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Climate Action Gaming Experiment: Methods and Example Results

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University of Illinois at Urbana-
Champaign

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Article

Climate Action Gaming Experiment: Methods and Example Results

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1 **Abstract:** Simulation participants are each assigned one of six regions that together span
2 the globe. Participants make quinquennial policy decisions on greenhouse gas emissions,
3 recapture of CO₂ from the atmosphere, and/or modification of the global albedo. Costs of
4 climate change and of implementing policy decisions impact each region's gross domestic
5 product. Results are shown where regions most adversely affected by effects of greenhouse
6 gas emissions resort to increases in the earth's albedo to reduce net solar insolation. These
7 actions induce temperate region countries to reduce net greenhouse gas emissions. An
8 example outcome is a trajectory to the year 2195 of atmospheric greenhouse emissions and
9 concentrations, sea level, and global average temperature.

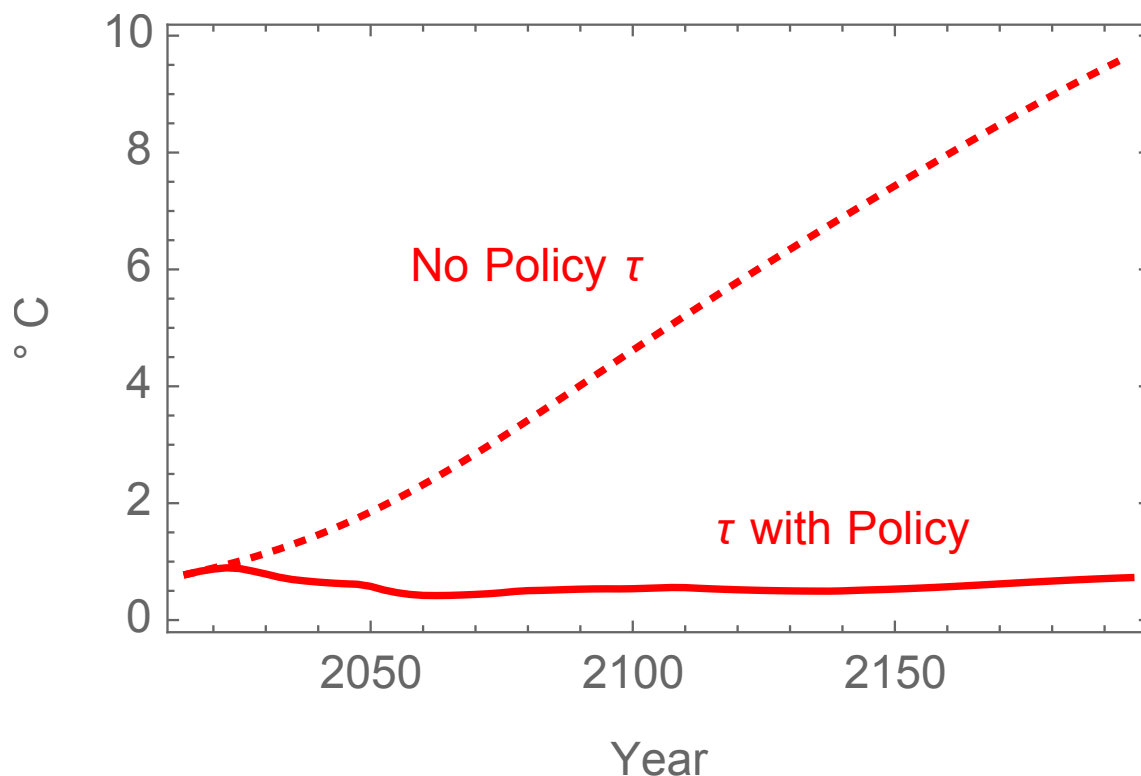
10 **Keywords:** climate change; model; solar radiation management; simulation

11 1. Introduction

12 A U.S. National Research Council (NRC) study has concluded that anthropogenic modification of the
13 earth's albedo is a not unlikely response to growing impact of climate change [1]. The Intergovernmental
14 Panel on Climate Change (IPCC) has estimated the probability of impacts of climate change resulting
15 from various levels of emissions of greenhouse gases, but without accounting for anthropogenic albedo
16 management in the scenarios used [2]. Neither the NRC nor the IPCC reports estimate the probability of
17 actual outcomes for climate change, with or without albedo modification. This omission is problematic
18 for those involved in land use planning, management of aquatic environments, and a variety sectors
19 likely to be impacted by climate change, as they are currently left with little guidance on the probability
20 of actual likely outcomes for climate change.

21 Carbon and nitrogen cycle models that account for biological activities of numerous species [3,4]
22 generally do not explicitly model the expected feedback of increased greenhouse gas concentrations on
23 human actions that are driving rapid changes in those concentrations. The present paper thus presents
24 methodology and example results of an experimental approach to quantifying the impact of climate
25 change on human decisions about net greenhouse gas emissions and albedo management.

26 **Figure 1.** Industrial era global average temperature increment, τ , from 2015 to 2195 with
27 (solid curve) and without (dashed curve) participants policy decisions.



28

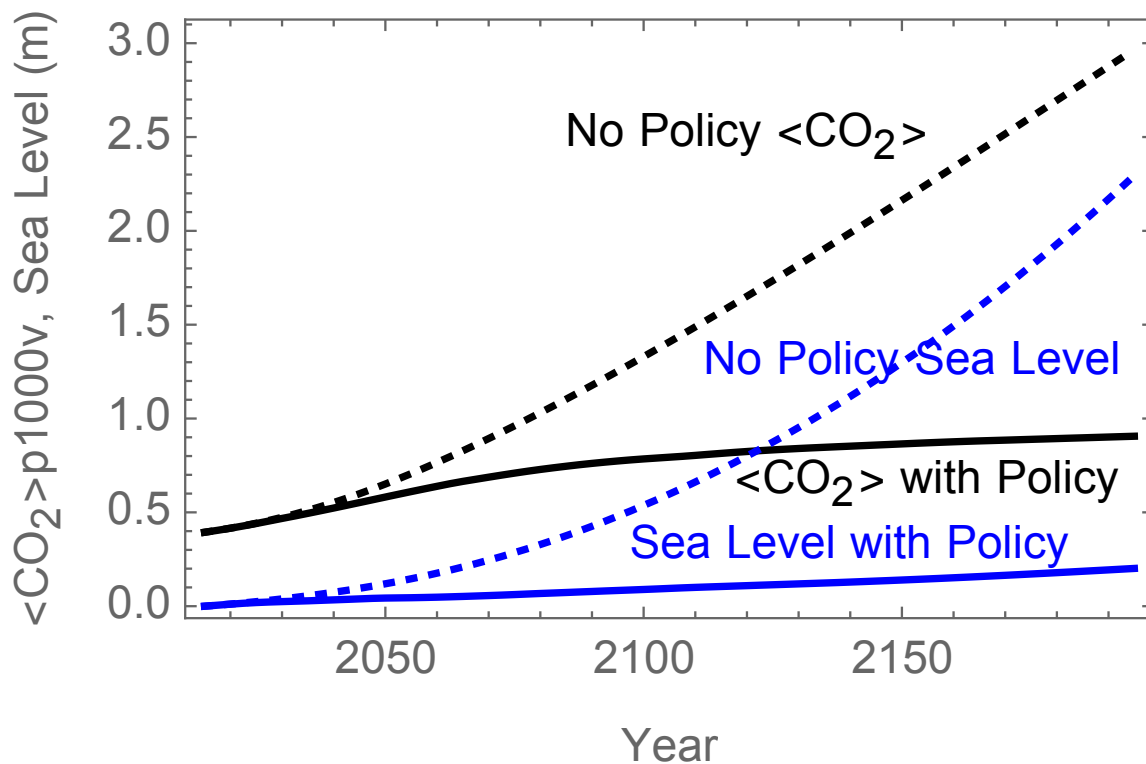
29 A simulation is described here that uses results of an interactive simulation exercise to modify a
30 reference set of future conditions that are based upon extrapolation of historical trends. In the simulation,
31 participants represent different groups of countries (with these groups here called regions) and attempt
32 to maximize their economic gains while dealing with a changing climate. This approach provides an

33 experimental framework for investigating outcomes for human influences on future climate change.
 34 Simple by design compared to complex global circulation models, this simulation is neither a prediction
 35 of the future nor a method of policy prescription. Rather, it presents a new way to look at a complex
 36 problem that involves both natural science and human factors.

37 The basic setup of the model divides the world into six regions and extrapolates each region's gross
 38 domestic product (GDP) and population into the future in a manner consistent with extensive historical
 39 time-series data [5–15]. A fraction of each region's GDP is diverted to that region's "pot balance,"
 40 which is used to determine scoring in the simulation game. Direct costs of albedo management and of
 41 reductions in net greenhouse gas emissions are charged to each pot balance, as are costs of impacts from
 42 climate change.

43 Managers of each simulation can adjust model parameters to investigate how different assumptions
 44 (e.g. a higher estimated cost of sea-level rise or new research and development lowering the cost
 45 of greenhouse gas emissions) affect participants' behavior and the ultimate outcome. A complete
 46 description of the simulation model is given as an appendix in Section 4 below. Tabular and in-text
 47 values of reference values for subscripted symbols in Section 4 define the reference model behind the
 48 results described here.

