# ONLINE APPENDIX

# Relative Prices and Climate Policy:

## How the Scarcity of Non-Market Goods Drives Policy Evaluation

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**Abstract:** Climate change not only impacts production and market consumption, but also the relative scarcity of non-market goods, such as environmental amenities. We study fundamental drivers of the resulting relative price changes, their potential magnitude, and their implications for climate policy in Nordhaus's DICE model, thereby addressing one of its key criticisms. We propose plausible ranges for these relative prices changes based on best available evidence. Our central calibration reveals that accounting for relative prices is equivalent to decreasing pure time preference by 0.6 percentage points and leads to a more than 50 percent higher social cost of carbon.

**JEL-Classifications:** Q01, Q54, H43, D61, D90

**Keywords:** Climate policy, discounting, non-market goods, social cost of carbon, substitutability

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## A.1 Derivation of the relative price effect

To derive the relative price effect of non-market goods, $RPE_t = \frac{d}{dt}\left(\frac{U_{E_t}}{U_{c_t}}\right)\left(\frac{U_{E_t}}{U_{c_t}}\right)^{-1}$ (Equation 4), we first compute marginal utilities with respect to the two goods for utility function (2):

$$U_{E_t} = \alpha(E_t - \overline{E})^{\theta-1}\left[\alpha(E_t - \overline{E})^{\theta} + (1-\alpha)c_t^{\theta}\right]^{\frac{1-\eta-\theta}{\theta}} \tag{A.1}$$

$$U_{c_t} = (1-\alpha)c_t^{\theta-1}\left[\alpha(E_t - \overline{E})^{\theta} + (1-\alpha)c_t^{\theta}\right]^{\frac{1-\eta-\theta}{\theta}}. \tag{A.2}$$

We thus have

$$\frac{U_{E_t}}{U_{c_t}} = \frac{\alpha}{(1-\alpha)}\left(\frac{E_t - \overline{E}}{c_t}\right)^{\theta-1} \tag{A.3}$$

The time derivative of this marginal rate of substitution is given by:

$$\frac{d}{dt}\left(\frac{U_{E_t}}{U_{c_t}}\right) = (\theta-1)\frac{\alpha}{(1-\alpha)}\left(\frac{E_t - \overline{E}}{c_t}\right)^{\theta-2}\left[\frac{\dot{E}_t}{c_t} - \frac{(E_t - \overline{E})\dot{c}_t}{{c_t}^2}\right] \tag{A.4}$$

With the growth rates $g_i$ of the two goods $i \in (E, c)$ defined as $g_{i_t} = \frac{\dot{i}_t}{i_t}$, we can rewrite this time derivative using $\dot{i}_t = g_{i_t} i_t$ as:

$$\begin{aligned}\frac{d}{dt}\left(\frac{U_{E_t}}{U_{c_t}}\right) &= \frac{\alpha}{(1-\alpha)}\left(\frac{E_t - \overline{E}}{c_t}\right)^{\theta-1}(\theta-1)\left(\frac{c_t}{E_t - \overline{E}}\right)\left[\frac{g_{E_t}E_t}{c_t} - \frac{(E_t - \overline{E})g_{c_t}c_t}{{c_t}^2}\right] \\ &= (1-\theta)\frac{\alpha}{(1-\alpha)}\left(\frac{E_t - \overline{E}}{c_t}\right)^{\theta-1}\left[g_{c_t} - \frac{E_t}{E_t - \overline{E}}g_{E_t}\right].\end{aligned} \tag{A.5}$$

The relative price effect of non-market goods is therefore given by

$$RPE_t = \frac{\frac{d}{dt}\left(\frac{U_{E_t}}{U_{c_t}}\right)}{\left(\frac{U_{E_t}}{U_{c_t}}\right)} = (1-\theta)\left[g_{c_t} - \frac{E_t}{E_t - \overline{E}}g_{E_t}\right]. \tag{A.6}$$

The relative price effect of non-market goods, i.e. the change in relative prices over time, is thus the same as the difference in the two good-specific discount rates (see Weikard and Zhu (2005) or Drupp (2018) for derivations in continuous time).

## A.2 Calibration of non-market damages

### A.2.1 Calibration for Section 3

In Section 3, we replicate the analysis of Sterner and Persson (2008) in DICE-2016R2. Thus, we do not consider a subsistence requirement in the consumption of non-market goods. The non-market good climate damage coefficient $\psi$ is calibrated for a temperature increase of $T = 3°\text{C}$ as follows:

$$W_0\Big(E_0, (1-D_0^{\phi})C_0, L_0\Big) = W_0\Big((1-D_0^{\psi})E_0, (1-D_0^{\kappa})C_0, L_0\Big) \quad \Leftrightarrow \tag{A.7}$$

$$\alpha E_0^{\theta} + (1-\alpha)\Big((1-D_0^{\phi})C_0\Big)^{\theta} = \alpha\Big(\frac{E_0}{1+\psi T^2}\Big)^{\theta} + (1-\alpha)\Big((1-D_0^{\kappa})C_0\Big)^{\theta}$$

We can solve this for the non-market climate damage parameter $\psi$ as follows:

$$\psi = \left[E_0\left(E_0^{\theta} + \frac{1-\alpha}{\alpha}\left(\Big((1-D_0^{\phi})C_0\Big)^{\theta} - \Big((1-D_0^{\kappa})C_0\Big)^{\theta}\right)\right)^{-\frac{1}{\theta}} - 1\right]T^{-2}. \tag{A.8}$$

Sterner and Persson (2008) assume that the initial amount of the non-market good is equal to the starting value for material consumption, i.e. $C_0 = E_0$. In this case equation (A.8) reduces to

$$\psi = \frac{1}{T^2}\left[\left(\frac{1-\alpha}{\alpha}(1-D_0^{\phi})^{\theta} + 1 - \frac{1-\alpha}{\alpha}(1-D_0^{\kappa})^{\theta}\right)^{-\frac{1}{\theta}} - 1\right]. \tag{A.9}$$

### A.2.2 Calibration for Sections 4 and 5

In the presence of a subsistence requirement in the consumption of non-market goods the calibration is modified as follows:

$$W_0\Big(E_0, (1-D_0^{\phi})C_0, L_0\Big) = W_0\Big((1-D_0^{\psi})E_0, (1-D_0^{\kappa})C_0, L_0\Big) \quad \Leftrightarrow \tag{A.10}$$

$$\alpha\left(E_0 - \overline{E}\right)^{\theta} + (1-\alpha)\Big((1-D_0^{\phi})C_0\Big)^{\theta} = \alpha\Big(\frac{E_0}{1+\psi T^2} - \overline{E}\Big)^{\theta} + (1-\alpha)\Big((1-D_0^{\kappa})C_0\Big)^{\theta}$$

We can solve this for the non-market climate damage parameter $\psi$ as follows:

$$\psi = \left[E_0\left(\overline{E} + \left[\left(E_0 - \overline{E}\right)^{\theta} + \frac{1-\alpha}{\alpha}\left(\Big((1-D_0^{\phi})C_0\Big)^{\theta} - \Big((1-D_0^{\kappa})C_0\Big)^{\theta}\right)\right]^{\frac{1}{\theta}}\right)^{-1} - 1\right]T^{-2}. \tag{A.11}$$

## A.3 Relative prices and comparison of climate policy paths until 2300, with 100% additional non-market damages as in Sterner and Persson (2008)

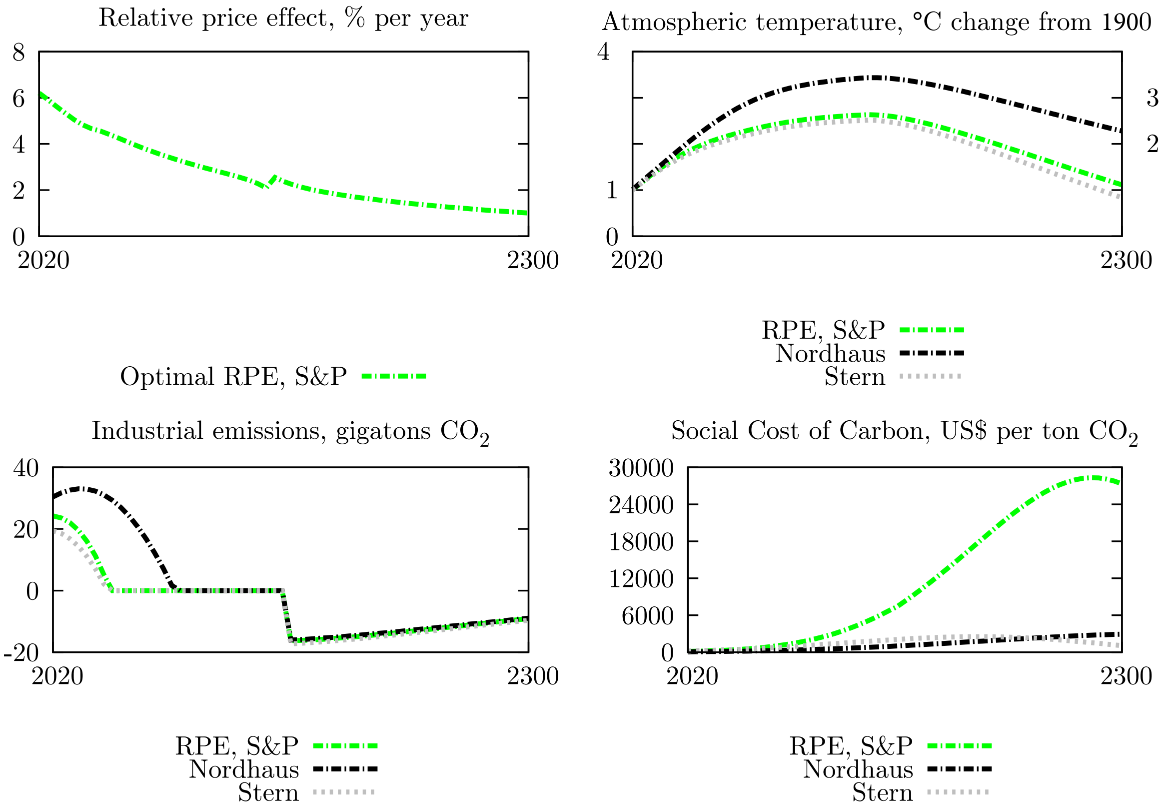


Figure A.1: Relative price effect (*RPE*) and comparison of climate policy paths for a time horizon up to 2300 and 100% additional non-market damages. Otherwise, see description of Figure 1.

