guardrails.

5. Conclusions

Given commonly assumed central estimates of climate sensitivity, and an ice sheet sensitivity estimate derived from past ice sheet changes, the rate threshold for temperature (0.2°C decade⁻¹) and the absolute and rate thresholds for sea level rise (1 m absolute, 5 cm decade⁻¹) are not attainable in this simulation framework. Limiting absolute temperature change to 2°C is still an achievable target should climate sensitivity be 3°C or less, but immediate and drastic mitigative action is required, which might violate assumed tolerable decarbonization rates. Emissions reductions required to limit changes in surface ocean pH to less than 0.2 units globally are less stringent, provided emissions reductions start now. These results indicate that because of

global inaction on climate change, achievement of climate targets avoiding dangerous ocean impacts has become very difficult, and in some cases impossible.

This analysis addresses mitigation of CO₂ emissions only. Neglecting non-CO₂ mitigation biases results in unrealistic high/fast CO₂ emissions reduction. Mitigating emissions of other non-CO₂ GHGs would increase the leeway for action and could have a large influence on the attainability of the temperature guardrails in particular. In the case of sea level rise, the current primary uncertainty in allowable emissions is the sensitivity of ice sheets to warming. Emissions complying with ocean acidification guardrails are the least uncertain of those examined as they are independent of both climate sensitivity and non-CO₂ GHG emissions. Emissions pathways obeying the temperature and sea level rise guardrails are influenced by the relatively short time horizon of the analysis owing to the thermal inertia of the earth system. Allowable twenty-first-century emissions would likely be lower if the long-term climate commitment was considered.

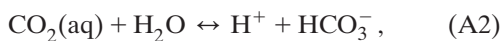
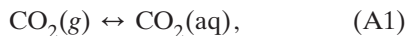
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APPENDIX

Additional ACC2 Model Description

a. Computation of pH

Global mean pH and the thermodynamic equilibria of marine carbonate species [CO₂(aq), HCO₃⁻, and CO₃²⁻] are computed in ACC2 to model the saturation effect in ocean CO₂ uptake under rising CO₂ concentration. A more detailed description can be found in Tanaka (2008, sections 2.1.2 and 2.1.4). The following chemical reactions govern the marine carbonate system:



These equations represent the dissolution and hydration of carbon dioxide [Eq. (A1)], the dissociation of carbon dioxide into bicarbonate, hydrogen, and carbonate [Eqs. (A2) and (A3)], the self-dissociation of water [Eq. (A4)], and the dissociation of borate [Eq. (A5)].

Characterization of the carbonate system requires the estimates of two of the following four measurable quantities: pH, total alkalinity ([TA]), dissolved inorganic carbon ([DIC]), and the CO₂ partial pressure (pCO₂) (Park 1969; Millero 2006). These quantities are defined as follows:

$$\text{pH} = -\log_{10}([\text{H}^+]), \quad (\text{A6})$$

$$[\text{TA}] = 2[\text{CO}_3^{2-}] + [\text{HCO}_3^-] + [\text{B}(\text{OH})_4^-] + [\text{OH}^-] - [\text{H}^+], \quad (\text{A7})$$

$$[\text{DIC}] = [\text{CO}_3^{2-}] + [\text{HCO}_3^-] + [\text{CO}_2(\text{aq})], \quad (\text{A8})$$

$$\text{pCO}_2 = \frac{1}{K_0^*} [\text{CO}_2(\text{aq})]. \quad (\text{A9})$$

In Eq. (A9), K_0^* is the inverse of Henry's constant. A constant value for [TA] is assumed because a significant amount of carbonate precipitation or dissolution or addition of alkalinity from land did not occur during the historical period of the model run (Mackenzie and Lerman 2006) and is assumed negligible for the next hundreds of years. Also, pCO₂ is given in each time step in the model. The remaining two variables pH and [DIC] are determined by solving the following two equations:

$$[\text{TA}] = \text{pCO}_2 K_0^* \left(1 + \frac{K_1^*}{[\text{H}^+]} + \frac{K_1^* K_2^*}{[\text{H}^+]^2} \right) + \frac{[\text{B}(\text{OH})_4^-] + [\text{B}(\text{OH})_3]}{1 + \frac{[\text{H}^+]}{K_B^*}} + \frac{K_w^*}{[\text{H}^+]} - [\text{H}^+], \quad (\text{A10})$$

$$[\text{DIC}] = \text{pCO}_2 K_0^* \left(1 + \frac{K_1^*}{[\text{H}^+]} + \frac{K_1^* K_2^*}{[\text{H}^+]^2} \right). \quad (\text{A11})$$

Here K_1^* , K_2^* , K_w^* , and K_B^* are the thermodynamic equilibrium constants associated with Eqs. (A2)–(A5), respectively. These constants are given as a function of mixed-layer temperature (Millero 1995; Millero et al. 2006).

b. Sea level calculation

Global sea level rise in ACC2 is calculated following expressions given in the Third Assessment Report (TAR) of the IPCC (Houghton et al. 2001, appendix 11.1), where it is a sum of contributions from mass loss from the Greenland and Antarctic ice sheets in response to ongoing and past climate change, thermal expansion, the loss of mass from glaciers and small ice caps, runoff from thawing permafrost, and sediment deposition on the sea floor. Contributions from the AIS, GIS, permafrost, thermal expansion, and sediment deposition are parameterized as functions of global mean temperature. The contribution of glaciers and small ice caps (g) is calculated as

$$g(t) = 0.934g_u(t) - 1.165g_u^2(t), \quad (\text{A12})$$

where g_u is the loss of mass with respect to the glacier steady state without consideration of area contraction and is derived from an integration of global temperature with respect to time. This is an empirical relationship taken from a quadratic fit to the atmosphere–ocean GCM (AOGCM) scenario IS92a (Houghton et al. 2001, ch. 11). This relationship holds until around 2160, whereupon the second term grows larger than the first and glaciers and small ice caps show net growth, an unphysical result.

