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# Regional Welfare Impacts from Options for Limiting Global Average Temperature

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# Regional Welfare Impacts from Options for Limiting Global Average Temperature

**Abstract**

Extrapolation of historical trends in anthropogenic atmospheric carbon dioxide emissions is compared to results with new policy options. One approach is to multiply historical extrapolation of global emissions by a factor with a decline from 1 to a smaller multiple, e.g. on a timescale of about 30 years. Another allows for solar radiation management via anthropogenic stratospheric sulfur injection by one or more of sixteen geographic regions, in order to limit global average temperature to a chosen target level. An economic measure of impacts on human welfare is compared for different versions of these two approaches. That measure is time-integrated discounted utility of per capita consumption. That measure is computed with and without empathy, which involves geographical regions counting part of others' welfare as part of their own. Inter-regional fund transfers that cover all or part of a region's expenditures used for limiting carbon emissions can be used to encourage broader inter-regional cooperation. These exercises pose interesting questions about how choices will ultimately be made between use of one or both of carbon emissions limitations and solar radiation management.

**Keywords:** temperature, carbon, sulfur, welfare, empathy

## 1 Introduction

The approach taken here is heavily influenced by experience with participant simulation exercises of international interactions on climate change policies as described by Singer and Matchett (2016). That experience highlighted the need for an integrated assessment model that produces an economic measure of impacts both of changes in atmospheric carbon dioxide concentration <$CO_2$> and regionally and annually averaged temperature, with enough flexibility to allow for carbon emissions limitations, solar radiation management (SRM), or both. The model used that was designed for that purpose is called Climate Action Gaming Experiment (CAGE), c.f. Supplementary Information below. As used here, the CAGE model also provides an integrated platform for a single user to investigate an interesting series of questions about how implementation of future policy options for carbon emissions limitation and SRM might affect regional values of an economic measure of human welfare. Those options include all or some of sixteen geographic regions partially or completely eliminating anthropogenic carbon emissions in the form of $CO_2$, stabilizing or reducing global average temperature using stratospheric sulfur injection, and phasing out SRM by augmenting emissions limitations with removal of atmospheric $CO_2$. The Discussion section below lists eight dilemmas concerning these options that results presented herein highlight as being as yet unresolved.

There are both connections with and differences from previous studies. For economic impacts of climate change, the FUND 3.9 framework is used, but with revisions or replacements of its influences on economic production. A description of the FUND 3.9 model is given by Waldhoff et al. (2014), along with a link to its documentation from Anthoff and Tol (2014b). That framework was chosen because it is one that allows accounting separately for economic impacts of changes in $<CO_2>$ and global average temperature, $\tau$, e.g. via stratospheric sulfur injection similar to that described by Smith (2019). Impacts on economic productivity due to changes in $<CO_2>$ include those on agriculture, forestry, upper ocean acidity, and in human productively as modified by changes in ventilation systems. Impacts associated with changes in $\tau$ include those on agriculture, forestry, water supply, heating, cooling, sea level, mortality and morbidity from disease, and storms. The accompanying Supplemental Information (SI) lists the parameters varied to get the results herein, the complete set of equations solved, and values of other parameters that are set the same for all of those results.

Rather than reporting an abstract number of "utils," the CAGE model outputs economic measures of welfare for each region in millions of person-years. One person-year is the difference between a person living for a year at a bare subsistence level of consumption and a sustainable but low income, which is also the difference between living on the low income and a potentially comfortable but not luxurious middle income (c.f. SI Section 6.6). This approach makes the economic implications for human life of modeled outcomes clearer to simulation participants than more conventional measures such as trillions of dollars of net present value integrated well into a distant future. However, a number based on evolution of per capita consumption in itself cannot be expected to encompass all of what in ordinary speech is thought of as human welfare. As a reminder of this limitation, total time-integrated discounted utility of per capita consumption is repeatedly referred to in the Results section here more briefly as "computed welfare."

# 2 Methodology

## 2.1 Model Overview

A guiding principle here is choosing simplicity over complexity, constrained by requirements of compatibility with historical data sets. That approach is particularly important for time-limited interactive simulation exercises where participants need to be able to expeditiously access and understand calculated results for policy proposals. For the stand-alone exploratory work presented here, comparative simplicity is also helpful for making the underlying equations in the SI more transparently connected to the results presented.

The ordinary differential equations used here are each first order for the global heat balance and sea level, a first order pair for the global carbon balance, and analytic approximations to solutions of a second order equation for climate change impacts on capital stock for each region. There are also analytic solutions for global nitrous oxide and methane balances and for cumulative industrial carbon emissions. This level of simplicity is achieved by avoiding solutions either for short-term transients or for cases where results for computed welfare depend substantially on changes for several times longer than a social discounting timescale. The accompanying Supplementary Information describes all of this.

Following a procedure used by Foster and Rahmstorf (2011), rapid historical changes in global average temperature were removed from the data used for calibration of global heat balance parameters by using data-calibrated models of influences of the El Niño Southern Oscillation (ENSO), Schwabe solar cycles with periods of approximately 11 years, and of volcanic stratospheric sulfur injections exceeding a specified threshold. The global heat balance equation used is $c_{th}\tau' = F - \tau/\lambda$ where $\tau'$ is the rate of change of $\tau$, and $F$ is radiative forcing in W/m$^2$ from equations in SI Sections 4.1 and 4.4. Heat balance parameter values listed in Table S3 are $c_{th} = 28.49$ (W/m$^2$)/°C and $\lambda = 0.5175$°C/(W/m$^2$). The data calibration of these two parameters and their implications are discussed in SI Section 6.5.

Regional impacts of short-term ENSO and solar cycle variations are implicitly assumed already to be incorporated into historical trends used to calibrate parameters used for extrapolations of background economic development that will be modified by climate change. Very large volcanic eruptions on the scale of some in the nineteenth century are assumed to be rare enough to leave it to subsequent possible work incorporating a stochastic model of their future occurrence, e.g. as in Papale (2018), and their economic effects.

The global carbon balance model has a time-varying fraction of carbon emissions being promptly and durably sequestered away from the atmosphere and upper ocean (c.f. SI Section 4.3). That allows for solution of only two coupled differential equations with constant coefficients, yielding an even simpler approach than used, for example, in Pathfinder by Bossy et al. (2022) or Hector by Dorheim et al. (2020). The model used here nevertheless allows fitting of both historical data and results from a comprehensive global circulation model calculation with future cessation of anthropogenic carbon emissions reported by MacDougall et al. (2020) and Jones et al. (2020).

