The effect of health benefits on climate change mitigation policies:

Background document*

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Masako Ikefuji
Department of Environmental and Business Economics, University of Southern Denmark

Jan R. Magnus
Department of Econometrics & Operations Research, VU University Amsterdam

Hiroaki Sakamoto
School of Social Sciences, Waseda University

This document is written to serve as background to our paper 'The effect of health benefits on climate change mitigation policies'. It deals primarily with the calibration of the parameters in our model, but it also discusses the background of some of the equations in the model, and other details that are too lengthy for the paper.

*E-mail addresses: ikefuji@sam.sdu.dk (Ikefuji), jan@janmagnus.nl (Magnus), h.sakamoto4@kurenai.waseda.jp (Sakamoto).

Contents

1 The model

We first recall the model equations. Output $Y_{j,t}$ is produced from capital $K_{j,t}$ and labor $L_{j,t}$ through a Cobb-Douglas production function:

$$Y_{j,t} = \psi_{j,t} K_{j,t}^{\epsilon} L_{j,t}^{1-\epsilon}. \tag{1}$$

Labor is determined by

$$L_{j,t} = (1 - p_{j,t}^c)(1 - p_{j,t}^a) N_{j,t}, \tag{2}$$

where $N_{j,t}$ denotes population. The variables $p_{j,t}^c$ and $p_{j,t}^a$ represent fractions of the population suffering from climate-induced diseases and air-pollution-induced diseases, respectively. We assume $p_{j,t}^c$ and $p_{j,t}^a$ depend on regional temperature $Z_{j,t}$ and regional sulfur dioxide emission $E_{j,t}^a$, respectively:

$$p_{j,t}^c = \beta_{1,j}^c + \beta_{2,j}^c (Z_{j,t})^{\beta_{3,j}^c}, \qquad p_{j,t}^a = \beta_{j,t}^a E_{j,t}^a. \tag{3}$$

Regional temperature is determined through a dynamic equation in which *global* carbon concentration M_t and *regional* sulfur dioxide emission $E_{j,t}^a$ play a role:

$$\begin{aligned} Z_{j,t+1} = {} & \tau_{0,j} + \tau_1 Z_{j,t} + \tau_2 Z_t + \tau_j^c \log(M_{t+1}) \\ & + \tau_{1,j}^a E_{j,t+1}^a + \tau_{2,j}^a \log(1 + \tau_{3,j}^a E_{j,t+1}^a). \end{aligned} \tag{4}$$

Here, $Z_t = \sum_j \omega_j Z_{j,t}$ denotes global temperature, and ω_j is the fraction of landmass in region j compared to world landmass.

Global carbon concentration is given by

$$M_{t+1} = (1 - \delta^c) M_t + \sum_j E_{j,t}^c, \tag{5}$$

where $E_{j,t}^c$ denotes regional carbon emission. Carbon and sulfur emissions are determined by

$$\begin{pmatrix} E_{j,t}^c \\ E_{j,t}^a \end{pmatrix} = \begin{pmatrix} \sigma_{j,t}^{cc} & \sigma_{j,t}^{ca} \\ \sigma_{j,t}^{ac} & \sigma_{j,t}^{aa} \end{pmatrix} \begin{pmatrix} 1 - \mu_{j,t}^c \\ 1 - \mu_{j,t}^a \end{pmatrix} Y_{j,t}, \tag{6}$$

where $\mu_{j,t}^c$ and $\mu_{j,t}^a$ denote the emission control rates of carbon dioxide and sulfur dioxide, respectively.

The damage $D_{j,t}$ due to climate change (excluding health impacts) is subtracted from the gross output. The net output $Y_{j,t} - D_{j,t}$ can then be spent on consumption $C_{j,t}$, investment $I_{j,t}$, or emission abatement $A_{j,t}$:

$$Y_{j,t} - D_{j,t} = C_{j,t} + I_{j,t} + A_{j,t}. \tag{7}$$

We specify the damage as

$$\frac{D_{j,t}}{Y_{j,t}} = \frac{d_{j,t}}{1+d_{j,t}}, \qquad d_{j,t} = \gamma_{1,j} Z_{j,t} + \gamma_{2,j}(Z_{j,t})^2. \tag{8}$$

Abatement cost is given by

$$\frac{A_{j,t}}{Y_{j,t}} = \alpha^c_{j,t}(\mu^c_{j,t})^{\xi^c} + \alpha^a_{j,t}(\mu^a_{j,t})^{\xi^a}. \tag{9}$$

The capital accumulation process is given by

$$K_{j,t+1} = (1-\delta^k)K_{j,t} + I_{j,t}. \tag{10}$$

Finally, we define regional welfare W_j by

$$W_j = \sum_t \frac{1}{(1+\rho)^t} L_{j,t} \log(1 + C_{j,t}/N_{j,t}), \tag{11}$$

so that welfare is determined not only by per capita consumption C/N but also by the fraction of healthy people L/N in the region.

2 Differential form of the model

To better understand the mechanism of the model we also present it in condensed differential form. This gives

$$(dY_{j,t}) = \frac{\partial Y_{j,t}}{\partial K_{j,t}}(dK_{j,t}) + \frac{\partial Y_{j,t}}{\partial L_{j,t}}(dL_{j,t})$$

and

$$(dL_{j,t}) = \frac{\partial L_{j,t}}{\partial p^c_{j,t}}\frac{\partial p^c_{j,t}}{\partial Z_{j,t}}(dZ_{j,t}) + \frac{\partial L_{j,t}}{\partial p^a_{j,t}}\frac{\partial p^a_{j,t}}{\partial E^a_{j,t}}(dE^a_{j,t})$$

for output and labor, and

$$\begin{aligned}(dK_{j,t+1}) &= (C_{j,t}/Y_{j,t} + I_{j,t}/Y_{j,t})(dY_{j,t}) - (dC_{j,t}) + (1-\delta^k)(dK_{j,t}) \\ &\quad - \frac{\partial D_{j,t}}{\partial Z_{j,t}}(dZ_{j,t}) - \frac{\partial A_{j,t}}{\partial \mu^c_{j,t}}(d\mu^c_{j,t}) - \frac{\partial A_{j,t}}{\partial \mu^a_{j,t}}(d\mu^a_{j,t}), \\ (dM_{t+1}) &= (1-\delta^c)(dM_t) + (dE^c_{j,t}),\end{aligned}$$

and

$$(dZ_{j,t+1}) = (\tau_1 + \tau_2\omega_j)(dZ_{t,j}) + \frac{\partial Z_{j,t+1}}{\partial M_{t+1}}(dM_{t+1}) + \frac{\partial Z_{j,t+1}}{\partial E^a_{j,t+1}}(dE^a_{j,t+1})$$

for the three dynamic equations, where

$$(dE^c_{j,t}) = -\sigma^{cc}_{j,t}Y_{j,t}(d\mu^c_{j,t}) - \sigma^{ca}_{j,t}Y_{j,t}(d\mu^a_{j,t}) + (E^c_{j,t}/Y_{j,t})(dY_{j,t})$$

and

$$(dE^a_{j,t}) = -\sigma^{ac}_{j,t}Y_{j,t}(d\mu^c_{j,t}) - \sigma^{aa}_{j,t}Y_{j,t}(d\mu^a_{j,t}) + (E^a_{j,t}/Y_{j,t})(dY_{j,t}).$$

Important is the relationship between output Y and labor L. More labor leads to more output through the production function. More output leads to more air pollution, more asthma, and less labor. Hence, output and labor are determined simultaneously.

3 Variables and parameters

The model equations include endogenous and exogenous variables, and parameters. The endogenous variables are determined by the model (apart from three initial values), but the exogenous variables and the parameters must by calibrated. Before we discuss how we have done this, we list the variables and parameters required.

The variables in the model (with description and unit of measurement) are listed in Table 1; the parameters in Table 2. In the two tables we either provide the calibrated values or refer to another table or equation. The initial values are given in Table 3 for capital. The initial value for regional temperature $Z_{j,0}$ is normalized to zero, which is allowed because there is a constant $\tau_{0,j}$ taking care of the regional differences. The initial value $M_0 =$ 809.4.

3.1 Control variables

Consumption: $C_{j,t}$
Abatement fractions: $\mu^c_{j,t}$, $\mu^a_{j,t}$

3.2 Endogenous variables

Dynamic variables: $K_{j,t+1}$, $Z_{j,t+1}$, M_{t+1}
Output and labor: $Y_{j,t}$, $L_{j,t}$
Investment: $I_{j,t}$
Abatement cost: $A_{j,t}$

Damage: $D_{j,t}$, $d_{j,t}$
Emissions: $E^c_{j,t}$, $E^a_{j,t}$
Fractions of people with disease: $p^c_{j,t}$, $p^a_{j,t}$
Global temperature: Z_t
Welfare: W_j

3.3 Exogenous variable

Population: $N_{j,t}$

3.4 Initial values

Initial values: $K_{j,0}$, $Z_{j,0}$, M_0

3.5 Parameters

Time dimension: $T = 40$ (2005–2200; one period is five years)
Region dimension: $J = 11$
Global parameters: ϵ, ρ, ξ^c, ξ^a, δ^c, δ^k
Disease: $\beta^c_{1,j}$, $\beta^c_{2,j}$, $\beta^c_{3,j}$, $\beta^a_{j,t}$
Damage: $\gamma_{1,j}$, $\gamma_{2,j}$
Abatement: $\alpha^c_{j,t}$, $\alpha^a_{j,t}$
Temperature: $\tau_{0,j}$, τ_1, τ_2, τ^c_j, $\tau^a_{1,j}$, $\tau^a_{2,j}$, $\tau^a_{3,j}$
Land weights: ω_j
Production efficiency: $\psi_{j,t}$
Emissions: $\sigma^{cc}_{j,t}$, $\sigma^{ca}_{j,t}$, $\sigma^{ac}_{j,t}$, $\sigma^{aa}_{j,t}$

4 Definition of the regions

4.1 Our regions

We consider a world consisting of the following eleven regions:

USA (USA and Canada): United States of America, and Canada

EUR (Western Europe): Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, and United Kingdom

JPN (Japan): Japan

AUS (Australia and Oceania): Australia, Fiji, Kiribati, New Caledonia, New Zealand, Papua New Guinea, Polynesia, Samoa, Solomon Islands, Tonga, and Vanuatu

FSU (Former Soviet Union and Eastern Europe): Albania, Armenia, Azerbaijan, Belarus, Bosnia and Herzegovina, Georgia, Greenland, Kazakhstan, Kyrgyzstan, Macedonia, Moldova, Montenegro, Russia, Serbia, Tajikistan, Turkmenistan, Ukraine, and Uzbekistan

CHN (China and centrally planned Asia): China, Laos, Macao, Mongolia, and Vietnam

IND (India and South Asia): Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, and Sri Lanka

SEA (South East Asia): Brunei, East Timor, Indonesia, South Korea, Malaysia, Myanmar, Philippines, Singapore, and Thailand

LAM (Latin America and Caribbean): Argentina, Bahamas, Barbados, Belize, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominican Republic, Ecuador, El Salvador, Guatemala, Guyana, Haiti, Honduras, Jamaica, Mexico, Nicaragua, Panama, Paraguay, Peru, Suriname, Trinidad and Tobago, Uruguay, and Venezuela

MEN (Middle East and North Africa): Algeria, Bahrain, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libyan Arab Jamahiriya, Morocco, Oman, Quatar, Saudi Arabia, Sudan, Syrian Arab Republic, Tunisia, United Arab Emirates, and Yemen

AFR (Sub-Sahara Africa): Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Central African Republic, Chad, Comoros, Democratic Republic of Congo, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, Sierra Leone, Somalia, South Africa, Swaziland, Togo, Uganda, Tanzania, Zambia, and Zimbabwe

This regional specification is based on IPCC (2000) and WHO (2003). Table 4 provides some characteristics of each region.

4.2 Comparison with RICE regions

The RICE model of Nordhaus and Yang (1996) considers 10 regions The first 6 are: USA, Japan, China, European Union, the former Soviet Union, and India The other 4 regions are: Brazil and Indonesia, 11 large countries, 38 medium-sized countries, and 137 small countries. For our purpose, this 10-region world is less suitable, because of the large heterogeneous remainder groups. Homogeneity of regions is essential to us, particularly in calibrating the health equations.

Nordhaus and Boyer (2000) define 8 regions: USA, China, OECD Europe, Russia and Eastern Europe, and four income groups: Other high income (Japan, Canada, Australia, etc), Middle income (Brazil, South Korea, etc., and high income OPEC), Lower middle income, and low income.

Slightly better in this respect is the 12-region RICE model of Nordhaus (2010). Here the first 6 regions are: USA, Japan, China, European Union, Russia, and India. And the other 6 regions are: Eurasia, Middle East, Africa, Latin America, Other high income regions, and Other developing regions in Asia. This division of the world is closer to what we would require than the 10 regions of Nordhaus and Yang (1996), but still there are two heterogeneous remainder groups. This is why we have defined our own set of 11 regions.

5 Calibration

5.1 Damage function

Our damage function is based on RICE model of Nordhaus (2010). In the RICE model, however, health impacts of temperature change are already incorporated in the damage function. To avoid double counting of health impacts, we recalibrate the damage function. Let $D_j^*(Z_{j,t})$ be the original damage function in RICE model, and let $H_j(Z_{j,t})$ be the health impacts estimated by Nordhaus and Boyer (2000). We calibrate our damage function $D_j(Z_{j,t})$ such that

$$D_j(Z_{j,t}) = D_j^*(Z_{j,t}) - H_j(Z_{j,t}), \tag{12}$$

for each j. As is clear from Figures 2 and 3, the recalibrated damage in our model is smaller than the original RICE model, as of course it should be.

5.2 Climate-induced health impacts

Our climate-induced disease function is calibrated based on McMichael *et al.* (2004). They estimate the associated increase or decrease of disease burden in different regions under alternative projections of climate change in the future. The estimates are provided in terms of relative risk, which is defined as the likely proportional change in the burden of each disease, compared to the situation if climate change were not to occur. For instance, they estimate that the relative risk of malaria will be 1.14 in AFR-E region (a group of African countries with high vulnerability) in 2030 under the scenario of no climate policy. This means the disease burden of malaria in the region will increase by 14% due to climate change.

Let $\mathrm{RR}_{i,t}^d$ be the relative risk of disease d in region i at period t. Here, we use i for the index of region because regional specification of McMichael *et al.* (2004) is different from ours. As an approximation, we assume the following relationship between relative risk and temperature change:

$$\mathrm{RR}_{i,t}^d = 1 + \eta_{1,i}^d \left(Z_{i,t}\right)^{\eta_{2,i}^d} . \tag{13}$$

Using the estimates (Tables 20.8, 20.9, 20.10, and 20.15) of McMichael *et al.* (2004), we arrive at the parameter values given in Table 5. As is illustrated in the table, climate change will bring some health benefits, such as lower cold-related mortality (due to cardiovascular disease), but the benefits will be greatly outweighed by increased rates of other diseases, particularly infectious diseases and malnutrition in developing regions.

Following WHO (2008a), we measure the burden of disease by disability-adjusted life years lost (DALYs) due to diseases. To be more precise, we define $p_{j,t}^c$ by DALYs per capita:

$$p_{j,t}^c = \frac{\mathrm{DALY}_{j,t}}{N_{j,t}}, \qquad \mathrm{DALY}_{j,t} = \sum_d \mathrm{DALY}_{j,t}^d, \tag{14}$$

where $\mathrm{DALY}_{j,t}^d$ is the DALYs of diseases d in region j at period t. DALYs measures how many life years will be lost due to diseases. One unit of DALY of malaria, for example, means that one life year of a person is lost due to malaria. Mortality and morbidity are counted with different weights. To calibrate the initial value of $p_{j,t}^c$, we use the estimate of age-standardized DALYs by country provided by WHO (2008a).

Using the estimated relative risk function, we obtain

$$\begin{aligned} \mathrm{DALY}_{i,t}^d &= \mathrm{DALY}_{i,0}^d \times \mathrm{RR}_{i,t}^d \\ &= \mathrm{DALY}_{i,0}^d + \mathrm{DALY}_{i,0}^d \eta_{1,i}^d \left(Z_{i,t}\right)^{\eta_{2,i}^d} , \end{aligned} \tag{15}$$

for each WHO region. We then compute the corresponding $\mathrm{DALY}_{j,t}^d$ in each region j of our 11-region framework based on population weights $\chi_{i,j}$. Then the fraction of life years lost due to climate-induced diseases can be computed as

$$p_{j,t}^c = p_{j,0}^c + p_{j,0}^c \sum_d \sum_i \chi_{i,j} \eta_{1,i}^d \left(Z_{j,t}\right)^{\eta_{2,i}^d} . \tag{16}$$

Based on this damage estimate, we arrive at the climate-induced disease function

$$p^c_{j,t} = \beta^c_{1,j} + \beta^c_{2,j}(Z_{j,t})^{\beta^c_{3,j}}, \tag{17}$$

which is illustrated in Figure 4.

As is pointed out by McMichael *et al.* (2004), the effects of climate change are predicted to be heavily concentrated in poorer regions (Africa and India), where the most important climate-sensitive health outcomes are already common, and where vulnerability to climate effects is greatest.

The expected health damage in Africa is mainly due to malaria. While we estimate large changes in the relative risk of malaria in regions at the edge of the current distribution of malaria ($\eta^d_{1,i}$ is larger in Asia and Latin America), the baseline disease burden is much larger in Africa ($\text{DALY}_{i,0}$ is very large in Africa). As a result, most of the additional malaria burden is expected in Africa. The damage in India, on the other hand, comes from a more diverse set of sources: diarrhoea and malnutrition, as well as malaria. As is shown in Table 5, the relative risk functions of diarrhoea and malnutrition are more concave than that of malaria. This is why the health damage function of India is more concave while the health damage in Africa is almost linear in temperature change.

It is worth noting that we take the current DALYs per capita, $p^c_{j,0}$, as a baseline for each region, independent of regional economic development in the future. This is because we think it is highly uncertain how future DALYs in a region change as the region develops. Technically, we could specify the relationship between DALYs and economic growth in the model. But it will be rather arbitrary.

5.3 Air-pollution-induced health impacts

Our air-pollution-induced disease function is calibrated based on Spadaro and Rabl (1999), who estimated health impacts of several air pollutants based on the impact pathway approach. They showed that, although uncertainty remains, the damage of air pollution can be well represented by a simple formula. In particular, they estimated the typical damage cost per tonne of sulfur dioxide, which then can be converted to DALYs. We estimate that the marginal damage in terms of DALYs per capita is 0.00042 per teragram of sulfur dioxide.

Moreover, in order to capture regional differences, we take into account urbanization and population density. Predicted trends of urbanization around the world are provided by United Nations (2009). We assume the marginal damage of sulfur emission is 2 times larger when all of the population lives in urbanized areas. This is a conservative estimate compared with Holland *et al.* (1998), who suggest that the marginal impact could be 5 to 15 times larger in highly urbanized areas. Since the estimation of Spadaro and Rabl (1999) assumes population density of 80 persons/km^2, we also adjust the marginal impact of sulfur emission by factor of $\mathrm{PD}_j/80$, where PD_j is population density in urban areas in region j. Data of population density is taken from CIESIN (2005).

Hence, we assume the following relationship:

$$p^a_{j,t} = \frac{\mathrm{DALY}_{j,t}}{N_{j,t}} = \beta^a_0 \frac{\mathrm{PD}_j}{80} \left[(1 - r_{j,t}) + \nu r_{j,t}\right] E^a_{j,t}, \tag{18}$$

where $\beta^a_0 = 0.0002385$ is the marginal damage in terms of DALYs per capita (excluding the effect of population density), $r_{j,t} \in [0, 1]$ is the urbanization ratio (fraction of population living in urban areas), and $\nu = 2$ is a scaling factor for the damage in highly urbanized areas. Note that if we assume one unit of DALY is worth 3 times the per capita output as suggested in WHO (2001), (18) can be converted to

$$\text{Monetary cost of } \mathrm{SO_2} \text{ in terms of euro} = 10.2 \times 10^9 \times E^a_{j,t}, \tag{19}$$

for Europe in 2005, where we assume 1 euro is worth 1.2 dollars. This equation matches the estimate of Spadaro and Rabl (1999).