Two modifications are made to the sea level calculation in ACC2 for the purposes of this study. To avoid the unphysical result of growing glacier and small ice caps after 2160, a smoothing function is implemented after a critical level of sea level rise (g_{critical} , with a corresponding temperature T_{critical}) where contribution to sea level rise from glaciers and small ice caps follows an exponential curve to a prescribed maximum. This smoothing function is described in Eq. (A13), where g_{smooth} is the difference between the prescribed maximum sea level rise and g_{critical} , and S_{init} is the slope of the function immediately before g_{critical} :

$$g(T) = g_{\text{critical}} + g_{\text{smooth}}[1 - e^{S_{\text{init}}(-g_{\text{smooth}})(T - T_{\text{critical}})}]. \quad (\text{A13})$$

Meehl et al. (2007) estimate the total potential sea level contribution from glaciers and small ice caps to be between 0.15 and 0.37 m. The values of g_{critical} (0.28 m relative to preindustrial equilibrium, of which 0.03 m had already occurred by 2000 in ACC2) and g_{smooth} (0.07 m) are selected based on these estimates, so that total glacial contribution does not exceed 0.35 m for any scenario. In this new method, Eq. (A12) calculates glacier contribution to sea level rise up until the g_{critical} value is reached, whereupon it is replaced by Eq. (A13). Having a continuous sea level contribution for glaciers and small ice caps is critical for setting a guardrail in DICE.

Second the calculation of thermal expansion is modified from one based on surface temperature to one derived from the thermal anomaly throughout the water column as calculated by the energy balance model DOECLIM. The parameterization in Houghton et al. (2001, appendix 11.1) is used, where sea level rise due to thermal expansion is relative to that in year 1990. To calculate thermal expansion explicitly, the interior ocean temperature is first found as a function of depth and time (T_0). Using a pure diffusion model without upwelling, where heat diffusion is described as follows,

$$\text{for } 0 < z < z_B : \frac{\partial}{\partial t} T_o(z, t) = \kappa_v \frac{\partial^2}{\partial z^2} T_o(z, t), \quad (\text{A14})$$

$$\text{B.C. : } T_o(0, t) = T_s(t), \quad \frac{\partial}{\partial z} T_o(z_B, t) = 0, \quad (\text{A15})$$

$$\text{I.C. : } T_o(z, 0) = 0. \quad (\text{A16})$$

In this case, the upper boundary ($z = 0$) to the mixed layer has the same temperature as the mixed layer T_s , and the heat flux into the ocean floor at $z = z_B$ vanishes. The solution for T_o is solved analytically by Kriegler (2005, appendix B):

$$T_o(z, t) = T_s(t) - \int_0^t \dot{T}_s(t') \text{Erf} \left[\frac{z}{2\sqrt{\kappa_v(t-t')}} \right] dt' + \sum_{n=1}^{+\infty} (-1)^n \int_0^t \dot{T}_s(t') \left\{ \text{Erf} \left[\frac{2nz_B - z}{2\sqrt{\kappa_v(t-t')}} \right] - \text{Erf} \left[\frac{2nz_B + z}{2\sqrt{\kappa_v(t-t')}} \right] \right\} dt', \quad (\text{A17})$$

where T_s is ocean surface temperature, z is ocean depth, κ_v is the vertical diffusivity with a value of $0.55 \text{ cm}^2 \text{ s}^{-1}$, n is a bottom correction term, and Erf is the error function.

The series in Eq. (A17) converges quickly, so the only terms of importance are that of the zeroth-order term describing the behavior of an infinitely deep ocean and

one to three next-order bottom correction terms. Inclusion of the bottom correction terms in Eq. (A17) is not necessary for the length of time the model is run as it makes only a small difference in the thermal profile (roughly 9 mm by 2200). Once the thermal profile is calculated, T_o is plugged in to the linearized equation of state:

$$\rho(z, t) = \rho_0(z) \{1 - \alpha [T_o(z, t) - T_0(z)] + \beta [S(z, t) - S_0(z)]\}. \quad (\text{A18})$$

In Eq. (A18), ρ is density, α is a coefficient of thermal expansion ($1.7 \exp -4 \text{ K}^{-1}$), β is the coefficient of saline contraction, and S is salinity. Constant salinity is assumed for simplification, and the last term drops out. Rearranging Eq. (A18) to isolate both ρ terms on one side gives a ratio of change for each time step in each depth. Multiplying this ratio by the layer thickness at each depth and summing over z yields the thermal expansion in meters.

This explicit calculation adds the capability of tracking the evolution of interior ocean temperature and density profiles, an improvement over the impulse response approach. The estimate of thermal expansion produced using the updated equation is lower than that produced by the impulse response function while still being within the range estimated by Meehl et al. (2007).

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