## A.4 Re-calibration of the model

### (1) Derivation of $\eta_C$

We make use of Equations 2 and Equation 8 with $\overline{E} = 0$ to recalibrate the effective elasticity of marginal utility of market consumption, $\eta_C$, such that the model with relative prices yields the same paths of market consumption and investments as the standard DICE version. We have

$$U = \frac{1}{1-\eta}\left[\alpha\left(E_t - \overline{E}\right)^{\theta} + (1-\alpha)\, c_t^{\theta}\right]^{\frac{1-\eta}{\theta}}, \tag{A.12}$$

$$U_C = (1-\alpha)c_t^{\theta-1}\left[\alpha\left(E_t - \overline{E}\right)^{\theta} + (1-\alpha)\, c_t^{\theta}\right]^{\frac{1-\eta-\theta}{\theta}}, \tag{A.13}$$

$$\begin{aligned} U_{CC} &= (1-\alpha)c^{\theta-1}\frac{1}{c}(\theta-1)\left[\alpha\left(E_t - \overline{E}\right)^{\theta} + (1-\alpha)c_t^{\theta}\right]^{\frac{1-\eta-\theta}{\theta}} \qquad (A.14)\\ &+ (1-\alpha)c^{\theta-1}\left[\alpha\left(E_t - \overline{E}\right)^{\theta} + (1-\alpha)\, c_t^{\theta}\right]^{\frac{1-\eta-\theta}{\theta}}\frac{(1-\alpha)c^{\theta-1}}{\alpha E^{\theta} + (1-\alpha)c^{\theta}}(1-\eta-\theta)\\ &= (1-\alpha)c^{\theta-1}c^{-1}\left[\alpha\left(E_t - \overline{E}\right)^{\theta} + (1-\alpha)\, c_t^{\theta}\right]^{\frac{1-\eta-\theta}{\theta}} \times \qquad (A.15)\\ &\left[(\theta-1) + (1-\eta-\theta)\frac{(1-\alpha)c^{\theta}}{\alpha\left(E_t - \overline{E}\right)^{\theta} + (1-\alpha)\, c_t^{\theta}}\right] \end{aligned}$$

Combining these ingredients yields the effective elasticity of marginal utility of market consumption, $\eta_C$, as

$$\eta_C = -\frac{U_{cc}c}{U_c} = (1-\theta) - (1-\eta-\theta)\,\frac{(1-\alpha)c_t^{\theta}}{\alpha\left(E_t - \overline{E}\right)^{\theta} + (1-\alpha)c_t^{\theta}}. \tag{A.16}$$

Defining the value share of the consumption good as $\beta^* = \frac{(1-\alpha)c_t^{\theta}}{\alpha\left(E_t-\overline{E}\right)^{\theta}+(1-\alpha)c_t^{\theta}}$, (cf. Gerlagh and van der Zwaan (2002), Hoel and Sterner (2007), Traeger (2011)), this can be rewritten as

$$\eta_C = \beta^*\eta + (1-\beta^*)(1-\theta) \tag{A.17}$$

That is, when the full value share accrues to market consumption goods, the effective elasticity of marginal utility of market consumption, $\eta_C$, equals the overall elasticity of marginal utility, $\eta$. Yet, as soon as non-market goods have a positive value share, the degree of substitutability matters for the effective elasticity of marginal utility of market consumption.

### (2) Time-path of $\eta(t)$ used for re-calibration

| $\theta = -1$ (left column) | | $\theta = 1$ (right column) | |
|---|---|---|---|
| 0 | 1.388889 | 0 | 1.611111 |
| 1 | 1.399128 | 1 | 1.584113 |
| 2 | 1.407008 | 2 | 1.563337 |
| 3 | 1.413283 | 3 | 1.546792 |
| 4 | 1.418342 | 4 | 1.533453 |
| 5 | 1.422468 | 5 | 1.522575 |
| 6 | 1.425869 | 6 | 1.513609 |
| 7 | 1.428699 | 7 | 1.506148 |
| 8 | 1.431075 | 8 | 1.499881 |
| 9 | 1.433088 | 9 | 1.494575 |
| 10 | 1.434805 | 10 | 1.490046 |
| 11 | 1.436281 | 11 | 1.486154 |
| 12 | 1.437558 | 12 | 1.482786 |
| 13 | 1.438670 | 13 | 1.479854 |
| 14 | 1.439644 | 14 | 1.477285 |
| 15 | 1.440501 | 15 | 1.475023 |
| 16 | 1.441261 | 16 | 1.473020 |
| 17 | 1.441937 | 17 | 1.471237 |
| 18 | 1.442543 | 18 | 1.469638 |
| 19 | 1.443090 | 19 | 1.468192 |
| 20 | 1.443587 | 20 | 1.466877 |
| 21 | 1.444036 | 21 | 1.465682 |
| 22 | 1.444443 | 22 | 1.464596 |
| 23 | 1.444813 | 23 | 1.463606 |
| 24 | 1.445148 | 24 | 1.462703 |
| 25 | 1.445452 | 25 | 1.461880 |
| 26 | 1.445729 | 26 | 1.461127 |
| 27 | 1.445982 | 27 | 1.460439 |
| 28 | 1.446211 | 28 | 1.459812 |
| 29 | 1.446423 | 29 | 1.459230 |
| 30 | 1.446618 | 30 | 1.458691 |
| 31 | 1.446798 | 31 | 1.458192 |
| 32 | 1.446965 | 32 | 1.457731 |
| 33 | 1.447119 | 33 | 1.457305 |

| | | | |
|---|---|---|---|
| 34 | 1.447261 | 34 | 1.456910 |
| 35 | 1.447393 | 35 | 1.456544 |
| 36 | 1.447515 | 36 | 1.456205 |
| 37 | 1.447629 | 37 | 1.455891 |
| 38 | 1.447735 | 38 | 1.455600 |
| 39 | 1.447833 | 39 | 1.455330 |
| 40 | 1.447925 | 40 | 1.455078 |
| 41 | 1.448011 | 41 | 1.454845 |
| 42 | 1.448091 | 42 | 1.454627 |
| 43 | 1.448166 | 43 | 1.454424 |
| 44 | 1.448237 | 44 | 1.454235 |
| 45 | 1.448303 | 45 | 1.454059 |
| 46 | 1.448365 | 46 | 1.453894 |
| 47 | 1.448423 | 47 | 1.453739 |
| 48 | 1.448478 | 48 | 1.453595 |
| 49 | 1.448530 | 49 | 1.453459 |
| 50 | 1.448579 | 50 | 1.453333 |
| 51 | 1.448625 | 51 | 1.453214 |
| 52 | 1.448668 | 52 | 1.453102 |
| 53 | 1.448710 | 53 | 1.452996 |
| 54 | 1.448749 | 54 | 1.452897 |
| 55 | 1.448786 | 55 | 1.452804 |
| 56 | 1.448821 | 56 | 1.452716 |
| 57 | 1.448855 | 57 | 1.452633 |
| 58 | 1.448887 | 58 | 1.452555 |
| 59 | 1.448917 | 59 | 1.452481 |
| 60 | 1.448946 | 60 | 1.452411 |
| 61 | 1.448973 | 61 | 1.452345 |
| 62 | 1.449000 | 62 | 1.452282 |
| 63 | 1.449025 | 63 | 1.452222 |
| 64 | 1.449048 | 64 | 1.452166 |
| 65 | 1.449071 | 65 | 1.452112 |
| 66 | 1.449093 | 66 | 1.452061 |
| 67 | 1.449114 | 67 | 1.452013 |
| 68 | 1.449134 | 68 | 1.451967 |
| 69 | 1.449153 | 69 | 1.451923 |

| | | | |
|---|---|---|---|
| 70 | 1.449171 | 70 | 1.451881 |
| 71 | 1.449188 | 71 | 1.451841 |
| 72 | 1.449205 | 72 | 1.451803 |
| 73 | 1.449221 | 73 | 1.451767 |
| 74 | 1.449236 | 74 | 1.451732 |
| 75 | 1.449251 | 75 | 1.451699 |
| 76 | 1.449265 | 76 | 1.451668 |
| 77 | 1.449278 | 77 | 1.451638 |
| 78 | 1.449291 | 78 | 1.451609 |
| 79 | 1.449303 | 79 | 1.451581 |
| 80 | 1.449315 | 80 | 1.451555 |
| 81 | 1.449327 | 81 | 1.451530 |
| 82 | 1.449337 | 82 | 1.451505 |
| 83 | 1.449348 | 83 | 1.451482 |
| 84 | 1.449358 | 84 | 1.451460 |
| 85 | 1.449367 | 85 | 1.451439 |
| 86 | 1.449377 | 86 | 1.451418 |
| 87 | 1.449386 | 87 | 1.451398 |
| 88 | 1.449394 | 88 | 1.451379 |
| 89 | 1.449402 | 89 | 1.451361 |
| 90 | 1.449410 | 90 | 1.451343 |
| 91 | 1.449418 | 91 | 1.451325 |
| 92 | 1.449426 | 92 | 1.451308 |
| 93 | 1.449435 | 93 | 1.451289 |
| 94 | 1.449443 | 94 | 1.451270 |
| 95 | 1.449453 | 95 | 1.451247 |
| 96 | 1.449466 | 96 | 1.451219 |
| 97 | 1.449483 | 97 | 1.451181 |
| 98 | 1.449508 | 98 | 1.451123 |
| 99 | 1.449552 | 99 | 1.451024 |
| 100 | 1.449493; | 100 | 1.451158; |

**(3) Figure 2 with re-calibrated $\eta(t)$**

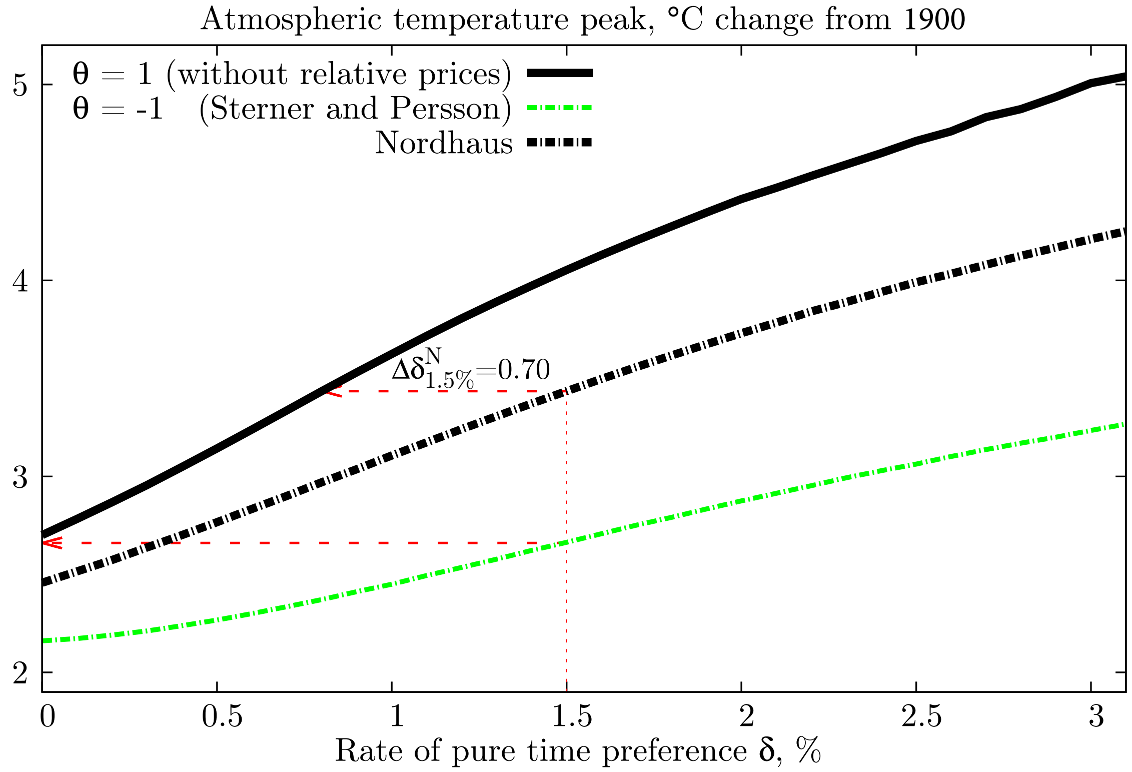


Figure A.2: The comparative influence of introducing relative prices on peak temperature with re-calibrated elasticity of marginal utility. The Figure depicts peak temperature as a function of the rate of pure time preference, $\delta$, for different degrees of substitutability, $\theta$. The solid black line shows the comparison case of perfect substitutability, i.e. without relative prices. The green line depicts the substitutability assumption of Sterner and Persson, with $\theta = -1$, and the dashed black line the 'Nordhaus' case. A model run with relative prices is compared to a run without but with a higher $\delta$ such that peak temperature is the same across both runs.