By defining

$$\beta^a_{j,t} = \beta^a_0 (\mathrm{PD}_j/80) \left[(1 - r_{j,t}) + \nu r_{j,t}\right], \tag{20}$$

we arrive at

$$p^a_{j,t} = \beta^a_{j,t} E^a_{j,t}, \tag{21}$$

which is illustrated in Figure 5. As is clear from the figure, developing regions with high population density are relatively more vulnerable to air pollution.

In Figure 5, urbanization ratio $r_{j,t}$ is fixed at $r_{j,0}$ for illustration. Since we assume $r_{j,t}$ changes over time, the marginal impact of sulfur emission changes over time. The projected urbanization ratio is given by United Nations (2009) up to 2050. We assume $r_{j,t}$ grows exponentially and converges to 0.95 around 2200. The parameters controlling growth rate of $r_{j,t}$ are chosen such that the UN projection is replicated at each period until 2050. The calibrated trend is shown in Figure 6.

5.4 Population

As a reference point of calibration of the economic modules, we use the Intergovernmental Panel on Climate Change SRES A2 marker scenario (IPCC, 2000). This scenario is characterized by relatively slow economic growth, large population growth, and delayed development of renewable energy. We choose the A2 scenario because relatively less stringent sulfur control is assumed in this scenario, and thus the implementation of air-pollution reduction policies is left to decision makers.

Since all of the SRES scenarios use a 4-region framework, the population projection of A2 scenario is provided only in a highly aggregated level. But a downscaled data is prepared by Center for International Earth Science Information Network of Columbia University (CIESIN, 2002). Based on their country-level data, we reconstruct A2 scenario projection for eleven regions in our framework. The calibrated population trend is shown in Figure 7.

5.5 Emission intensities

Our emission equations are given by

$$E^c_{j,t} = \sigma^{cc}_{j,t}(1 - \mu^c_{j,t})Y_{j,t} + \sigma^{ca}_{j,t}(1 - \mu^a_{j,t})Y_{j,t}, \tag{22}$$

$$E^a_{j,t} = \sigma^{ac}_{j,t}(1 - \mu^c_{j,t})Y_{j,t} + \sigma^{aa}_{j,t}(1 - \mu^a_{j,t})Y_{j,t}, \tag{23}$$

where we assume $\sigma^{ca}_{j,t} = 0$ for all regions. Suppose a climate policy $\mu^c_{j,t} > 0$ is implemented without introducing additional sulfur control policy (i.e., $\mu^a_{j,t} = 0$). Let $\mu^{ac}_{j,t}$ be the reduction rate of sulfur dioxide due to this climate policy, that is

$$\mu^{ac}_{j,t} = \frac{\left[\sigma^{aa}_{j,t}Y_{j,t} + \sigma^{ac}_{j,t}Y_{j,t}\right] - \left[\sigma^{aa}_{j,t}Y_{j,t} + \sigma^{ac}_{j,t}(1 - \mu^c_{j,t})Y_{j,t}\right]}{\sigma^{aa}_{j,t}Y_{j,t} + \sigma^{ac}_{j,t}Y_{j,t}}, \tag{24}$$

or

$$\frac{\sigma^{ac}_{j,t}}{\sigma^{aa}_{j,t}} = \frac{\mu^{ac}_{j,t}/\mu^c_{j,t}}{1 - \mu^{ac}_{j,t}/\mu^c_{j,t}}. \tag{25}$$

Note that $\mu^{ac}_{j,t}/\mu^c_{j,t}$ represents how much sulfur emission is reduced due to carbon reduction policies. We first estimate $\mu^{ac}_{j,t}/\mu^c_{j,t}$ for developed regions (OECD countries) and developing regions (China and India) based on Bollen *et al.* (2009), which is then used to compute $\sigma^{ac}_{j,t}/\sigma^{aa}_{j,t}$ by (25). We assume the calibrated ratios $\sigma^{ac}_{j,t}/\sigma^{aa}_{j,t}$ of OECD and China and India can be extrapolated to other developed and developing regions as well.

In the baseline scenario, we normalize $\mu^c_{j,t} = \mu^a_{j,t} = 0$. Hence, our emission equations in the baseline scenario can be written as

$$\sigma^{cc}_{j,t} = \frac{E^c_{j,t}}{Y_{j,t}}, \qquad \sigma^{aa}_{j,t} = \left[\frac{1}{1 + \sigma^{ac}_{j,t}/\sigma^{aa}_{j,t}}\right] \frac{E^a_{j,t}}{Y_{j,t}}. \tag{26}$$

Then, given the calibrated trend of $\sigma^{ac}_{j,t}/\sigma^{aa}_{j,t}$, both $\sigma^{cc}_{j,t}$ and $\sigma^{aa}_{j,t}$ can be computed from a downscaled version of SRES A2 scenario. The downscaled output data is taken from CIESIN (2002). We construct a region-level emission projection under SRES A2 scenario based on EPA98 5i scenario, which uses the same Atmospheric Stabilization Framework model with similar assumptions to A2 scenario (Sankovski, 1998). To downscale emission scenario, we use the methodology of Gaffin *et al.* (2004). The calibrated trends of $\sigma^{cc}_{j,t}$ and $\sigma^{aa}_{j,t}$ are shown in Figures 8 and 9. Finally, we plug $\sigma^{aa}_{j,t}$ back into (25) to obtain $\sigma^{ac}_{j,t}$ (Figure 10).

5.6 Abatement cost

Abatement cost is given by

$$A_{j,t} = \alpha^c_{j,t}\left(\mu^c_{j,t}\right)^{\xi^c} Y_{j,t} + \alpha^a_{j,t}\left(\mu^a_{j,t}\right)^{\xi^a} Y_{j,t}, \tag{27}$$

where we assume $\xi^c = \xi^a = 2.8$ based on Nordhaus (2010). As for $\alpha^c_{j,t}$ and $\alpha^a_{j,t}$, first notice that the marginal abatement cost is computed by

$$-\frac{\partial A_{j,t}}{\partial E^c_{j,t}} = -\frac{\partial A_{j,t}}{\partial \mu^c_{j,t}}\frac{\partial \mu^c_{j,t}}{\partial E^c_{j,t}} - \frac{\partial A_{j,t}}{\partial \mu^a_{j,t}}\frac{\partial \mu^a_{j,t}}{\partial E^c_{j,t}}, \tag{28}$$

$$-\frac{\partial A_{j,t}}{\partial E^a_{j,t}} = -\frac{\partial A_{j,t}}{\partial \mu^c_{j,t}}\frac{\partial \mu^c_{j,t}}{\partial E^a_{j,t}} - \frac{\partial A_{j,t}}{\partial \mu^a_{j,t}}\frac{\partial \mu^a_{j,t}}{\partial E^a_{j,t}}. \tag{29}$$

Recall that the emission equations can be rewritten as

$$\mu^c_{j,t} = 1 - \frac{E^c_{j,t}}{\sigma^{cc}_{j,t} Y_{j,t}}, \tag{30}$$

$$\mu^a_{j,t} = 1 - \frac{1}{\sigma^{aa}_{j,t}}\left[\frac{E^a_{j,t}}{Y_{j,t}} - \frac{\sigma^{ac}_{j,t}}{\sigma^{cc}_{j,t}}\frac{E^c_{j,t}}{Y_{j,t}}\right], \tag{31}$$

and thus

$$-\frac{\partial A_{j,t}}{\partial E^c_{j,t}} = \frac{\xi^c \alpha^c_j \left(\mu^c_{j,t}\right)^{\xi^c - 1}}{\sigma^{cc}_{j,t}} - \frac{\sigma^{ac}_j \xi^a \alpha^a_j \left(\mu^a_{j,t}\right)^{\xi^a - 1}}{\sigma^{aa}_{j,t}\sigma^{cc}_{j,t}}, \tag{32}$$

$$-\frac{\partial A_{j,t}}{\partial E^a_{j,t}} = \frac{\xi^a \alpha^a_j \left(\mu^a_{j,t}\right)^{\xi^a - 1}}{\sigma^{aa}_{j,t}}. \tag{33}$$

Along the baseline path, the marginal abatement cost of 'last drop of carbon emission' is

$$-\left.\frac{\partial A_{j,t}}{\partial E^c_{j,t}}\right|_{\mu^c_{j,t}=1, \mu^a_{j,t}=0} = \frac{\xi^c \alpha^c_j}{\sigma^{cc}_{j,t}}. \tag{34}$$

This must be equal to the price of backstop technology, $m_{j,t}$, which is estimated by Nordhaus (2010). Then we can compute $\alpha^c_{j,t}$ by

$$\alpha^c_{j,t} = \frac{\sigma^{cc}_{j,t}}{\xi^c} m_{j,t}. \tag{35}$$

The price of backstop technologies will decline over time:

$$m_{j,t} = m_{j,0} \left[\upsilon + (1-\upsilon)(1-g^m)^t \right], \tag{36}$$

where g^m is the decline rate of $m_{j,t}$ and $\upsilon \in (0,1)$ controls the price of backstop technologies in the far distant future. We assume $\upsilon = 0.1$ and $g^m = 0.0246$ based on Nordhaus (2010).

As for sulfur abatement cost, note that some sulfur mitigation measures are already assumed in the A2 scenario. This means that calibration of sulfur abatement cost needs to reflect these baseline sulfur mitigation activities. Since we calibrate sulfur intensity of output under the normalization of $\mu^a_{j,t} = 0$, the default sulfur reduction policies are all captured by $\sigma^{aa}_{j,t}$. In order to take advantage of this fact, we first construct a global (averaged) marginal abatement curve, and then differentiate the marginal abatement cost across regions based on the calibrated value of $\sigma^{aa}_{j,t}$.

Our construction of global marginal abatement cost curve is based on Bahn and Leach (2008). We approximate the global marginal abatement cost curve by

$$\text{MAC}^a(\mu^a) = \frac{\xi^a \alpha^a \left(\mu^a\right)^{\xi^a - 1}}{\bar{\sigma}^{aa}}, \tag{37}$$

where $\bar{\sigma}^{aa} = 0.0934$ is the output-weighted average of sulfur intensity $\sigma^{aa}_{j,0}$. Then we choose the value of α^a such that the global marginal abatement cost curve in Bahn and Leach (2008) is replicated.

We also assume the sulfur abatement cost will decline over time in a similar way to carbon mitigation cost. More precisely, we assume

$$\alpha^a_{j,t} = \alpha^a_t = \alpha^a \left[\upsilon + (1-\upsilon)(1-g^m)^t \right]. \tag{38}$$

Then we plug this back into the marginal abatement cost function of each region. As a result, the marginal abatement cost of sulfur dioxide is given by

$$-\frac{\partial A_{j,t}}{\partial E^a_{j,t}} = \frac{\xi^a \alpha^a_t \left(\mu^a_{j,t}\right)^{\xi^a - 1}}{\sigma^{aa}_{j,t}}. \tag{39}$$

Notice that this marginal abatement cost function depends on $\sigma^{aa}_{j,t}$, which captures the default sulfur mitigation activities. Hence, the abatement costs are differentiated across regions, depending on how stringent sulfur control measures are taken under A2 scenario. The calibrated marginal abatement cost curve is shown in Figure 11.

5.7 Temperature

We follow, in essence, the approach used in version 5.1 of the MERGE model, originally developed by Manne and Richels (1995) in the spirit of Budyko (1969) and Sellers (1969). We specify regional temperature dynamics as

$$Z_{j,t+1} - Z_{j,t} = \zeta_{0,j} + \zeta_1 \left(X^c_{j,t+1} - Z_{j,t} \right) + X^a_{j,t+1} + \zeta_2 \left(Z_t - Z_{j,t} \right), \tag{40}$$

where $X^c_{j,t}$ denotes the potential temperature due to carbon concentration and $X^a_{j,t}$ represents the regional cooling effect of sulfur emission. Possible interaction between temperatures in different regions can be captured by $\zeta_2 > 0$. We assume $\zeta_2 = 0.1$ since the impact of dimming is primarily local (Magnus *et al.*, 2011).

We define $X^c_{j,t}$ by

$$X^c_{j,t} - Z_{j,0} = \lambda \phi_j F^c_t, \qquad F^c_t = F^c_{\times 2} \frac{\log(M_t/M_{1750})}{\log(2)}, \tag{41}$$

where λ is the climate sensitivity and F^c_t is the radiative forcing from carbon concentration M_t. According to global circulation analyses, temperature will not uniformly change around the world (Manne *et al.*, 1995). This fact is captured by ϕ_j, which satisfies $\sum_j \omega_j \phi_j = 1$. We choose the values of ϕ_j based on Schlesinger *et al.* (2000).

We construct $X^a_{j,t}$ based on Harvey *et al.* (1997), who suggest that the radiative forcing $F^a_{j,t}$ of sulfur emission is determined by

$$F^a_{j,t} = q_j \left[F^{a,dir}_{1990} \frac{E^a_{j,t}}{E^a_{j,1990}} + F^{a,ind}_{1990} \frac{\log(1 + \tau_j E^a_{j,t})}{\log(1 + \tau_j E^a_{j,1990})} \right], \tag{42}$$

where $F^{a,dir}_{1990}$ and $F^{a,ind}_{1990}$ are direct and indirect radiative forcings of sulfur in 1990 at global level. The global radiative forcing is decomposed into regional radiative forcing according to regional contribution to global sulfur emission in the base year (i.e., 1990). This is done by defining q_j by

$$q_j = E^a_{j,1990} \Big/ \sum_j E^a_{j,1990}. \tag{43}$$

Then, as in MERGE, we define $X^a_{j,t}$ by

$$X^a_{j,t} = \lambda \left(F^a_{j,t} - F^a_{j,0} \right). \tag{44}$$

Combining terms we arrive at our temperature equation:

$$\begin{aligned} Z_{j,t+1} = {} & \tau_{0,j} + \tau_1 Z_{j,t} + \tau_2 Z_t + \tau^c_j \log(M_{t+1}) \\ & + \tau^a_{1,j} E^a_{j,t+1} + \tau^a_{2,j} \log(1 + \tau^a_{3,j} E^a_{j,t+1}). \end{aligned} \tag{45}$$

This equation resembles the corresponding temperature equations (10) and (11) in Magnus *et al.* (2011), but (a) the timing of the impact of M_t and $E^a_{j,t}$ is adjusted because we consider five-year periods (not one-year periods); (b) the coefficients of the M_t and $E^a_{j,t}$ equations are region-specific in our case; and (c) the impact function of $E^a_{j,t}$ is slightly different. Without loss of generality we may assume that all temperatures are normalized so that $Z_{j,0} = 0$ in every region. This only affects the calibration and interpretation of the constant term $\tau_{0,j}$. This assumption will be made throughout.

The simulated temperature change under IPCC A2 scenario is plotted in Figure 12. The simulated global and regional temperature changes are close to those reported in Schlesinger *et al.* (2000). To see the impact of sulfur emission, we decompose the total temperature change into two parts: temperature change due to carbon concentration, and temperature change due to sulfur emission. The former is computed by fixing sulfur emission at the level of initial period, and the latter is defined as the difference between total change and carbon-induced change. The computed temperature change due to sulfur emission is shown in Figure 13.

We choose the value of carbon depreciation rate, δ^c, such that the carbon concentration under A2 scenario will be around 1780 GtC or 836 ppmv at the end of this century (Schlesinger *et al.*, 2000).

5.8 Initial values of stock variables

Carbon concentration of initial period $M_0 = 809.4$ is taken from Keeling *et al.* (2001). By definition, $Z_{j,0}$ is normalized to zero, and thus $Z_0 = \sum_j \omega_j Z_{j,0} = 0$. The initial value of capital $K_{j,0}$ is computed by the standard arbitrage condition:

$$\frac{\epsilon Y_{j,0}}{K_{j,0}} - \delta_1^k = i_1, \tag{46}$$

where i_1 is interest rate (annual value) and δ_1^k is the annualized value of capital depreciation rate. The left hand side of this equation is the net marginal output of investment. Following Nordhaus (2010), we set $i_1 = 0.05$ for all regions. The calibrated values of $K_{j,0}$ are listed in Table 3.

Following Nordhaus (2010), we set $\epsilon = 0.3$, $\delta^k = 0.41$, and $\delta_1^k = 0.10$.

5.9 Welfare and productivity

We define regional welfare W_j by

$$W_j = \sum_t \frac{1}{(1+\rho)^t} N_{j,t} \,\mathrm{E}\left[U_{j,t}\right], \tag{47}$$

where the expectation operator is to be interpreted as

$$\mathrm{E}\left[U_{j,t}\right] = (1 - p_{j,t})u_{j,t} + p_{j,t}u_{j,t}^{d}, \tag{48}$$

where $p_{j,t}$ denotes the probability of losing healthy life due to diseases, so that

$$1 - p_{j,t} = (1 - p_{j,t}^{c})(1 - p_{j,t}^{a}) = \frac{L_{j,t}}{N_{j,t}},$$

and $u_{j,t}^{d}$ denotes the utility for that incident. We normalize $u_{j,t}^{d} = 0$. The utility of healthy individuals is $u_{j,t}$, defined as

$$u_{j,t} = \log(1 + C_{j,t}/N_{j,t}). \tag{49}$$

Combining terms we find

$$W_j = \sum_{t} \frac{1}{(1+\rho)^t} L_{j,t} \log(1 + C_{j,t}/N_{j,t}). \tag{50}$$

Following Nordhaus and Yang (2000), we assume $\rho = 0.159$, the annualized value of which is 0.030.

The final step of the calibration is to choose $\psi_{j,t}$, the exogenous trends of total factor productivity. We compute the baseline solution of our model iteratively to find the value for this parameter which minimizes the squared sum of differences between the baseline solution and IPCC A2 scenario. In this process, we especially focus on output and emissions.

We define the baseline solution as a set of control variables which maximize the time-variant Negishi-weighted social welfare

$$W = \sum_{t} \sum_{j} \frac{1}{(1+\rho)^t} \theta_{j,t} N_{j,t}\, \mathrm{E}\left[U_{j,t}\right], \tag{51}$$

under the constraint that $\mu_{j,t}^{c} = \mu_{j,t}^{a} = 0$ for all j and all t. Here, $\theta_{j,t}$ denotes Negishi weight for region j at period t. The procedure of computing Negishi weights is explained in Nordhaus and Yang (1996). The result of this calibration process is shown in Figure 14. The performance of the calibrated model can be seen in Figures 15 to 17. In the figures, dotted lines with markers indicate the projection under IPCC A2 scenario while solid lines without markers indicate the baseline solution of the calibrated model.

6 Results for the two policy scenarios

In reporting our results we focus on six variables:

output $Y_{j,t}$,
temperature $Z_{j,t}$,
CO_2 emissions $E^c_{j,t}$,
SO_2 emissions $E^a_{j,t}$,
probability of CO_2-induced disease: $p^c_{j,t}$, and
probability of SO_2-induced disease: $p^a_{j,t}$.

The development over time is given in Figures 18 to 29.

7 Sensitivity analysis

Our model parameters are carefully calibrated, but their values remain uncertain. In this section we analyze the sensitivity of our results to changes in the assumed parameter values. It turns out that our results are fairly robust. The equilibrium path does not change much when we use different values for the exogenous parameters. Hence, in general, the uncertainty surrounding parametrization does not appear to entail a serious problem in our model. Yet, some of the uncertain parameters play more important roles than others. We first restrict our attention to two key parameters controlling the indirect radiative forcing of sulfate and the rate of time preference, and then provide a concise analysis for a larger set of parameters. As a reference point, the benchmark result for five selected regions and for all eleven regions combined are summarized in Table 15.