The FUND 3.9 documentation from Anthoff and Tol (2014b,a) includes tables for five scenarios, all with per capita income continuing to grow appreciably out to year 2300. NEW extrapolates an approximation to solutions to a welfare maximization model for per capita GDP with productivity growing logistically with time and parameters calibrated to historical data region by region. This approach captures a tendency towards an observed decrease with time of per capital GDP growth rates in industrialized countries, e.g. as exemplified by data from for the United States in Martin (2017).

In extrapolating carbon emissions, FUND 3.9 compensates for enduring substantial growth in per capita GDP by using tables with continuing declines in energy per unit of economic production. CAGE instead includes flexible options for policies that modify extrapolation of direct fits to historical data on global carbon emissions using logistic functions and their temporal derivatives, and accounting for future effects of elasticity of demand for fluid fossil fuels with global resource depletion. This approach provides CAGE with facilitates both transparency and straightforward ability to investigate implications of implementation of a wide range of policy options without needing to choose amongst a limited set of externally provided detailed scenario properties.

## 2.2 Complementarity with Some other Benefit-cost Models

Particularly with the economic impact simplifications noted above, in nomenclature described by Weyant (2021), CAGE, like FUND, is more of the benefit-cost than detailed process type of model. Other benefit-cost models referred to by Weyant include PAGE09 from Hope (2011), and DICE described by Nordhaus (2017), c.f. RICE models with regional disaggregation as described by Yang (2022) and Gazzotti (2019). PAGE09 calculates discounted climate impacts as per capita GDP weighted numbers in T$US that are functions of temperature, a somewhat different approach than in CAGE and, for example, RICE50+ by Gazzotti (2019).

Climate change impacts are treated here as a perturbation on a background economy using an Euler-Lagrange equation for the resulting perturbation of total capital stock for each region. Those differential equations are linear, with inhomogeneous terms that are sums of coefficients dependent on the evolution of the background economy and each of seventeen additive "damage functions" and their temporal derivatives. When the timescales for evolution of those driving terms are long compared to a "capitalization time" $\bar{t}$ with an estimated value of 7.76 years, then the terms proportional to time derivatives of the capital stock perturbation can be dropped and an approximate analytic solution is obtained (c.f. SI Section 6.8). This approach helps both with transparency and computational efficiency.

A limitation of the approach used in CAGE is that it is designed neither to model very rapid changes in drivers of climate change impacts nor passage through "tipping points," c.f. Lenton et al. (2008), that lead to realms where the historically data-calibrated physical balance models it uses are no longer appropriate. The inclusion from the outset of an option for comparatively inexpensive solar radiation management, and the implicit assumption of possible foresight in its use as a resort to avoid reaching tipping points, makes the complication of their inclusion in the CAGE model less of a pressing need.

# 3 Results

Results from a sequence of example applications are described here. Climate change impact on total discounted utility of per capita consumption, integrated from a specified year into a distant and heavily discounted future, is used for each example as an economic measure of human welfare.

A summary of the content of these examples is as follows.

3.1. “No Deals,” as viewed from different decision times for potential alternatives
3.2. SRM, vs. “Global Full Green Deal” transitions to zero net carbon emissions
3.3. Global Partial Green Deals for lower but non-0 net carbon emissions ± empathy
3.4. Global Partial Green Deals with transfer payments for costs of decarbonization
3.5. Partial Green Deals with not all regions reducing extrapolated emissions
3.6. Comparing global average temperature stabilization to reduction with SRM
3.7. Limiting implementation of global cooling via SRM by a low latitude region
3.8. Attempting to use SRM as a transition to a later move to 0 net carbon emissions

A theme threading through these examples is a search for a path to stabilization of global average temperature that increases the computed welfare of all regions without permanent use of SRM. No such path was found amongst the using the variety of searches described below. That outcome highlights interesting questions for possible further research that are listed below in the Discussion section.

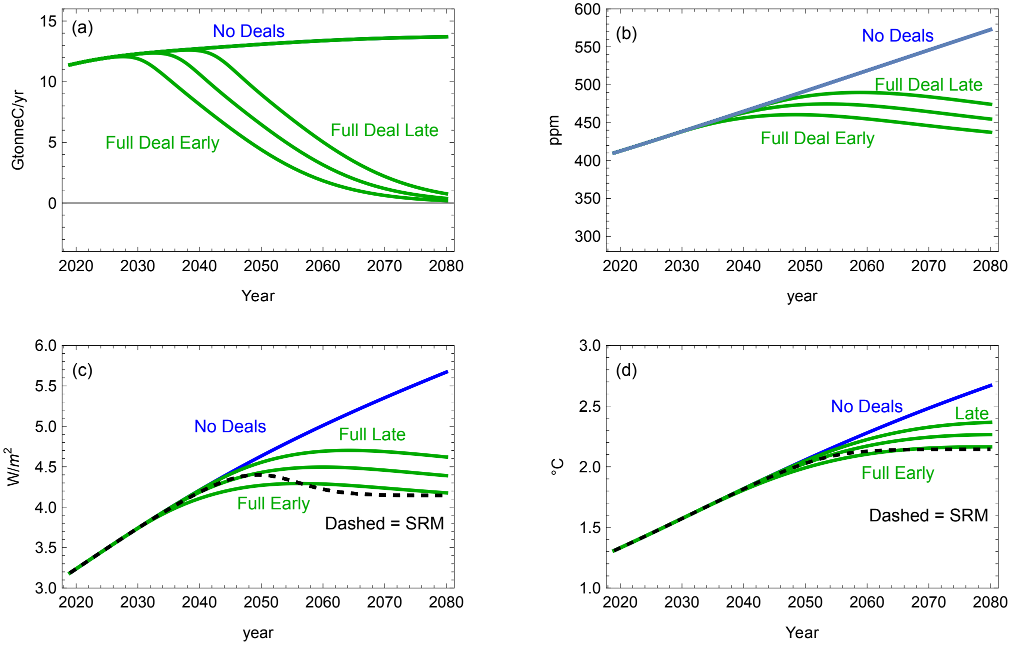
The results presented here are from a model with limited applicability using the set of varied parameters listed in SI Section 1. They all use the large set of fixed parameters listed in SI Section 5, some of which are subject to a considerable amount of uncertainty. Enough background information was encountered during literature survey and data calibration of model parameters to support a systematic analysis of the influence of such uncertainties, but that substantial exercise lies beyond the scope of the present work. Thus, it is to be emphasized here that the point of the exercise described here is to present quantitative results that highlight interesting questions, not to be interpreted as an attempt to provide answers to those questions in the absence of additional detailed work using various possible analysis tools.