## A.5 Relative prices and comparison of climate policy paths until 2100, with 25% additional non-market damages as in the standard DICE-2016R2

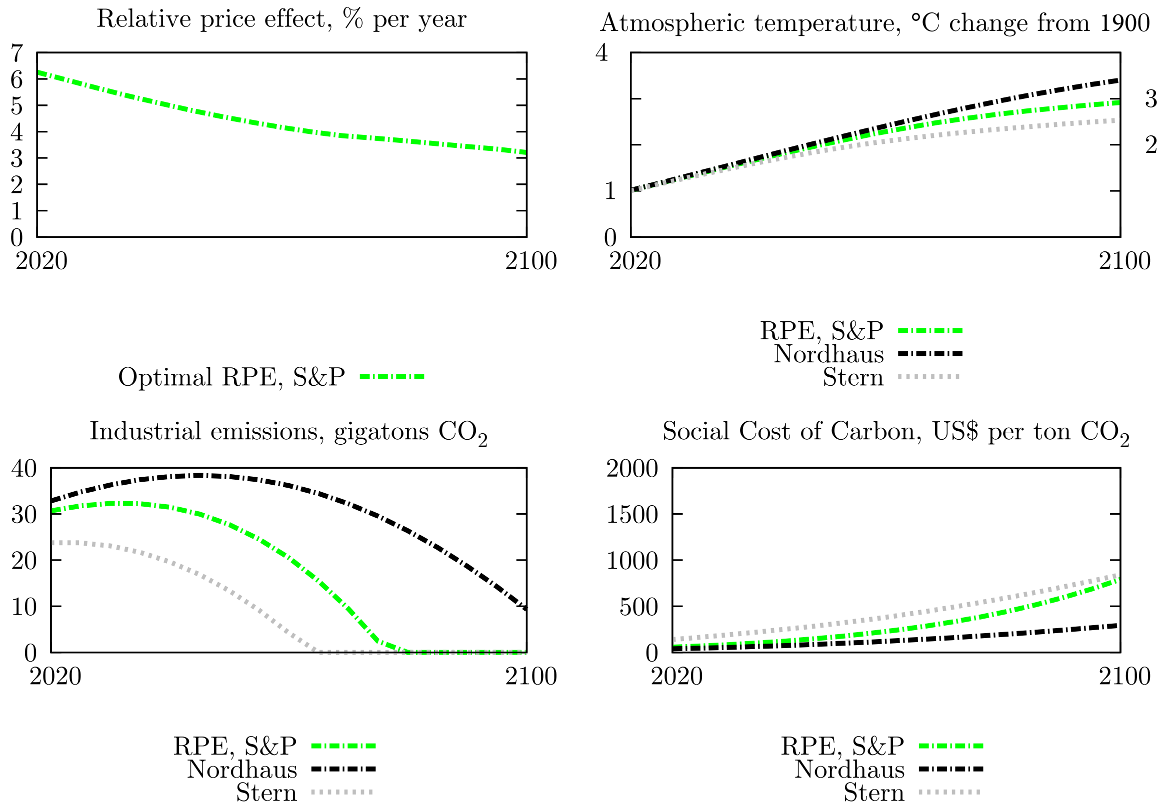


Figure A.3: Relative price effect (*RPE*) and comparison of climate policy paths for a time horizon up to 2100 and 25% additional non-market damages.

## A.6 Relative prices, substitutability and the equivalent reduction in pure time preference

Table A.1: Degree of substitutability ($\theta$) and the corresponding *RPE's* equivalent effect in terms of a reduction of pure time preference ($\Delta\delta$)*

| $\theta_i$ | $\Delta\delta_{1.5\%}^{\theta_i}$ | Reference or relation |
|---|---|---|
| 1 | 0 | Perfect substitutes |
| 0.8 | 0.05 | |
| 0.6 | 0.12 | Drupp (2018) |
| 0.4 | 0.18 | |
| 0.2 | 0.4 | |
| 0 | 0.6 | Cobb-Douglas, Gollier (2010) |
| -0.2 | 0.85 | |
| -0.333 | 1.01 | Kopp et al. (2012) |
| -0.4 | 1.09 | |
| -0.66 | 1.4 | Equivalent to Stern's (2007) lower $\delta$ |
| -0.78 | 1.5 | |
| -1 | not defined | Sterner and Persson (2008) |
| -2.3 | not defined | Lowest indirect empirical estimates |

* This analysis is conducted without our replication of Sterner and Persson (2008).

## A.7 Additional drivers of the relative price effect: Initial value of non-market goods and share of non-market goods in utility

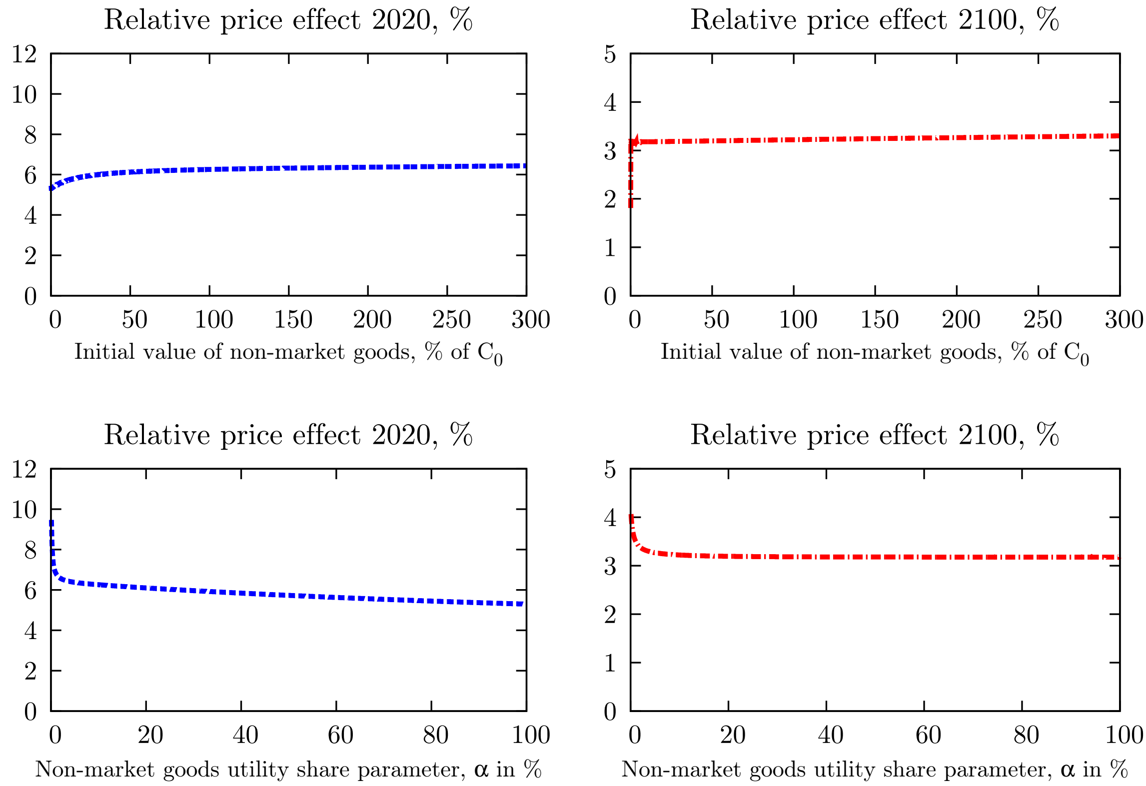


Figure A.4: Additional drivers of the relative price effect (I). Top to bottom: The impact of the initial value of non-market goods and the share of non-market goods in utility on the *RPE* in 2020 (left) and in 2100 (right).

## A.8 Empirical estimates of the substitutability parameter

Table A.2: Indirect empirical estimates of the substitutability parameter*

| Study | Mean $\theta$ | Type of good |
|---|---|---|
| Alberini et al. (2018) | 0.46 | Environmental goods: Climate change mitigation |
| Alberini et al. (2006) | 0.53 | Reduction in mortality risk |
| Aldy et al. (1999) | 0.58 | Environmental goods: Nature conservation |
| Ara and Tekesin (2016) | 0.43 | Health improvements |
| Ara and Tekesin (2017) | 0.10 | Health improvements |
| Barbier et al. (2017) | 0.74 | Environmental goods: Water or air quality |
| Basili et al. (2006) | 0.58 | Environmental goods: Water or air quality |
| Broberg (2010) | 0.75 | Environmental goods: Nature conservation |
| Clark and Kahn (1988) | 0.10 | Cultural goods |
| Cuevas-Alvarado et al. (2016) | 0.73 | Environmental goods: All others |
| Czajkowski et al. (2017) | 0.72 | Environmental goods: Water or air quality |
| Czajkowski and Scasny (2010) | 0.36 | Environmental goods: Water or air quality |
| Dickie (2005) | 0.86 | Health improvements |
| Doucouliagos et al. (2014) | 0.48 | Reduction in mortality risk |
| Francisco (2015) | 0.52 | Environmental goods: Water or air quality |
| Hammitt et al. (2019) | -2.00 | Reduction in mortality risk |
| Hammitt and Herrera-Araujo (2018) | 0.11 | Reduction in mortality risk |
| Hökby and Söderqvist (2003) | 0.32 | Environmental goods: All others |
| Huhtala and Pouta (2008) | 0.90 | Environmental goods: All others |
| Jacobsen and Hanley (2009) | 0.62 | Environmental goods: Nature conservation |
| Johannesson et al. (1993) | 0.82 | Health improvements |
| Li et al. (2016) | 0.90 | Environmental goods: Climate change mitigation |
| Lindhjem et al. (2011) | 0.20 | Reduction in mortality risk |
| Lindhjem and Tuan (2012) | 0.27 | Environmental goods: Nature conservation |
| Martini and Tiezzi (2014) | -0.16 | Environmental goods: Water or air quality |
| Masiye and Rehnberg (2005) | 0.71 | Health improvements |
| Masterman and Viscusi (2018) | 0.18 | Reduction in mortality risk |
| McLeod (1984) | 0.34 | Cultural goods |
| Milligan et al. (2014) | 0.45 | Reduction in mortality risk |
| Nastis and Mattas (2018) | 0.04 | Environmental goods: Climate change mitigation |
| Navrud and Strand (2018) | -0.02 | Environmental goods: Nature conservation |
| Ready et al. (2002) | 0.41 | Environmental goods: Water or air quality |
| Riera et al. (2006) | 0.01 | Reduction in mortality risk |
| Robinson et al. (2019) | -0.50 | Reduction in mortality risk |
| Scandizzo and Ventura (2010) | 0.55 | Environmental goods: Nature conservation |
| Tuan et al. (2009) | -0.98 | Cultural goods |
| Tyllianakis and Skuras (2016) | 0.26 | Environmental goods: Water or air quality |
| Viscusi and Aldy (2003) | 0.50 | Reduction in mortality risk |
| Wang and Mullahy (2006) | -0.42 | Environmental goods: Water or air quality |
| Zan and Scharff (2017) | -2.30 | Reduction in mortality risk |

* A separate data file contains more details on these 40 as well as the 41 non-relevant studies.