First, the value of indirect radiative forcing of aerosols is highly uncertain (IPCC, 2007). As a benchmark, we assumed a value of -0.8W/m^2, while the 90% confidence interval estimated by the IPCC ranges from -0.3 to -1.8W/m^2. To check whether our result is robust to this uncertainty, we examined how cumulative carbon and sulfur emissions in 2050 change when the indirect cooling effect of sulfate aerosol is assumed to be weaker (-0.3W/m^2) or stronger (-1.8W/m^2). When perturbing this parameter, other parameters are not recalibrated.

The results are summarized in the top panel of Table 16. The table shows *inter alia* that if we assume that the indirect effect is -0.3W/m^2, then carbon emission of USA in 2050 under the Nash scenario decreases by 0.69% compared to the benchmark result, and if we assume that the indirect effect is -1.8W/m^2, then it increases by 1.33%. The directions of the changes are intuitive, because the weaker negative radiative forcing of aerosol implies that SO_2 can be reduced without causing a temporary temperature hike and vice versa. When we use different values for the parameter, the equilibrium path does not change much, except for SO_2 emission in AFR. This relates to the second conclusion in the paper. A reduction of air pollutants brings about a temporary increase in temperature through the local brightening effect and this side effect is particularly serious in Africa. This is why SO_2 emission in AFR is relatively more sensitive to the radiative forcing of aerosol. Hence this result indicates that our conclusion will be less pronounced when $F_{1990}^{a,ind} = -0.3$ while it will be rather more pronounced when $F_{1990}^{a,ind} = -1.8$.

Another parameter which relates to the novel features of our model is the rate of time preference. As mentioned in the paper, climate-related and air-pollution-related health benefits materialize on different time scales. This means that the trade-off between the two types of health benefits may be influenced by the time preference rate. In the benchmark case we assumed a time preference rate of 3% per year. We now examine how the results change when the annual rate of time preference is lower (2%) or higher (4%).

The results are summarized in the bottom panel of Table 16. The sensitivity is now larger, but in most of the cases considered here the deviation from the benchmark is around 3%. One exception is the optimal CO_2 emission for the case when the time preference rate is lower. This lack of robustness is a problem and has been noticed by others as well (Nordhaus and Yang, 1996). Changes in time preference rate do not alter the qualitative characteristics of our results.

The sensitivity result of the Nash scenario is possibly somewhat counter-intuitive, because carbon emission increases when the rate of time preference is lowered. One would expect that a lower time preference rate implies a stronger incentive to abate carbon emission. That is actually the case because the carbon *control rate* μ^c, which reflects the incentive to control emission, increases in every region as a result of lowering the time preference rate. A lower time preference rate, on the other hand, leads to more investment, more production in subsequent periods, and to more carbon emission in the future. In the Nash scenario, the latter effect outweighs the former, because the return to carbon abatement is only partially taken into account. When the benefit of carbon abatement is fully incorporated (Optimal scenario), a lower time preference rate results in a reduction of carbon emission.

For a larger set of parameters, table 17 summarizes the sensitivity results. In each case we consider the effect on only CO_2 emissions in 2050 of increasing or decreasing one parameter value by 30%, compared to the benchmark results. The table is representative in the sense that the sensitivity of other variables show a similar pattern. We see that the equilibrium carbon emission levels are quite robust (less than 6% change from benchmark). The impacts of increasing and decreasing parameter values are more or less symmetric. The signs of the changes are the same across regions with a few notable exceptions. For parameters concerning global issues (τ^c, γ, β_2^c), the Optimal scenario is more sensitive than the Nash scenario, while the opposite is true for parameters concerning local issues (σ^{ac}, τ^a, β^a).

One of the most uncertain parameters in climate-economy models is the climate sensitivity, that is, the impact of atmospheric carbon concentration on the global mean temperature. In our benchmark, the parameter τ^c is chosen such that the global mean temperature increases by 3.4 °C at the end of this century if no climate policies are implemented. A 30% increase (decrease) in τ^c for all regions leads to a temperature increase of 0.5 °C more (less) than the 3.4 °C benchmark. Since higher (lower) climate sensitivity implies larger (smaller) benefits of climate policy, both the incentive and rationale for reducing carbon emissions will increase (decrease) compared to the benchmark.

Another important uncertainty is in how much sulfur emission can be reduced via climate policies. This is captured by the parameter σ^{ac} in the emission equations, which we calibrated based on Bollen *et al.* (2009b), who estimated the size of sulfur emission reduction for a given global climate policy. Since climate policy in our analysis is endogenous, the estimate may not be accurate. Thus, we uniformly increased (and decreased) the parameter value for all regions, and recalibrated the whole emission equation so that the baseline levels of carbon and sulfur emissions are kept unchanged. We find that the equilibrium level of carbon emission in CHN is relatively sensitive to changes in cross-emission coefficient. This is to be expected, because CHN is in the most favorable position in terms of secondary benefit of climate policy.

We examined the implications of uncertainty in the local dimming effect of sulfur dioxide emissions by uniformly changing the values of the corresponding parameters (τ^a's). Larger (smaller) values of these parameters imply a stronger (weaker) local dimming effect. We see that, if the dimming effect of sulfur dioxide is weaker than in the benchmark, then regions will be able to utilize the potential of sulfur emission reduction via climate policies without causing a temporary jump of local temperature, and hence more carbon emission will be mitigated. A stronger dimming effect results in less stringent climate policy.

The columns for γ, β_2^c, and β^a represent sensitivity to economic and health impacts of climate change and air pollution. A larger value of γ means that climate damage is larger, implying a larger benefit of carbon mitigation at the global level. At a regional level it provides an incentive to avoid a short-term temperature increase caused by SO_2 reduction (local brightening), which in turn implies a smaller ancillary benefit of climate policies. As a result, a larger value for γ does not necessarily reduce carbon emission at a regional level. In fact, CHN has a weaker incentive to mitigate carbon emission in the Nash scenario (0.02% increase in equilibrium emission) for a larger climate damage.

Our results are more sensitive to the parameter controlling air-pollution-induced health damage than climate-related damages. This is partly because air pollution is caused by a flow variable, while climate damages depend on a stock variable. AFR is an exception in terms of its sensitivity to β_2^c. For a smaller health damage of temperature increase, implied by a lower value of β_2^c, CO_2 emissions decrease in AFR (by 0.12%) while they increase in the other developing regions. This is an indication that in AFR, it is the severe climate-related health impact that suppresses the additional mitigation incentive from ancillary benefits. A smaller β_2^c means that the trade-off between better air quality and climate-related health benefit is relaxed, which enables AFR to utilize the potential of sulfur emission reduction through climate policies in the region.

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9 Figures

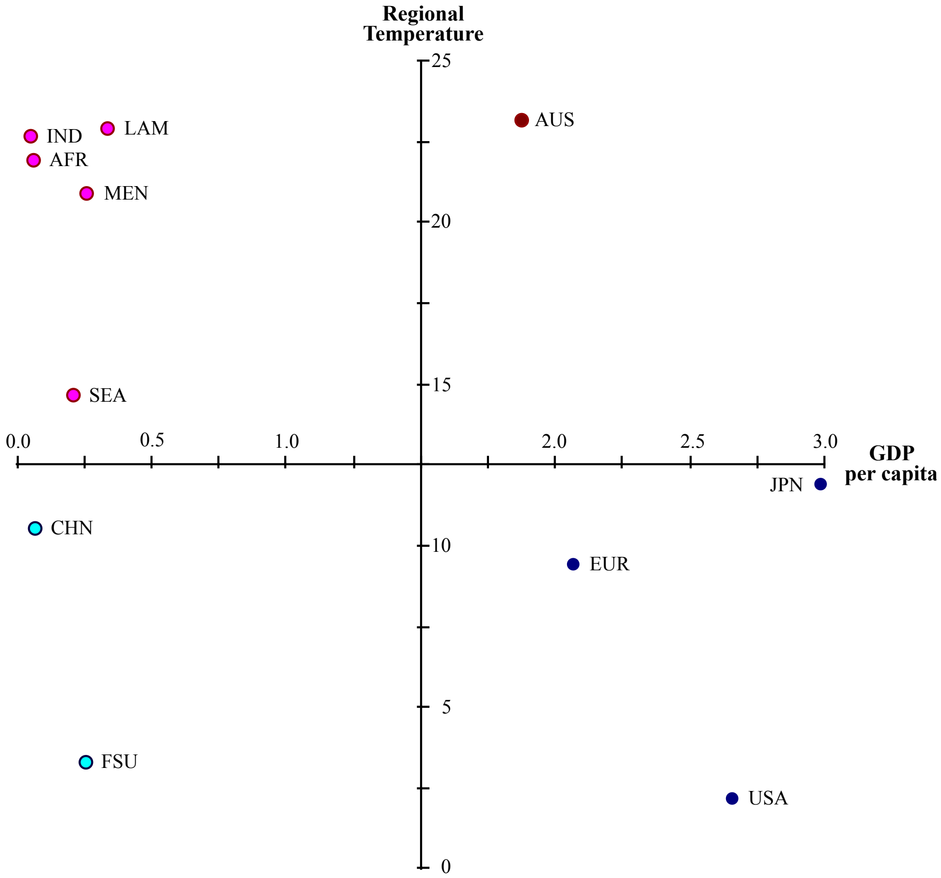

Figure 1: Characterization of regions in terms of temperature and output

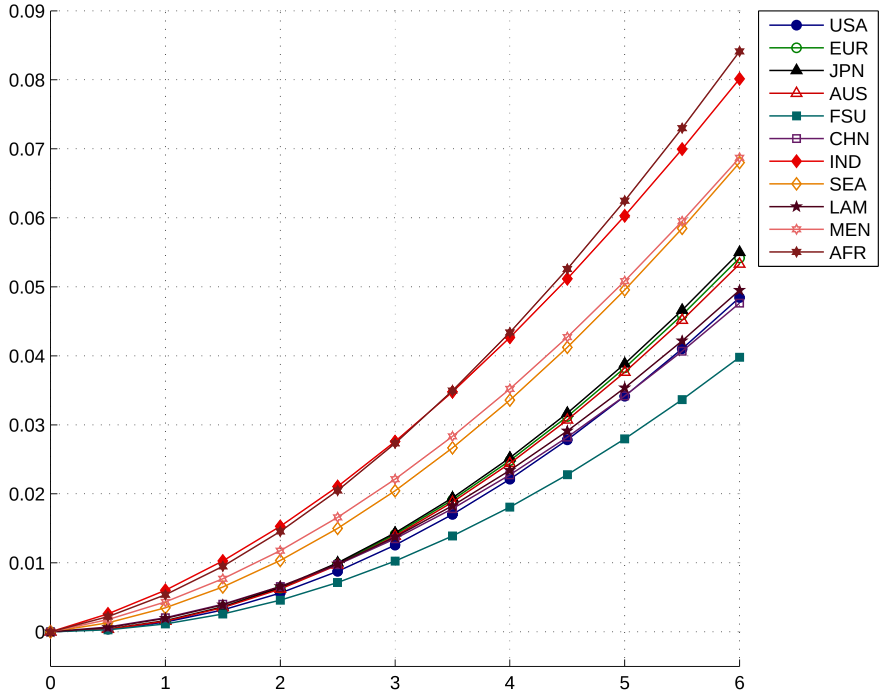

Figure 2: Damage per output, $D^*_{j,t}/Y_{j,t}$, of RICE, including health impacts

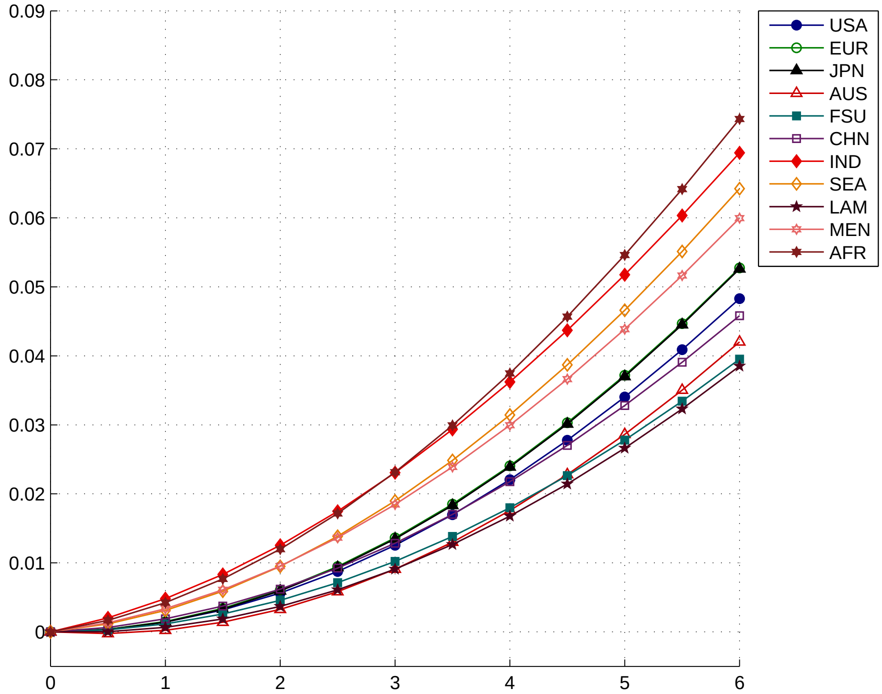

Figure 3: Recalibrated damage per output, $D_{j,t}/Y_{j,t}$, excluding health impacts

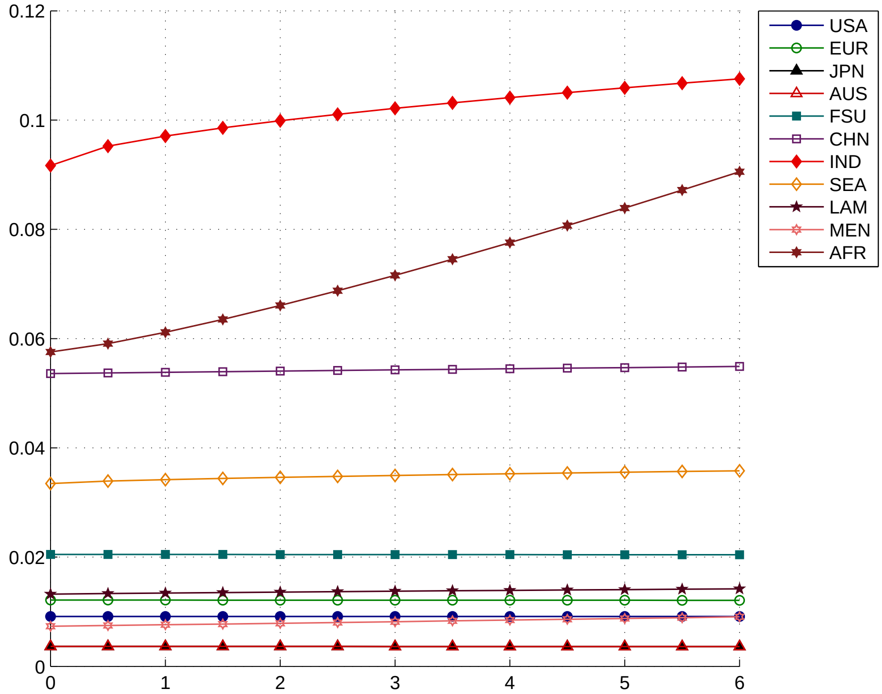

Figure 4: Climate-induced DALYs per capita, $p^c_{j,t}$, as a function of temperature change

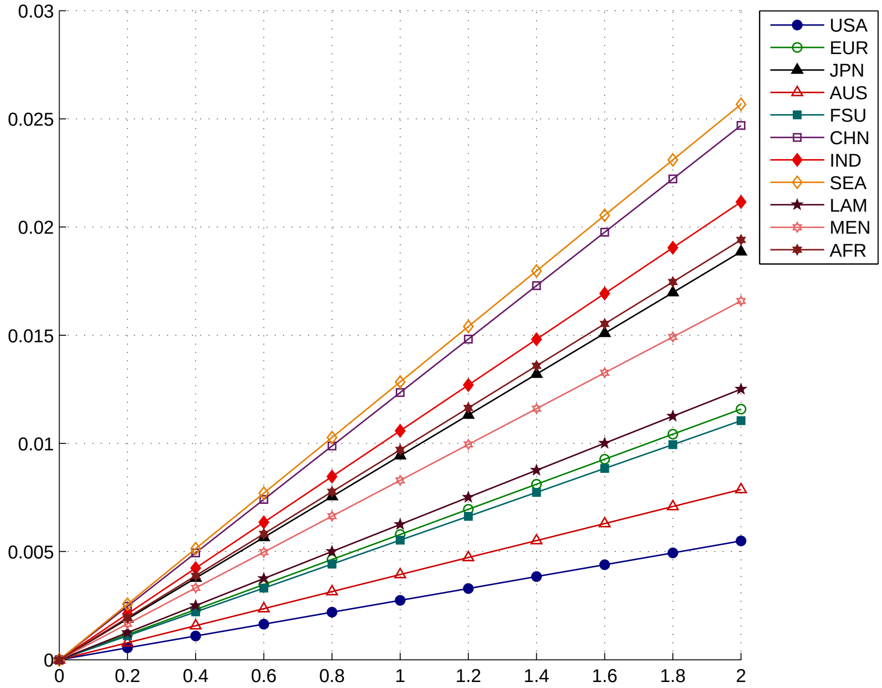

Figure 5: Air-pollution-induced DALYs per capita, $p^a_{j,t}$, as a function of $E^a_{j,t}$