49 **Figure 2.** Atmospheric CO₂ concentrations in parts per thousand by volume, and increase of
 50 sea level over its 2015 value, with (solid curves) and without (dashed curves) participants'
 51 policy decisions.



52

53 If participants take no actions, in the year 2195 the atmospheric CO₂ concentration in parts per million
 54 by volume (ppmv) reaches 2876, the global average temperature has increased by 9.5°C above the
 55 preindustrial reference level listed below in Table 3, and sea level has risen 217 cm over its 2015 value.

56 Figures 1 and 2 compares these outcomes to one set of results following from participants' decisions, as
 57 discussed in Section 2.6.

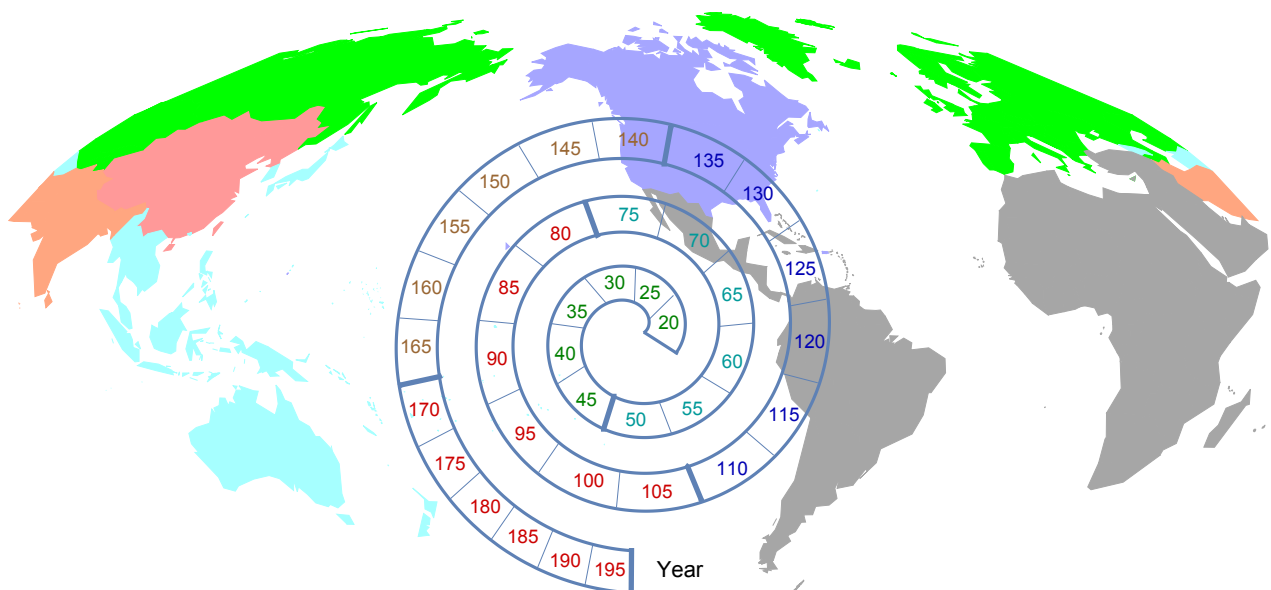
58 2. Methods and Example Results

59 The section summarizes simulation methods. This summary is followed by a description of results
 60 of a simulation exercise by groups of undergraduate students at the University of Illinois at Urbana-
 61 Champaign.

62 2.1. Extrapolation of Historical Trends

63 This section describes a reference case extrapolation of historical data, which serves as the basis
 64 for the simulation. The simulation begins by dividing the world into six regions: China+, US+, EU+,
 65 India+, Oceania, and G121. The G121 group consists of Latin America, Africa, and the Middle East
 66 (c.f. Figure 3).

67 **Figure 3.** Map of six regions used. The spiral indicates decision times in years after Julian
 68 year 2000, with bold lines at the end of the 30-year "generations" when participants are
 69 tasked with having positive pot balances.



70

71

72 The reference case includes extrapolations of each region's historical gross domestic product (GDP),
 73 along with extrapolation of emissions of CO₂, N₂O, and volatile fluorine compounds. Other greenhouse
 74 gas emissions are not included because it is assumed that changes in their contribution to radiative forcing
 75 will be small enough to be overshadowed by policies affecting these three categories of greenhouse
 76 gas. Reference CO₂ emissions for each country were estimated by multiplying the amount of energy
 77 a region was expected to use, extrapolated over time, by the extrapolated carbon intensity of energy
 78 use. The extrapolated population for countries or groups of countries in each region were added to form

79 a reference case estimate for the evolution of GDP. For methods used for extrapolation of population,
80 GDP, energy use rates, and ratios of carbon emissions rates to energy use rates (i.e. carbon intensity),
81 see Singer et al. [16]. Fossil fuel resources, including coal and unconventional natural gas and oil [17],
82 are assumed to be large enough to allow higher than zero carbon intensity of energy production in the
83 absence of new policy decisions limiting carbon burning for the duration of the time covered by the
84 simulation. It should be noted that, in the extrapolations of carbon intensity of energy production, the
85 difference between the carbon intensity of all-coal commercial energy use and a long term limit carbon
86 intensity declines exponentially with cumulative carbon use in each region, and this decline in some
87 cases is in part a result of national policies. Thus, the “no policy” extrapolations referred to here are
88 most accurately described as involving “no new policy” decisions by simulation participants beyond
89 those already accounted for in extrapolation of historical trends.

90 Anthropogenic increases in N₂O emissions result primarily from use of agricultural fertilizers.
91 Fertilizer that is not taken up by plants is metabolized by organisms in soil or water, leading to the release
92 of N₂O. Since the majority of the world's agriculture focuses on the production of the eight major cereal
93 grains (rice, wheat, maize, barley, sorghum, millet, oats, and rye), this simulation uses each region's
94 production of these grains, as a fraction of total world production, to estimate their contribution to global
95 N₂O emissions, c.f. [19,20]. This approach implicitly assumes that over time the current fractions of the
96 world's cereal grains grown in each of the six regions remain constant. If the players take no action, N₂O
97 emissions increase in proportion to global population growth.

98 A variety of fluorine compounds act as greenhouse gases. Releases include refrigerants not recycled,
99 foam blowing agents, and compounds used for other industrial processes. The inorganic compounds
100 NF₃ and SF₆ used in material processing have very long atmospheric lifetimes, as does C₂F₆ [2]. The
101 compounds included in this model and their atmospheric residence times are listed in Section 4.1. For
102 the purposes of this simulation, the net effect of anthropogenic increases in methane concentrations
103 and other secular trends in the solar radiation balance other than periodic oscillations in incident solar
104 irradiance are approximated as having already been stabilized by 2015.

105 2.2. Cost of Changing Emissions Levels

106 For reductions of greenhouse gas emissions, participants make decisions in the form of a percent
107 reduction (e.g. a 5% reduction indicates the region is emitting 95% of reference case values). The cost
108 for implementing these reductions is subtracted from each participant's pot balance.

109 The costs for reductions in CO₂ emissions depend on energy decarbonization fractions. It is relatively
110 cheap to achieve a small decarbonization fraction by replacing carbon intensive fuels such as coal with
111 less carbon intensive fuels such as natural gas; but after about 60% decarbonization is reached the cost
112 of further decarbonization increases steeply (see Figure 4). There is also a cost associated with rapid
113 buildup of carbon emissions, as described in Section 4.2.

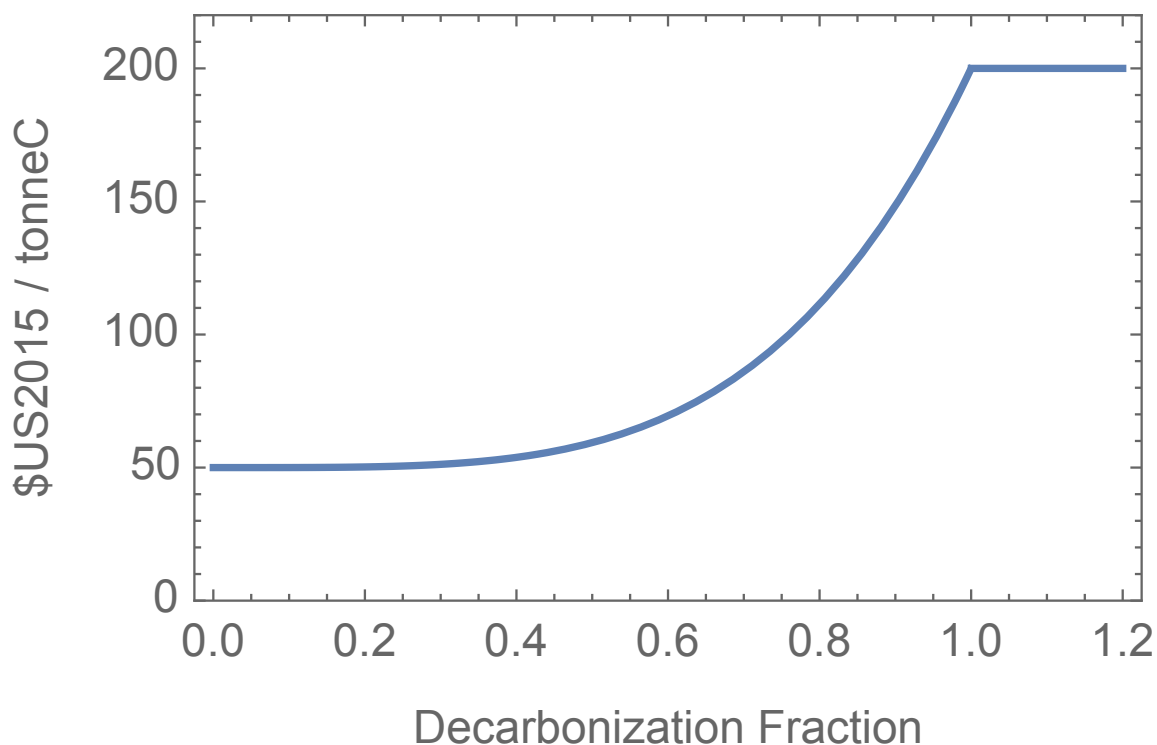
114 To reach levels of decarbonization exceeding 100%, it is possible to chemically sequester carbon after
115 its release into the atmosphere [18], resulting in costs as illustrated on the horizontal line on the right
116 hand side of Figure 4. Participants can also choose to use biosequestration in the form of biochar and