## 3.1 Description of Results

The results presented here start with a comparison of implementation of a global “Full Green Deal”’ to extrapolation of historical trends without new policy initiatives. The Full Green Deal multiplies historical extrapolations of anthropogenic emissions of carbon in the form of $CO_2$ by factors using formulas and parameters described in SI Section 4.3 and Tables S0 and S1. The resulting global emissions and evolution of $<CO_2>$, total radiative forcing, and global average temperature ($\tau$) are plotted in Fig. 1. The point of the comparison of the solid curves in Fig. 1 is that delaying the costs of an asymptotic approach to zero carbon emissions does not result in an increase in computed welfare except for small increases for two regions, as reported in Table 1. The point of the comparison between the dashed and lower solid curves in Fig. 1d is that using SRM instead of a Full Green deal leads to higher computed welfare, as reported in Table 2.

Compared to a new Coupled Model Intercomparison Projects round 6 (CIMP6) “no climate policy” scenario SPP3-7.0, the NoDeals carbon emissions plotted in Fig. 1a are substantially lower. That difference is due to the use of a logistic function for the dominant industrial component of global emission to fit estimates of historical carbon emissions through 2019, with an inflection point in 2002 listed in Table S2 and the

**Fig. 1**



Plotted are (a) $e_c$, (b) $<\mathrm{CO}_2>$, (c) radiative forcing, and (d) $\tau$, with $e_c$ global anthropogenic carbon emission and $<\mathrm{CO}_2>$ atmospheric concentration in parts per million by volume. Definitions: Radiative forcing, increase since Julian year 1750 with neglect of the difference in that year of solar radiative forcing from its average from 1745 through 1755; $\tau$, increase in global average temperature over a value that would be in equilibrium with that level of radiative forcing

rate of increase of those emissions declining thereafter. At its start in 2015, the SPP3-7.0 global emissions curve approximately matches historical estimates but has a larger slope than historical estimates through 2019 and an inflection point in about 2060 with an *increasing* slope thereafter. The No Deals case in Fig. 1a is close to the SP4-6.0 carbon emissions curve from 2019–2050, but the SP4-6.0 emissions decrease by a factor of 2 from 2050 to 2100. The No Deals case interestingly provides a different data-calibrated perspective on extrapolation of global anthropogenic carbon emissions than any of CIMP6 scenarios described by Hausfather (2020).

Most of the results presented here have an underlying "all or nothing" assumption. In that context, even regions that would have higher computed welfare with unilateral implementation of the Partial Green Deal emissions limits discussed below would nevertheless convince the others that they would not proceed with those limits without universal cooperation with a global Green Deal. This is a strong assumption, but looking at its implications does lead to some interesting results.

Also plotted, as dashed (SRM) curves in Fig. 1d and 1c, are total evolution of $\tau$ to a maximum of 2.14°C and the corresponding total radiative forcing. That upper limit on $\tau$ is an additional 0.83°C above the year 2019 value of 1.31°C of a curve fitted to historical data. The difference between the No Deals and SRM curves in Figure 1c is the amount of radiative shielding needed to achieve the temperature limit plotted as a dashed curve in Fig. 1d.

## 3.2 Computed Welfare Impacts with No Deals as Viewed from Different Years

The computed welfare results presented here start with impacts $\Delta\bar{W}$, for each of the regions illustrated in Fig. 2, of climate change as viewed from vantage points of Julian years 2025, 2031, 2037, and 2043. Welfare computed from these vantage points has the integration range for the welfare integral over time of total discounted utility of per capita consumption starting from these various years and continuing for 300 years, which is enough times the inverse of the social discount rate to make contributions from further future integration negligible.

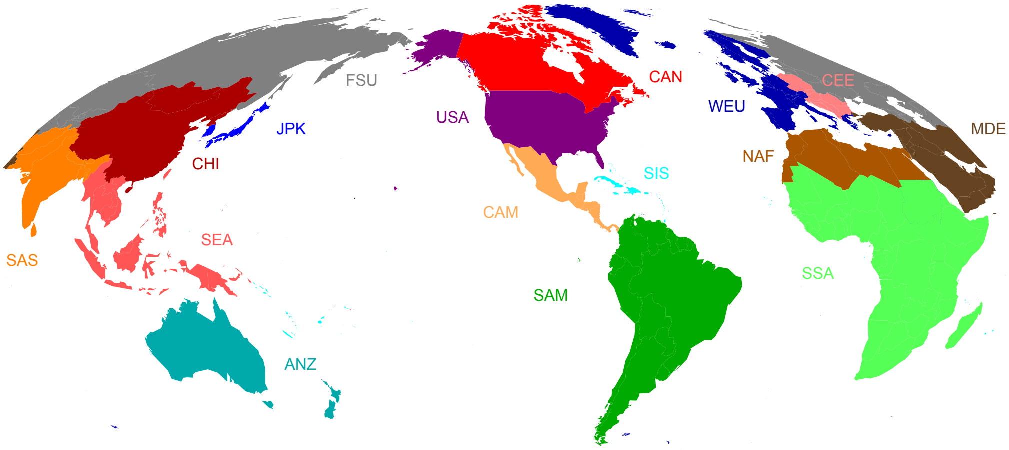
The computed results denoted $\bar{W}_0$ in Table 1 are integrals of exponentially discounted population increase since Julian year 1820 times utility of per capita consumption, computed without accounting for impacts of climate change on economic productivity, using formulas in SI Section 4.8. Also using the formulas in SI Section 4.8, the changes $\Delta\bar{W}$ are approximations to differences in that computed welfare with and without accounting for climate change impacts on economic productivity. As described in the SI, only increases in population and per capita consumption over constant base in each region are included when evaluating the welfare integrals. While a detailed model of the effects of uneven distribution of wealth, influence on decision making, and productivity within populations is avoided for simplicity, the approach used does recognize that instead assuming internal equality in those matters is highly idealized.