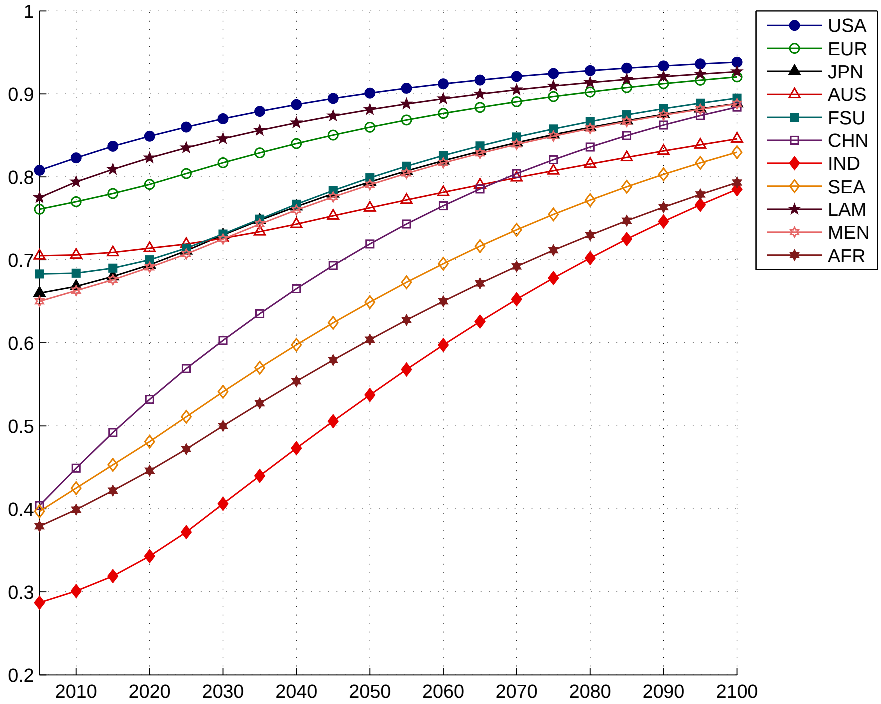

Figure 6: Calibrated future trend of urbanization, $r_{j,t}$

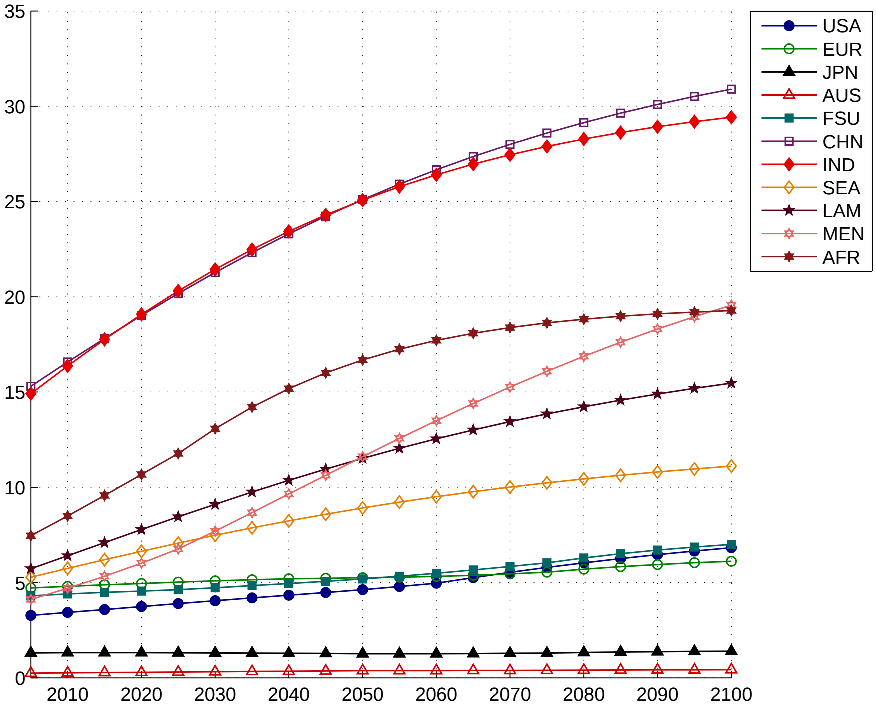

Figure 7: Calibrated population, $N_{j,t}$

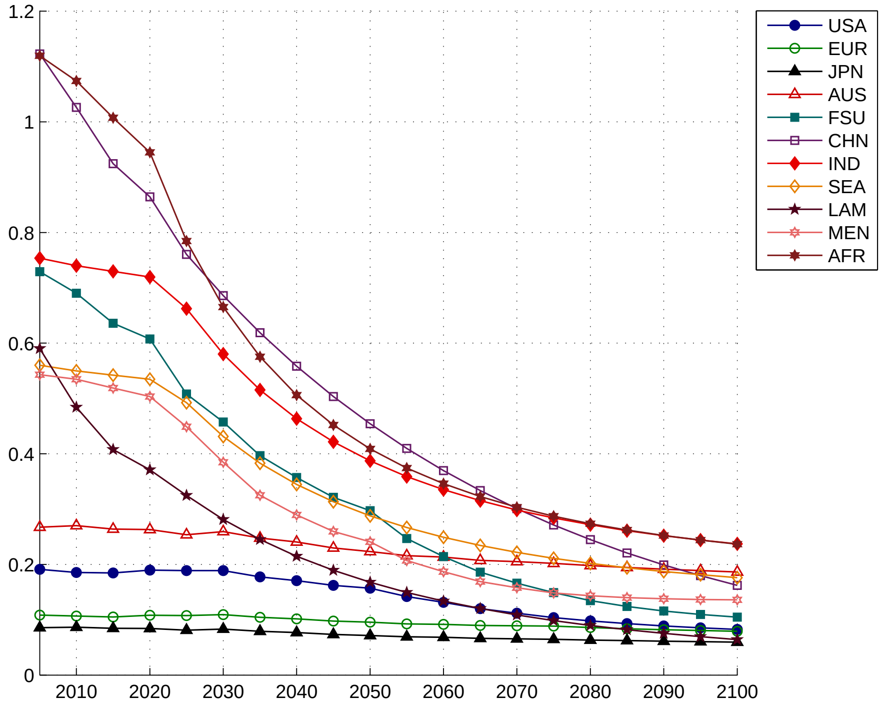

Figure 8: Calibrated carbon emission intensity, $\sigma_{j,t}^{cc}$

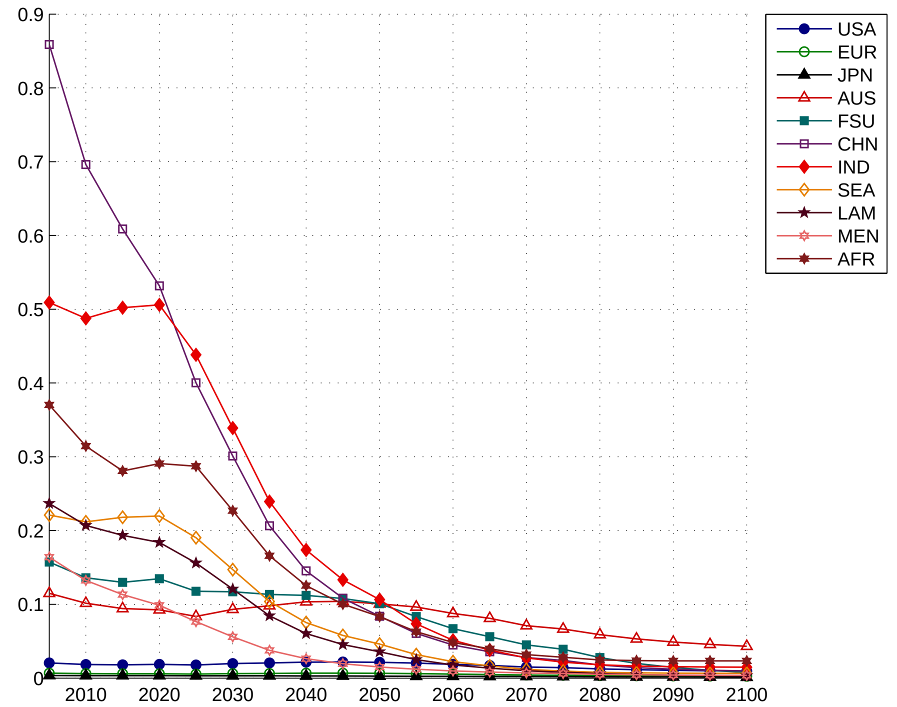

Figure 9: Calibrated sulfur emission intensity, $\sigma^{aa}_{j,t}$

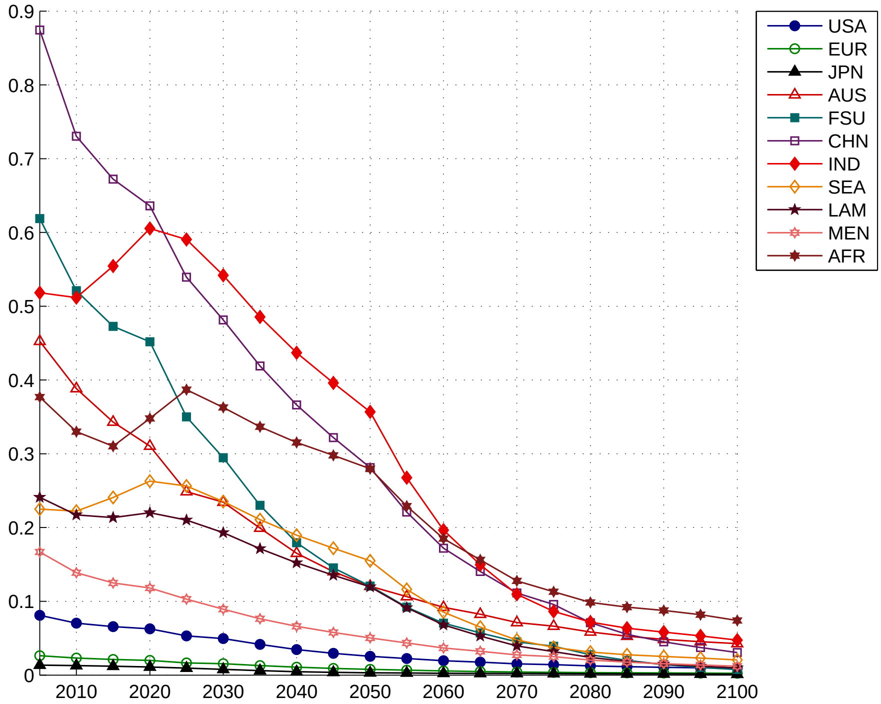

Figure 10: Calibrated trend of $\sigma^{ac}_{j,t}$

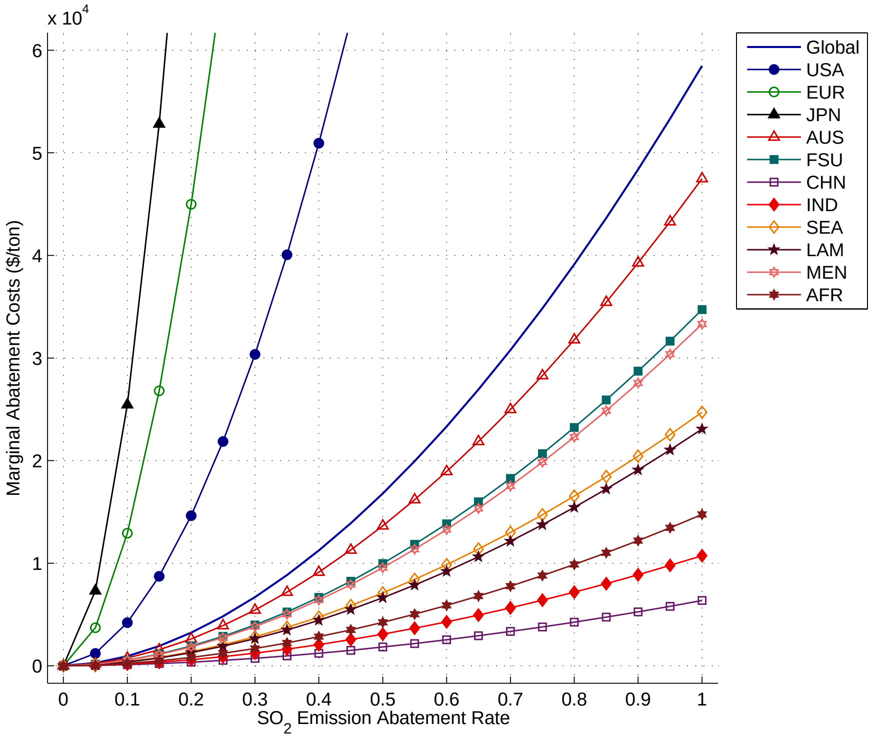

Figure 11: Calibrated marginal abatement cost curve of sulfur emission

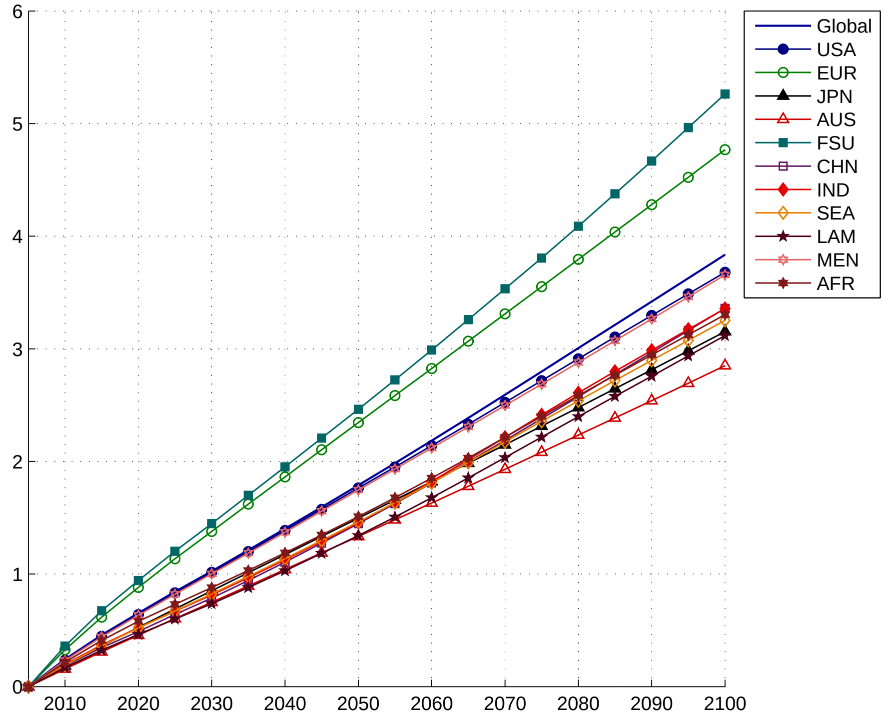

Figure 12: Total temperature change under IPCC A2 scenario

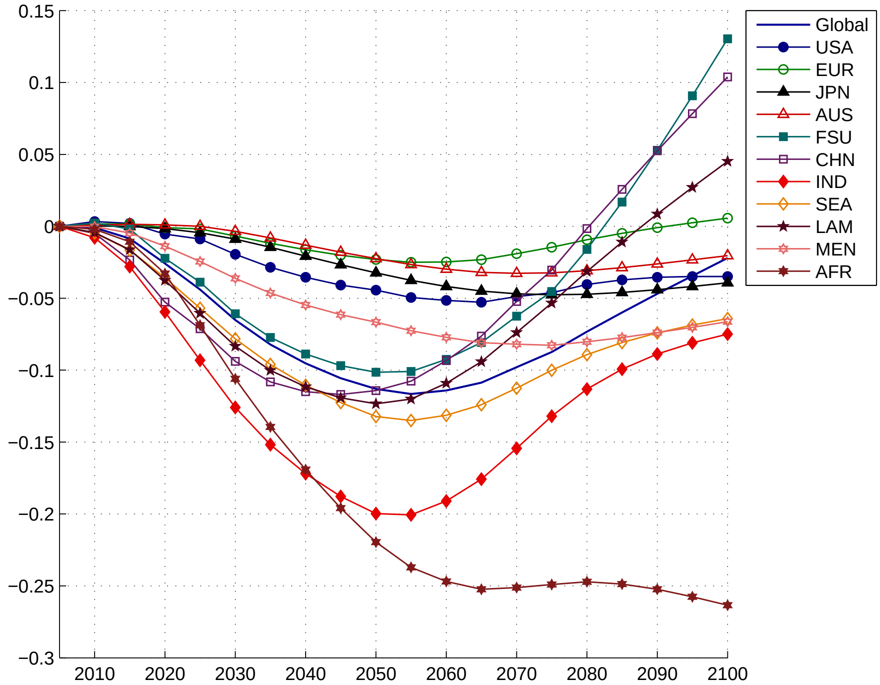

Figure 13: Temperature change due to sulfur under IPCC A2 scenario

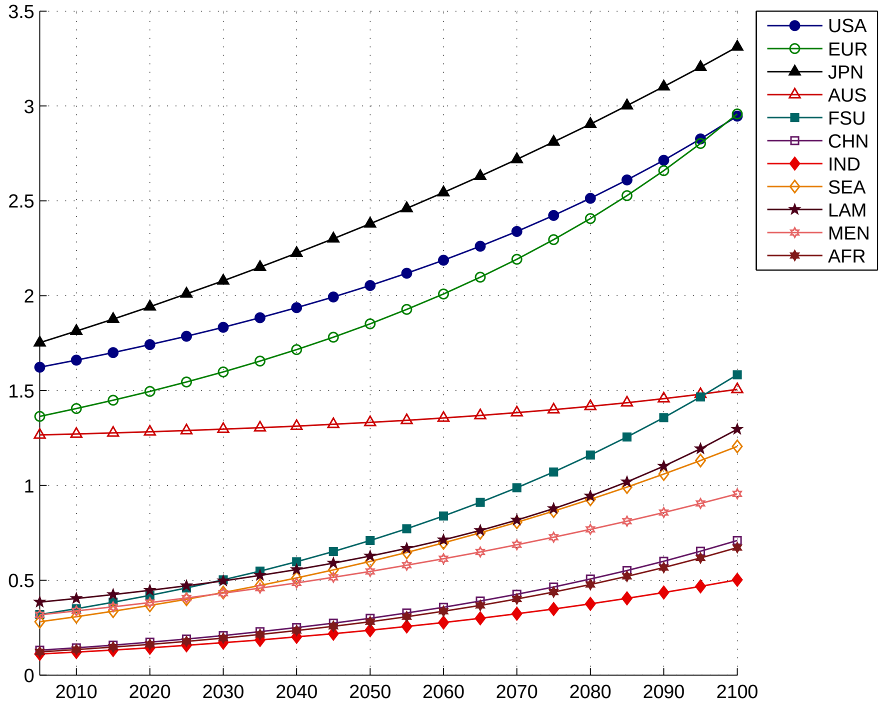

Figure 14: Calibrated growth of total factor productivity, $\psi_{j,t}$

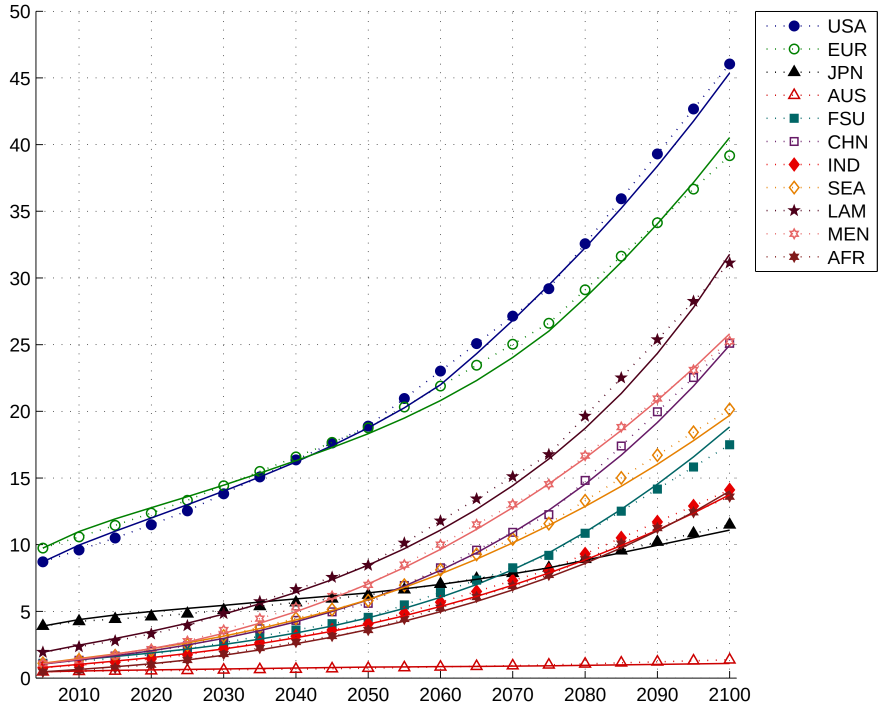

Figure 15: Comparison between IPCC A2 and our model in terms of $Y_{j,t}$

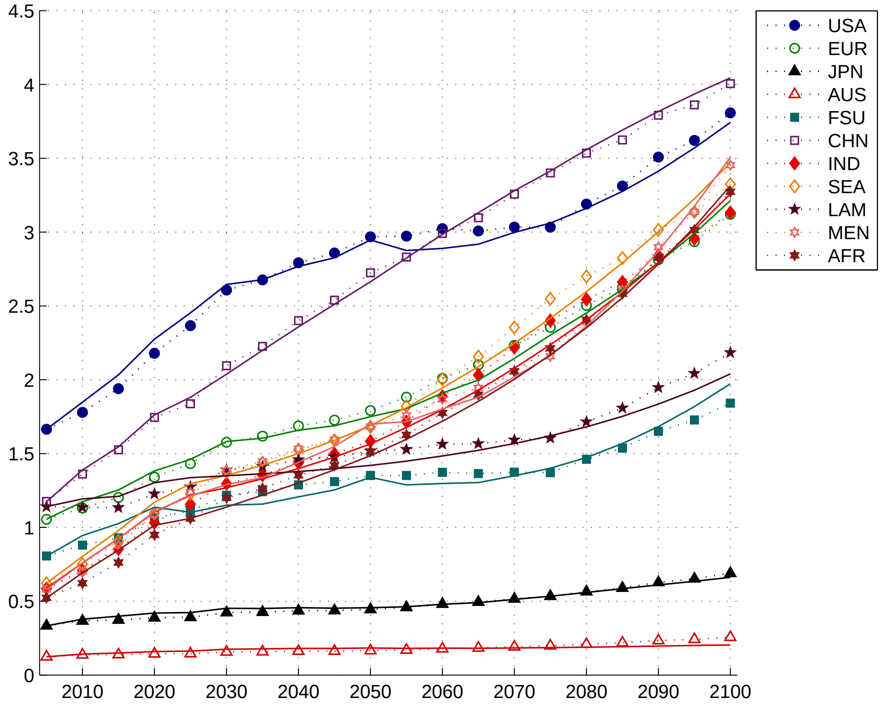

Figure 16: Comparison between IPCC A2 and our model in terms of $E^c_{j,t}$

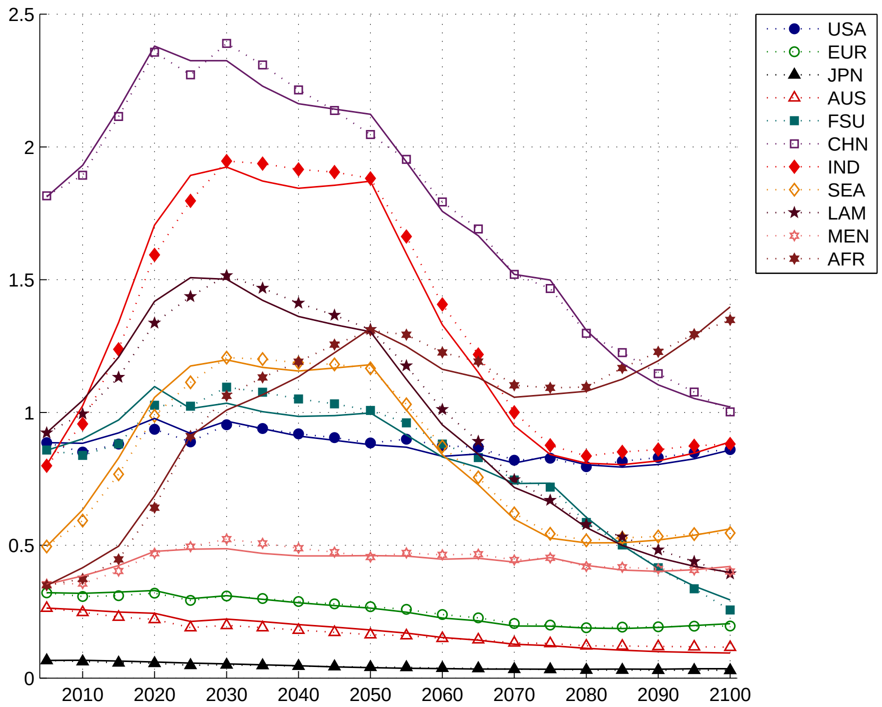

Figure 17: Comparison between IPCC A2 and our model in terms of $E^a_{j,t}$

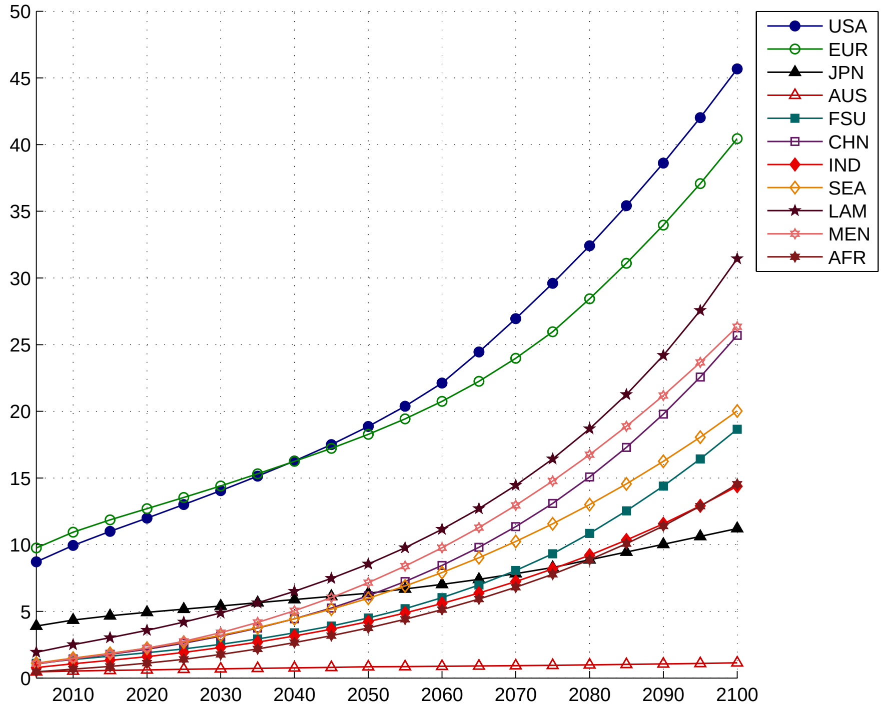

Figure 18: Trajectories of $Y_{j,t}$ in the Nash scenario

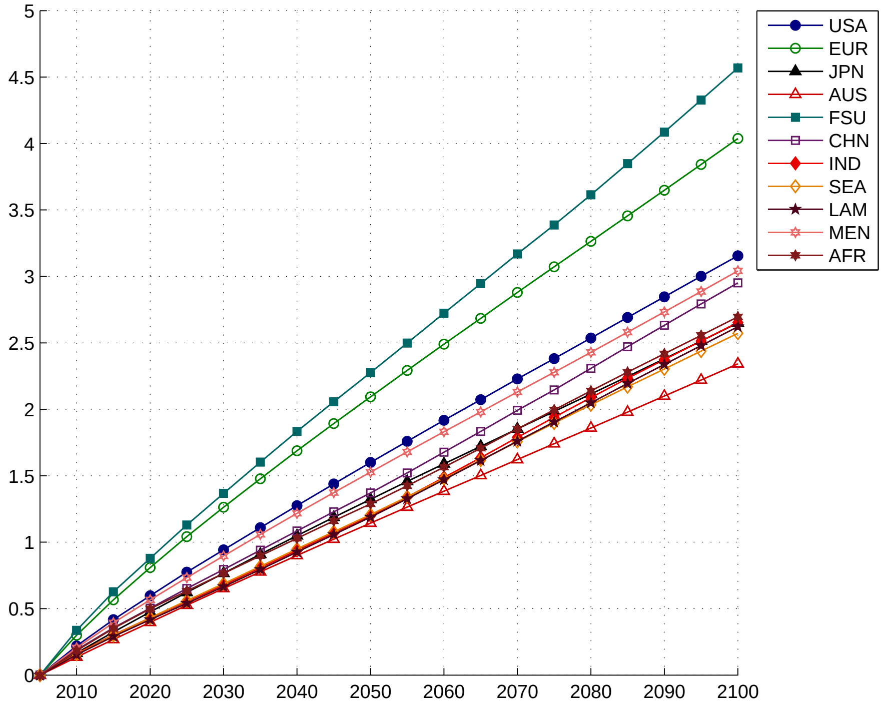

Figure 19: Trajectories of $Z_{j,t}$ in the Nash scenario

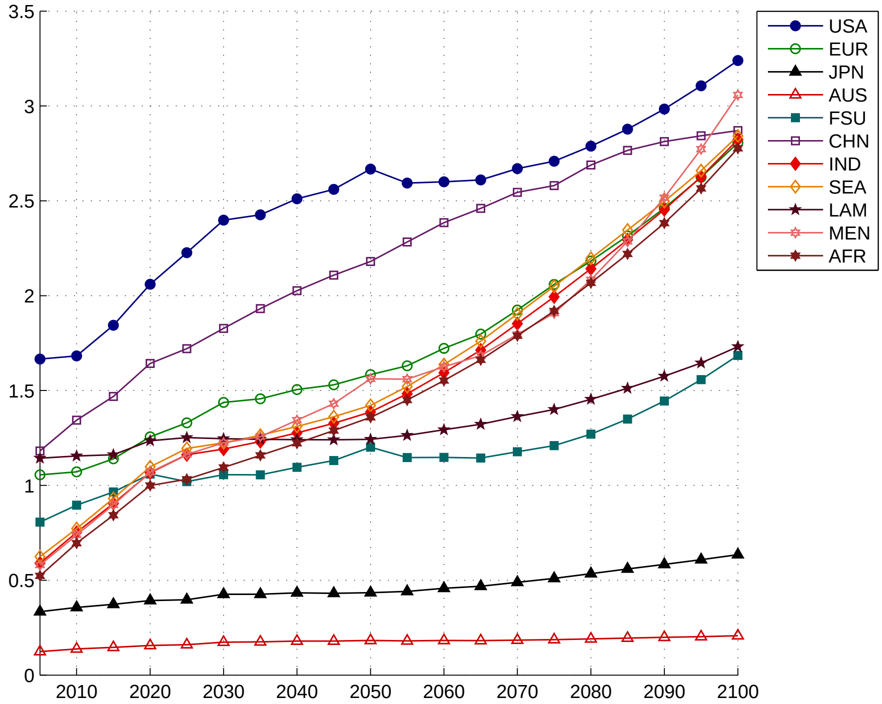

Figure 20: Trajectories of $E^c_{j,t}$ in the Nash scenario

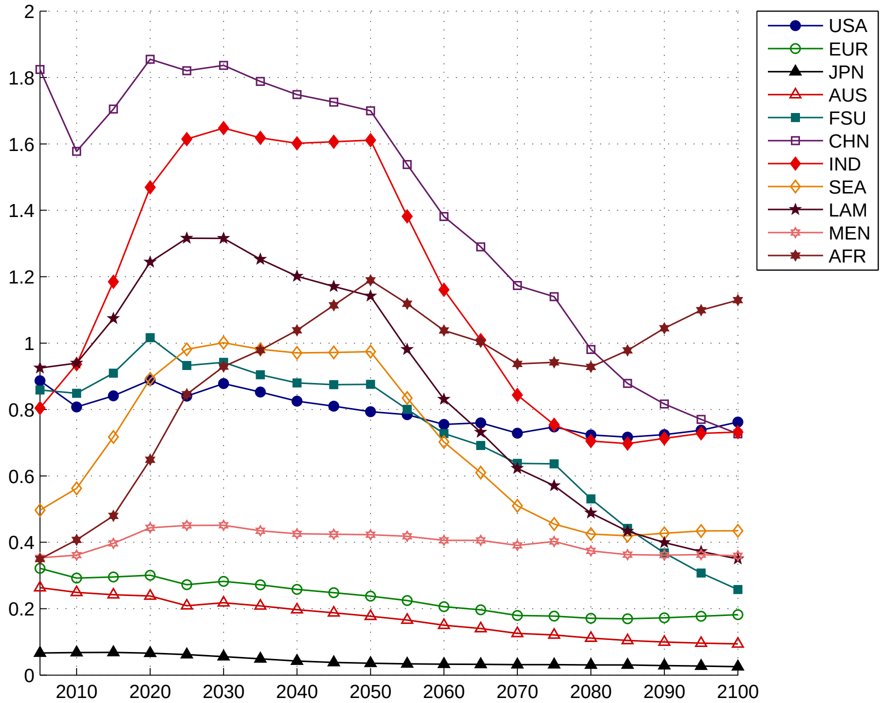

Figure 21: Trajectories of $E^a_{j,t}$ in the Nash scenario

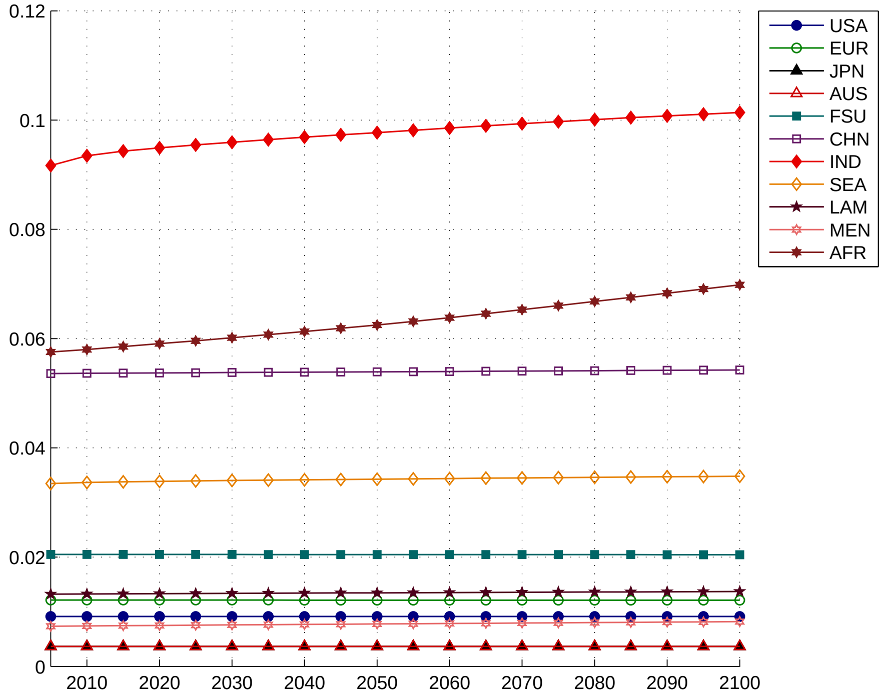

Figure 22: Trajectories of $p^c_{j,t}$ in the Nash scenario

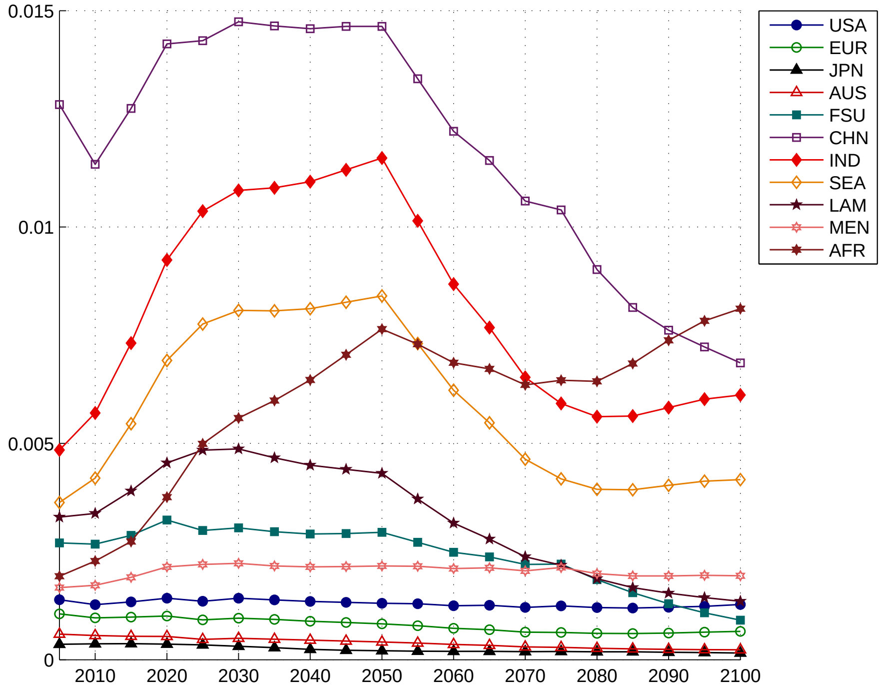

Figure 23: Trajectories of $p^a_{j,t}$ in the Nash scenario

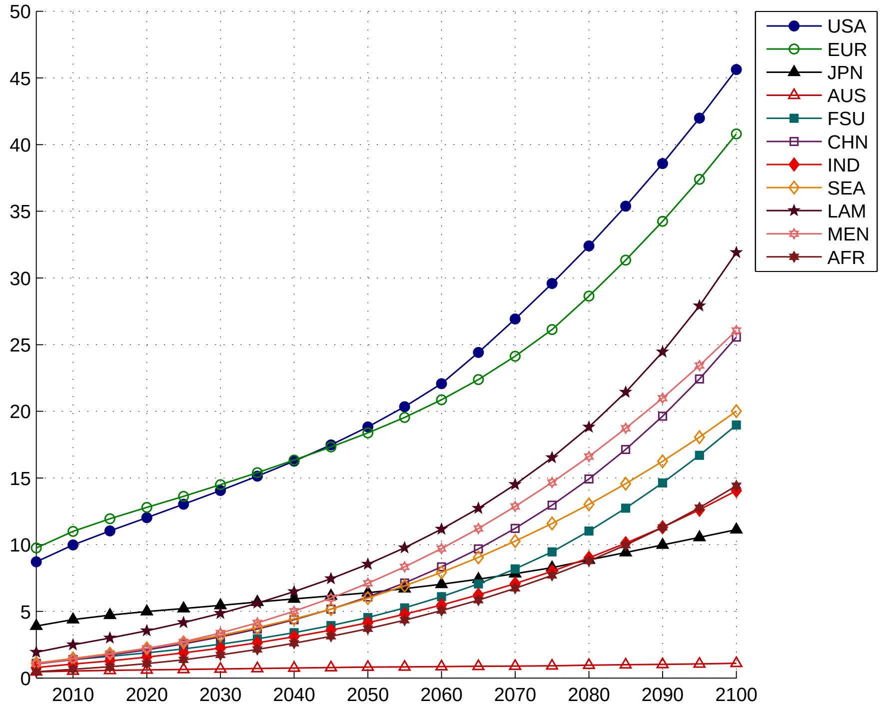

Figure 24: Trajectories of $Y_{j,t}$ in the Optimal scenario

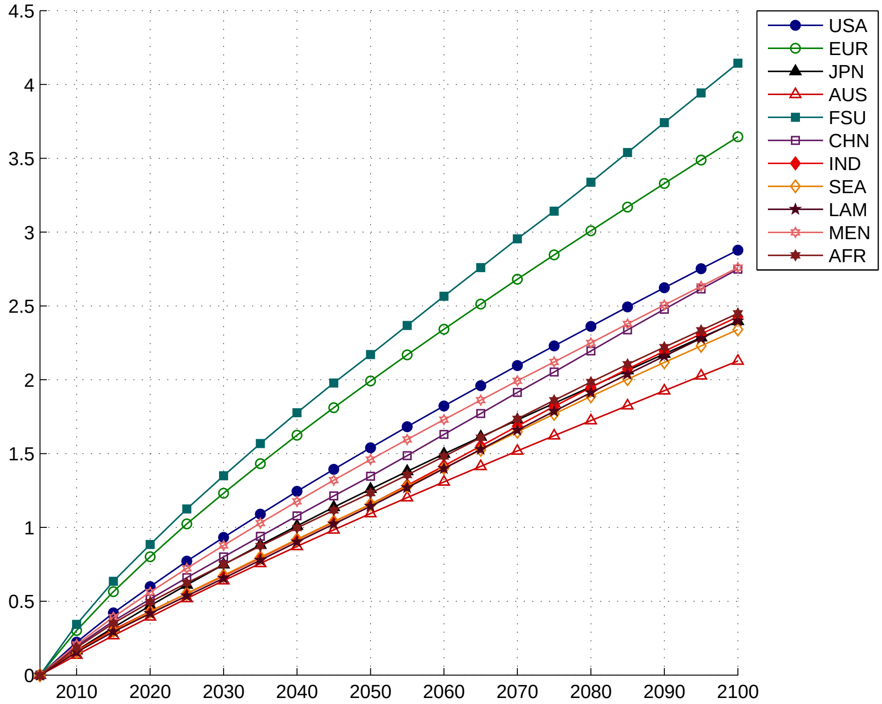

Figure 25: Trajectories of $Z_{j,t}$ in the Optimal scenario

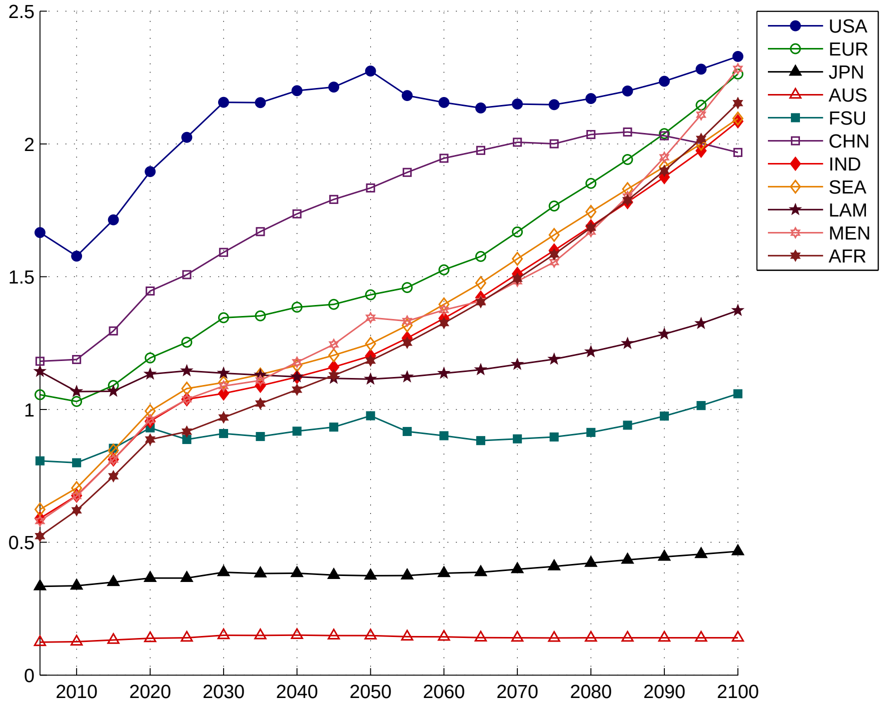

Figure 26: Trajectories of $E^c_{j,t}$ in the Optimal scenario

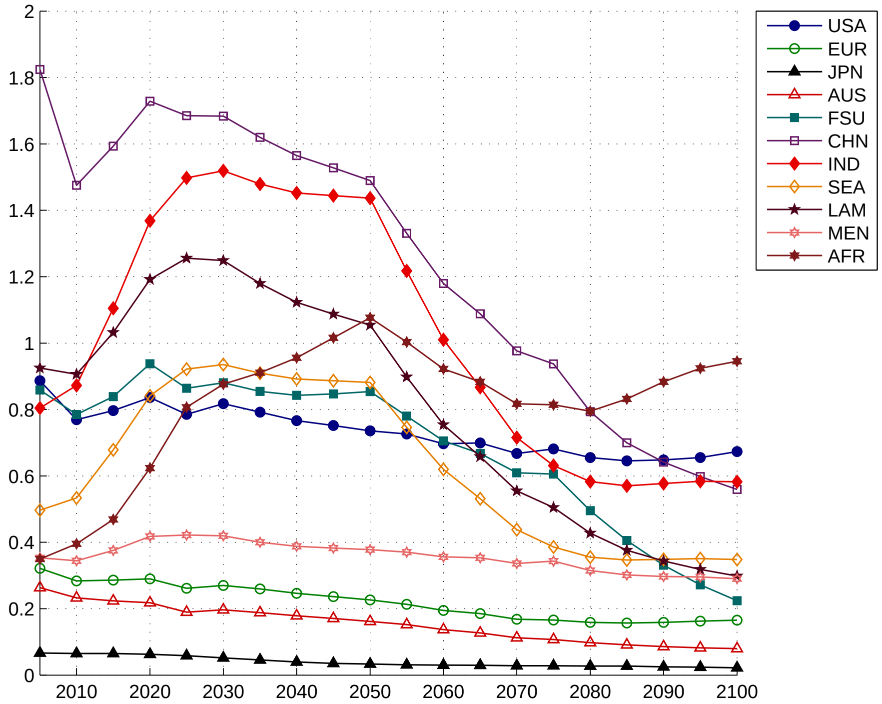

Figure 27: Trajectories of $E^a_{j,t}$ in the Optimal scenario

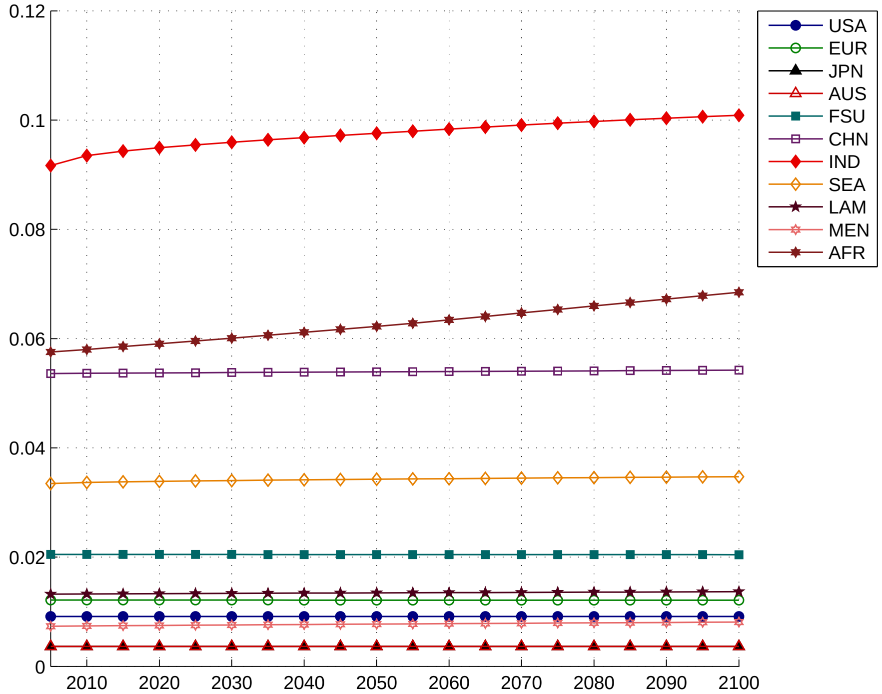

Figure 28: Trajectories of $p^c_{j,t}$ in the Optimal scenario

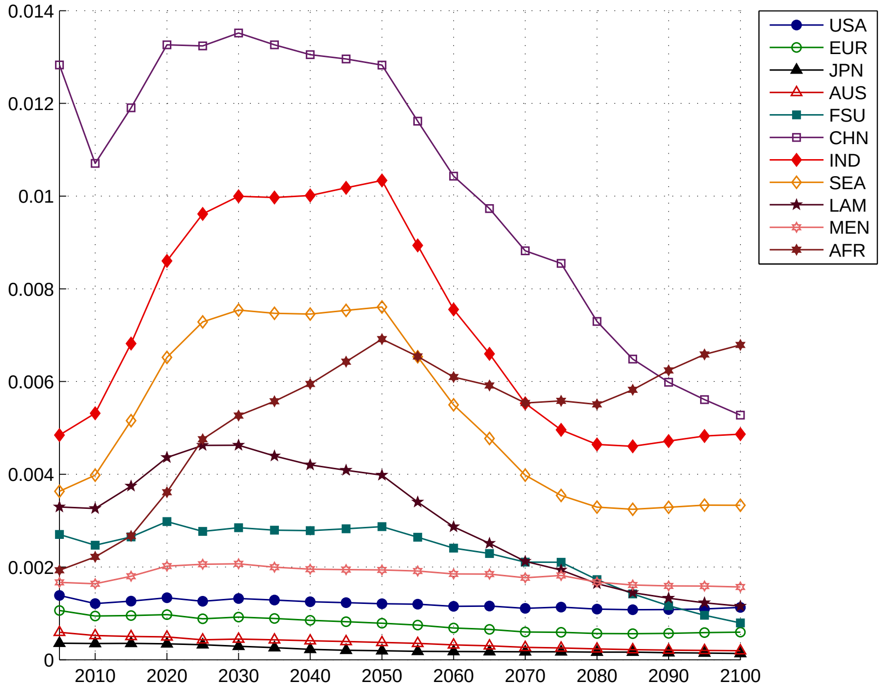

Figure 29: Trajectories of $p^a_{j,t}$ in the Optimal scenario

10 Tables

Symbol	Value	Description	Unit
Endogenous			
$Y_{j,t}$	—	Output	trillion US$
$K_{j,t}$	—	Capital	—
$L_{j,t}$	—	Labor force	100 million
$p^c_{j,t}$	—	Fraction of pop. suffering from temp.-induced diseases	—
$p^a_{j,t}$	—	Fraction of pop. suffering from sulfur-induced diseases	—
$Z_{j,t}$	—	Regional temperature change relative to 2005	°C
Z_t	—	Global temperature change relative to 2005	°C
$E^c_{j,t}$	—	Carbon dioxide emission	GtC
$E^a_{j,t}$	—	Sulfur dioxide emission	10TgS
$\mu^c_{j,t}$	—	Carbon control rate	—
$\mu^a_{j,t}$	—	Sulfur control rate	—
M_t	—	Carbon concentration (global)	GtC
$D_{j,t}$	—	Damage from temperature increase	trillion US$
$d_{j,t}$	—	Damage from temperature increase	—
$A_{j,t}$	—	Abatement cost	trillion US$
$I_{j,t}$	—	Investment	trillion US$
$C_{j,t}$	—	Consumption	trillion US$
W_j	—	Regional welfare	—
Exogenous			
$N_{j,t}$	Table 9	Population (Section 5.4)	100 million

Table 1: List of variables in the model

Symbol	Value	Description	Section
$\gamma_{1,j}$	Table 7	Linear damage coefficient	5.1