117 other methods of immobilizing biological carbon. However, the rate of biosequestration is limited by
118 each region's arable land area, as discussed in Section 4.1.

119 If a region has already reached a high level of energy decarbonization, it may become at least
120 temporarily more cost effective for it to offer to pay for part of another region's decarbonization, in
121 lieu of some of the further reductions in its own carbon emissions. A simple implementation of this
122 option used here allows each of the three initially high per capita CO₂ emitters, China+, USA+ and
123 EU+, to pay half of the cost for augmenting reductions in the carbon emissions of exactly one other
124 region, namely Ocean, India+, and G121 respectively.

125 The cost for reducing anthropogenic N₂O emissions increases quadratically with the emissions
126 reduction fraction. This assumption is consistent with the idea that agriculture is the dominant source
127 anthropogenic N₂O emissions, and that net proceeds from application of nitrogen fertilizers are a
128 quadratic function of the amount of N₂O emissions [21]. The cost of reducing emissions of volatile
129 fluorine greenhouse gas compounds is assumed to be a linear function of the reduction amounts.
130 Equations for each can be found in Section 4.1.

131 **Figure 4.** Average cost per metric ton of energy decarbonization as a function of
132 decarbonization fraction.



133

134 2.3. Direct Costs of Solar Radiation Management

135 Participants also have the option of implementing up to three albedo management techniques to reduce
136 the amount of sunlight that reaches earth's surface, thereby cooling the planet and helping offset warming
137 caused by the greenhouse effect. These options include injection of sulfur into the stratosphere either

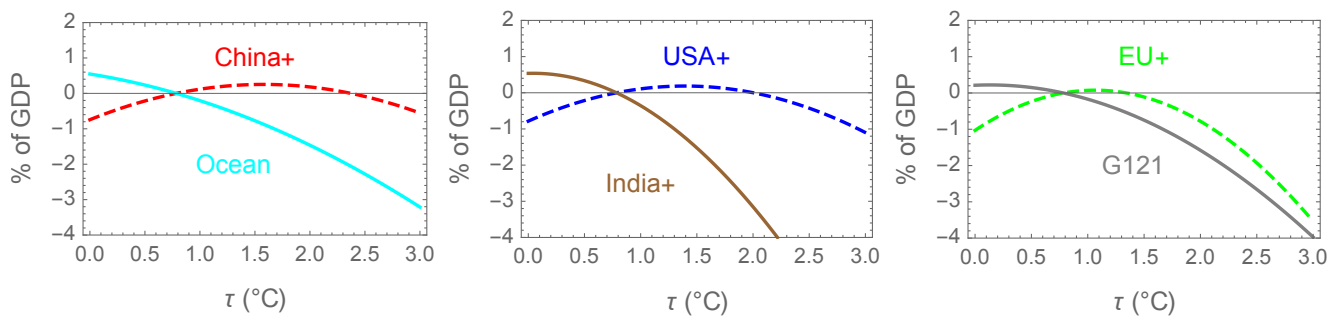
globally or in a localized stratospheric arctic area, or low altitude lofting of salt water to create clouds [1, 22–24]. The equations describing the costs for each of these methods are included in Section 4.2.

If a region chooses to inject sulfur into the stratosphere globally, that region alone will incur the direct costs of the process, but the resulting drop in global temperature will affect the pot balances of all of the regions in the simulation. c.f. [25,26]. This differential effect is primarily a function of latitude, with more temperate regions (China+, USA+, and EU+) having higher optimum steady state temperatures than the other regions. Tropical and subtropical countries have lower optimum steady state temperatures, giving them an incentive to decrease the temperature significantly, through albedo management. However, overcooling of the earth has significant negative impacts on the economies of the China+, US+, and EU+ regions (c.f. Figure 5).

Injecting sulfur into the arctic stratosphere also effects global average albedo, but at greater cost for the same amount of impact on global average temperature. However, arctic stratospheric sulfur injection preferentially increases albedo over the arctic ice sheets, reducing land ice melting, and thus benefiting the Ocean and India+ regions that are assumed to be particularly sensitive to increases in sea level.

The other solar radiation management option presented to participants is low altitude salt water lofting, which seeds cloud formation. The clouds reflect sunlight, cooling the earth. Low altitude seawater lofting can increase rainfall along the coast in arid regions but reduce rainfall elsewhere. The expected economic impact of shifting rainfall patterns is not well know and is not included in the simulation exercise.

Figure 5. Change in GDP in each region vs. global average temperature.



2.4. Global Physical Balances

Participants' decisions on emissions reductions and solar radiation management contribute to the global heat balance, global greenhouse gas concentrations, and global sea level change, all of which change throughout the simulation as participants make policy decisions. These values in turn affect each participant's pot balance. Section 4.1 gives the equations used for this part of the model, which is described in qualitative terms here.

The global heat balance accounts for thermal inertia of a 335-meter deep ocean surface layer and the difference between insolation (minus reflected energy) and thermal emission. The global average albedo decreases with increasing global average temperature, and decreases with implementation of solar radiation management, c.f. [27]. The thermal emissivity decreases with the net effect of increasing

169 global average temperature on atmospheric water and with increasing concentrations of anthropogenic
170 greenhouse gases. In light of ocean thermal inertia, solar insolation variations on 11 and 22-year cycles
171 are neglected, but the effects of an 88 year Gleisburg cycle, and an assumed 600 year cycle with a
172 minimum c. 1700, are included [16,28–30].

173 The rate of change in the amount of carbon dioxide in the atmosphere depends on anthropogenic
174 emissions, the amount of carbon dioxide already present, and the global average temperature [16,28].
175 These dependences occur in large part because the surface ocean layer can absorb a fraction of global
176 carbon emissions, but this fraction decreases over time if the oceans become more acidic, warmer, or
177 both.

178 The concentrations of nitrous oxide and volatile fluorine compounds in the atmosphere at a given time
179 during the simulation depend on extrapolated anthropogenic sources and removal rates proportional
180 to increases over preindustrial concentration levels. Nitrous oxide is assumed to have a preindustrial
181 concentration of 270 ppbv (parts per billion by volume), while volatile fluorine compounds are assumed
182 to have preindustrial concentrations with negligible effect on net insolation [2]. The compounds included
183 in the simulation and their atmospheric lifetimes are described in Section 4.1.

184 The model includes estimates of sea level change due to thermal expansion and melting of northern
185 hemisphere land ice. The rate of land ice melting depends on global average temperature, the volume
186 of land ice (and thus the average height of land ice and its surface temperature), and the amount of
187 arctic stratospheric sulfur injection. The net effects of land ice melting and changes in precipitation in
188 Antarctica [2]. are less well understood and are not included.

189 2.5. Fund Balances

190 Throughout the simulation, participants have their current and extrapolated pot balances updated with
191 every policy decision input. The extrapolations assume that the most recently entered policy decisions
192 are carried forward until the last quinquennium before the end of the twenty-second century. Fund
193 balances are affected by changes in global average temperature, by sea level and atmospheric CO₂
194 concentrations, and by the costs of emissions reductions and solar radiation management measures.
195 Increases in atmospheric CO₂ levels over preindustrial values decrease pot balances even if global
196 average temperature is held constant, due to direct effects on human physiology [32] and other
197 environmental effects including ocean acidification. In addition to these changes, the participants' pot
198 balances accrue interest over time. Negative balances are charged interest, which can make it difficult to
199 ever recover from a substantially negative pot balance.