Economic productivity for each region is of the form $(1 + \epsilon D)a$ where $a$ is a different logistic function for each region (c.f. SI Section 4.7). Since $\epsilon = 0.01$, the values of the regional climate change impact functions as plotted in Fig. 3 are in percents. Economic production for each region is economic productivity times powers of capital stock and labor with constant returns to scale, meaning that the exponents $\omega$ and $\alpha$ in those power add to 1. Consumption is production less investment that accounts for depreciation and the rate of change of capital stock.

Concerning the results plotted in Fig. 3, a summary in Rose et al. (2022) of responses of global GDP to increases in global average temperature in a variety of studies makes a distinction between approaches described as based on "statistical methodologies" and "structural modelling'.' The results presented here fall in the structural category, with the tendency in that category towards "broader adaptation responses." The formulation used here yields less negative impacts of climate change on economic productivity than would be expected if one of several statistical methodology approaches referenced by Rose et al. (2022) were used.

The results listed in Table 1, are for "No Deals," which means no carbon emissions limitations and no SRM. As time progresses, the productivity impacts of climate change eventually become less favorable. However, for the four regions plotted in

**Fig. 2**



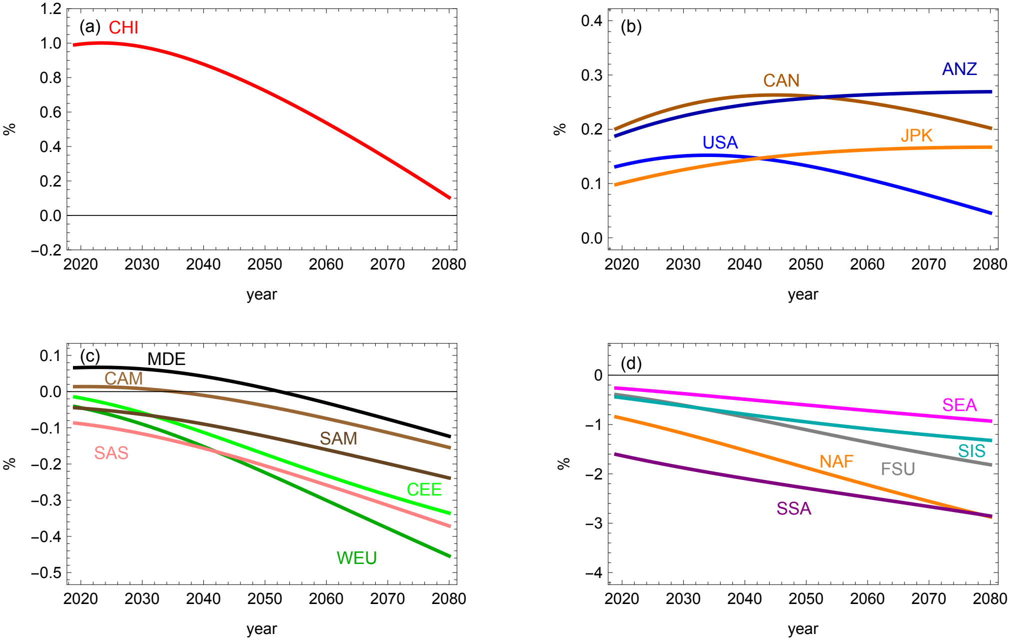
Geographic regions are USA (United States), CAN (Canada), WEU (Western Europe), CEE (Central and Eastern Europe, including Baltic countries), FSU (Former Soviet Union), MDE (Middle East), CAM (Central America), SAM (South America), SAS (South Asian States), SEA (Southeast Asia and Taiwan), CHI (China, Mongolia, and North Korea), NAF (Mediterranean Africa, including Western Sahara), SSA (Non-Mediterranean Africa), and SIS (Small Island States, including Puerto Rico)

Fig. 3b, positive climate change impacts peak respectively in 2034 (for USA), 2045 (for CAN), 2081 (for JPK) and 2090 (for ANZ). All of the other regions have increasingly less positive or more negative impacts after 2023. For the years covered in Table 1, just waiting for the productivity impact climate change to become less favorable by itself produces very little or no computed welfare change incentive for carbon emissions reductions for several regions.

Note that the differences from climate change impacts on computed welfare as viewed from 2037 are about two to four orders of magnitude smaller than the total regional computed welfare without climate change impacts, which are listed in the last rows in the top and bottom halves of Table 1. This observation underlies the decision made here to expand economic impacts of climate change in powers of $\epsilon = 0.01$. With this approach, terms proportional to $\epsilon^0$ describe a background regional economy model calibrated without accounting for anthropogenic climate change, and only terms proportional to $\epsilon^1$ are retained for a description of the economic impacts of anthropogenic climate change.

The next topic addressed here is how accounting for costs of implementing carbon emissions limitations affects the computed welfare results shown in Table 1. First, “Full Global Green Deal” policy options that asymptotically approach zero anthropogenic carbon emissions are compared to an example with SRM only. Then policy options on carbon emissions limitations that do not tend all the way to zero anthropogenic carbon emissions are examined.

**Fig. 3**



Computed “No Deals” differences, from Julian year 1990 to the year on the abscissa, in climate change percent impacts on economic productivity, for the regions described in Fig. 2

**Table 1** No Deals Mperson-yrs Welfare as Viewed from Future Years

| Year/Region | USA | CAN | WEU | JPK | ANZ | CEE | FSU | MDE |
|---|---|---|---|---|---|---|---|---|
| $\Delta\bar{W}$ | | | | | | | | |
| 2025 | 1.5 | 0.58 | -7 | 1.42 | 0.66 | -1.4 | -35 | -3.5 |
| 2031 | 1.3 | 0.57 | -8 | 1.47 | 0.68 | -1.6 | -39 | -4.3 |
| 2037 | 1.0 | 0.56 | -9 | 1.50 | 0.71 | -1.8 | -42 | -5.3 |
| 2043 | 0.7 | 0.53 | -10 | 1.53 | 0.73 | -1.9 | -45 | -6.3 |
| $\bar{W}_0$ | | | | | | | | |
| 2037 (Gperson-yr) | 46 | 6 | 34 | 15 | 5 | 9 | 27 | 53 |
| Year/REgion | CAM | SAM | SAS | SEA | CHI | NAF | SSA | SIS |
| $\Delta\bar{W}$ | | | | | | | | |
| 2025 | -2.5 | -9 | -79 | -49 | 30 | -67 | -1701 | -6.2 |
| 2031 | -2.8 | -10 | -86 | -52 | 20 | -74 | -1874 | -6.7 |
| 2037 | -3.3 | -11 | -95 | -56 | 11 | -80 | -2052 | -7.1 |
| 2043 | -3.8 | -13 | -104 | -60 | 2 | -86 | -2236 | -7.6 |
| $\bar{W}_0$ | | | | | | | | |
| 2037 (Gperson-yr) | 23 | 55 | 239 | 95 | 121 | 34 | 242 | 6 |