$\gamma_{2,j}$	Table 7	Quadratic damage coefficient	5.1
$\beta^c_{1,j}$	Table 7	Parameter in temperature-induced disease function	
$\beta^c_{2,j}$	Table 7	Parameter in temperature-induced disease function	5.2
$\beta^c_{3,j}$	Table 7	Parameter in temperature-induced disease function	
$\beta^a_{j,t}$	Equation (20)	Parameter in air-pollution-induced disease function	5.3
$\sigma^{cc}_{j,t}$	Table 11	Parameter in emission equation	
$\sigma^{ca}_{j,t}$	0	Parameter in emission equation	5.5
$\sigma^{ac}_{j,t}$	Table 13	Parameter in emission equation	
$\sigma^{aa}_{j,t}$	Table 12	Parameter in emission equation	
$\alpha^c_{j,t}$	Equation (35)	Parameters in carbon abatement cost function	
$\alpha^a_{j,t}$	Equation (38)	Parameters in sulfur abatement cost function	5.6
ξ^c	2.8	Parameters in carbon abatement cost function	
ξ^a	2.8	Parameters in sulfur abatement cost function	
$\tau_{0,j}$	Table 7	Parameter in temperature equation	
τ_1	0.724	Parameter in temperature equation	
τ_2	0.1	Parameter in temperature equation	
τ^c_j	Table 7	Parameter in temperature equation	5.7
$\tau^a_{1,j}$	Table 7	Parameter in temperature equation	
$\tau^a_{2,j}$	Table 7	Parameter in temperature equation	
$\tau^a_{3,j}$	Table 7	Parameter in temperature equation	
δ^c	0.026	Carbon depreciation rate per 5 years	5.7
ϵ	0.3	Capital's share of income	5.8
δ^k	0.410	Capital depreciation rate per 5 years	5.8
ρ	0.159	Rate of time preference per 5 years	5.9
$\psi_{j,t}$	Table 14	Total factor productivity	5.9
ω_j	Table 4	Relative landmass	—

Table 2: List of parameters in the model

	USA	EUR	JPN	AUS	FSU	CHN	IND	SEA	LAM	MEN	AFR
$K_{j,0}$	17.426	19.484	7.806	0.928	2.213	2.096	1.556	2.222	3.866	2.137	0.935

Table 3: Calibrated value of initial capital stock $K_{j,0}$

	Pop	Area	$Y_{j,t}/N_{j,t}$	Emissions		Temp	Diseases	
				CO_2	SO_2		$p^c_{j,t}$	$p^a_{j,t}$
	(10^6)	(%)	(US$)	(GtC)	(TgS)	(°C)	(%)	(%)
USA	328	14.46	26,572	1.66	8.9	2.2	0.91	0.14
EUR	471	3.57	20,670	1.06	3.2	9.4	1.21	0.11
JPN	131	0.28	29,859	0.33	0.7	11.9	0.36	0.04
AUS	25	6.34	18,757	0.12	2.6	23.2	0.36	0.06
FSU	431	17.75	2570	0.81	8.6	3.3	2.04	0.27
CHN	1530	10.31	685	1.18	18.2	10.5	5.35	1.29
IND	1492	2.18	522	0.59	8.0	22.7	9.16	0.48
SEA	528	3.25	2106	0.62	5.0	14.7	3.34	0.36
LAM	573	16.66	3374	1.14	9.2	22.9	1.32	0.33
MEN	412	6.54	2596	0.58	3.5	20.9	0.73	0.17
AFR	746	18.64	627	0.52	3.5	21.9	5.75	0.19

Table 4: Selected characteristics for each region in 2005. *Sources:* CIESIN (2002) for population and output, World Bank (2010) for area, United Nations (2009) for urbanization ratio, and Mitchell *et al.* (2004) for temperature. Carbon and sulfur emissions are computed based on Sankovski (1998) and Gaffin *et al.* (2004). Disease ratios are computed based on Equation (3).

	Malaria		Cardiovascular disease		Diarrhoea		Malnutrition	
	$\eta_{1,i}^{d}$	$\eta_{1,i}^{d}$	$\eta_{1,i}^{d}$	$\eta_{1,i}^{d}$	$\eta_{1,i}^{d}$	$\eta_{1,i}^{d}$	$\eta_{1,i}^{d}$	$\eta_{1,i}^{d}$
AFR-D	0.026078	1.698841	0.006020	1.000013	0.068696	0.764335	0.035940	0.500000
AFR-E	0.168059	1.519167	0.004865	1.000006	0.071861	0.758908	0.037059	0.500000
AMR-A	0.381690	1.376924	0.000000	1.000000	0.000000	1.000000	0.000000	1.000000
AMR-B	0.191571	1.352769	0.005196	1.000002	0.000000	1.000000	0.061188	0.500000
AMR-D	0.141834	1.757767	0.005796	1.000025	0.044562	1.001409	0.064768	0.500000
EMR-B	0.000000	1.000000	0.002476	1.000001	0.000000	1.000000	0.030623	0.500000
EMR-D	0.190006	1.342394	0.002669	1.000005	0.079200	1.111345	0.089862	0.500000
EUR-A	0.000000	1.000000	−0.000884	1.000001	0.000000	1.000000	0.000000	1.000000
EUR-B	0.000000	1.000000	−0.001054	1.000000	0.020858	0.500000	0.000000	1.000000