200 Participants were instructed that successful completion of their contribution to the simulation exercise
201 involved achieving the maximum end pot balance for their own region, subject to a constraint of no
202 negative pot balance for their region at the end of each previous 30-year period and a limit of 1 ppmv/year
203 change in atmospheric CO₂ concentration from 2190 to 2195. These instructions were designed to
204 provide an incentive to emphasize approaching a state of environmental sustainability at minimum cost
205 in the long term, but not at the expense of nearer term costs of policies that might be politically infeasible
206 to implement.

207 If participants choose to inject sulfur into the stratosphere globally, the resulting global haze will
 208 interfere with astronomy and solar thermal electric energy systems but may increase solar to chemical
 209 energy conversion by some photosynthetic organisms. The net costs associated with these impacts
 210 are hard to quantify with information that is presently available. A small net globally distributed cost
 211 included in the current version of the simulation serves mostly as a placeholder until the implications of
 212 these effects can be studied in more depth.

213 2.6. A Six Region Simulation Exercise

214 After ten other trial runs, a simulation as described in the previous five sections was run in
 215 sequential discussion sections of two different undergraduate classes at the University of Illinois at
 216 Urbana-Champaign. The classes were comprised primarily of junior and senior level students with a
 217 broad mix of undergraduate majors. The results presented here are an example of how the simulation can
 218 be employed to study the human and scientific factors that may affect global climate change negotiations.

219 This simulation used the following percentages of each region's annual GDP as inputs to its pot
 220 balance: China+ 1.12, USA+ 0.84, EU+ 0.76, Ocean 1.42, India+ 1.24, and G121 1.02. These fractions
 221 were assigned to make it possible but not easy for each region to maintain a positive balance throughout
 222 the simulation without resorting to global albedo management. Some of the other parameter values that
 223 differ from region to region are listed in Table 1. Ocean and India+ are the only regions with higher
 224 values for susceptibility to sea level rise, in order to simulate the vulnerability of low-lying parts of the
 225 Ocean region and of Bangladesh in the India+ region to higher sea levels. "Biochar..." in Table 1 refers
 226 to the sum of all processes of net carbon biosequestration.

Table 1. Region dependent parameters

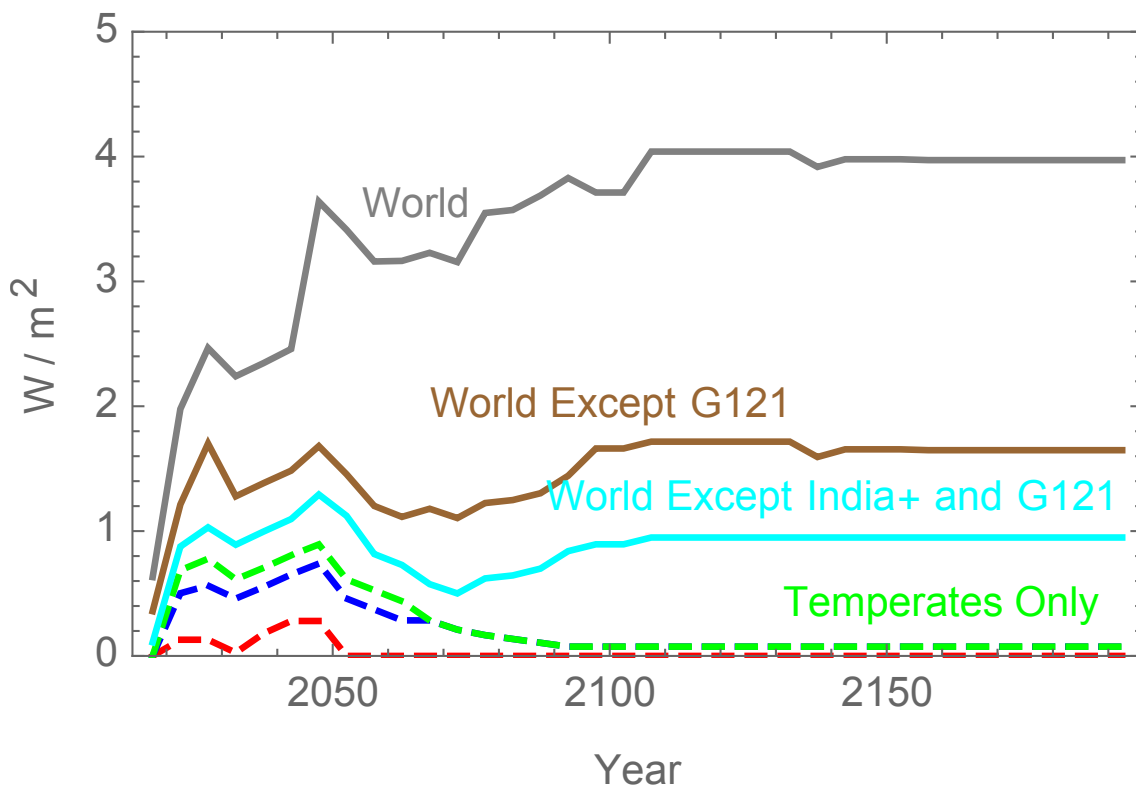
227 Parameter	China+	USA+	EU+	Ocean	India+	G121
Relative Sea Rise Cost	1	1	3	3	1	1
Max GtC/yr Biochar...	0.11	0.22	0.13	0.22	0.32	0.88

229 In this simulation, the policies for reducing emissions of four volatile fluorine compounds that are
 230 used as refrigeration agents were fixed before the simulation began so that they reduced the no-policy
 231 emissions by 20% every five years until the reduction reached 80%, with the reduction set to 95%
 232 after another five years and remaining fixed thereafter. Reductions of emissions of SF₆, NF₃, and
 233 C₂F₆, which have atmospheric lives of 2600 years or more, were incremented by 20% in each of
 234 the first five quinquennia. Leaving reducing emissions of the other three volatile fluorine compounds
 235 (listed in Section 4.2) included in the simulation to policy decisions brings the relevance of volatile
 236 fluorine compounds to the attention of participants while avoiding the distraction of multiple decisions
 237 on different classes of such compounds and avoiding a final state where the atmospheric concentrations
 238 of very long lived are still building up without effective limits. In the example situation, participants
 239 reduced the emissions of the volatile fluorine compounds under their control to zero by 2095.

240 By decarbonization of energy resources, and chemical and biological carbon sequestration,
 241 atmospheric CO₂ concentration was 910 ppmv by the end of the simulation in year 2195, well under
 242 the reference level then of 2876 ppmv without any policy decisions by participants. The rate of change
 243 in carbon dioxide concentration in the simulated atmosphere at this time was 1 ppmv/year from 2190
 244 to 2195, which indicates that the simulation had achieved the target approximation of sustainability
 245 assigned to the participants.

246 The growth of carbon emissions stabilized early on, at about 2025, and remained stabilized until 2060.
 247 It took an abrupt increase in solar radiation management (SRM) via global albedo increase to convince
 248 temperate regions to decarbonize further. SRM was primarily implemented by the predominantly
 249 tropical and subtropical regions, Ocean, India+ and G121. The SRM techniques used by Ocean,
 250 India+ and the G121 regions (see Figure 6) began to over-cool the planet from the perspective of the
 251 temperate regions, with global average temperatures reaching a low in 2055 of just 0.42°C above a
 252 preindustrial reference level. This result induced policies that caused global CO₂ emissions to drop after
 253 2060. Temperature gradually recovered to 0.76°C above preindustrial times, reflecting a compromise in
 254 between the optimum values for the temperate and more tropical regions.

255 **Figure 6.** Solar radiation management by region. Included in curves from the lowermost
 256 upward are China+, USA+, EU+, Ocean, India+, and G121.