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## A.9 Optimal versus business as usual growth rates of the market and non-market good

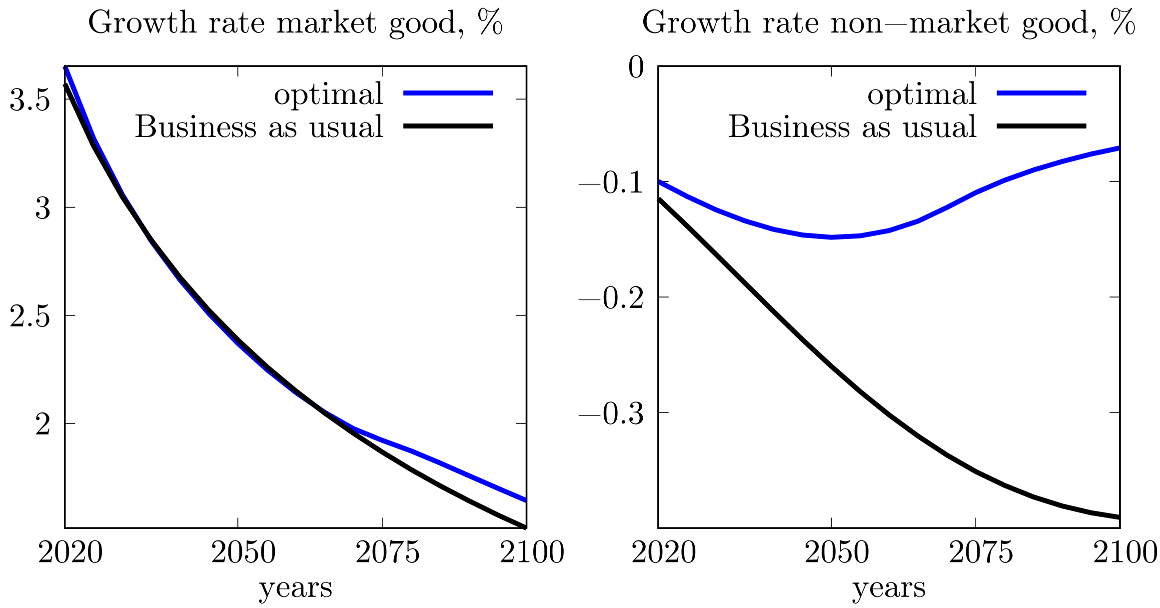


Figure A.5: Optimal versus business as usual growth rates of the market good (left) and non-market good (right) using the central calibration of our plausible ranges model.

## A.10 Code

### A.10.1 AMPL code to produce Figure 1

#### (1) AMPL mod-file Nordhaus

```
# Nordhaus, DICE 2016R2
# To work with the run-file, this mod-file should be named: DICE_Nordhaus_2016.mod

# PARAMETERS
#Time horizon
param T:=100;
# Preferences
param eta default 1.45;  # I-EMUC
param rho default 0.015;  # time preference rate
# for Stern use param rho default 0.001;
# discount factor
param R {t in 0..T}>=0;
let R[0]:=1;
let {t in 1..T} R[t] := R[t-1]/((1+rho)^5);

# for sensitivity analysis and figure 2 use: param R {t in 0..T}:= 1*exp(-rho*5*t);

# Population and its dynamics
param L0:=7403;  #initial world population 2015 (millions)
param gL0:=0.134;  #growth rate to calibrate to 2050 pop projection
param L {t in 0..T}>=0;
let L[0]:=L0;
let {t in 1..T} L[t]:=L[t-1]*((11500/L[t-1])^gL0);

# Technology and its dynamics
param gamma:=0.3;   #capital elasticity in production function
param deltaK:=0.100;  #depreciation rate on capital (per year)
param Qgross0:=105.5;  #Initial world gross output 2015 (trill 2010 USD)
param K0:=223;  #initial capital value 2015 (trillions 2010 USD)
param A0:=5.115;  #initial level of total factor productivity
param gA0:=0.076;  #initial growth rate for TFP per 5 years
param deltaA:=0.005;  #decline rate of TFP per 5 years
```

```
param gA {t in 0..T}>=0;
let {t in 0..T} gA[t]:=gA0*exp(-deltaA*5*(t));

param A {t in 0..T}>=0;
let A[0]:=A0;
let {t in 1..T} A[t]:=A[t-1]/(1-gA[t-1]);

# Emission parameters, where sigma is the carbon intensity or CO2-output ratio
param gsigma0:=-0.0152;  #initial growth of sigma (coninuous per year ),
param deltasigma:=-0.001;  #decline rate of decarbonization per period
param ELand0:=2.6;  #initial Carbon emissions from land 2015 (GtCO2 per period)
param deltaLand:=0.115;  #decline rate of land emissions (per period)
param EInd0:=35.85;  #Industrial emissions 2015 (GtCO2 per year)
param Ecum0:=400;  #Initial cumulative emissions (GtCO2)
param mu0:=.03;  #Initial emissions control rate; under BAU: 0.00
param Lambda0:=0;  #Initial abatement costs
param sigma0:=EInd0/(Qgross0*(1-mu0));
#initial sigma (kgCO2 per output 2005 USD in 2010)

param gsigma {t in 0..T};
let gsigma[0]:=gsigma0;
let {t in 1..T} gsigma[t]:=gsigma[t-1]*((1+deltasigma)^5);

param sigma {t in 0..T}>=0;
let sigma[0]:=sigma0;
let {t in 1..T} sigma[t]:=sigma[t-1]*exp(gsigma[t-1]*5);

param ELand {t in 0..T}>=0;
let ELand[0]:=ELand0;
let {t in 1..T} ELand[t]:=ELand[t-1]*(1-deltaLand);

# Carbon cycle
param MAT0=851;  # Initial Concentration in atmosphere 2015 (GtC)
param MUP0:=460;  # Initial Concentration in upper strata 2015 (GtC)
param MLO0:=1740;  # Initial Concentration in lower strata 2015 (GtC)
param MATEQ:=588;  # Equilibrium concentration in atmosphere (GtC)
param MUPEQ:=360;  # Equilibrium concentration in upper strata (GtC)
param MLOEQ:=1720;  # Equilibrium concentration in lower strata (GtC)
```

```
# Flow parameters (carbon cycle transition matrix)
# correspond to the bXX parameters in Nordhaus)
param phi12:=0.12;
param phi23:=0.007;
param phi11=1-phi12;
param phi21=phi12*MATEQ/MUPEQ;
param phi22=1-phi21-phi23;
param phi32=phi23*MUPEQ/MLOEQ;
param phi33=1-phi32;

# Climate model parameters
param nu:=3.1;  # Equilibrium temperature impact (°C per doubling CO2)
param Fex0:=0.5;  # 2015 forcings of non-CO2 GHG (Wm-2)
param Fex1:=1.0;  # 2100 forcings of non-CO2 GHG (Wm-2)
param TLO0:=0.0068;  # Initial lower stratum temperature change (°C from 1900)
param TAT0:=0.85;  # Initial atmospheric temp change (°C from 1900)
param xi1:=0.1005;  # Speed of adjustment parameter for atmospheric temperature
param xi3:=0.088;  # Coefficient of heat loss from atmosphere to oceans
param xi4:=0.025;  # Coefficient of heat gain by deep oceans
param kappa:=3.6813;  # Forcings of equilibrium CO2 doubling (Wm-2)
param xi2=kappa/nu;  # climate model parameter
param Fex {t in 0..T}>=0;
let {t in 0..17} Fex[t]:=Fex0+1/17*(Fex1-Fex0)*(t);  # external forcing (Wm-2)
let {t in 18..T} Fex[t]:=Fex1;
# external forcing (Wm-2)
# is assumed to be constant and equal to Fex1 from 2100 onward
# see e.g. Traeger (2014, Fig.1)

# climate damage parameters
param Psi:=0.003622;
# 0.00236 damage quadratic term for 25% add on NMD; for 100% add on: 0.003622
param TATlim default 12; # upper bound on atm. temperature change

# abatement cost
param Theta:=2.6;  # Exponent of control cost function
param pback0:=550;  # Cost of backstop 2010 $ per tCO2 2015
param gback:=0.025;  # Initial cost decline backstop cost per period
```

```
param cprice0:=2;  # Initial base carbon price (2010$ per tC02)

param pback {t in 0..T}>=0;
let pback[0]:=pback0;
let {t in 1..T} pback[t]:=pback[t-1]*(1-gback);

param phead {t in 0..T}=pback[t]*sigma[t]/Theta/1000;

# VARIABLES

# capital (trillions 2010 USD)
var K {t in 0..T}>=1;

# Gross output (trillions 2010 USD)
var Qgross {t in 0..T}=A[t]*((L[t]/1000)^(1-gamma))*(K[t]^gamma);

# carbon reservoir atmosphere (GtC)
var MAT {t in 0..T}>=10;

# carbon reservoir upper ocean (GtC)
var MUP {t in 0..T}>=100;

# carbon reservoir lower ocean (GtC)
var MLO {t in 0..T}>=1000;

# total radiative forcing (Wm-2)
var F {t in 0..T}=kappa*((log(MAT[t]/MATEQ))/log(2))+Fex[t];

# atmospheric temperature change (°C from 1900)
var TAT {t in 0..T}>=0, <=TATlim;

# ocean temperature (°C from 1900)
var TLO {t in 0..T}>=-1, <=20;

# damage fraction
var Omega {t in 0..T}=Psi*(TAT[t])^2;

# damages (trillions 2010 USD)
```

```
var damage {t in 0..T}=Omega[t]*Qgross[t];

# emission control
var mu {t in 0..T}>=0;

# abatement costs (fraction of output)
var Lambda {t in 0..T}=Qgross[t]*phead[t]*(mu[t]^Theta);

# industrial emissions
var EInd {t in 0..T}=sigma[t]*Qgross[t]*(1-mu[t]);

# total emissions
var E {t in 0..T};

# maximum cumulative extraction fossil fuels (GtC)
var Ecum {t in 0..T}<=6000;

# Marginal cost of abatement (carbon price)
var cprice {t in 0..T}=pback[t]*mu[t]^(Theta-1);

# output net of damages and abatement (trillions 2010 USD)
var Q {t in 0..T}=(Qgross[t]*(1-Omega[t]))-Lambda[t];

# per capita consumption (1000s 2010 USD]
var c {t in 0..T} >= .1;

# aggregate consumption
var C {t in 0..T} = L[t]*c[t]/1000;

# Investment (trillions 2005 USD)
var I {t in 0..T}>=0;

# utility
var U {t in 0..T} =c[t]^(1-eta)/(1-eta);

# total period utility
var U_period {t in 0..T}=U[t]*R[t];
```

```
# welfare/objective function
var W=sum{t in 0..T} L[t]*U[t]*R[t];

# welfare optimization
maximize objective_function: W;
subject to constr_accounting {t in 0..T}:
C[t]=Q[t]-I[t];
subject to constr_emissions {t in 0..T}:
E[t]=EInd[t]+ELand[t];
subject to constr_capital_dynamics {t in 1..T}:
K[t]=(1-deltaK)^5*K[t-1]+5*I[t-1];
subject to constr_cumulativeemissions {t in 1..T}:
Ecum[t]=Ecum[t-1]+(EInd[t-1]*5/3.666);
subject to constr_atmosphere {t in 1..T}:
MAT[t]=E[t]*(5/3.666)+phi11*MAT[t-1]+phi21*MUP[t-1];
subject to constr_upper_ocean {t in 1..T}:
MUP[t]=phi12*MAT[t-1]+phi22*MUP[t-1]+phi32*MLO[t-1];
subject to constr_lower_ocean {t in 1..T}:
MLO[t]=phi23*MUP[t-1]+phi33*MLO[t-1];
subject to constr_atmospheric_temp {t in 1..T}:
TAT[t]=TAT[t-1]+xi1*((F[t]-xi2*TAT[t-1])-(xi3*(TAT[t-1]-TLO[t-1])));
subject to constr_ocean_temp {t in 1..T}:
TLO[t]=TLO[t-1]+xi4*(TAT[t-1]-TLO[t-1]);

# Initial conditions
subject to initial_capital:  K[0] = K0;
subject to initial_Ecum:  Ecum[0]=Ecum0;
subject to initial_MAT:  MAT[0]=MAT0;
subject to initial_MUP:  MUP[0]=MUP0;
subject to initial_MLO:  MLO[0]=MLO0;
subject to initial_TLO:  TLO[0]=TLO0;
subject to initial_TAT:  TAT[0]=TAT0;
subject to initial_control:  mu[0]=mu0;
subject to control1 {t in 1..28}:  mu[t]<=1;
subject to control2 {t in 29..T}:  mu[t]<=1.2; # from 2150
#subject to control_BAU {t in 1..T}: mu[t]=0;
```