EUR-C	0.323285	1.363677	−0.001073	1.000000	0.010523	0.500000	0.000000	1.000000
SEAR-B	0.000000	1.000000	0.010669	1.000020	0.000000	1.000000	0.066032	0.500000
SEAR-D	0.011079	2.000000	0.006404	1.000009	0.081492	0.637350	0.177938	0.500000
WPR-A	0.507029	1.394066	−0.001048	1.000001	0.000000	1.000000	0.000000	1.000000
WPR-B	0.377250	1.423824	0.000000	1.000000	0.000000	1.000000	0.010080	0.500000

Table 5: Parameter values in relative risk function for WHO regions

Symbol	Value	Description	Unit
δ_1^k	0.10	Annualized rate of capital depreciation	—
i_1	0.05	Annual interest rate	—
$\mathrm{RR}_{j,t}$	—	Relative risk due to climate change	—
$\eta_{1,i}^d$	Table 5	Parameter in relative risk function	—
$\eta_{2,i}^d$	Table 5	Parameter in relative risk function	—
$\mathrm{DALY}_{j,t}$	—	Disability adjusted life years lost	life year
$\chi_{i,j}$	Table 8	Population weight to convert WHO region to 11-region	—
β_0^a	0.00023	Parameter in air-pollution-induced disease function	—
PD_j	Table 7	Population density in urban areas	person/km^2
ν	2	Parameter in air-pollution-induced disease function	—
$r_{j,t}$	Table 10	Urbanization ratio	—
$m_{j,t}$	Table 7	Price of backstop technologies	—
υ	0.1	Parameter in marginal abatement cost function	—
g^m	0.0246	Decline rate of the price of backstop technologies	—
α^a	0.0195	Parameter in marginal abatement cost function of sulfur	—
$\bar{\sigma}^a$	0.0934	Output-weighted average of sulfur intensity	—
ζ_1	0.1761	Lag of temperature adjustment	—
ζ_2	0.1	Influence of global temperature on regional temperature	—
ϕ_j	Table 7	Regional adjustment parameter of climate sensitivity	—
λ	0.7	Climate sensitivity	°C/Wm^{-2}
M_{1750}	596.4	Carbon concentration in 1750	GtC
$F_{j,t}^c$	—	Radiative forcing due to carbon concentration	W/m^2
$F_{\times 2}^c$	4.1	Radiative forcing when carbon concentration doubled	W/m^2
$F_{j,t}^a$	—	Radiative forcing due to sulfur dioxide	W/m^2
$F_{1990}^{a,dir}$	−0.3	Direct radiative forcing due to sulfur in 1990	W/m^2
$F_{1990}^{a,ind}$	−0.8	Indirect radiative forcing due to sulfur in 1990	W/m^2
$E_{j,1990}^a$	Table 7	Sulfur dioxide emission in 1990	10TgS
e_j	Table 7	Parameter in sulfur radiative forcing function	—

Table 6: List of variables and parameters in the underlying model

	USA	EUR	JPN	AUS	FSU	CHN	IND	SEA	LAM	MEN	AFR
$\beta^c_{1,j}$	0.009	0.012	0.004	0.004	0.020	0.054	0.092	0.033	0.013	0.007	0.058
$\beta^c_{2,j} \times 10^3$	0.000	−0.007	−0.003	−0.003	−0.011	0.239	5.000	0.709	0.0217	0.260	4.000
$\beta^c_{3,j}$	1.000	0.998	1.000	1.000	1.000	0.946	0.601	0.664	0.846	1.051	1.233
$\mathrm{PD}_j/80$	3.624	7.853	13.563	5.510	7.837	21.000	19.626	21.941	8.412	11.994	16.797
$\tau_{0,j}$	−4.337	−6.202	−3.538	−2.971	−6.767	−3.480	−3.896	−3.723	−3.255	−4.422	−4.149
τ^c_j	0.696	0.978	0.555	0.468	1.077	0.572	0.619	0.588	0.522	0.698	0.656
$\tau^a_{1,j}$	−0.031	−0.031	−0.031	−0.031	−0.031	−0.031	−0.031	−0.031	−0.031	−0.031	−0.031
$\tau^a_{2,j}$	−0.102	−0.083	−0.003	−0.006	−0.175	−0.083	−0.020	−0.010	−0.035	−0.022	−0.035
$\tau^a_{3,j}$	1.352	1.651	37.519	21.896	0.786	1.644	6.668	13.498	3.846	6.103	3.925
$m_{j,0}$	1.134	1.764	1.764	1.512	0.756	0.882	1.386	1.260	1.638	1.386	1.386
$\gamma_{1,j} \times 10^3$	0.005	−0.070	−0.154	−1.199	0.020	0.671	3.311	1.458	−0.557	1.900	2.415
$\gamma_{2,j} \times 10^3$	1.409	1.558	1.568	1.418	1.139	1.222	1.520	1.663	1.205	1.455	1.828
ϕ_j	0.970	1.357	0.762	0.616	1.533	0.791	0.767	0.730	0.702	0.944	0.866
$E^a_{j,1990}$	1.205	0.987	0.043	0.075	2.074	0.992	0.245	0.121	0.424	0.267	0.415
e_j	0.739	0.606	0.027	0.046	1.272	0.608	0.150	0.074	0.260	0.164	0.255