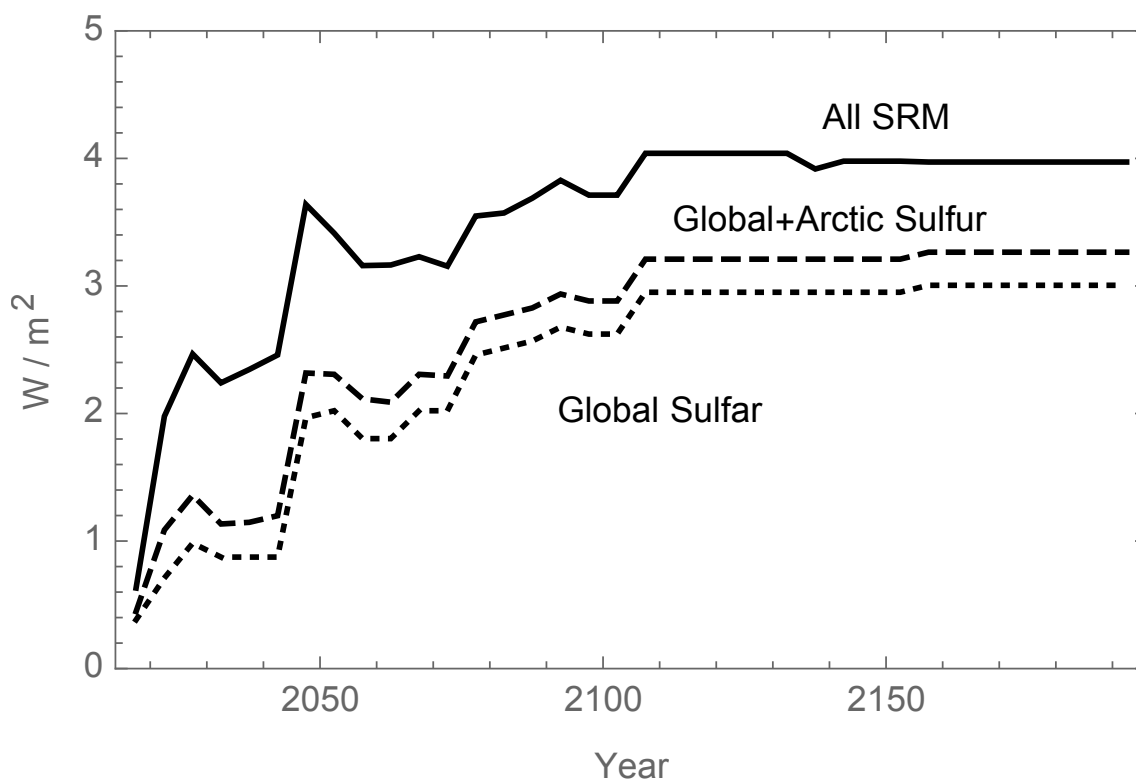
257

258 Of the SRM methods available to participants, global stratospheric sulfur injection was the most
 259 popular choice (see Figure 7). This choice was modeled as incurring lower direct costs of implementation
 260 than the other two options, namely arctic stratospheric sulfur injection and low altitude salt water lofting

261 (c.f. Section 4.2). In this version of the simulation, global stratospheric sulfur injection was disabled for
 262 China+, the USA+ and the EU+ regions during the first six rounds of negotiation, because in previous
 263 simulations other participants in these regions had over-used global injection to the detriment of their own
 264 GDPs before fully understanding the consequences. Arctic stratospheric sulfur injection and low altitude
 265 seawater lofting were enabled and used on an exploratory basis from the outset by the temperature
 266 regions, with summed effect indicated by the dashed curves in Figure 6.

267 Final balances in trillions of U.S. dollars are listed in Table 2. (All dollar figures are inflation adjusted
 268 to year 2015 U.S. purchasing power parity.) Overall, at the end of the simulation, the global sum of pot
 269 balances was 461 trillion dollars, which represents 1.17 times the total extrapolated annual GDP in 2195.

270 **Figure 7.** Global albedo modification for solar radiation management, by type.



271

Table 2. Example simulation pot balances

Year	China+	USA+	EU+	Ocean	India+	G121
2045	4	4	3	8	5	6
2075	7	7	6	24	7	20
2105	12	12	8	46	29	30
2135	13	13	9	82	42	34
2165	12	12	11	151	65	28
2195	13	13	15	285	101	9

273

274 The economic effects of the global average cooling mentioned above are reflected in Table 2. From
275 2045 to 2075, the temperature declined from 0.65°C to 0.44°C. The tropical countries experienced a
276 consequent rise in pot balances. The G121 region postponed the cost of decarbonization of energy
277 sources until it was able to afford reductions of CO₂ without ever having a negative fund balance. This
278 outcome is qualitatively consistent with the assertions of some developing countries in modern climate
279 negotiations that developing countries need to move forward with economic development without
280 incurring large direct costs for limiting their greenhouse gas emissions.

281 *2.7. Variations of the Climate Change Simulation Game*

282 The simulation results described above were a product of the particular model described qualitatively
283 Sections 2.1-2.5 and quantitatively in Section 4. The Excel spreadsheets used to support that simulation
284 allow for many possible modifications for purposes of education, research, and support of public policy
285 formulation. For example, another simulation exercise used 60% of the energy decarbonization costs
286 shown in Figure 3. This simulation had a qualitatively similar outcome to the one described here, but
287 the final atmospheric CO₂ concentration dropped from 795 to 793 ppmv between 2190 and 2195. The
288 participants in the simulation producing this result were different sets of undergraduate and graduate
289 students. Only with a large number of randomized trials would it be possible to discern whether
290 such difference in outcome are due to differences in the participant set or differences in the simulation
291 parameters.

292 To add an element of randomness to the simulation, the Excel spreadsheet includes an ability to
293 sample probability distributions to select model parameters. Conducting a large number of simulations
294 using such probability distribution sample and sets of participants randomly selected from a sizeable
295 pool would account for both differences between participants and uncertainty in parameters. The Excel
296 spreadsheet also allows for simulation parameters to evolve over time through a Markov process. After
297 each 30-year generation, samples from a log-normal probability distribution with mean 1.0 can multiply
298 the then-current value of each selected parameter, with the variance of the probability distribution
299 decreasing with each successive generation. With this approach, even the most astute participants are
300 only gradually able to discern from the model results the limit to which the varying parameters are
301 approaching. While these probability distribution features are incorporated in the model for possible
302 future use, running large numbers of simulations to explore the implications of uncertainties in model
303 parameters is beyond the scope of the present work. Also, while many of the key parameters in the global
304 heat and carbon balance models and the reference case GDP and energy and carbon use models were at
305 one point calibrated against observational data (c.f. [6] and references therein), these calibration exercises
306 need to be updated and extended to calibrate probability distributions for model parameters. In particular,
307 the parameters in the land ice model and most of the parameters in the financial model should be viewed
308 as place holders pending a very extensive review of the literature to assign probability distributions to
309 model parameters. That would be quite a complex task that could take years to accomplish; hence the
310 report in the present work on results using the current state of the simulation model.

311 The simulation could also be expanded to more participants with regions being smaller groups of
312 countries or single countries. In progress at the time of writing is calibration of demographics, GDP,
313 and energy and carbon use for a set of 63 different regions, many of which consist of only one country.
314 Groups of these countries and regions could be combined to support up to 63 participants per simulation.

315 The simulation has also been conducted with each participant being given a time limit for entering
316 policy decisions and the Excel file being updated upon each entry via Google Drive. This, in principle,
317 allows for participants who are geographically distributed and not otherwise in contact with each other.
318 While this approach functions with a small number of participants, use of a dedicated server with faster
319 response time may be necessary with substantially more than six participants.

320 The simulations performed so far have been in an exploratory mode, with each simulation conducted
321 at least somewhat differently than the previous one. Some aspects of how the simulation implementation
322 methods affect the results have nevertheless become apparent. First, the results of the simulation appear
323 to be less erratic if the participants have previously accomplished a “queen or king of the world” exercise,
324 where they individually chose all regions’ policies and try to achieve a globally optimal result. An
325 interesting observation is that global end pot balances resulting from a subsequent interactive simulation
326 have uniformly been substantially lower than the average achieved by each participant acting in “queen
327 or king of the world” mode.

328 Each simulation has had a moderator, in some cases mostly passively just collecting policy decisions
329 and entering them in the spreadsheet, and in other cases more actively providing input on the likely
330 implications of policy choices and sometimes encouraging participants to talk with each other about
331 upcoming policy decisions. It is not surprising that end global pot balance tends to be higher with
332 an active and well informed moderator. This observation indicates the importance of choosing the
333 moderator’s background and role carefully both during simulation exercise design and in real world
334 global interactions on climate change policy.

335 Another observation from simulations done so far is that the choice of the percentage of total GDP
336 for each region assigned to the regions pot balance has a significant psychological effect on participants’
337 policy choices. Participants who have negative pot balances frequently report feeling “too poor” for more
338 reduction in carbon emissions even if they represent regions with high per capita GDP. The importance
339 of this psychological effect could be investigated by increasing the percentages of GDP assigned to pot
340 balances and tasking participants with trying to maintain higher balances than participants in previous
341 simulations, rather than trying to avoid negative balances.

342 **3. Conclusions**

343 The work described here provides an interesting starting point for experimental exploration of
344 possibilities for future policy responses to expectations of results of climate change. Both the formulation
345 of the model and experimental design require considerable additional work before being useful as
346 quantitative tools for estimating probability distributions for actual future outcomes for climate change.
347 However, even at the present stage the simulations have proven both to be a useful educational tool
348 and to provide some qualitative insights into how solar radiation management might interact with policy
349 constraints on net emissions of greenhouse gases.

350 4. Appendix on Computational Methods

351 4.1. Physical Balances

352 Atmospheric carbon content c_a in trillions of metric tons (TtC) is related to atmospheric carbon
 353 dioxide concentraton $\langle \text{CO}_2 \rangle$ in ppt1000v (parts per thousand by volume) by $\langle \text{CO}_2 \rangle = c_4 c_a$ where
 354 $c_4 = 1/2.13$. Atmospheric carbon content evolves according to the equation

$$\frac{dc_a}{dy} = \left(c_8 + c_9 \frac{c_a - c_5}{c_a + c_6 c_5} + c_{10} \frac{\tau}{\tau + c_{11}} \right) E_c - \frac{c_a - c_5}{c_7} \quad (1)$$

355 Here y is time in years after Julian year 2000. The term containing the constant c_9 accounts for reduction
 356 of the fraction of anthropogenic CO_2 emissions promptly moved into non-atmospheric reservoirs as
 357 $\langle \text{CO}_2 \rangle$ increases. The term containing the constant c_{10} accounts for the impact of increasing global
 358 average and surface ocean layer temperature on CO_2 uptake in non-atmospheric reservoirs. Here E_c is
 359 the global sum of a reference set of regional atmospheric carbon emissions that have each been multiplied
 360 by linearly interpolated values of factors $(1 - f_c)$ determined from participants' inputs as discussed
 361 above. Over a wide range of conditions, the solutions of this equation reproduce well within modeling
 362 uncertainties the results from the more complex four-chamber global carbon balance used by Singer et
 363 al. [16,28,31]. Each region has a maximum rate of carbon biosequestration that is based on its forestry
 364 potential. Each participant specifies her or his fraction of this maximum as an input value G_{bio} .