**(2) AMPL mod-file, RPE, S&P**

```
# DICE 2016R2 with Relative Prices
# To work with the run-file, this mod-file should be named: DICE_2016_RPE.mod
# for central calibration for Section 5 change parameters according to table 3
# PARAMETERS
#Time horizon
param T default 100;

# Preferences
param eta default 1.45; #I-EMUC central calibration: 1.35
param rho default 0.015; #time preference rate; central calibration: 0.011

# relative prices additions
param zeta default -1; #substitution parameter S\&P 2008

#central calibration: -0.11
#for a model run without relative prices:1

param beta default 0.1; #share of non-market good in utility function
param EQbar default 0; #subsistence level of non-market good
#central calibration: 7.77

param cbar default 0; #subsistence level of consumption per capita

# Discount factor
param R {t in 0..T}>=0;
let R[0]:=1;
let {t in 1..T} R[t] := R[t-1]/((1+rho)^5);

#for sensitivity analysis and figure 2/5: param R {t in 0..T}:= 1*exp(-rho*5*t);

# Population and its dynamics
param L0:=7403; #initial world population 2015 (millions)
param gL0:=0.134; #growthrate to calibrate to 2050 pop projection
param L {t in 0..T}>=0;
let L[0]:=L0;
let {t in 1..T} L[t]:=L[t-1]*((11500/L[t-1])^gL0);
```

```
# Technology and its dynamics
param gamma:=0.3;   #capital elasticity in production function
param deltaK:=0.1;  #depreciation rate on capital (per year)
param Qgross0:=105.5;  #Initial world gross output 2015 (trill 2010 USD)
param K0:=223;  #initial capital value 2015 (trillions 2010 USD)
param A0:=5.115;  #initial level of total factor productivity
param gA0 :=0.076;  #initial growth rate for TFP per 5 years
param deltaA default 0.005; #decline rate of TFP per 5 years
#central calibration: 0.005

param gA {t in 0..T} := gA0*exp(-deltaA*5*t);  # growth rate for TFP per period

param A {t in 0..T}>=0;
let A[0]:=A0;
let {t in 1..T} A[t]:=A[t-1]/(1-gA[t-1]);

# Emission parameters
param gsigma0:=-0.0152;  #initial growth of sigma (coninuous per year )
param deltasigma:=-0.001;  #decline rate of decarbonization per period
param ELand0:=2.6;  #initial Carbon emissions from land 2015 (GtCO2 per period)
param deltaLand:=0.115;  #decline rate of land emissions (per period)
param EInd0:=35.85;  #Industrial emissions 2015 (GtCO2 per year)
param Ecum0:=400;  #Initial cumulative emissions (GtCO2)
param mu0:=.03;  #Initial emissions control rate for base year 2010
param Lambda0:=0;  #Initial abatement costs
param sigma0:=EInd0/(Qgross0*(1-mu0));#initial sigma
#(kgCO2 per output 2005 USD in 2010)

param gsigma {t in 0..T};
let gsigma[0]:=gsigma0;
let {t in 1..T} gsigma[t]:=gsigma[t-1]*((1+deltasigma)^5);

param sigma {t in 0..T}>=0;
let sigma[0]:=sigma0;
let {t in 1..T} sigma[t]:=sigma[t-1]*exp(gsigma[t-1]*5);

param ELand {t in 0..T}>=0;
let ELand[0]:=ELand0;
```

```
let {t in 1..T} ELand[t]:=ELand [t-1]*(1-deltaLand);

# Carbon cycle
param MAT0=851;  # Initial Concentration in atmosphere 2015 (GtC)
param MUP0:=460;  # Initial Concentration in upper strata 2015 (GtC)
param MLO0:=1740;  # Initial Concentration in lower strata 2015 (GtC)
param MATEQ:=588;  # Equilibrium concentration in atmosphere
#(pre-industrial atmos. carbon) (GtC)
param MUPEQ:=360;  # Equilibrium concentration in upper strata (GtC)
param MLOEQ:=1720;  # Equilibrium concentration in lower strata (GtC)

# Flow parameters
param phi12:=0.12;
param phi23:=0.007;
param phi11=1-phi12;
param phi21=phi12*MATEQ/MUPEQ;
param phi22=1-phi21-phi23;
param phi32=phi23*MUPEQ/MLOEQ;
param phi33=1-phi32;

# Climate model parameters
param nu:=3.1;  # Equilibrium temperature impact (°C per doubling CO2)
param Fex0:=0.5;  # 2015 forcings of non-CO2 GHG (Wm-2)
param Fex1:=1.0;  # 2100 forcings of non-CO2 GHG (Wm-2)
param TLO0:=0.0068;  # Initial lower stratum temperature change (°C from 1900)
param TAT0:=0.85;  # Initial atmospheric temp change (°C from 1900)
param xi1:=0.1005;  # Speed of adjustment parameter for atmospheric temperature
param xi3:=0.088;  # Coefficient of heat loss from atmosphere to oceans
param xi4:=0.025;  # Coefficient of heat gain by deep oceans
param kappa:=3.6813;  # Forcings of equilibrium CO2 doubling (Wm-2)
param xi2=kappa/nu;  # climate model parameter

# external forcing (Wm-2)
#assumed to be constant and equal to Fex1 from 2100 onward,
#see e.g. Traeger (2014, Fig.1)
param Fex {t in 0..T}>=0;
let {t in 0..18} Fex[t]:=Fex0+1/18*(Fex1-Fex0)*(t);
let {t in 19..T} Fex[t]:=Fex1;
```

```
# Climate damage parameters
param Psi default 0.00181;  # market damage term without 25% adjustment
# damage quadratic term with 25% adjustment is 0.00236
param MD default 0.0163;
# market damages for 3°C warming above preindustrial according to Nordhaus (2017)
param NMD default 0.0163;
# corresponds to 100% NMD add on; with 25% add on 0.00494
# central calibration: 0.0165
param TD=MD+NMD; # total climate damages

param TATlim default 12; # upper bound on atm. temperature change

# Abatement cost
param Theta:=2.6;  # Exponent of control cost function
param pback0:=550;  # Cost of backstop 2010 $ per tCO2 2015
param gback:=0.025;  # Initial cost decline backstop cost per period

param pback {t in 0..T}>=0;
let pback[0]:=pback0;
let {t in 1..T} pback[t]:=pback[t-1]*(1-gback);

param phead {t in 0..T}=pback[t]*sigma[t]/Theta/1000;

# VARIABLES
# capital (trillions 2010 USD)
var K {t in 0..T}>=1;

# Gross output (trillions 2010 USD)
var Qgross {t in 0..T}=A[t]*((L[t]/1000)^(1-gamma))*(K[t]^gamma);

# carbon reservoir atmosphere (GtC)
var MAT {t in 0..T}>=10;

# carbon reservoir upper ocean (GtC)
var MUP {t in 0..T}>=100;

# carbon reservoir lower ocean (GtC)
```

```
var MLO {t in 0..T}>=1000;

# total radiative forcing (Wm-2)
var F {t in 0..T}=kappa*((log(MAT[t]/MATEQ))/log(2))+Fex[t];

# atmospheric temperature change (°C from 1900)
var TAT {t in 0..T}>=0, <=TATlim;

# ocean temperature (°C from 1900)
var TLO {t in 0..T}>=-1, <=20;

# damage fraction
var Omega {t in 0..T}=Psi*(TAT[t])^2;

# damages (trillions 2010 USD)
var damage {t in 0..T}=Omega[t]*Qgross[t];

# emission control
var mu {t in 0..T}>=0;

# abatement costs (fraction of output)
var Lambda {t in 0..T}=Qgross[t]*phead[t]*(mu[t]^Theta);

# industrial emissions
var EInd {t in 0..T}=sigma[t]*Qgross[t]*(1-mu[t]);

# total emissions
var E {t in 0..T};

# maximum cumulative extraction fossil fuels (GtC)
var Ecum {t in 0..T}<=6000;

# Marginal cost of abatement (carbon price)
var cprice {t in 0..T}=pback[t]*mu[t]^(Theta-1);

# output net of damages and abatement(trillions 2010 USD)
var Q {t in 0..T}=(Qgross[t]*(1-Omega[t]))-Lambda[t];
```

```
# per capita consumption (1000s 2010 USD]
var c {t in 0..T} >= .1;

# aggregate consumption
var C {t in 0..T} = L[t]*c[t]/1000;

# Investment(trillions 2005 USD)
var I {t in 0..T}>=0;

# non-market good
var EQ {t in 0..T}>=0.0000001 <=1000;

# Non-market damages scaling parameter including subsistence requirement

# including sub
var a {t in 0..T} =(1/(nu^2))*(EQ[0]*(EQbar+((EQ[0]-EQbar)^(zeta)
+((1-beta)/beta)*(((1-TD)*C[0])^(zeta)-((1-MD)*C[0])^(zeta)))^(1/zeta))^(-1)-1);

# growth rate of market good

var g_C {t in 0..T-1} = (C[t+1]-C[t])/C[t];

# growth rate of non market good

var g_EQ {t in 0..T-1} = ((EQ[t+1]-EQ[t])/EQ[t]);

# relative price effect

var RPE {t in 0..T-1} =(1-zeta)*(g_C[t]-((EQ[t]/(EQ[t]-EQbar))*g_EQ[t]));

# utility

var U {t in 0..T}= (((1-beta)*(c[t])^(zeta)+
beta*((EQ[t]-EQbar)*1000/L[t])^(zeta))^((1-eta)/zeta))/(1-eta);

# welfare/objective function
var W=sum{t in 0..T} L[t]*U[t]*R[t];
```

```
maximize objective_function: W;
subject to initial_consumption:  c[0]=10.4893;
subject to constr_accounting {t in 0..T}:
C[t]=Q[t]-I[t];
subject to constr_emissions {t in 0..T}:
E[t]=EInd[t]+ELand[t];
subject to constr_capital_dynamics {t in 1..T}:
K[t]=(1-deltaK)^5*K[t-1]+5*I[t-1];
subject to constr_cumulativeemissions {t in 1..T}:
Ecum[t]=Ecum[t-1]+(EInd[t-1]*5/3.666);
subject to constr_atmosphere {t in 1..T}:
MAT[t]=E[t]*(5/3.666)+phi11*MAT[t-1]+phi21*MUP[t-1];
subject to constr_upper_ocean {t in 1..T}:
MUP[t]=phi12*MAT[t-1]+phi22*MUP[t-1]+phi32*MLO[t-1];
subject to constr_lower_ocean {t in 1..T}:
MLO[t]=phi23*MUP[t-1]+phi33*MLO[t-1];
subject to constr_atmospheric_temp {t in 1..T}:
TAT[t]=TAT[t-1]+xi1*((F[t]-xi2*TAT[t-1])-(xi3*(TAT[t-1]-TLO[t-1])));
subject to constr_ocean_temp {t in 1..T}:
TLO[t]=TLO[t-1]+xi4*(TAT[t-1]-TLO[t-1]);

# Initial conditions
subject to initial_capital:  K[0] = K0;
subject to initial_Ecum:  Ecum[0]=Ecum0;
subject to initial_MAT:  MAT[0]=MAT0;
subject to initial_MUP:  MUP[0]=MUP0;
subject to initial_MLO:  MLO[0]=MLO0;
subject to initial_TLO:  TLO[0]=TLO0;
subject to initial_TAT:  TAT[0]=TAT0;
subject to initial_control:  mu[0]=mu0;
subject to control1 {t in 1..28}:  mu[t]<=1;
subject to control2 {t in 29..T}:  mu[t]<=1.2; # from 2150
subject to initial_EQ:  EQ[0]=C[0];
subject to constr_EQ {t in 1..T}:  EQ[t]=(EQ[0]/(1+a[t]*(TAT[t]^2)));
```