Table 7: List of region-specific parameter values

	USA	EUR	JPN	AUS	FSU	CHN	IND	SEA	LAM	MEN	AFR
AFR-D	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0221	0.0616	0.4386
AFR-E	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.5486
AMR-A	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0194	0.0000	0.0000
AMR-B	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.7909	0.0000	0.0000
AMR-D	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.1676	0.0000	0.0000
EMR-B	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.2772	0.0000
EMR-D	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0184	0.0000	0.0000	0.0616	0.0128
EUR-A	0.0000	0.8470	0.0000	0.0000	0.0414	0.0000	0.0000	0.0000	0.0000	0.0125	0.0000
EUR-B	0.0000	0.1530	0.0000	0.0000	0.3692	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
EUR-C	0.0000	0.0000	0.0000	0.0000	0.5893	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SEAR-B	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0145	0.5645	0.0000	0.0000	0.0000
SEAR-D	0.0000	0.0000	0.0000	0.0000	0.0000	0.0163	0.9671	0.0960	0.0000	0.0000	0.0000
WPR-A	0.0000	0.0000	1.0000	1.0000	0.0000	0.0000	0.0000	0.0172	0.0000	0.0000	0.0000
WPR-B	0.0000	0.0000	0.0000	0.0000	0.0000	0.9837	0.0000	0.3223	0.0000	0.0000	0.0000

Table 8: Population weights $\chi_{i,j}$ to convert 14 regions to 11 regions

	USA	EUR	JPN	AUS	FSU	CHN	IND	SEA	LAM	MEN	AFR
2005	3.2790	4.7131	1.3071	0.2474	4.3051	15.2994	14.9153	5.2757	5.7293	4.1153	7.4579
2010	3.4293	4.8035	1.3220	0.2618	4.3989	16.5729	16.3719	5.7417	6.4099	4.6989	8.4922
2015	3.5828	4.8808	1.3245	0.2757	4.4820	17.8146	17.7630	6.1982	7.0951	5.3321	9.5699
2020	3.7398	4.9522	1.3180	0.2893	4.5514	19.0158	19.0761	6.6417	7.7778	6.0148	10.6741
2025	3.8965	5.0215	1.3088	0.3034	4.6269	20.1697	20.3029	7.0693	8.4513	6.7586	11.7768
2030	4.0499	5.0885	1.3017	0.3183	4.7226	21.2713	21.4388	7.4790	9.1100	7.7022	13.0707
2035	4.1980	5.1497	1.2970	0.3333	4.8370	22.3169	22.4824	7.8691	9.7490	8.6701	14.2051
2040	4.3393	5.1944	1.2884	0.3472	4.9500	23.3042	23.4345	8.2385	10.3644	9.6507	15.1791
2045	4.4804	5.2256	1.2757	0.3602	5.0627	24.2321	24.2980	8.5866	10.9533	10.6330	16.0014
2050	4.6280	5.2516	1.2617	0.3737	5.1853	25.1004	25.0768	8.9130	11.5133	11.6070	16.6861
2055	4.7886	5.2817	1.2620	0.3758	5.3268	25.9099	25.7761	9.2181	12.0432	12.5640	17.2502
2060	4.9650	5.3243	1.2655	0.3794	5.4875	26.6619	26.4015	9.5020	12.5420	13.4963	17.7109
2065	5.2578	5.3824	1.2731	0.3837	5.6602	27.3584	26.9588	9.7653	13.0095	14.3976	18.0846
2070	5.5338	5.4564	1.2843	0.3879	5.8419	28.0016	27.4539	10.0090	13.4459	15.2629	18.3860
2075	5.7924	5.5446	1.2985	0.3926	6.0315	28.5941	27.8925	10.2337	13.8519	16.0885	18.6281
2080	6.0332	5.7017	1.3283	0.4021	6.2881	29.1387	28.2802	10.4405	14.2283	16.8718	18.8219
2085	6.2565	5.8342	1.3517	0.4100	6.5100	29.6381	28.6221	10.6303	14.5763	17.6110	18.9765
2090	6.4626	5.9453	1.3701	0.4166	6.7008	30.0953	28.9233	10.8043	14.8972	18.3055	19.0997
2095	6.6520	6.0381	1.3844	0.4220	6.8638	30.5131	29.1880	10.9635	15.1923	18.9552	19.1977
2100	6.8256	6.1155	1.3956	0.4264	7.0023	30.8943	29.4204	11.1088	15.4631	19.5606	19.2755
2105	6.9841	6.1797	1.4042	0.4300	7.1196	31.2417	29.6242	11.2414	15.7113	20.1230	19.3372
2110	7.1284	6.2329	1.4109	0.4330	7.2186	31.5579	29.8028	11.3621	15.9382	20.6436	19.3861
2115	7.2595	6.2769	1.4161	0.4354	7.3019	31.8453	29.9591	11.4719	16.1453	21.1243	19.4248
2120	7.3783	6.3133	1.4201	0.4374	7.3719	32.1064	30.0957	11.5717	16.3342	21.5670	19.4555
2125	7.4858	6.3433	1.4232	0.4390	7.4305	32.3433	30.2152	11.6623	16.5061	21.9738	19.4797
2130	7.5829	6.3680	1.4256	0.4403	7.4795	32.5580	30.3195	11.7445	16.6625	22.3468	19.4989
2135	7.6704	6.3883	1.4274	0.4413	7.5205	32.7526	30.4106	11.8190	16.8046	22.6882	19.5141
2140	7.7492	6.4050	1.4289	0.4422	7.5547	32.9288	30.4901	11.8864	16.9336	23.0001	19.5261
2145	7.8200	6.4188	1.4300	0.4429	7.5832	33.0882	30.5594	11.9475	17.0506	23.2848	19.5355
2150	7.8836	6.4301	1.4308	0.4434	7.6070	33.2323	30.6199	12.0027	17.1566	23.5441	19.5430
2155	7.9407	6.4393	1.4315	0.4439	7.6267	33.3626	30.6726	12.0526	17.2525	23.7801	19.5490
2160	7.9919	6.4470	1.4320	0.4443	7.6432	33.4803	30.7185	12.0978	17.3394	23.9946	19.5536
2165	8.0377	6.4532	1.4323	0.4446	7.6569	33.5867	30.7585	12.1385	17.4180	24.1894	19.5573
2170	8.0787	6.4584	1.4326	0.4448	7.6683	33.6827	30.7934	12.1753	17.4890	24.3662	19.5603
2175	8.1154	6.4626	1.4329	0.4450	7.6777	33.7693	30.8237	12.2086	17.5532	24.5264	19.5626
2180	8.1482	6.4660	1.4330	0.4452	7.6856	33.8475	30.8502	12.2386	17.6112	24.6716	19.5644
2185	8.1775	6.4689	1.4332	0.4453	7.6921	33.9180	30.8732	12.2656	17.6636	24.8030	19.5658
2190	8.2037	6.4712	1.4333	0.4454	7.6975	33.9816	30.8932	12.2900	17.7109	24.9219	19.5670
2195	8.2271	6.4731	1.4334	0.4455	7.7020	34.0390	30.9107	12.3120	17.7535	25.0295	19.5679
2200	8.2480	6.4747	1.4334	0.4456	7.7058	34.0907	30.9259	12.3319	17.7920	25.1267	19.5686

Table 9: Population $N_{j,t}$

	USA	EUR	JPN	AUS	FSU	CHN	IND	SEA	LAM	MEN	AFR
2005	0.8080	0.7610	0.6600	0.7050	0.6830	0.4040	0.2870	0.3970	0.7750	0.6500	0.3790
2010	0.8230	0.7700	0.6680	0.7060	0.6840	0.4490	0.3010	0.4250	0.7940	0.6630	0.3990
2015	0.8370	0.7800	0.6800	0.7090	0.6900	0.4920	0.3190	0.4530	0.8090	0.6760	0.4220
2020	0.8490	0.7910	0.6940	0.7140	0.7000	0.5320	0.3430	0.4810	0.8230	0.6910	0.4460
2025	0.8600	0.8040	0.7110	0.7190	0.7140	0.5690	0.3720	0.5110	0.8350	0.7070	0.4720
2030	0.8700	0.8170	0.7300	0.7260	0.7310	0.6030	0.4060	0.5410	0.8460	0.7250	0.5000
2035	0.8790	0.8290	0.7478	0.7340	0.7490	0.6351	0.4398	0.5699	0.8560	0.7430	0.5273
2040	0.8871	0.8401	0.7643	0.7430	0.7670	0.6651	0.4731	0.5976	0.8652	0.7600	0.5538
2045	0.8944	0.8504	0.7797	0.7530	0.7836	0.6931	0.5056	0.6240	0.8735	0.7758	0.5793
2050	0.9009	0.8598	0.7940	0.7627	0.7988	0.7191	0.5373	0.6492	0.8810	0.7905	0.6040
2055	0.9067	0.8685	0.8072	0.7722	0.8128	0.7431	0.5680	0.6730	0.8879	0.8042	0.6276
2060	0.9120	0.8764	0.8195	0.7814	0.8257	0.7652	0.5975	0.6954	0.8941	0.8168	0.6502
2065	0.9167	0.8838	0.8308	0.7903	0.8374	0.7854	0.6257	0.7165	0.8997	0.8284	0.6717
2070	0.9209	0.8905	0.8412	0.7990	0.8481	0.8039	0.6526	0.7363	0.9048	0.8392	0.6921
2075	0.9246	0.8966	0.8508	0.8074	0.8578	0.8207	0.6781	0.7548	0.9094	0.8491	0.7115
2080	0.9280	0.9023	0.8597	0.8156	0.8667	0.8360	0.7022	0.7720	0.9136	0.8583	0.7298
2085	0.9310	0.9075	0.8678	0.8235	0.8748	0.8499	0.7250	0.7881	0.9174	0.8667	0.7471
2090	0.9336	0.9122	0.8753	0.8312	0.8821	0.8624	0.7463	0.8030	0.9208	0.8744	0.7634
2095	0.9360	0.9165	0.8822	0.8386	0.8887	0.8738	0.7663	0.8168	0.9239	0.8815	0.7788
2100	0.9382	0.9205	0.8885	0.8458	0.8948	0.8840	0.7850	0.8296	0.9267	0.8880	0.7931
2105	0.9401	0.9241	0.8942	0.8528	0.9002	0.8932	0.8025	0.8415	0.9292	0.8939	0.8066
2110	0.9418	0.9274	0.8995	0.8595	0.9052	0.9014	0.8187	0.8524	0.9315	0.8994	0.8192
2115	0.9433	0.9304	0.9044	0.8661	0.9097	0.9089	0.8338	0.8625	0.9335	0.9044	0.8310
2120	0.9446	0.9332	0.9088	0.8724	0.9137	0.9155	0.8477	0.8717	0.9354	0.9090	0.8420
2125	0.9458	0.9357	0.9128	0.8785	0.9174	0.9215	0.8606	0.8803	0.9370	0.9132	0.8522
2130	0.9469	0.9380	0.9165	0.8844	0.9207	0.9269	0.8726	0.8881	0.9385	0.9170	0.8618
2135	0.9478	0.9401	0.9199	0.8901	0.9237	0.9317	0.8836	0.8953	0.9399	0.9205	0.8706
2140	0.9487	0.9420	0.9230	0.8956	0.9264	0.9359	0.8937	0.9019	0.9411	0.9237	0.8789
2145	0.9494	0.9437	0.9258	0.9010	0.9288	0.9398	0.9030	0.9080	0.9422	0.9266	0.8865
2150	0.9501	0.9453	0.9284	0.9061	0.9310	0.9432	0.9116	0.9135	0.9432	0.9293	0.8936
2155	0.9507	0.9468	0.9307	0.9111	0.9330	0.9463	0.9195	0.9186	0.9441	0.9317	0.9002
2160	0.9512	0.9481	0.9329	0.9159	0.9348	0.9490	0.9267	0.9232	0.9449	0.9339	0.9063
2165	0.9517	0.9493	0.9348	0.9205	0.9364	0.9514	0.9334	0.9275	0.9456	0.9359	0.9120
2170	0.9521	0.9504	0.9366	0.9250	0.9378	0.9536	0.9395	0.9314	0.9463	0.9378	0.9172
2175	0.9525	0.9514	0.9382	0.9293	0.9392	0.9555	0.9450	0.9349	0.9468	0.9394	0.9221
2180	0.9529	0.9523	0.9397	0.9334	0.9403	0.9573	0.9501	0.9381	0.9474	0.9410	0.9266
2185	0.9532	0.9531	0.9411	0.9374	0.9414	0.9588	0.9548	0.9411	0.9478	0.9424	0.9307
2190	0.9534	0.9539	0.9423	0.9413	0.9424	0.9602	0.9591	0.9438	0.9483	0.9437	0.9346
2195	0.9537	0.9545	0.9434	0.9450	0.9432	0.9614	0.9630	0.9463	0.9487	0.9448	0.9381
2200	0.9539	0.9552	0.9445	0.9486	0.9440	0.9625	0.9665	0.9485	0.9490	0.9459	0.9414

Table 10: Urbanization ratio $r_{j,t}$

	USA	EUR	JPN	AUS	FSU	CHN	IND	SEA	LAM	MEN	AFR
2005	0.1911	0.1083	0.0856	0.2673	0.7290	1.1227	0.7536	0.5600	0.5900	0.5429	1.1192
2010	0.1854	0.1068	0.0864	0.2700	0.6901	1.0261	0.7398	0.5498	0.4840	0.5347	1.0738
2015	0.1846	0.1051	0.0844	0.2637	0.6359	0.9243	0.7296	0.5422	0.4076	0.5189	1.0073
2020	0.1896	0.1083	0.0842	0.2630	0.6074	0.8644	0.7194	0.5347	0.3710	0.5036	0.9447
2025	0.1888	0.1074	0.0812	0.2537	0.5080	0.7604	0.6624	0.4923	0.3248	0.4490	0.7844
2030	0.1888	0.1094	0.0830	0.2593	0.4575	0.6859	0.5802	0.4312	0.2813	0.3846	0.6652
2035	0.1775	0.1044	0.0792	0.2476	0.3966	0.6188	0.5153	0.3830	0.2451	0.3250	0.5753
2040	0.1708	0.1017	0.0770	0.2406	0.3572	0.5582	0.4635	0.3445	0.2148	0.2895	0.5061
2045	0.1622	0.0977	0.0736	0.2298	0.3212	0.5035	0.4215	0.3133	0.1893	0.2597	0.4519
2050	0.1571	0.0955	0.0714	0.2231	0.2971	0.4542	0.3872	0.2878	0.1678	0.2409	0.4088
2055	0.1419	0.0926	0.0691	0.2159	0.2467	0.4097	0.3588	0.2667	0.1494	0.2070	0.3742
2060	0.1314	0.0918	0.0683	0.2133	0.2143	0.3696	0.3351	0.2491	0.1338	0.1867	0.3459
2065	0.1200	0.0896	0.0663	0.2072	0.1859	0.3334	0.3152	0.2343	0.1203	0.1689	0.3227
2070	0.1118	0.0892	0.0656	0.2050	0.1662	0.3008	0.2984	0.2217	0.1087	0.1579	0.3034
2075	0.1039	0.0885	0.0646	0.2018	0.1491	0.2713	0.2840	0.2111	0.0986	0.1485	0.2872
2080	0.0980	0.0860	0.0634	0.1980	0.1346	0.2448	0.2717	0.2019	0.0898	0.1433	0.2736
2085	0.0930	0.0838	0.0623	0.1945	0.1239	0.2208	0.2611	0.1941	0.0821	0.1400	0.2621
2090	0.0889	0.0820	0.0613	0.1915	0.1158	0.1992	0.2520	0.1873	0.0754	0.1380	0.2523
2095	0.0855	0.0805	0.0604	0.1888	0.1096	0.1797	0.2440	0.1813	0.0694	0.1367	0.2438
2100	0.0825	0.0793	0.0597	0.1864	0.1048	0.1621	0.2371	0.1762	0.0642	0.1359	0.2366
2105	0.0800	0.0782	0.0590	0.1843	0.1010	0.1462	0.2310	0.1717	0.0595	0.1354	0.2303
2110	0.0779	0.0773	0.0584	0.1824	0.0981	0.1319	0.2257	0.1677	0.0554	0.1350	0.2249
2115	0.0761	0.0765	0.0578	0.1807	0.0957	0.1190	0.2210	0.1643	0.0516	0.1348	0.2202
2120	0.0745	0.0758	0.0574	0.1792	0.0938	0.1073	0.2169	0.1612	0.0483	0.1347	0.2161
2125	0.0732	0.0753	0.0569	0.1779	0.0923	0.0968	0.2133	0.1585	0.0453	0.1346	0.2125
2130	0.0720	0.0748	0.0566	0.1767	0.0910	0.0873	0.2101	0.1561	0.0427	0.1346	0.2094
2135	0.0710	0.0744	0.0562	0.1756	0.0900	0.0788	0.2072	0.1540	0.0402	0.1345	0.2066
2140	0.0701	0.0740	0.0559	0.1746	0.0892	0.0711	0.2047	0.1521	0.0380	0.1345	0.2042
2145	0.0694	0.0737	0.0556	0.1738	0.0886	0.0641	0.2024	0.1504	0.0360	0.1345	0.2021
2150	0.0687	0.0735	0.0554	0.1730	0.0880	0.0578	0.2004	0.1489	0.0342	0.1345	0.2002
2155	0.0681	0.0732	0.0552	0.1723	0.0876	0.0522	0.1986	0.1476	0.0326	0.1345	0.1986
2160	0.0676	0.0730	0.0550	0.1717	0.0872	0.0471	0.1970	0.1464	0.0311	0.1345	0.1971
2165	0.0672	0.0729	0.0548	0.1712	0.0870	0.0425	0.1956	0.1454	0.0297	0.1345	0.1958
2170	0.0668	0.0727	0.0546	0.1707	0.0867	0.0383	0.1943	0.1444	0.0284	0.1345	0.1947
2175	0.0665	0.0726	0.0545	0.1702	0.0865	0.0345	0.1932	0.1436	0.0272	0.1345	0.1937
2180	0.0662	0.0725	0.0544	0.1698	0.0864	0.0312	0.1922	0.1428	0.0262	0.1345	0.1928
2185	0.0659	0.0724	0.0542	0.1695	0.0862	0.0281	0.1913	0.1421	0.0252	0.1345	0.1920
2190	0.0657	0.0724	0.0541	0.1691	0.0861	0.0254	0.1905	0.1415	0.0243	0.1345	0.1913
2195	0.0655	0.0723	0.0541	0.1689	0.0860	0.0229	0.1897	0.1410	0.0234	0.1345	0.1907
2200	0.0653	0.0722	0.0540	0.1686	0.0860	0.0206	0.1891	0.1405	0.0226	0.1345	0.1901