365 Table 3 lists reference values of parameters common to all regions. It is to be emphasized that
 366 the reference parameter values listed in this appendix are not all meant to be the most likely values
 367 appropriate to simulating the future evolution and effects of climate change. Rather, particularly for
 368 costing model reference parameters listed in Section 4.2, values are chosen to illustrate points of
 369 particular educational interest. It is up to other users of the type of spreadsheets described here to insert
 370 parameter values appropriate to their particular interests.

371 The evolution of arctic land ice volume v , divided by its starting value at $y = 15$, is given by

$$dv/dy = -(1 - c_{13} G_{\text{artic}})(c_{14} - v)\tau/c_{15} \quad (2)$$

372 for $v > 0$ (with $dv/dy = 0$ when $v = 0$ so that v does not become negative). G_{artic} is the sum of regional
 373 input values as used in Equation (5) below, but at most 100%=1 if those inputs sum to more than 100%.
 374 The constant c_{13} is a measure of the summer to annually averaged global effect of arctic stratospheric
 375 sulfur injection, which is more than the ratio of the incident sunlight per unit area times the surface
 376 area of the whole globe to that for the arctic, i.e. a large number. For the example described above, the
 377 differential effect of arctic vs. global stratospheric sulfur in injection had not yet been implemented in
 378 the model, so that exercise in effect had $c_{13} = 0$. Thus, in the exercise described above, the effect of
 379 using arctic instead of global stratospheric sulfur injection is just to avoid the direct negative economic
 380 effects of a global stratospheric haze that are described below. Here τ is the increase in global average
 381 temperature over a pre-industrial reference level. The inclusion of the factor $(c_{14} - v)$ accounts for the
 382 temperature on the surface of the Greenland ice sheet increasing as its altitude decreases as a result of

383 accumulated melting, in addition to the melting proceeding faster for larger values of τ . For the results
 384 presented here, $c_{14} = 2$.

385 The increase in global mean sea level, M in meters, over its year 2015 accounts for land ice melting
 386 and thermal expansion of the surface ocean layer:

$$M = c_{55}(1 - v) + c_{57}(T - T_0) + c_{58}(T - T_0)^2 \quad (3)$$

Table 3. Physical parameters

Symbol	Value	Units	Meaning
c_4	1/2.13	pp1000v/TtC	Conversion factor
c_5	0.5964	TtC	Preindustrial average
c_6	0.5	1	Ocean saturation parameter
c_7	1350	yr	Timescale for CO ₂ sinking to deep ocean
c_8	0.48	1	Preindustrial fraction of CO ₂ retained in atmosphere
c_9	0.40	1	Maximum non-atmospheric CO ₂ saturation effect
c_{10}	0.12	1	Maximum thermal effect on atmospheric CO ₂ retention
c_{13}	0	1	Differential effect of arctic sulfur on ice melting
c_{14}	2	1	Ice altitude effect parameter
c_{15}	4000	years	Arctic land ice melting timescale parameter
c_{17}	30.667	(W/m ²)°K/yr	Ocean surface layer thermal inertia parameter
c_{18}	341.5	(W/m ²)	Surface- and time-average reference insolation
387 c_{19}	286.85	°K	Time-averaged preindustrial global average temperature
c_{20}	1.16	1	c_{20} - c_{22} is the preindustrial average albedo
c_{21}	0.87	1	c_{21} - c_{23} is the preindustrial effective emissivity
c_{22}	0.86055	1	Ice albedo parameter
c_{23}	0.24685	1	Temperature effect on effective emissivity
c_{26}	0.0002	1	Insolation fractional increase at Gleisburg cycle maximum
c_{27}	0.0004	1	Insolation fractional increase at long sunspot cycle maximum
c_{28}	-3	years	Time of Gleisburg cycle maximum, measured from year 2000
c_{29}	-3	years	Time of long period sunspot cycle maximum, "
c_{30}	88	yr	Gleisburg cycle period
c_{31}	600	yr	Long sunspot cycle period
c_{40}	0.0160	1	Maximum global sulfur fractional effect on net insolation
c_{41}	0.0038	1	Maximum arctic sulfur fractional effect on net global insolation
c_{42}	0.0090	1	Maximum saltwater lofting effect on net global insolation
c_{55}	7.66	m	Sea level rise from all northern hemisphere land ice
c_{57}	0.031462	m/°K	Linear term thermal expansion coefficient
c_{58}	0.000138	m/(°K) ²	Quadratic term thermal expansion coefficient

Global average temperature evolves as

$$c_{17} \frac{d\tau}{dy} = c_{18}(\mu - G)(1 - c_{20} + c_{22}(T/T_0)^2) - c_{24}(1 + \tau/T_0)^4(c_{21} - c_{23}(T/T_0)^2 - F) \quad (4)$$

389 Here $\tau = T - T_0 = T - c_{19}$ is the change in global average temperature T from a preindustrial reference
 390 value of $c_{19} = 286.85^\circ K$. Also, $c_{24} = \sigma T_0^4$, where $\sigma = 5.6704 \times 10^{-8} \text{ W}/(\text{m}^2 \text{ }^\circ\text{K}^4)$ is the Stefan-
 391 Boltzmann constant. The reference surface ocean thermal inertia timescale used here is $c_{17}=30.667$
 392 $(\text{W}/\text{m}^2)(\text{yr}/^\circ\text{K})$, as in Singer et al. [16]. The factor μ includes small sinusoidal variations with periods
 393 of 88 and 600 years affecting the solar insolation with surface averaged reference value $c_{18} = (1366/4)$
 394 W/m^2 . The effects of the short-period variable 11-year sunspot cycles are assumed to average out, so
 395 those periodic variations in insolation are not included. The formula for μ is

$$\mu = 1 + c_{26} \text{Cos}[2\pi(y - c_{28})/c_{30}] + c_{27} \text{Cos}[2\pi(y - c_{29})/c_{31}] \quad (5)$$

396 The global effect of solar radiation management is given by the sum $G = c_{40}G_{\text{sulfur}} + c_{41}G_{\text{arctic}} + c_{42}G_{\text{salt}}$
 397 of the effects of global coverage stratospheric sulfur injection G_{sulfur} , seasonal arctic stratospheric sulfur
 398 injection G_{arctic} , and low-altitude salt water lofting G_{salt} . The costs associated with the components of
 399 G are described in Section 4.2. The radiative forcing effect of increases in atmospheric greenhouse gas
 400 concentrations over reference levels is given by the sum $F = F_C + F_F + F_N$ of effects of CO_2 , volatile
 401 fluorine compounds, and N_2O . The formula for F_C is $F_C = c_{33} \text{Ln}[c_a/c_4]$, where the reference value used
 402 for the results presented here is $c_{33} = 0.0068$.

The formula for the effect of nitrous oxide on global average temperature is

$$F_N = c_{52}(\sqrt{N} - \sqrt{c_{44}}) - (F_{MN} - c_{45}) \quad (6)$$

where

$$F_{MN} = c_{46} \text{Ln}[1 + c_{48}(c_{47}N)^{c_{50}} + c_{49}(c_{47}N)^{c_{51}}] \quad (7)$$

403 Here $c_{44} = 270$ is the preindustrial atmospheric N_2O concentration in parts per billion by volume (ppbv).
 404 The factor F_{MN} accounts for overlapping methane and nitrous oxide absorption bands. The constant
 405 $c_{47} = 1803$ is a recent reference value for the atmospheric methane concentration in ppbv. The result
 406 from this formula for F_N is less than that from a simple linear function $0.00315(N - c_{44})$ by only 0.4
 407 percent for $N = 329$ ppbv but by 12 percent for the no-reductions result of $N = 506$ ppbv for year 2195.
 408 Reference values of parameters in the N_2O balance model are listed in Table 4.