### (3) AMPL run-file

```
reset;
model DICE_2016_RPE.mod; # add a "#" in a S\&P-RPE run
#model DICE_Nordhaus_2016.mod; # delete "#" in a Nordhaus run
option solver knitroampl;
solve;
# Produce overview of results in a csv format
# change file name to "Results_Figure1_Nordhaus.csv" during the Nordhaus run
# change file name to "Results_Figure1_RPE-SP.csv" during the RPE-SP run

for {i in 0..T-1}
{printf "%f\t", i>Results_Figure1_RPE-SP.csv;
printf "%f\t", (((RPE[i]+1)^(1/5))-1)*100>Results_Figure1_RPE-SP.csv;
# delete this RPE line during Nordhaus run
printf "%f\t", EInd[i]> Results_Figure1_RPE-SP.csv;
printf "%f\t", TAT[i]>Results_Figure1_RPE-SP.csv;
printf "%f\n", -1000*constr_emissions[i]/constr_accounting[i]>
Results_Figure1_RPE-SP.csv;}
```

### A.10.2 AMPL code to produce Figure 2

```
# use the same mod files as for figure 1 with the following changes
# change equation for time preference rate to
# param R {t in 0..T}:= 1*exp(-rho*5*t);
# set the substitution parameter zeta equal to 1 for the run without RPE
# run the following AMPL run file
# change the file name of the csv-file for each run as preferred, e.g.:
# Nordhaus, Sterner and Persson (SP), without relative prices
reset;
model DICE_2016_RPE.mod; # add a "#" in a Nordhaus run
#model DICE_Nordhaus_2016.mod; # delete "#" in a Nordhaus run
option solver knitroampl;
solve;
# Produce sensitivity analysis in csv format
for {i in 0.000001 .. 0.032 by 0.001}
{ let rho:=i;
solve;
printf "%.5f\t", rho>Results_Figure2_SP.csv;
printf "%.5f\n", max {t in 0..T} TAT[t]>Results_Figure2_SP.csv;
}
```

### A.10.3 AMPL code for Figure 3 and Figure 4

```
# use the AMPL mod file RPE, S\&P (as for figure 1 and 2)
# change equation for time preference rate to param R {t in 0..T}:= 1*exp(-rho*5*t);
# run the following AMPL run-file
# note that for the decline rate of TFP deltaA the sensitivity analysis
# needs to be done manually, i.e.
# change deltaA in the mod-file from 0 to 0.05 in some steps
# solve the model each time
# print the RPE in 2020 and 2100 for every deltaA similar to other variables

reset;
model DICE_2016_RPE.mod;
option solver knitroampl;
solve;

# Produce sensitivity analysis in csv format
for {i in -4 .. 1.1 by 0.03}
{let zeta:=i;
solve;
printf "%.5f\t", i>Results_Figure3_Theta.csv;
printf "%.5f\t", (((RPE[1]+1)^(1/5))-1)*100>Results_Figure3_Theta.csv;
printf "%.5f\n", (((RPE[17]+1)^(1/5))-1)*100>Results_Figure3_Theta.csv;
}

reset;
model DICE_2016_RPE.mod;
option solver knitroampl;
solve;

for {i in 0.000 .. 0.11 by 0.001}
{let NMD:=i;
solve;
printf "%.5f\t", i>Results_Figure3_NMD.csv;
printf "%.5f\t", (((RPE[1]+1)^(1/5))-1)*100>Results_Figure3_NMD.csv;
printf "%.5f\n", (((RPE[17]+1)^(1/5))-1)*100>Results_Figure3_NMD.csv;
}
```

```
reset;
model DICE_2016_RPE.mod;
option solver knitroampl;
solve;

for {i in 0 .. 40 by 0.5}
{ let EQbar:=i;
solve;
printf "%.5f\t", i>Results_Figure3_Sub.csv;
printf "%.5f\t", (((RPE[1]+1)^(1/5))-1)*100>Results_Figure3_Sub.csv;
printf "%.5f\n", (((RPE[17]+1)^(1/5))-1)*100>Results_Figure3_Sub.csv;
}

reset;
model DICE_2016_RPE.mod;
option solver knitroampl;
solve;

for {i in 0.000001 .. 0.085 by 0.001}
{let rho:=i;
solve;
printf "%.5f\t", rho>Results_Figure4_delta.csv;
printf "%.5f\t", (((RPE[1]+1)^(1/5))-1)*100>Results_Figure4_delta.csv;
printf "%.5f\n", (((RPE[17]+1)^(1/5))-1)*100>Results_Figure4_delta.csv;
}

reset;
model DICE_2016_RPE.mod;
option solver knitroampl;
solve;

for {i in 0.0001 .. 5.2 by 0.02}
{let eta:=i;
solve;
printf "%.5f\t", eta>Results_Figure4_eta.csv;
printf "%.5f\t", (((RPE[1]+1)^(1/5))-1)*100>Results_Figure4_eta.csv;
printf "%.5f\n", (((RPE[17]+1)^(1/5))-1)*100>Results_Figure4_eta.csv;}
```

### A.10.4 AMPL code for figure 5

#### (1) AMPL dat-file, Plausible Ranges

```
# this is the random data generated from raw data by Drupp et al. (2018)
# save this file as random_delta_eta.dat to be compatible with the run-file

param nruns:=1000;

param rhos:=
1 0.015
2 0.00000001
3 0.02
4 0.01
5 0.03
6 0.03
7 0.001
8 0.005
9 0.00000001
10 0.00000001
11 0.01
12 0.00000001
13 0.001
14 0.001
15 0.005
16 0.01
17 0.00000001
18 0.02
19 0.015
20 0.00000001
21 0.04
22 0.00000001
23 0.00000001
24 0.00000001
25 0.03
26 0.00000001
27 0.00000001
28 0.001
29 0.02
```

30 0.04
31 0.02
32 0.00000001
33 0.01
34 0.00000001
35 0.01
36 0.03
37 0.003
38 0.03
39 0.02
40 0.00000001
41 0.00000001
42 0.02
43 0.001
44 0.02
45 0.025
46 0.005
47 0.005
48 0.01
49 0.001
50 0.01
51 0.03
52 0.02
53 0.015
54 0.01
55 0.01
56 0.01
57 0.002
58 0.01
59 0.00000001
60 0.00000001
61 0.001
62 0.025
63 0.00000001
64 0.00001
65 0.02
66 0.005
67 0.04

68 0.01
69 0.01
70 0.01
71 0.001
72 0.07
73 0.005
74 0.04
75 0.02
76 0.04
77 0.005
78 0.00000001
79 0.01
80 0.01
81 0.01
82 0.02
83 0.02
84 0.00000001
85 0.01
86 0.00000001
87 0.02
88 0.001
89 0.02
90 0.03
91 0.06
92 0.00000001
93 0.02
94 0.01
95 0.005
96 0.001
97 0.001
98 0.03
99 0.06
100 0.06
101 0.01
102 0.00000001
103 0.00000001
104 0.03
105 0.00001

106 0.00000001
107 0.02
108 0.005
109 0.02
110 0.00000001
111 0.00000001
112 0.00000001
113 0.00000001
114 0.008
115 0.00001
116 0.06
117 0.00000001
118 0.02
119 0.015
120 0.02
121 0.005
122 0.005
123 0.005
124 0.00000001
125 0.01
126 0.001
127 0.00001
128 0.01
129 0.01
130 0.005
131 0.00000001
132 0.01
133 0.005
134 0.08
135 0.001
136 0.00000001
137 0.00000001
138 0.00000001
139 0.00000001
140 0.00000001
141 0.001
142 0.025
143 0.00000001

144 0.01
145 0.01
146 0.003
147 0.00000001
148 0.02
149 0.015
150 0.015
151 0.00001
152 0.04
153 0.01
154 0.00000001
155 0.00000001
156 0.01
157 0.00000001
158 0.00000001
159 0.03
160 0.00005
161 0.00000001
162 0.001
163 0.01
164 0.01
165 0.00000001
166 0.001
167 0.03
168 0.02
169 0.00001
170 0.003
171 0.01
172 0.00000001
173 0.005
174 0.00000001
175 0.005
176 0.0025
177 0.07
178 0.01
179 0.01
180 0.02
181 0.02

| | |
|---|---|
| 182 | 0.03 |
| 183 | 0.001 |
| 184 | 0.00000001 |
| 185 | 0.02 |
| 186 | 0.0001 |
| 187 | 0.00000001 |
| 188 | 0.005 |
| 189 | 0.00000001 |
| 190 | 0.00000001 |
| 191 | 0.00000001 |
| 192 | 0.01 |
| 193 | 0.00001 |
| 194 | 0.005 |
| 195 | 0.01 |
| 196 | 0.00000001 |
| 197 | 0.00000001 |
| 198 | 0.04 |
| 199 | 0.01 |
| 200 | 0.015 |
| 201 | 0.01 |
| 202 | 0.005 |
| 203 | 0.002 |
| 204 | 0.00000001 |
| 205 | 0.001 |
| 206 | 0.02 |
| 207 | 0.00000001 |
| 208 | 0.005 |
| 209 | 0.02 |
| 210 | 0.005 |
| 211 | 0.001 |
| 212 | 0.02 |
| 213 | 0.00000001 |
| 214 | 0.02 |
| 215 | 0.01 |
| 216 | 0.001 |
| 217 | 0.00000001 |
| 218 | 0.08 |
| 219 | 0.00000001 |

220 0.02
221 0.00000001
222 0.04
223 0.02
224 0.00000001
225 0.025
226 0.02
227 0.005
228 0.00000001
229 0.00000001
230 0.08
231 0.005
232 0.03
233 0.00000001
234 0.001
235 0.025
236 0.00000001
237 0.04
238 0.005
239 0.03
240 0.01
241 0.015
242 0.03
243 0.02
244 0.01
245 0.02
246 0.02
247 0.001
248 0.005
249 0.02
250 0.01
251 0.01
252 0.01
253 0.02
254 0.01
255 0.01
256 0.01
257 0.02

```
258 0.01
259 0.00000001
260 0.001
261 0.008
262 0.001
263 0.01
264 0.00000001
265 0.00000001
266 0.02
267 0.00000001
268 0.005
269 0.001
270 0.00000001
271 0.03
272 0.00000001
273 0.005
274 0.01
275 0.003
276 0.025
277 0.01
278 0.06
279 0.01
280 0.00000001
281 0.0025
282 0.00000001
283 0.00000001
284 0.02
285 0.00000001
286 0.00000001
287 0.00000001
288 0.01
289 0.025
290 0.001
291 0.001
292 0.02
293 0.005
294 0.00000001
295 0.001
```

296 0.00000001
297 0.001
298 0.012
299 0.01
300 0.00000001
301 0.00000001
302 0.00000001
303 0.005
304 0.00000001
305 0.02
306 0.01
307 0.00000001
308 0.005
309 0.00000001
310 0.00000001
311 0.00000001
312 0.001
313 0.005
314 0.02
315 0.03
316 0.02
317 0.00000001
318 0.03
319 0.01
320 0.03
321 0.025
322 0.02
323 0.00000001
324 0.005
325 0.01
326 0.005
327 0.005
328 0.01
329 0.00000001
330 0.00000001
331 0.00000001
332 0.02
333 0.01

334 0.005
335 0.03
336 0.00000001
337 0.00000001
338 0.005
339 0.00000001
340 0.01
341 0.001
342 0.005
343 0.00000001
344 0.02
345 0.03
346 0.00000001
347 0.005
348 0.01
349 0.001
350 0.02
351 0.00000001
352 0.03
353 0.01
354 0.01
355 0.00000001
356 0.01
357 0.05
358 0.02
359 0.008
360 0.008
361 0.005
362 0.02
363 0.03
364 0.03
365 0.001
366 0.02
367 0.02
368 0.00000001
369 0.02
370 0.00000001
371 0.02