**Table 2** Differences from No Deals Mperson-yrs of Welfare

| Type / Region: | USA | CAN | WEU | JPK | ANZ | CEE | FSU | MDE |
|---|---|---|---|---|---|---|---|---|
| Early | -32 | -4.5 | -27 | -15 | -4.3 | -8.5 | -21 | -60 |
| Intermediate | -28 | -4.1 | -24 | -13 | -3.9 | -7.5 | -19 | -54 |
| Late | -24 | -3.5 | -21 | -11 | -3.4 | -6.4 | -16 | -47 |
| Costlier SRM | 1.3 | -1.1 | 2.7 | -2.5 | -1.2 | -1.3 | 9 | 0.7 |
| Cheaper SRM | 1.8 | -0.2 | 4.0 | -0.8 | -0.4 | 0.1 | 15 | 3.9 |
| Free SRM | 2.0 | 0.2 | 4.6 | 0.1 | 0.1 | 0.9 | 18 | 5.6 |

| Type / Region: | CAM | SAM | SAS | SEA | CHI | NAF | SSA | SIS |
|---|---|---|---|---|---|---|---|---|
| Early | -30 | -70 | -357 | -79 | -73 | -19 | -284 | -6.8 |
| Intermediate | -27 | -63 | -321 | -70 | -63 | -17 | -279 | -6.2 |
| Late | -23 | -54 | -276 | -59 | -52 | -14 | -251 | -5.3 |
| Costlier SRM | -4.4 | 0.7 | 21 | 16 | 38 | 21 | 296 | -6.7 |
| Cheaper SRM | 0.8 | 5.1 | 30 | 17 | 39 | 24 | 425 | -1.1 |
| Free SRM | 3.5 | 7.4 | 34 | 18 | 39 | 26 | 490 | 1.8 |

## 3.3 Different Signs of Computed Welfare Impacts with Full Green Deal vs. SRM

The upper three rows for each region Table 2 list changes in computed welfare from the No Deals case respectively for the Early, Intermediate, and Late Green Deals plotted in Fig. 1. (The other solid curves in Fig. 1 are intermediate between the ones labeled "Early" and "Late.") These are influenced by a percentage productivity impact of implementing a fractional carbon emissions limitation $f(t)$ that is modeled as $3.76\omega f^{1.86}$, based on a Congressional Business Office (2009) report, with capital fraction of production $\omega = 0.675$. For simplicity, the same productivity impact formula for what is usually called mitigation was used for all sixteen regions. Use of region-dependent parameters, as in Gazzotti (2019), should not alter the result that all of the Full Green Deal results in Table 1 are negative, unless those parameters gave a result for $f(t)$ enough lower than that for the USA region. In any case, the result for the USA region would still be negative and thus preclude cooperation of that region in a global Full Green Deal if avoiding a decrease in computed welfare compared to No Deals were a deciding factor. All of the computed welfare values from here on are as viewed from Julian year 2031. Accounting for the mitigation cost of Full Green Deal carbon emissions limitations, implementing such limitations leads to a *decrease* in computed welfare for each region. This negative result holds even with the 16 year delay in emissions reductions from the Early to Late Full (and even later) Green Deal cases.

These results suggest asking whether using SRM to accomplish a temperature limitation similar to a Full Green Deal can lead to an increase in computed welfare for all of the geographic regions. The Early Full Green Deal and SRM example in Fig. 1d have a very similar temperature evolution. The lowest three rows for each region in Table 2 list the computed welfare differences between the SRM and No Deals radiative forcing trajectories plotted in Fig. 1c. Cases with SRM are classified here as involving a "deal" in the sense of a global understanding on avoiding interference with SRM deployment, even by countries with capabilities for military interference and/or economic coercion.

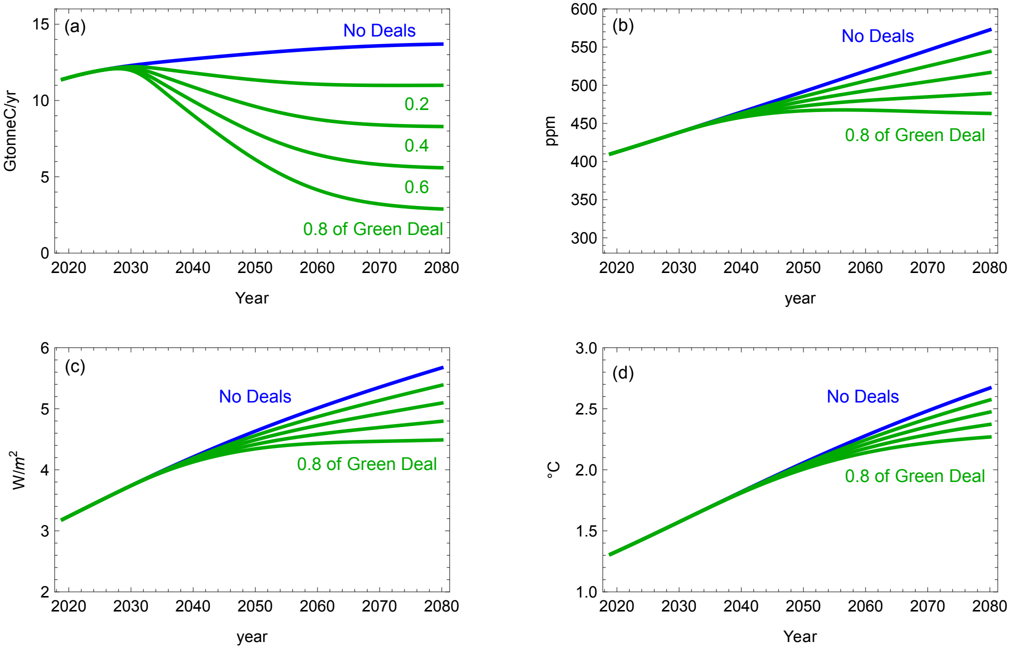
Computed welfare with SRM depends on the choice of results obtained by Laasko et al. (2022) with two different stratospheric microphysics models for estimating the dependence of SRM radiative shielding on the annual rate of injection of sulfur into the stratosphere. For both models, a fit to radiative shielding (the negative of radiative forcing) as a function the sulfur injection rate is $\Delta F = (1 - e^{-S_{\text{SRM}}/S_{\text{ref}}})F_{\text{type}}$. Parameters of this fit for a model referred to as "modal," $F_{\text{type}} = 6.27$ W/m$^2$, lead to more costly SRM than $F_{\text{type}} = 15.55$ for the model referred to as "sectional." (The $F_{\text{type}} = 6.27$ W/m$^2$ is "costlier" because it takes more sulfur injection to get the same temperature limit, not because the cost per MtonneS is different.) If another region bears the full direct cost of implementing SRM to effect the dashed lines in Figures 1c and 1d as in the last sets of rows in Table 2, computed separately for each region alone paying the direct cost of SRM, then the other regions have the uniformly positive cumulative welfare results shown in the last rows of the top and bottom halves of Table 2. The preceding two rows show that there is indeed always another region that can bear that cost alone and still have a positive difference in computed welfare compared to the no SRM outcome. This result holds even using the more costly model fit for $\Delta F$ as a function of stratospheric sulfur injection rate. The failure of Full Green Deals to provide higher computed welfare than SRM suggests examining whether a global Partial Green Deal increases computed welfare without resort to SRM.