Table 4. Global nitrous oxide parameters

Symbol	Value	Units	Meaning
c_{43}	5	yr	Times over which N ₂ O emissions are held constant
c_{44}	270	ppbv	Preindustrial atmospheric N ₂ O concentration
c_{45}	0.149	ppbv	Preindustrial < CH ₄ > correction to N ₂ O forcing
c_{46}	0.47	W/m ²	Coefficient for < CH ₄ > correction to N ₂ O forcing
c_{47}	1803	ppbv	< CH ₄ > for correction to N ₂ O forcing
c_{48}	2.01×10^{-5}	ppbv ^{-2c_{50}}	Coefficient for < CH ₄ > correction to N ₂ O forcing
c_{49}	1.52×10^{-15}	ppbv ^{-2c_{51}}	Coefficient for < CH ₄ > correction to N ₂ O forcing
c_{50}	0.75	1	Exponent for < CH ₄ > correction to N ₂ O forcing
c_{51}	1.52	1	Exponent for < CH ₄ > correction to N ₂ O forcing
c_{52}	0.12	(W/m ²)/√ppbv	Coefficient for N ₂ O forcing
c_{53}	121	yr	Inverse of excess atmospheric N ₂ O clearing rate

The effect of future changes in the atmospheric methane concentration is not accounted for here. This is because the rate of methane emissions has recently nearly stabilized and methane has a short atmospheric lifetime compared to the time scales of primary interest here. If there are nevertheless substantial future increases in the atmospheric methane concentration, it is assumed here that the resulting radiative forcing will be cancelled by global albedo increase at a cost that is insubstantial compared to that for reducing radiative forcing from other greenhouse gases.

Table 5. Parameters for volatile fluorine compounds

HFC Code	Chemical Formula	Life (yr)	Force (W/m ²)/ppbv	mol wt gm/mol	initial kt	b_1 kt/yr	b_2 yr	b_3 yr
HFC32	CH ₂ F ₂	5.6	0.11	52.02	5.34	48.6	77.6	30.6
HFC43-10	CF ₃ CF ₂ (CHF) ₂ CF ₃	17.1	0.40	141.09	0.21	497.6	71.9	57.4
HFC125	CHF ₂ CF ₃	32.6	0.23	82.02	5.34	155.4	76.5	30.2
HFC134a	CH ₂ CF ₃	14.6	0.16	83.03	0.21	2625.8	103.0	37.0
HFC143	CH ₃ CF ₃	48.3	0.13	62.03	5.34	120.8	77.1	30.4
HFC227ea	CH ₃ CHF ₂ CF ₃	36.5	0.26	114.04	0.21	266.8	135.9	42.7
HFC245ca	CH ₂ F ₂ CH ₂ CF ₃	6.6	0.21	134.05	5.34	1493.8	145.5	43.4
	SF ₆	10000	0.10	88.00	0.21	131.7	73.6	37.2
	C ₂ F ₆	2600	0.26	138.01	5.34	35.5	60.1	35.5
	NF ₃	3200	0.52	146.60	0.21	30.8	2047.3	35.1

Also,

$$F_F = \sum_{k=1}^{10} F_k \quad (8)$$

419 where $F_k = b_{4,k}A_k$ for $k = 1 \dots 10$, and A_k are the atmospheric contents in ktonne of ten volatile fluorine
 420 compounds. Here $b_{4,k}$ are the forcing coefficients listed in the fourth column of Table 5, multiplied by
 421 c_4A_C/M_k where c_4A_C/M_k , with $c_4 = 1/2.13$, $A_C = 12.0107$ the atomic weight of carbon, and M_k
 422 are the molecular weights listed in Table 5. The factors c_4A_C/M_k convert total ktonne of each fluorine
 423 compound in the atmosphere to parts per billion by volume (ppbv). The values of A_k evolve as

$$dA_k/dt = E_k - A_k/b_{5,k} \quad (9)$$

424 where E_k are global emissions rates and $b_{5,1} \dots b_{5,10}$ are the atmospheric lifetimes listed in the third
 425 column in Table 5. The starting values for A_k at $y = 15$ are listed in Table 5. Reference values for the
 426 other parameters pertinent to volatile fluorine compounds are also listed in Table 5.

427 Global emissions based on logistic fits to IPCC scenario A2 extrapolations [2] are divided in
 428 proportion to each region's GDP in order to estimate the values of E_{0k} as functions of time. The year
 429 2100 A2 scenario value for HFC43-10 was multiplied by 3/4 to make it similar to the other fits instead
 430 of having a half-maximum in Julian year 2364. The logistic fits are of the form

$$b_{k,1}/(1 + e^{-(y-b_{k,2})/b_{k,3}}) \quad \text{for } k = 1 \dots 10 \quad (10)$$

Atmospheric nitrous oxide concentration N evolves as the solution to the equation

$$dN/dt = S - (N - c_{44})/c_{52} \quad (11)$$

431 with the initial condition $N = 327.6$ ppbv at $t = 2015$. Here $c_{52} = 121$ years. The source term is
 432 $S = \sum_{n=1}^6 S_n$ with $S_n = (1 - r_n)f_nG$ where f_n is the fraction of global anthropogenic nitrous oxide
 433 emissions in reference year 2011 for region n . In the absence of reductions (i.e. if all $r_n=0$), G is
 434 $G = PL$ where $P = \sum_{n=1}^6 P_n$, and $P_n = p_{0n} + p_{1n}/(1 + \text{Exp}[-(p_{2n} - t)/p_{3n}]) - Q_n$ with $t = 2000 + y$
 435 and the values of the constants listed in Table 6, and $Q_n = p_{0n} + p_{1n}/(1 + \text{Exp}[-(p_{2n} - 1860)/p_{3n}])$.
 436 The logistic function $L = 4.81(0.6236 + 0.3571/(1 + \text{Exp}[-(1968.05 - t)/2.701]))$ accounts for an
 437 increase the incremental nitrogen in nitrous oxide emissions over 1860 values per incremental population
 438 increasing from about 0.62 (kg/yr)/person before widespread use of manufactured nitrogen fertilizer
 439 to about 0.98 (kg/yr)/person thereafter. The leading coefficient of 4.81 converts Mtonne (10^9 kg) of
 440 atmospheric nitrogen in nitrous oxide to ppbv of N_2O .

Table 6. Region dependent nitrous oxide parameters

Symbol	Units	China+	USA+	EU+	Ocean	India+	G121
p_0	Gpersons	0.388	0.011	0.231	0.080	0.224	0.114
p_1	Gpersons	1.525	0.593	0.827	1.073	2.801	4.974
p_2	Julian year	1965.76	1993.23	1936.01	1979.40	1999.04	2028.10
p_3	Years	19.14	48.62	19.90	28.27	28.97	33.11
f	1	0.142	0.204	0.169	0.204	0.117	0.163

443 The above differential equations for c_a , τ , v and N are solved using a simple Euler method with a
 444 time step equal to $\delta = 2.5$ years. That is, equations of the form $dX/dt = R$ are advanced by setting
 445 $X_{j+1} = X_j + R_j\delta$, where R_j is evaluated using results from time y_j , where $y_j = 12.5 + j$ for as many
 446 values of j as desired. Values for even numbers j are taken to approximate averages over five year
 447 periods for the purpose of estimating changes in pot balances. Exact analytic solutions for atmospheric
 448 contents of volatile fluorine compounds are used, with emissions E_k approximated as constant averages
 449 in each 5-year period between initial and final emission levels over the 5-year period as specified by
 450 participants' inputs.

451 4.2. Costing

452 Each parameter in the costing model has a spreadsheet representation as a scalar times a vector with
 453 number of components equal to the number of regions. Here these products are denoted by a letter d with
 454 a subscript. Reference values of these parameters listed in Table 7 are the same for all regions, except
 455 for the greater sensitivity of the Ocean region to incremental sea level rise due to melting of arctic land
 456 ice as indicated in Table 1. However, the spreadsheet includes options for making any or all of these
 457 parameters different for different regions.

458 The fraction of GDP lost due to direct effects of $\langle \text{CO}_2 \rangle$ buildup is determined by d_4 as in Equation 2
 459 above. (Herein, GDP means annual gross domestic product.) The fractional change in GDP that is added
 460 (algebraically) to pot balances as a result of changes in arctic land ice volume is $-d_5(1 - v)$.

Some of the financial parameters are different for each region. For example, the fractional change in
 GDP as a function of τ that is added to pot balances is

$$d_{26} \left(\frac{1}{1 + d_6(\tau - d_{25}) + d_7(\tau - d_{25})^2} - 1 - 0.001d_8 \right) \quad (12)$$

461 Reference values of some parameters that are different for more than one region are listed in Table 8.

462 Example results for such quadratic functions are plotted as percentages in Figure 5. These values are
 463 adapted from examples from Nordhaus and Boyer [25] as reported by Bosello and Roson [26]. Added
 464 to each pot balance also is the fractional change in GDP that depends on the rate of change of τ and is
 465 equal to $-d_9(d\tau/dy)^2$.

The direct change in pot balance for reduction of annual atmospheric carbon emissions for a region is
 given by

$$-d_{10}(1 + \text{Min}[d_{13}, d_{11}f_c^{d_{12}}])f_cE_{c0} \quad (13)$$

466 where E_{c0} is the region's no additional policy carbon emissions rate. For the results shown here, $d_{13} =$
 467 $d_{11} = 3$ and $d_{12} = 4$. The marginal cost per metric ton of energy decarbonization that that gives this
 468 average cost is $d_{10}(1 + 15f_c^4)$. For the reference example results shown above, $d_{10}=50\$/\text{tC}$, giving a
 469 marginal cost of $\$143/\text{tC}$ for $f_c = 0.58$. In 2010, Enkvist et al.[34] estimated a marginal cost from new
 470 coal carbon and sequestration plants at $f_c = 0.58$ of about 40 euro/ tCO_2 by 2030, which corresponds to
 471 $\$200/\text{tC}$ in the monetary units used here. However, these authors estimate a zero marginal cost at about
 472 $f_c = 0.21$, so their average cost at $f_c = 0.58$ is lower than what would result from the formula used here
 473 with $d_{10}=(200/143)50\$/\text{tC}$. In the approach used here, the marginal cost of decarbonization is always
 474 positive. This approach reflects an assumption that large scale energy decarbonization up to a point of

475 zero marginal cost continues to be precluded by system inefficiencies (such as non-nuclear renewable
476 energy mandates being used instead of across the board carbon emission taxes).