372 0.003
373 0.001
374 0.00000001
375 0.00001
376 0.02
377 0.0001
378 0.00000001
379 0.06
380 0.01
381 0.00000001
382 0.005
383 0.00000001
384 0.002
385 0.01
386 0.03
387 0.02
388 0.01
389 0.01
390 0.08
391 0.00000001
392 0.001
393 0.00000001
394 0.00000001
395 0.01
396 0.005
397 0.025
398 0.00000001
399 0.00000001
400 0.001
401 0.00000001
402 0.00000001
403 0.00000001
404 0.06
405 0.00000001
406 0.003
407 0.00000001
408 0.005
409 0.02

410 0.00000001
411 0.005
412 0.02
413 0.00001
414 0.00000001
415 0.001
416 0.00000001
417 0.001
418 0.01
419 0.00000001
420 0.01
421 0.005
422 0.00000001
423 0.015
424 0.01
425 0.01
426 0.02
427 0.00000001
428 0.001
429 0.005
430 0.02
431 0.01
432 0.003
433 0.002
434 0.01
435 0.00000001
436 0.01
437 0.01
438 0.01
439 0.06
440 0.01
441 0.001
442 0.01
443 0.012
444 0.002
445 0.03
446 0.00000001
447 0.00000001

448 0.00001
449 0.001
450 0.02
451 0.03
452 0.02
453 0.008
454 0.04
455 0.00000001
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460 0.001
461 0.001
462 0.00000001
463 0.01
464 0.01
465 0.02
466 0.00000001
467 0.00000001
468 0.01
469 0.001
470 0.015
471 0.00000001
472 0.005
473 0.001
474 0.00000001
475 0.001
476 0.00000001
477 0.001
478 0.00000001
479 0.002
480 0.0001
481 0.005
482 0.04
483 0.001
484 0.003
485 0.002

486 0.001
487 0.01
488 0.005
489 0.01
490 0.00000001
491 0.03
492 0.02
493 0.025
494 0.005
495 0.01
496 0.005
497 0.02
498 0.0001
499 0.00000001
500 0.025
501 0.00000001
502 0.02
503 0.005
504 0.005
505 0.025
506 0.001
507 0.02
508 0.02
509 0.005
510 0.001
511 0.02
512 0.02
513 0.0005
514 0.00000001
515 0.005
516 0.015
517 0.002
518 0.02
519 0.01
520 0.00000001
521 0.00000001
522 0.01
523 0.03

524 0.00000001
525 0.01
526 0.001
527 0.02
528 0.01
529 0.07
530 0.01
531 0.00000001
532 0.00000001
533 0.00000001
534 0.07
535 0.05
536 0.025
537 0.02
538 0.01
539 0.00000001
540 0.02
541 0.005
542 0.005
543 0.03
544 0.00001
545 0.00000001
546 0.00000001
547 0.00000001
548 0.02
549 0.00000001
550 0.025
551 0.001
552 0.00000001
553 0.001
554 0.00000001
555 0.00000001
556 0.001
557 0.01
558 0.01
559 0.001
560 0.00000001
561 0.005

562 0.01
563 0.02
564 0.03
565 0.00000001
566 0.00000001
567 0.03
568 0.00000001
569 0.001
570 0.0001
571 0.00000001
572 0.001
573 0.0005
574 0.00000001
575 0.00000001
576 0.005
577 0.008
578 0.001
579 0.01
580 0.001
581 0.02
582 0.02
583 0.00005
584 0.00000001
585 0.001
586 0.005
587 0.001
588 0.01
589 0.001
590 0.00000001
591 0.02
592 0.005
593 0.02
594 0.005
595 0.00000001
596 0.01
597 0.005
598 0.01
599 0.0005

600 0.015

601 0.025

602 0.00000001

603 0.02

604 0.01

605 0.025

606 0.00000001

607 0.02

608 0.02

609 0.02

610 0.00000001

611 0.01

612 0.025

613 0.001

614 0.00001

615 0.01

616 0.02

617 0.02

618 0.00000001

619 0.02

620 0.01

621 0.00000001

622 0.03

623 0.01

624 0.008

625 0.001

626 0.015

627 0.001

628 0.00000001

629 0.00000001

630 0.00000001

631 0.00000001

632 0.02

633 0.001

634 0.02

635 0.03

636 0.005

637 0.005

638 0.00000001
639 0.001
640 0.08
641 0.0005
642 0.00000001
643 0.005
644 0.02
645 0.001
646 0.00000001
647 0.02
648 0.01
649 0.00000001
650 0.01
651 0.00000001
652 0.03
653 0.06
654 0.01
655 0.00005
656 0.005
657 0.00000001
658 0.002
659 0.01
660 0.025
661 0.00005
662 0.015
663 0.00000001
664 0.02
665 0.015
666 0.0025
667 0.01
668 0.002
669 0.001
670 0.015
671 0.02
672 0.01
673 0.01
674 0.01
675 0.001

676 0.00000001
677 0.01
678 0.02
679 0.00000001
680 0.02
681 0.005
682 0.07
683 0.002
684 0.07
685 0.005
686 0.015
687 0.00001
688 0.05
689 0.03
690 0.00000001
691 0.00000001
692 0.00000001
693 0.01
694 0.005
695 0.0005
696 0.03
697 0.001
698 0.01
699 0.00000001
700 0.005
701 0.01
702 0.00000001
703 0.01
704 0.005
705 0.00000001
706 0.02
707 0.01
708 0.00000001
709 0.001
710 0.01
711 0.00000001
712 0.00000001
713 0.01

714 0.01
715 0.01
716 0.001
717 0.02
718 0.0025
719 0.025
720 0.00000001
721 0.02
722 0.001
723 0.001
724 0.001
725 0.00000001
726 0.02
727 0.00001
728 0.003
729 0.01
730 0.03
731 0.06
732 0.01
733 0.00000001
734 0.03
735 0.001
736 0.00000001
737 0.00000001
738 0.00000001
739 0.01
740 0.005
741 0.025
742 0.00000001
743 0.01
744 0.05
745 0.02
746 0.01
747 0.01
748 0.005
749 0.01
750 0.002
751 0.00001

752 0.005
753 0.005
754 0.05
755 0.00000001
756 0.00000001
757 0.00000001
758 0.02
759 0.001
760 0.01
761 0.025
762 0.025
763 0.005
764 0.00000001
765 0.02
766 0.00000001
767 0.00000001
768 0.02
769 0.00000001
770 0.00000001
771 0.00000001
772 0.01
773 0.025
774 0.001
775 0.01
776 0.00000001
777 0.00000001
778 0.01
779 0.01
780 0.08
781 0.005
782 0.04
783 0.08
784 0.00000001
785 0.02
786 0.01
787 0.00000001
788 0.01
789 0.00000001

790 0.015
791 0.008
792 0.015
793 0.008
794 0.02
795 0.001
796 0.00000001
797 0.00000001
798 0.03
799 0.03
800 0.02
801 0.00001
802 0.00000001
803 0.001
804 0.005
805 0.01
806 0.001
807 0.05
808 0.001
809 0.01
810 0.00000001
811 0.01
812 0.01
813 0.001
814 0.00000001
815 0.015
816 0.001
817 0.005
818 0.00000001
819 0.03
820 0.001
821 0.00000001
822 0.03
823 0.01
824 0.005
825 0.02
826 0.00000001
827 0.00000001

828 0.02
829 0.00000001
830 0.02
831 0.00000001
832 0.001
833 0.08
834 0.003
835 0.03
836 0.07
837 0.001
838 0.03
839 0.02
840 0.01
841 0.01
842 0.00000001
843 0.00000001
844 0.04
845 0.02
846 0.00001
847 0.005
848 0.00000001
849 0.005
850 0.0001
851 0.0001
852 0.03
853 0.00001
854 0.02
855 0.01
856 0.001
857 0.00000001
858 0.005
859 0.06
860 0.01
861 0.02
862 0.00000001
863 0.001
864 0.00000001
865 0.00000001

866 0.02
867 0.03
868 0.001
869 0.00000001
870 0.01
871 0.00000001
872 0.005
873 0.02
874 0.00000001
875 0.08
876 0.005
877 0.005
878 0.01
879 0.001
880 0.003
881 0.02
882 0.012
883 0.02
884 0.01
885 0.01
886 0.00000001
887 0.03
888 0.00000001
889 0.001
890 0.03
891 0.02
892 0.00000001
893 0.03
894 0.02
895 0.00000001
896 0.005
897 0.001
898 0.01
899 0.00000001
900 0.01
901 0.015
902 0.00000001
903 0.01

904 0.00000001

905 0.00000001

906 0.00000001

907 0.08

908 0.00000001

909 0.001

910 0.01

911 0.00001

912 0.001

913 0.001

914 0.01

915 0.005

916 0.008

917 0.03

918 0.00000001

919 0.005

920 0.00000001

921 0.00000001

922 0.00000001

923 0.005

924 0.001

925 0.02

926 0.02

927 0.01

928 0.00001

929 0.00000001

930 0.02

931 0.01

932 0.00000001

933 0.001

934 0.02

935 0.005

936 0.00000001

937 0.001

938 0.005

939 0.01

940 0.005

941 0.01

942 0.01
943 0.015
944 0.05
945 0.03
946 0.002
947 0.001
948 0.0001
949 0.02
950 0.002
951 0.02
952 0.02
953 0.00000001
954 0.001
955 0.00000001
956 0.06
957 0.02
958 0.01
959 0.005
960 0.00000001
961 0.00000001
962 0.05
963 0.0005
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965 0.02
966 0.01
967 0.01
968 0.05
969 0.001
970 0.02
971 0.01
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973 0.00000001
974 0.00000001
975 0.008
976 0.005
977 0.00000001
978 0.02
979 0.01

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980 0.08
981 0.005
982 0.0025
983 0.02
984 0.06
985 0.0005
986 0.005
987 0.025
988 0.02
989 0.00000001
990 0.00000001
991 0.01
992 0.008
993 0.00000001
994 0.001
995 0.01
996 0.00000001
997 0.005
998 0.00000001
999 0.00000001
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4 0.50000000
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9 1.00000010
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12 0.50000000
13 0.50000000
14 0.50000000
15 2.00000000
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21 1.30000000
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44 0.20000000
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49 1.00000010
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53 0.20000000