### 3.4 Partial Green Deals without and with Empathy

Except for JPK (Japan and South Korea) and ANZ (Australia and New Zealand), all sixteen regions show an increase in computed welfare over the No Green Deal Case with some level of global Partial Green Deal. The Green Deal fractions that produce these maxima are listed in the first rows of numbers for each region in Table 3, with 0 entries for JPK and ANZ. That no Partial Green Deal fractions allow for an increase of computed welfare in all regions compared to No Green Deal raises the question of whether there are other approaches to calculating welfare impacts that would lead to a different conclusion.

Including empathy adds a fraction of all other regions' computed welfare to each region's own computed welfare. Implications of including empathy in computed welfare estimates are illustrated for each region by the second rows of numbers in Table 3. The value $f_{emp,ref}$=0.05 for the USA region is the fraction of year 2020 U.S. GDP allocated for nonmilitary aid to Sub-Saharan Africa, per Haines (2009). Non-military U.S. foreign aid is dominated by aid to Africa, so this result is used as a rough estimate of $f_{emp,ref}$=0.05. Using the equations in SI Section 4.8, the empathy factor for each other region is scaled from that for the USA region by multiplying by the ratio of that region's evolving population increase over year 1820 to that of the USA, and by the ratio, to the power of $\theta$=1.345 from SI Table 4, of the increment per capita GDP over the base value of that region to that of the USA region. That is, the effect of empathy on computed welfare is assumed to be experienced individually per person and more with higher than lower capita income. Thus, in Table 3 the higher per capita income regions have the maximum Green Deal fraction affected more by accounting for empathy than do the lower per capita income regions.

**Fig. 4**



For Green Deal fractions 0 to 0.8 by increments of 0.2: (a) global anthropogenic carbon emissions, (b) $<CO_2>$, (c) total radiative forcing, and (d) $\tau$

## 3.5 Transfer Payments

Even accounting for empathy, the largest uniform global Green Deal fraction consistent with all regions not having a lower computed welfare than with the No Deals outcome is only 0.05. An alternative to having each region pay the full cost of limiting carbon emissions is to have one or more other regions pay for fractions or all of that cost. Adjusting those fractions in increments of ±0.01 to the numbers in Table 3 allowed for a uniform Partial Green Deal fraction of 0.221, with empathy included. For the negative transfer fraction numbers in Table 3, the costs to regions of carbon emissions limitation are multiplied by $(1 + f_{\mathrm{pay}})$, with $f_{\mathrm{pay}}$ from Table 3 for that region. So, for a region with $f_{\mathrm{pay}} < 0$ limiting carbon emissions becomes less costly. Positive numbers in italics in Table 3 are the fractions of the sum of those transfer payments borne by the region for which a positive number is entered. Compared to the maximum global Partial Green Deal fraction of 0.05 in Table 3 without transfer payments, including those payments did increase the maximum global Partial Green Deal fraction. However, as evident from the curve trends in Fig. 4, a global Partial Green Deal fraction of 0.221 is not enough to nearly stabilize the computed global average temperature in the twenty-first century.

The specific results concerning transfer payments that are shown in Table 3 follow from the use of a common formula for impacts of emissions limitation mitigation for

**Table 3** Maximum Green Deal Fractions without and with Transfer Payments

| $f_{emp,ref}$ / Region: | USA | CAN | WEU | JPK | ANZ | CEE | FSU | MDE |
|---|---|---|---|---|---|---|---|---|
| 0 | 0.02 | 0.02 | 0.05 | 0 | 0 | 0.03 | 0.22 | 0.03 |
| 0.05 | 0.17 | 0.13 | 0.12 | 0.07 | 0.13 | 0.11 | 0.21 | 0.07 |
| 0.05 | 0.221 | 0.221 | 0.221 | 0.221 | 0.221 | 0.221 | 0.221 | 0.221 |
| *Transfer Fraction:* | 0.57 | 0 | -0.12 | -0.63 | 0 | -0.31 | 0 | -0.63 |
| 0.05 | 0.215 | 0.215 | 0.215 | 0.215 | 0.215 | 0.215 | 0.215 | 0.215 |
| *Transfer Fraction:* | *0.57* | *0* | *-0.14* | **0** | *0* | *-0.32* | *0* | *-0.64* |

| $f_{emp,ref}$ / Region: | CAM | SAM | SAS | SEA | CHI | NAF | SSA | SIS |
|---|---|---|---|---|---|---|---|---|
| 0 | 0.03 | 0.03 | 0.04 | 0.07 | 0.15 | 0.28 | 0.37 | 0.08 |
| 0.05 | 0.05 | 0.05 | 0.05 | 0.15 | 0.18 | 0.27 | 0.37 | 0.10 |
| 0.05 | 0.221 | 0.221 | 0.221 | 0.221 | 0.221 | 0.221 | 0.221 | 0.221 |
| *Transfer Fraction:* | *-0.76* | *-0.73* | *-0.70* | *0* | *0.40* | *0.03* | *-1* | *-0.48* |
| 0.05 | 0.215 | 0.215 | 0.215 | 0.215 | 0.215 | 0.215 | 0.215 | 0.215 |
| *Transfer Fraction:* | *-0.76* | *-0.74* | *-0.72* | *-0.01* | *0.40* | *0.03* | *-1* | *-0.49* |

all sixteen regions. How those results, and the associated maximum Partial Green Deal fraction that allows all regions an increase of computed welfare compared to No Deals, would change with such formulas being region dependent could readily be explored with a simple modification of the model; but that is beyond the scope of the work reported here.