477 The annual change in pot balances due to each region changing its emissions rate with time is given by
478 $-d_{14}\text{Max}[0, d(fcE_{co})/dy]$. With this formula included, regions can avoid extra costs by avoiding rapid
479 buildup of carbon-intensive energy systems, which is primarily a consideration for the China+ region.
480 To account for the costs of decommissioning carbon-intensive energy systems before the end of their
481 otherwise normal operating lifetimes, this formula should be modified to include costs for very rapid
482 energy decarbonization.

483 The formula $-d_{15}(1 + d_{43}f_{\text{bio}}/2)$ gives the annual T\$US2015 change in pot balances per Gtonne of
484 carbon annually biosequestered. This formula results from assuming that the marginal cost per unit
485 annual amount of carbon biosequestration increases linearly with the rate of biosequestration. The
486 maximum annual rates of biosequestration are given by d_{16} .

Table 7. Global financial parameters

Symbol	Value	Units	Meaning
d_4	0.0006	1	Parameter for fraction of GDP loss from direct $\langle \text{CO}_2 \rangle$ effect
d_5	0.0004	1	Minimum fraction of GDP loss from arctic land ice melting (c.f. Table 1)
d_9	10	(yr/°K) ²	Parameter for fraction of GDP loss proportional to $(d\tau/dy)^2$
d_{10}	0.05	T\$/GtC	Initial cost of energy decarbonization
d_{11}	3	1	Coefficient of cost of changing carbonization vs. $ f_c $
d_{12}	4	1	Exponent for cost of changing carbonization vs. $ f_c $
d_{13}	3	1	Limiting parameter for cost of decarbonization
487 d_{14}	0.4	T\$(yr/GtC)	Annual cost proportional to rate of change of carbon emission
d_{15}	0.1	T\$/GtC	Cost of carbon biosequestration
d_{17}	6.9	T\$	Annual cost per fraction of maximum stratospheric injection
d_{18}	0.02	1	% of GDP lost per % of maximum global stratospheric sulfur
d_{19}	7.5	T\$	Annual cost per fraction of maximum arctic sulfur injection
d_{21}	16.2	T\$	Annual cost per fraction of maximum saltwater lofting
d_{23}	2.3	%	Annual interest rate on pot balances
d_{25}	1	°K	Reference temperature in warming damage functions
d_{26}	2	1	Multiplier for warming cost damage functions
d_{42}	2.9773	T\$/ppbv	Coefficient of cost of N ₂ O reductions
d_{43}	1	1	Coefficient for cost of biosequestration

Table 8. Region dependent financial parameters

Symbol	Units	China+	USA+	EU+	Ocean	India+	G121
d_6	1	-0.0041	-0.0042	-0.0050	0.0039	0.0050	0.0022
d_7	1	0.0020	0.0025	0.0049	0.0013	0.0049	0.0026
d_8	1	0.84082	0.83724	0.8941	-0.96895	-1.41385	-0.6234
d_{16}	GtC/yr	0.1100	0.2225	0.1300	0.2235	0.0320	0.7770
d_{24}	%	1.12	0.840	0.76	1.42	1.24	1.02

The annual direct cost in T\$US2015 to a region albedo via global stratospheric sulfur injection is

$$d_{17}c_{40}f_{\text{volcano}}f_S/100 \quad (14)$$

This cost corresponds to a cost in T\$US2015 per W/m^2 of radiative forcing of $d_{17}/c_{18} = 0.02$. Klepper and Resnick [22] refers to a range of 0.002 to 0.012 T\$ per W/m^2 for global sulfur (with references from 2008 to 2010 with no stated inflation adjustment.) To the extent that the range quoted in this reference is well reasoned, simulation participants have not been misled about the into adopting stratospheric sulfur injection just because its direct cost was substantially underestimated. The participants' policy entries for stratospheric sulfur injection are linearly interpolated between an entry for year y_j and y_{j+1} to get a costing value used for time midway between y_j and y_{j+1} . For example, a 1% decrease in $c_{18}(1 - c_{20} + c_{22}(T/T_0)^2)$ costs 1% of d_{17} T\$/yr. The fractional change in each region's GDP due to the globally summed rate thereof is d_{18} times the summed value of the global coverage stratospheric sulfur injection entries in the participants spreadsheets. If the sum of all regions' reductions in net insolation is greater than d_{27} , then each region's entered value is multiplied by d_{27} divided by that sum. Setting $d_{27} = 0$ creates a simpler version for which entries for stratospheric sulfur injection has no effect.

The factor f_{volcano} is set equal to 1 for every quinquennium during which there is no significant insertion of sulfur into the stratosphere due to volcanic eruptions. If the effect of volcanic eruptions on the global heat balance averaged over a quinquennium is equal to or larger than that due to the sum of participants choices, then the cost to those participants is set to zero by setting $f_{\text{volcano}} = 0$ for each participant for that quinquennium. If the effect of volcanic eruptions on the global heat balance is non-negligible but less than the global sum of participants decisions for stratospheric sulfur injection, then f_{volcano} is set equal to the ratio of the effect of volcanic eruptions to the sum of participants decisions for stratospheric sulfur. As described in Section 5.1, volcanic eruptions have no effect on the global heat balance if $f_{\text{volcano}} > 0$, since it is assumed that in such cases reductions in anthropogenic global stratospheric sulfur emissions over a five year period are equal to the increase in natural global stratospheric sulfur injection. Arctic volcanoes are assumed to have so little long term effect on land ice melting that only their effects on the global heat balance and thus on costs of global stratospheric sulfur injection costs are accounted for. Table 1 lists parameters from two examples of random samples from a stochastic model of future volcanic eruptions by Amman and Naveau [35]. For most purposes it suffices to choose one of these two examples but not inform participants ahead of time which is being used. If this is thought insufficient, simulation managers could use the method described by Amman and Naveau.

Table 9. Two volcanic radiative forcing options

Step	W yr/m ²	Step	W yr/m ²
6	2.08	9	1.76
8	3.88	15	0.21
9	0.92	24	0.77
10	1.40	30	1.20
11	2.32	32	8.48
12	2.42	36	1.20
21	0.29		
27	3.53		
29	0.43		
31	1.98		
35	0.77		

520

521 The change in pot balances per unit increase in G in the heat balance equation for each region using
 522 seasonal arctic stratospheric sulfur injection are given by $-d_{19}$. If the sum of all regions' reductions in
 523 net insolation is greater than 1, then each region's entered value is divided by that sum. The changes in
 524 pot balances per W/m² reduction for each region using low-altitude salt water lofting are given by $-d_{21}$.
 525 If the sum of all region's reductions in net insolation is greater than 1, then each region's entered value
 526 is multiplied by d_{22} divided by that sum.

527 The costs in T\$US2015/year per annual ktonne change in the absolute value $|E_{0k} - E_k|$ in emitted
 528 volatile fluorine compound of type k is $d_{k+30}|E_{0k} - E_k|$. Note that the use of absolute value in
 529 the formulas $d_{k+30}|E_{0k} - E_k|$ allows for the possibility of increasing emission of volatile fluorine
 530 compounds over their "no policy" emissions levels. These compounds are divided into three classes:
 531 refrigerants only, compounds with very long atmospheric half lives (SF₆, NF₃, and C₂F₆), and others
 532 (which include HFC43-10 and HCC 227ea). By far the largest component of the "other" category is
 533 HFC134a (i.e. CH₂FCF₃). HFC134a is used both as a foam blowing agent and a refrigerant and has an
 534 atmospheric lifetime of 14 years. By increasing production and release the "other" category temporarily,
 535 regions wanting a higher global average temperature have the option of sending a signal to other regions
 536 that those other regions need to limit their rates of stratospheric sulfur injection.

537 Added annually to each region's pot balance to help pay for various costs is d_{24} times that region's
 538 annual GDP. The annualized interest rate for earnings on positive balances and payments on negative
 539 balances are denoted as d_{23} .

540 The reference values of the parameters $d_{31} \dots d_{40}$ in the costing model for reducing emissions of
 541 volatile fluorine compounds are respectively 0.0001{3, 1, 3, 1, 3, 1, 3, 2, 2, 2} T\$US2015/yr. The cost
 542 of reducing nitrous oxide emissions in region n by a fraction r_n is $d_{42}r_n^2f_nR_n$, where R_n is the ratio of
 543 "no new policy" N₂O emissions from region n at time $t = 2015$ to the emissions from region n in 2015,
 544 and the values of f_n are listed in Table 6.

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548 Conflict of Interest

549 The authors declare no conflict of interest.

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