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### (2) AMPL mod-file, Plausible Ranges

```
# save this as DICE_2016_RPE_MonteCarlo.mod to be compatible with the run-file

# PARAMETERS
#Time horizon
param T default 100;
# number of runs for Monte Carlo analysis
param nruns;

# Preferences
param etas {1..nruns}; #I-EMUC consumption
param eta;
param rhos {1..nruns}; #time preference rate
param rho;

# relative prices additions
param zeta=min(Normal(-0.11,0.17),1);

#substitution parameter, first value is central calibration

param beta default 0.1; #share of non-market good in utility function
param EQbar=max(Normal(7.77,3.96),0); #subsistence level of non-market good

param cbar default 0; #subsistence level of consumption per capita

# Discount factor
param R {t in 0..T} = 1*exp(-rho*5*t);

# Population and its dynamics
param L0:=7403; #initial world population 2015 (millions)
param gL0:=0.134; #growthrate to calibrate to 2050 pop projection
param L {t in 0..T}>=0;
let L[0]:=L0;
let {t in 1..T} L[t]:=L[t-1]*((11500/L[t-1])^gL0);

# Technology and its dynamics
param gamma:=0.3; #capital elasticity in production function
param deltaK:=0.1; #depreciation rate on capital (per year)
```

```
param Qgross0:=105.5; #Initial world gross output 2015 (trill 2010 USD)
param K0:=223; #initial capital value 2015 (trillions 2010 USD)
param A0:=5.115; #initial level of total factor productivity
param gA0 :=0.076; #initial growth rate for TFP per 5 years
param deltaA=max(Normal(0.005,0.00255),0); #decline rate of TFP per 5 years

param gA {t in 0..T} := gA0*exp(-deltaA*5*t); # growth rate for TFP per period

param A {t in 0..T}>=0;
let A[0]:=A0;
let {t in 1..T} A[t]:=A[t-1]/(1-gA[t-1]);

# Emission parameters
param gsigma0:=-0.0152;  #initial growth of sigma (coninuous per year )
param deltasigma:=-0.001;  #decline rate of decarbonization per period
param ELand0:=2.6;  #initial Carbon emissions from land 2015 (GtCO2 per period)
param deltaLand:=0.115;  #decline rate of land emissions (per period)
param EInd0:=35.85;  #Industrial emissions 2015 (GtCO2 per year)
param Ecum0:=400;  #Initial cumulative emissions (GtCO2)
param mu0:=.03;  #Initial emissions control rate for base year 2015
param Lambda0:=0;  #Initial abatement costs
param sigma0:=EInd0/(Qgross0*(1-mu0));
#initial sigma (kgCO2 per output 2005 USD in 2010)

param gsigma {t in 0..T};
let gsigma[0]:=gsigma0;
let {t in 1..T} gsigma[t]:=gsigma[t-1]*((1+deltasigma)^5);

param sigma {t in 0..T}>=0;
let sigma[0]:=sigma0;
let {t in 1..T} sigma[t]:=sigma[t-1]*exp(gsigma[t-1]*5);

param ELand {t in 0..T}>=0;
let ELand[0]:=ELand0;
let {t in 1..T} ELand[t]:=ELand [t-1]*(1-deltaLand);

# Carbon cycle
param MAT0=851;  # Initial Concentration in atmosphere 2015 (GtC)
```

```
param MUP0:=460;  # Initial Concentration in upper strata 2015 (GtC)
param MLO0:=1740;  # Initial Concentration in lower strata 2015 (GtC)
param MATEQ:=588;  # Equilibrium concentration in atmosphere (GtC)
param MUPEQ:=360;  # Equilibrium concentration in upper strata (GtC)
param MLOEQ:=1720;  # Equilibrium concentration in lower strata (GtC)

# Flow parameters (carbon cycle transition matrix)

param phi12:=0.12;
param phi23:=0.007;
param phi11=1-phi12;
param phi21=phi12*MATEQ/MUPEQ;
param phi22=1-phi21-phi23;
param phi32=phi23*MUPEQ/MLOEQ;
param phi33=1-phi32;

# Climate model parameters
param nu:=3.1;  # Equilibrium temperature impact (°C per doubling CO2)
param Fex0:=0.5;  # 2015 forcings of non-CO2 GHG (Wm-2)
param Fex1:=1.0;  # 2100 forcings of non-CO2 GHG (Wm-2)
param TLO0:=0.0068;  # Initial lower stratum temperature change (°C from 1900)
param TAT0:=0.85;  # Initial atmospheric temp change (°C from 1900)
param xi1:=0.1005;  # Speed of adjustment parameter for atmospheric temperature
param xi3:=0.088;  # Coefficient of heat loss from atmosphere to oceans
param xi4:=0.025;  # Coefficient of heat gain by deep oceans
param kappa:=3.6813;  # Forcings of equilibrium CO2 doubling (Wm-2)
param xi2=kappa/nu;  # climate model parameter

# external forcing (Wm-2)
# is assumed to be constant and equal to Fex1 from 2100 onward
# see e.g. Traeger (2014, Fig.1)
param Fex {t in 0..T}>=0;
let {t in 0..18} Fex[t]:=Fex0+1/18*(Fex1-Fex0)*(t);
let {t in 19..T} Fex[t]:=Fex1;

# Climate damage parameters
param Psi default 0.00181;  # damage term without 25% adjustment;
# damage quadratic term with 25% adjustment is 0.00236
```

```
param MD default 0.0163; # market damages for 3°C warming (Nordhaus (2017))
param NMD=max(Normal(0.01646,0.0415),0);# non-market damages for 3°C warming
param TD=MD+NMD; # total damages
param TATlim default 12; # upper bound on atm. temperature change

# Abatement cost
param Theta:=2.6;  # Exponent of control cost function
param pback0:=550;  # Cost of backstop 2010 $ per tCO2 2015
param gback:=0.025;  # Initial cost decline backstop cost per period

param pback {t in 0..T}>=0;
let pback[0]:=pback0;
let {t in 1..T} pback[t]:=pback[t-1]*(1-gback);

param phead {t in 0..T}=pback[t]*sigma[t]/Theta/1000;

# VARIABLES

# capital (trillions 2010 USD)
var K {t in 0..T}>=1;

# Gross output (trillions 2010 USD)
var Qgross {t in 0..T}=A[t]*((L[t]/1000)^(1-gamma))*(K[t]^gamma);

# carbon reservoir atmosphere (GtC)
var MAT {t in 0..T}>=10;

# carbon reservoir upper ocean (GtC)
var MUP {t in 0..T}>=100;

# carbon reservoir lower ocean (GtC)
var MLO {t in 0..T}>=1000;

# total radiative forcing (Wm-2)
var F {t in 0..T}=kappa*((log(MAT[t]/MATEQ))/log(2))+Fex[t];

# atmospheric temperature change (°C from 1900)
var TAT {t in 0..T}>=0, <=TATlim;
```

```
# ocean temperature (°C from 1900)
var TLO {t in 0..T}>=-1, <=20;

# damage fraction
var Omega {t in 0..T}=Psi*(TAT[t])^2;

# damages (trillions 2010 USD)
var damage {t in 0..T}=Omega[t]*Qgross[t];

# emission control
var mu {t in 0..T}>=0;

# abatement costs (fraction of output)
var Lambda {t in 0..T}=Qgross[t]*phead[t]*(mu[t]^Theta);

# industrial emissions
var EInd {t in 0..T}=sigma[t]*Qgross[t]*(1-mu[t]);

# total emissions
var E {t in 0..T};

# maximum cumulative extraction fossil fuels (GtC)
var Ecum {t in 0..T}<=6000;

# Marginal cost of abatement (carbon price)
var cprice {t in 0..T}=pback[t]*mu[t]^(Theta-1);

# output net of damages and abatement(trillions 2010 USD)
var Q {t in 0..T}=(Qgross[t]*(1-Omega[t]))-Lambda[t];

# per capita consumption (1000s 2010 USD]
var c {t in 0..T} >= .1;

# aggregate consumption
var C {t in 0..T} = L[t]*c[t]/1000;

# Investment(trillions 2005 USD)
```

```
var I {t in 0..T}>=0;

# Non-market good
var EQ {t in 0..T}>=0.0000001 <=1000;

# Non-market damages scaling parameter including subsistence requirement

# including sub
var a {t in 0..T} =(1/(nu^2))*(EQ[0]*(EQbar+((EQ[0]-EQbar)^(zeta)
+((1-beta)/beta)*(((1-TD)*C[0])^(zeta)-((1-MD)*C[0])^(zeta)))^(1/zeta))^(-1)-1);

# growth rate of market good

var g_C {t in 0..T-1} = (C[t+1]-C[t])/C[t];

# growth rate of non-market good

var g_EQ {t in 0..T-1} = ((EQ[t+1]-EQ[t])/EQ[t]);

# relative price effect

var RPE {t in 0..T-1} =(1-zeta)*(g_C[t]-((EQ[t]/(EQ[t]-EQbar))*g_EQ[t]));

# utility

var U {t in 0..T}= (((1-beta)*(c[t])^(zeta)
+beta*((EQ[t]-EQbar)*1000/L[t])^(zeta))^((1-eta)/zeta))/(1-eta);

# welfare/objective function
var W=sum{t in 0..T} L[t]*U[t]*R[t];

maximize objective_function: W;
subject to initial_consumption:  c[0]=10.4893;
subject to constr_accounting {t in 0..T}:  C[t]=Q[t]-I[t];
subject to constr_emissions {t in 0..T}:  E[t]=EInd[t]+ELand[t];
subject to constr_capital_dynamics {t in 1..T}:
K[t]=(1-deltaK)^5*K[t-1]+5*I[t-1];
subject to constr_cumulativeemissions {t in 1..T}:
```

```
Ecum[t]=Ecum[t-1]+(EInd[t-1]*5/3.666);
subject to constr_atmosphere {t in 1..T}:
MAT[t]=E[t]*(5/3.666)+phi11*MAT[t-1]+phi21*MUP[t-1];
subject to constr_upper_ocean {t in 1..T}:
MUP[t]=phi12*MAT[t-1]+phi22*MUP[t-1]+phi32*MLO[t-1];
subject to constr_lower_ocean {t in 1..T}:
MLO[t]=phi23*MUP[t-1]+phi33*MLO[t-1];
subject to constr_atmospheric_temp {t in 1..T}:
TAT[t]=TAT[t-1]+xi1*((F[t]-xi2*TAT[t-1])-(xi3*(TAT[t-1]-TLO[t-1])));
subject to constr_ocean_temp {t in 1..T}:
TLO[t]=TLO[t-1]+xi4*(TAT[t-1]-TLO[t-1]);

# Initial conditions
subject to initial_capital:  K[0] = K0;
subject to initial_Ecum:  Ecum[0]=Ecum0;
subject to initial_MAT:  MAT[0]=MAT0;
subject to initial_MUP:  MUP[0]=MUP0;
subject to initial_MLO:  MLO[0]=MLO0;
subject to initial_TLO:  TLO[0]=TLO0;
subject to initial_TAT:  TAT[0]=TAT0;
subject to initial_control:  mu[0]=mu0;
subject to control1 {t in 1..28}:  mu[t]<=1;
subject to control2 {t in 29..T}:  mu[t]<=1.2; # from 2150

subject to initial_EQ:  EQ[0]=C[0];
subject to constr_EQ {t in 1..T}:  EQ[t]=(EQ[0]/(1+a[t]*(TAT[t]^2)));
```

**AMPL-run file, Plausible Ranges**

```
# DICE_2016_RPE_MonteCarlo.run
reset;
model DICE_2016_RPE_MonteCarlo.mod;
data random_delta_eta.dat;
option solver knitroampl;
for {i in 1..nruns} {
reset data zeta,deltaA,EQbar,NMD;
let eta:=etas[i];
let rho:=rhos[i];
solve;
display eta,rho,zeta,deltaA,EQbar,NMD;
# Produce csv-file with overview of parameters
printf "%f\t", eta>Results_figure5_parameters.csv;
printf "%f\t", rho>Results_figure5_parameters.csv;
printf "%f\t", zeta>Results_figure5_parameters.csv;
printf "%f\t", deltaA>Results_figure5_parameters.csv;
printf "%f\t", EQbar>Results_figure5_parameters.csv;
printf "%f\n", NMD>Results_figure5_parameters.csv;
# Produce csv-file with data for figure 5
for {t in 0..T-2}{
printf "%f\t", EInd[t]>Results_figure5_Emissions.csv;}
printf "%f\n", EInd[T-1]>Results_figure5_Emissions.csv;;
for {t in 0..T-2}{
printf "%f\t", TAT[t]>Results_figure5_Temperature.csv;}
printf "%f\n", TAT[T-1]>Results_figure5_Temperature.csv;
for {t in 0..T-2}{
printf "%f\t", -1000*constr_emissions[t]/constr_accounting[t]>
Results_figure5_SCC.csv;}
printf "%f\n", -1000*constr_emissions[T-1]/constr_accounting[T-1]>
Results_figure5_SCC.csv;
for {t in 0..T-2}{
printf "%f\t", (((RPE[t]+1)^(1/5))-1)*100>Results_figure5_RPE.csv;}
printf "%f\n", (((RPE[T-1]+1)^(1/5))-1)*100>Results_figure5_RPE.csv;
}
end
```