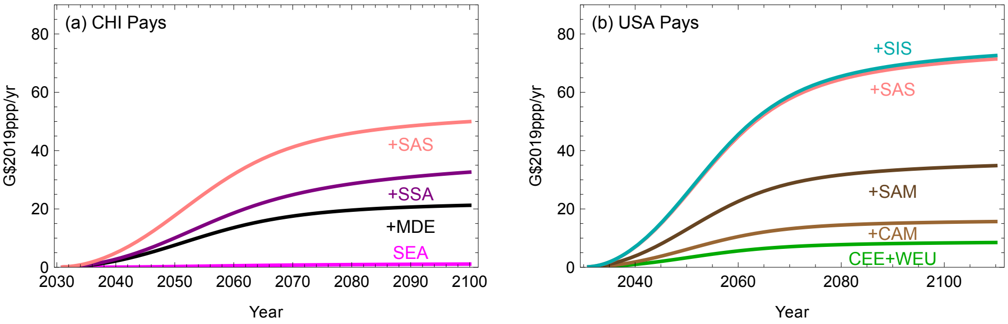
## 3.6 Not all Regions Agree to Partial Green Deal Carbon Emissions Limits

Rather than seeking a globally uniform partial Green Deal fraction, another possibility is to allow for one or more regions to avoid carbon emissions limitations, subject only to an agreement not to increase those emissions above their extrapolated No Deals values. For the rows of numbers just above double lines in Table 3, the JPK region keeps to that agreement without further carbon emissions limitations but does not receive any transfer payment. Then all other regions still have higher welfare than with No Deals up to Partial Green Deal fractions of 0.215. Fig. 5 shows an example of how transfer payments from the CHI and USA region could be divided amongst recipients for the "not Global" case where the JPK region neither limits its carbon emissions to below its No Deals extrapolated amounts nor receives transfer payments. That illustrates a case where not all regions need to participate adopt the same Partial Green Deal emissions limit, but it only slightly changes the overall outcome. These results suggest a more detailed examination of alternatives with one or more regions paying for the direct cost of SRM.

## 3.7 SRM for Global Average Temperature Reduction

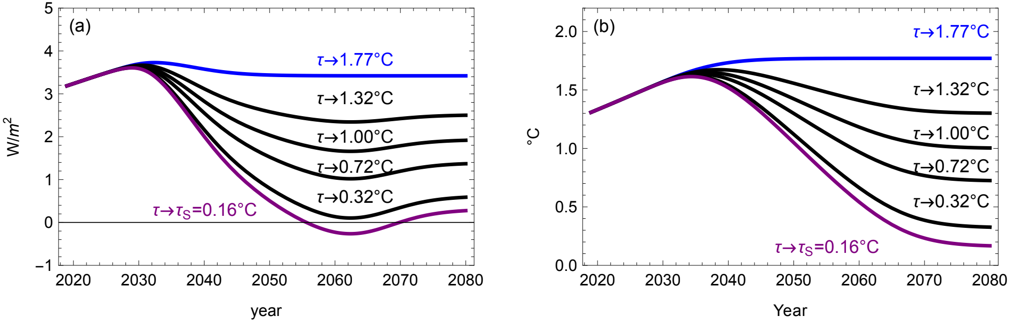
Fig. 6 plots results from use of SRM to stabilize $\tau$ or reduce it. The temperatures listed are for Julian year 2100. In descending order, the year 2100 temperatures in the intermediate curves correspond approximately to fits to historical data for 2019, 2005,

**Fig. 5**



Transfer payments for a Partial Green Deal without the JPK region: (a) from the CHI region, and (b) from the USA regions. Lowest curves are transfer payments. Differences between curves are transfer payments to the indicated recipient regions. Transfer payments from North Africa (NAF) are to the rest of Africa (SSA).

**Fig. 6**



Results with six levels of SRM, with notes for values of in Julian year 2100 of a) total radiative forcing and (b) $\tau$

1990, and 1946. The lowermost curve brings $\tau$ to the level $\tau_S = 0.16°\text{C}$ that stabilizes sea level with the model described in SI Section 4.5.

With the Southeast Asia (SEA) region paying for the less costly of the two models of SRM introduced above and no empathy, there are six regions that have computed welfare that is still increasing with lower long-term temperature even as low as $\tau_S$. Those are South America (SAM), South Asian States (SAS), Southeast Asia (SEA), North Africa (NAF), Non-Mediterranean Africa (SSA), and Small Island States (SIS). All of the other regions have computed welfare maximized at a higher long-term limit for $\tau$. Of those, the region that has the largest loss of computed welfare associated with cooling to well below its computed welfare maximizing temperature is CHI. With empathy accounted for as above, to the above list or regions with computed welfare increasing with decreasing long-term temperature at $\tau = \tau_S$ are added USA, WEU,

**Table 4** Year 2100 $\tau$(°C) Depending on SRM Payer

| Less costly SRM | Without Empathy | With Empathy |
|---|---|---|
| CHI alone | 1.55 | 1.07 |
| SEA alone | $\tau_S$ | $\tau_S$ |
| Costlier SRM | Without Empathy | With Empathy |
| CHI alone | 1.59 | 1.09 |
| SEA alone | 0.62 | 0.41 |
| CHI instead of SEA | 1.26 | 0.98 |
| SAS and SEA | 0.58 | 0.39 |
| CHI instead of SAS and SEA | 1.01 | 0.71 |

ANZ, and CEE. Those changes are primarily because of empathy with the SSA region in Africa.

With empathy, welfare for the CHI region with it paying for the direct cost of implementing SRM is maximized with a year 2100 $\tau$ of 1.04°C. The first row of numbers in Table 5 indicate that the CHI region has maximum computed welfare with a year 2100 temperature above 1°C even if that region pays for the direct cost of SRM. If the SEA region were to pay for enough SRM to reduce $\tau$ to $\tau_S = 0.16$°C, then the computed welfare of the CHI region would be lower. These observations raise the question of whether the CHI region might want to propose alternatives that would lead to a higher long-term temperature limit than $\tau \to \tau_S$.

## 3.8 Preempting Global Cooling by a Low Latitude Region

Table 4 lists somewhat higher than $\tau_S$ results for year 2100 values of $\tau$ with the CHI region paying for implementing SRM to bring that limit just enough for the SEA region to have the same computed welfare as it would for the implementing SRM itself to reduce global average temperature to maximize its own computed welfare.

Costlier SRM deprives the SEA region of some of its leverage to get the CHI region to agree to a low long-term limit $\tau$ while paying for SRM implementation. That can be compensated for by cooperation with the SAS region, even though the SAS region pays only 8.7% of the cost of SRM implementation without empathy or 7.1% with empathy. The long-term temperature limit that the CHI region accepts and implements gives the same computed welfare for the SSA region and a higher computed welfare for the SEA region than if SSA and SEA implemented and jointly paid for SRM to get a lower year 2100 temperature, with the result in the last row of numbers in Table 4.

These observations still leave open the question of whether SRM might be used transitorily before a later program of carbon emissions limitations replaces SRM. For the final example here, it suffices here to investigate this question with the costlier SRM model. That is because a negative answer to this question with costlier SRM would necessarily be followed by a negative answer with less costly SRM.

### 3.9 Temporary SRM

The costs of limiting carbon emissions could be put off into a more heavily discounted future by using SRM only temporarily to limit global average temperature, as discussed by MacMartin et al. (2018). This raises the question of whether computed welfare could be increased by eventually substituting carbon emissions limitation for SRM. For and example of this, the time scale for approach to zero carbon emissions is increased by 30 years. However, the delay in emissions reductions allows for more accumulation of $CO_2$ in the atmosphere. Some of that is removed by direct carbon capture and sequestration in order the maintain the same temperature while reducing the MtonneS/yr of SRM. That is done here by setting the Green Deal Fraction parameters $f$ for each region to 0.0456 more than 1. This results in net $CO_2$ removal from atmosphere and upper ocean equilibration starting in Julian year 2095. Without empathy, the resulting difference in Mperson-years of computed welfare results compared to the uppermost curve in Fig. 6b that yields temperature stabilization ranges from -4 for the ANZ region to -26 for USA, -85 for CHI, -305 for SAS, and -641 for SSA. With $f_{\mathrm{emp,ref}} = 0.05$, that range includes -7 for ANZ, -29 for USA, -173 for CHI, -323 for SAS, and -643 for SSA. Note that all of the results are negative, meaning that continuing with SRM results in a higher computed welfare for all regions. This is but one example of possible approaches to phasing out SRM, but it does illustrate one approach to addressing the question of whether a region that had started SRM would find a way to stop it without ending up with a lower computed welfare. The answer to that question in this very specific context is: no.

# 4 Discussion

Before discussing some of the questions addressed in connection with the above results, it is important to re-emphasize that the point of this particular exercise is to highlight those questions, not to attempt to provide answers. The reason for this caveat is that the model used has both limited complexity and that the above examples all use a set of input parameters, some of the values of which some are substantially uncertain. Here are some of those questions. In each case, answering each of these questions in the affirmative could be challenging.

4.1. Is it to be expected that waiting for a decade or two for negative impacts of climate change on productivity to become more imminent will be sufficient to then prompt a global launch on a path to zero net carbon emissions?

4.2. Are there no significant costs and/or dangers of stratospheric sulfur injection in addition to direct costs of deployment that will interfere with it becoming an alternative to greenhouse gas emission limitations as a path towards stabilizing global average temperature?

4.3. Is it to be expected that a sizable set of decision makers will all decide on carbon emissions limitations that substantially limit global average temperature increases if they each separately try to maximize their own welfare without placing a value on the welfare of other countries and regions?

4.4. Are transfer payments to cover part of the costs of carbon emissions limitation a technically and politically feasible mechanism for increasing the achievable level of

such limitations without resorting to solar radiation management?
4.5. Is there a viable incentive for some countries or regions to implement substantial limits on carbon emissions while others do little or nothing in that regard?
4.6. If one country or region implements stratospheric sulfur injection unilaterally (or in cooperation with a limited number of others), is there a globally acceptable trajectory of future global average temperature?
4.7. If one or more regions have an incentive to substantially reduce global average temperature via solar radiation management, what would be practicable incentives from others to forestall unwanted temperature reductions, and could an agreement on that be implemented?
4.8. Once implemented, is it likely that solar radiation management would later be terminated in favor of an approach that includes more substantial limitations on greenhouse gas emissions?

These questions are generally not new ones. Many have been discussed, some extensively, in existing literature, but they are all highlighted here together in the context of an integrated quantitative framework. Results from the exercises described above suggest that a particularly poignant outstanding question is whether solar radiation management will actually be used. Highlighting this question is in no way to either endorse the eventual use of SRM nor any particular approach to research directions that either further pursue or avoid it. One conceivably problematic aspect of possible future use of SRM became apparent when examining the results in Table 4 above. That is, the lower the apparent global average temperature goal of one or more regions using SRM, the more incentive there could be for adversely affected regions to interfere with SRM to reduce some negative impacts of global cooling, as discussed by Abatayo et al. (2020). This observation adds to other potential economic impacts of implementing SRM, e.g. as in Robock (2050), that are not included here because they remain difficult to quantify. As work on that proceeds, the model used here may provide a basis for one useful framework for incorporating its results into an integrated assessment analysis.

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## Author Contributions and Supplemental Information

CD and SK contributed respectively to computations used in preparing for and checking this work. CS originated, calibrated, programmed, and executed the model. RS consulted on design, performed literature review, and worked on revision of the manuscript. Other than this page, this report is as written in January of 2024.

A companion report entitled "Climate Action Game Experiment v.100 Code Design and Parameters" https://acdis.illinois.edu/sites/default/files/2025-03/CAGE%20Code%20Design%20and%20Parameters%202025%20%282%29.pdf by CS documents everything needed to reproduce the results herein except for the SAS and SEA row in Table 4, which used the percentage numbers in the second paragraph of Section 3.8.