Table 11: Carbon emission intensity $\sigma_{j,t}^{cc}$

	USA	EUR	JPN	AUS	FSU	CHN	IND	SEA	LAM	MEN	AFR
2005	0.0206	0.0067	0.0034	0.1150	0.1573	0.8588	0.5090	0.2210	0.2366	0.1639	0.3702
2010	0.0184	0.0060	0.0034	0.1014	0.1361	0.6960	0.4876	0.2117	0.2069	0.1323	0.3145
2015	0.0181	0.0058	0.0033	0.0942	0.1298	0.6087	0.5020	0.2180	0.1934	0.1131	0.2808
2020	0.0187	0.0059	0.0032	0.0925	0.1346	0.5316	0.5060	0.2197	0.1840	0.0986	0.2908
2025	0.0179	0.0055	0.0032	0.0837	0.1177	0.4003	0.4382	0.1903	0.1560	0.0765	0.2871
2030	0.0196	0.0061	0.0031	0.0931	0.1170	0.3011	0.3389	0.1472	0.1207	0.0558	0.2269
2035	0.0206	0.0064	0.0030	0.0981	0.1134	0.2064	0.2392	0.1038	0.0845	0.0376	0.1658
2040	0.0216	0.0067	0.0029	0.1033	0.1122	0.1454	0.1736	0.0754	0.0604	0.0263	0.1253
2045	0.0219	0.0067	0.0028	0.1041	0.1079	0.1083	0.1332	0.0578	0.0456	0.0194	0.1002
2050	0.0213	0.0065	0.0027	0.1006	0.1008	0.0838	0.1063	0.0462	0.0356	0.0150	0.0834
2055	0.0204	0.0060	0.0025	0.0964	0.0833	0.0607	0.0735	0.0319	0.0250	0.0119	0.0629
2060	0.0185	0.0053	0.0024	0.0875	0.0671	0.0449	0.0513	0.0223	0.0178	0.0096	0.0483
2065	0.0172	0.0048	0.0023	0.0810	0.0561	0.0357	0.0380	0.0165	0.0134	0.0082	0.0397
2070	0.0151	0.0041	0.0021	0.0710	0.0450	0.0278	0.0274	0.0119	0.0099	0.0068	0.0319
2075	0.0142	0.0038	0.0020	0.0666	0.0392	0.0239	0.0216	0.0094	0.0080	0.0062	0.0283
2080	0.0125	0.0033	0.0018	0.0589	0.0279	0.0178	0.0180	0.0078	0.0060	0.0051	0.0246
2085	0.0114	0.0030	0.0017	0.0531	0.0200	0.0142	0.0163	0.0071	0.0048	0.0045	0.0237
2090	0.0106	0.0028	0.0015	0.0489	0.0144	0.0120	0.0155	0.0067	0.0040	0.0041	0.0234
2095	0.0099	0.0027	0.0014	0.0456	0.0105	0.0106	0.0151	0.0066	0.0034	0.0039	0.0233
2100	0.0095	0.0025	0.0012	0.0431	0.0077	0.0097	0.0149	0.0065	0.0031	0.0038	0.0233
2105	0.0091	0.0024	0.0010	0.0411	0.0057	0.0090	0.0148	0.0064	0.0028	0.0037	0.0233
2110	0.0089	0.0024	0.0009	0.0395	0.0042	0.0085	0.0147	0.0064	0.0026	0.0037	0.0233
2115	0.0087	0.0023	0.0007	0.0383	0.0032	0.0081	0.0147	0.0064	0.0024	0.0036	0.0233
2120	0.0085	0.0023	0.0006	0.0373	0.0024	0.0079	0.0147	0.0064	0.0023	0.0036	0.0233
2125	0.0084	0.0022	0.0005	0.0365	0.0018	0.0077	0.0147	0.0064	0.0022	0.0036	0.0233
2130	0.0083	0.0022	0.0004	0.0358	0.0014	0.0075	0.0146	0.0064	0.0022	0.0036	0.0233
2135	0.0082	0.0022	0.0003	0.0353	0.0011	0.0074	0.0146	0.0064	0.0021	0.0036	0.0233
2140	0.0082	0.0022	0.0002	0.0348	0.0008	0.0073	0.0146	0.0064	0.0021	0.0036	0.0233
2145	0.0081	0.0022	0.0001	0.0344	0.0006	0.0073	0.0146	0.0064	0.0020	0.0036	0.0233
2150	0.0081	0.0022	0.0001	0.0342	0.0005	0.0072	0.0146	0.0064	0.0020	0.0035	0.0233
2155	0.0081	0.0021	0.0001	0.0339	0.0004	0.0072	0.0146	0.0064	0.0020	0.0035	0.0233
2160	0.0081	0.0021	0.0000	0.0337	0.0003	0.0072	0.0146	0.0064	0.0020	0.0035	0.0233
2165	0.0080	0.0021	0.0000	0.0335	0.0002	0.0071	0.0146	0.0064	0.0020	0.0035	0.0233
2170	0.0080	0.0021	0.0000	0.0334	0.0002	0.0071	0.0146	0.0064	0.0020	0.0035	0.0233
2175	0.0080	0.0021	0.0000	0.0333	0.0002	0.0071	0.0146	0.0064	0.0019	0.0035	0.0233
2180	0.0080	0.0021	0.0000	0.0332	0.0001	0.0071	0.0146	0.0064	0.0019	0.0035	0.0233
2185	0.0080	0.0021	0.0000	0.0331	0.0001	0.0071	0.0146	0.0064	0.0019	0.0035	0.0233
2190	0.0080	0.0021	0.0000	0.0331	0.0001	0.0071	0.0146	0.0064	0.0019	0.0035	0.0233
2195	0.0080	0.0021	0.0000	0.0330	0.0001	0.0071	0.0146	0.0064	0.0019	0.0035	0.0233
2200	0.0080	0.0021	0.0000	0.0330	0.0001	0.0071	0.0146	0.0064	0.0019	0.0035	0.0233

Table 12: Sulfur emission intensity $\sigma^{aa}_{j,t}$

	USA	EUR	JPN	AUS	FSU	CHN	IND	SEA	LAM	MEN	AFR
2005	0.0811	0.0263	0.0136	0.4524	0.6188	0.8744	0.5183	0.2250	0.2409	0.1669	0.3769
2010	0.0703	0.0230	0.0130	0.3884	0.5211	0.7304	0.5117	0.2222	0.2171	0.1388	0.3301
2015	0.0658	0.0213	0.0121	0.3430	0.4727	0.6722	0.5544	0.2407	0.2136	0.1249	0.3101
2020	0.0628	0.0199	0.0109	0.3105	0.4517	0.6360	0.6054	0.2628	0.2201	0.1180	0.3479
2025	0.0531	0.0164	0.0094	0.2487	0.3500	0.5394	0.5905	0.2564	0.2102	0.1030	0.3869
2030	0.0494	0.0153	0.0077	0.2345	0.2946	0.4813	0.5419	0.2353	0.1930	0.0893	0.3628
2035	0.0417	0.0130	0.0061	0.1992	0.2302	0.4190	0.4855	0.2108	0.1714	0.0764	0.3366
2040	0.0346	0.0107	0.0046	0.1652	0.1793	0.3662	0.4370	0.1897	0.1521	0.0661	0.3154
2045	0.0295	0.0091	0.0037	0.1402	0.1454	0.3219	0.3959	0.1719	0.1354	0.0578	0.2979
2050	0.0255	0.0078	0.0032	0.1204	0.1206	0.2813	0.3567	0.1549	0.1196	0.0503	0.2798
2055	0.0225	0.0067	0.0028	0.1064	0.0920	0.2210	0.2677	0.1162	0.0912	0.0435	0.2290
2060	0.0195	0.0056	0.0025	0.0919	0.0704	0.1720	0.1964	0.0853	0.0681	0.0368	0.1849
2065	0.0175	0.0049	0.0023	0.0824	0.0571	0.1405	0.1497	0.0650	0.0529	0.0323	0.1563
2070	0.0151	0.0041	0.0021	0.0712	0.0451	0.1113	0.1096	0.0476	0.0395	0.0273	0.1277
2075	0.0141	0.0037	0.0020	0.0663	0.0390	0.0958	0.0865	0.0375	0.0319	0.0249	0.1131
2080	0.0125	0.0033	0.0018	0.0584	0.0277	0.0710	0.0719	0.0312	0.0239	0.0204	0.0985
2085	0.0113	0.0030	0.0017	0.0528	0.0198	0.0553	0.0635	0.0276	0.0185	0.0175	0.0921
2090	0.0105	0.0028	0.0015	0.0485	0.0143	0.0451	0.0582	0.0253	0.0149	0.0155	0.0877
2095	0.0099	0.0026	0.0013	0.0453	0.0104	0.0373	0.0531	0.0230	0.0121	0.0138	0.0818
2100	0.0094	0.0025	0.0012	0.0428	0.0077	0.0306	0.0473	0.0205	0.0097	0.0120	0.0739
2105	0.0091	0.0024	0.0010	0.0408	0.0057	0.0247	0.0407	0.0177	0.0077	0.0102	0.0641
2110	0.0088	0.0024	0.0009	0.0392	0.0042	0.0193	0.0335	0.0145	0.0059	0.0083	0.0530
2115	0.0086	0.0023	0.0007	0.0380	0.0032	0.0145	0.0262	0.0114	0.0044	0.0065	0.0416
2120	0.0085	0.0023	0.0006	0.0370	0.0024	0.0115	0.0214	0.0093	0.0034	0.0052	0.0339
2125	0.0083	0.0022	0.0005	0.0362	0.0018	0.0097	0.0185	0.0080	0.0028	0.0045	0.0294
2130	0.0083	0.0022	0.0004	0.0355	0.0014	0.0086	0.0168	0.0073	0.0025	0.0041	0.0266
2135	0.0082	0.0022	0.0003	0.0350	0.0011	0.0080	0.0157	0.0068	0.0023	0.0038	0.0250
2140	0.0081	0.0022	0.0002	0.0346	0.0008	0.0076	0.0151	0.0066	0.0021	0.0037	0.0240
2145	0.0081	0.0021	0.0001	0.0342	0.0006	0.0073	0.0148	0.0064	0.0021	0.0036	0.0235
2150	0.0080	0.0021	0.0001	0.0339	0.0005	0.0072	0.0146	0.0063	0.0020	0.0035	0.0232
2155	0.0080	0.0021	0.0001	0.0337	0.0004	0.0072	0.0146	0.0063	0.0020	0.0035	0.0231
2160	0.0080	0.0021	0.0000	0.0335	0.0003	0.0071	0.0145	0.0063	0.0020	0.0035	0.0231
2165	0.0080	0.0021	0.0000	0.0333	0.0002	0.0071	0.0145	0.0063	0.0019	0.0035	0.0231
2170	0.0080	0.0021	0.0000	0.0332	0.0002	0.0071	0.0145	0.0063	0.0019	0.0035	0.0231
2175	0.0080	0.0021	0.0000	0.0330	0.0002	0.0071	0.0145	0.0063	0.0019	0.0035	0.0231
2180	0.0079	0.0021	0.0000	0.0330	0.0001	0.0071	0.0145	0.0063	0.0019	0.0035	0.0231
2185	0.0079	0.0021	0.0000	0.0329	0.0001	0.0070	0.0145	0.0063	0.0019	0.0035	0.0231
2190	0.0079	0.0021	0.0000	0.0328	0.0001	0.0070	0.0145	0.0063	0.0019	0.0035	0.0231
2195	0.0079	0.0021	0.0000	0.0328	0.0001	0.0070	0.0145	0.0063	0.0019	0.0035	0.0231
2200	0.0079	0.0021	0.0000	0.0327	0.0001	0.0070	0.0145	0.0063	0.0019	0.0035	0.0231

Table 13: Cross-emission intensity $\sigma_{j,t}^{ac}$

	USA	EUR	JPN	AUS	FSU	CHN	IND	SEA	LAM	MEN	AFR
2005	1.6230	1.3640	1.7520	1.2660	0.3190	0.1310	0.1110	0.2810	0.3850	0.3180	0.1220
2010	1.6603	1.4049	1.8133	1.2711	0.3499	0.1440	0.1212	0.3077	0.4039	0.3384	0.1342
2015	1.6999	1.4485	1.8766	1.2766	0.3835	0.1581	0.1322	0.3363	0.4243	0.3598	0.1475
2020	1.7417	1.4951	1.9419	1.2826	0.4199	0.1736	0.1441	0.3670	0.4464	0.3825	0.1621
2025	1.7861	1.5448	2.0092	1.2891	0.4593	0.1904	0.1569	0.3998	0.4705	0.4064	0.1779
2030	1.8333	1.5980	2.0787	1.2963	0.5019	0.2087	0.1706	0.4349	0.4966	0.4316	0.1952
2035	1.8834	1.6549	2.1504	1.3041	0.5480	0.2287	0.1854	0.4722	0.5251	0.4581	0.2141
2040	1.9366	1.7160	2.2243	1.3126	0.5977	0.2504	0.2013	0.5120	0.5562	0.4861	0.2346
2045	1.9933	1.7815	2.3005	1.3219	0.6514	0.2740	0.2183	0.5542	0.5902	0.5155	0.2570
2050	2.0537	1.8518	2.3791	1.3320	0.7092	0.2996	0.2365	0.5990	0.6274	0.5464	0.2812
2055	2.1180	1.9276	2.4602	1.3432	0.7715	0.3274	0.2561	0.6464	0.6682	0.5789	0.3076
2060	2.1868	2.0091	2.5438	1.3553	0.8385	0.3577	0.2769	0.6966	0.7131	0.6131	0.3363
2065	2.2602	2.0971	2.6299	1.3686	0.9105	0.3904	0.2993	0.7496	0.7625	0.6490	0.3675
2070	2.3387	2.1922	2.7187	1.3832	0.9879	0.4260	0.3231	0.8055	0.8170	0.6868	0.4012
2075	2.4229	2.2951	2.8102	1.3991	1.0709	0.4644	0.3485	0.8643	0.8773	0.7264	0.4379
2080	2.5131	2.4065	2.9045	1.4167	1.1598	0.5061	0.3756	0.9262	0.9441	0.7679	0.4775
2085	2.6099	2.5275	3.0017	1.4359	1.2551	0.5512	0.4044	0.9912	1.0183	0.8115	0.5205
2090	2.7140	2.6589	3.1018	1.4571	1.3571	0.6000	0.4350	1.0593	1.1009	0.8571	0.5670
2095	2.8260	2.8021	3.2050	1.4805	1.4662	0.6527	0.4676	1.1307	1.1930	0.9050	0.6174
2100	2.9467	2.9582	3.3112	1.5062	1.5828	0.7096	0.5023	1.2054	1.2961	0.9551	0.6718
2105	3.0770	3.1288	3.4207	1.5346	1.7072	0.7711	0.5390	1.2834	1.4116	1.0076	0.7305
2110	3.2083	3.3003	3.5308	1.5672	1.8362	0.8374	0.5787	1.3656	1.5330	1.0625	0.7926
2115	3.3404	3.4721	3.6415	1.6042	1.9697	0.9090	0.6214	1.4523	1.6602	1.1199	0.8581
2120	3.4733	3.6438	3.7528	1.6455	2.1076	0.9861	0.6676	1.5435	1.7932	1.1800	0.9271
2125	3.6068	3.8149	3.8646	1.6913	2.2496	1.0693	0.7175	1.6397	1.9320	1.2429	0.9996
2130	3.7409	3.9852	3.9771	1.7418	2.3956	1.1589	0.7713	1.7410	2.0766	1.3086	1.0758
2135	3.8755	4.1541	4.0901	1.7970	2.5455	1.2555	0.8294	1.8476	2.2269	1.3774	1.1557
2140	4.0105	4.3215	4.2038	1.8572	2.6992	1.3596	0.8922	1.9599	2.3829	1.4493	1.2394
2145	4.1458	4.4868	4.3180	1.9225	2.8564	1.4717	0.9599	2.0781	2.5446	1.5245	1.3270
2150	4.2814	4.6499	4.4328	1.9933	3.0170	1.5925	1.0331	2.2026	2.7119	1.6031	1.4186
2155	4.4172	4.8105	4.5482	2.0696	3.1808	1.7226	1.1121	2.3336	2.8848	1.6854	1.5143
2160	4.5532	4.9683	4.6642	2.1520	3.3479	1.8626	1.1974	2.4714	3.0632	1.7714	1.6141
2165	4.6894	5.1231	4.7809	2.2405	3.5179	2.0134	1.2895	2.6165	3.2472	1.8613	1.7183
2170	4.8257	5.2748	4.8982	2.3357	3.6908	2.1757	1.3890	2.7692	3.4367	1.9554	1.8268
2175	4.9621	5.4232	5.0162	2.4378	3.8664	2.3503	1.4965	2.9299	3.6316	2.0538	1.9399
2180	5.0986	5.5681	5.1349	2.5472	4.0448	2.5384	1.6126	3.0990	3.8320	2.1566	2.0576
2185	5.2352	5.7094	5.2544	2.6645	4.2256	2.7407	1.7381	3.2769	4.0378	2.2642	2.1800
2190	5.3719	5.8471	5.3746	2.7899	4.4089	2.9584	1.8736	3.4640	4.2491	2.3766	2.3073
2195	5.5086	5.9810	5.4955	2.9241	4.5946	3.1926	2.0200	3.6609	4.4658	2.4942	2.4397
2200	5.6454	6.1112	5.6173	3.0676	4.7826	3.4446	2.1781	3.8681	4.6879	2.6172	2.5772

Table 14: Total factor productivity $\psi_{j,t}$

			Nash				Optimal			
		2005	2025	2050	2075	2100	2025	2050	2075	2100
Temp change (°C)	USA	0.00	0.77	1.60	2.38	3.16	0.77	1.54	2.23	2.88
	EUR	0.00	1.04	2.10	3.08	4.04	1.02	1.99	2.85	3.65
	CHN	0.00	0.65	1.37	2.15	2.96	0.66	1.35	2.05	2.75
	IND	0.00	0.55	1.20	1.94	2.66	0.55	1.16	1.82	2.43
	AFR	0.00	0.63	1.29	2.00	2.70	0.62	1.23	1.86	2.45
	Global	0.00	0.74	1.53	2.34	3.15	0.73	1.47	2.18	2.88
CO_2 emission (GtC)	USA	1.67	2.23	2.67	2.71	3.24	2.03	2.28	2.15	2.33
	EUR	1.06	1.33	1.58	2.06	2.81	1.25	1.43	1.77	2.26
	CHN	1.19	1.73	2.19	2.59	2.88	1.52	1.84	2.01	1.97
	IND	0.59	1.17	1.39	2.00	2.83	1.04	1.21	1.60	2.09
	AFR	0.52	1.03	1.36	1.92	2.78	0.92	1.19	1.59	2.16
	Global	8.64	12.68	15.25	18.55	24.70	11.42	13.16	14.96	18.23
SO_2 emission (TgS)	USA	8.87	8.40	7.94	7.48	7.63	7.86	7.36	6.82	6.73
	EUR	3.22	2.73	2.38	1.78	1.82	2.61	2.26	1.66	1.66
	CHN	18.30	18.29	17.08	11.44	7.29	16.93	14.97	9.41	5.61
	IND	8.05	16.21	16.18	7.55	7.34	15.03	14.42	6.32	5.83
	AFR	3.50	8.48	11.92	9.44	11.32	8.08	10.79	8.16	9.48
	Global	71.59	93.68	91.83	59.88	50.61	87.68	83.48	52.13	41.93

Table 15: Temperature and emission trajectories for selected regions, 2005–2100

	$F^{a,ind}_{1990} = -0.3$				$F^{a,ind}_{1990} = -1.8$			
	CO_2		SO_2		CO_2		SO_2	
	Nash	Opt.	Nash	Opt.	Nash	Opt.	Nash	Opt.
USA	−0.69	−0.54	−0.88	−1.00	1.33	1.06	1.59	1.87
EUR	−0.47	−0.30	−0.61	−0.52	0.93	0.62	1.12	0.96
CHN	−0.31	−0.41	−0.52	−0.91	0.52	0.72	1.09	2.09
IND	−0.25	−0.13	−0.42	−0.39	0.45	0.25	0.94	0.93
AFR	−0.55	−0.49	−1.00	−1.68	0.93	0.75	2.25	5.71
Global	−0.40	−0.33	−0.55	−1.03	0.73	0.70	1.09	1.73

	$\rho = 0.02$ (annualized)				$\rho = 0.04$ (annualized)			
	CO_2		SO_2		CO_2		SO_2	
	Nash	Opt.	Nash	Opt.	Nash	Opt.	Nash	Opt.
USA	1.85	−7.78	3.36	−0.94	−2.66	2.55	−3.45	−1.12
EUR	1.85	−4.56	3.12	−0.17	−2.57	0.55	−3.26	−1.52
CHN	2.93	−9.39	3.22	−5.90	−3.19	3.05	−3.30	1.33
IND	3.25	−5.82	3.51	−3.50	−3.39	1.31	−3.50	0.14
AFR	2.79	−5.85	3.32	−2.62	−3.23	1.35	−3.48	−0.31
Global	2.68	−6.87	3.46	−3.23	−3.08	1.59	−3.47	−0.37

Table 16: Sensitivity of carbon and sulfur emissions in 2050 (percent change from benchmark) to changes in indirect radiative forcing of sulfate (top) and rate of time preference (bottom)

	climate sensitivity τ^c				cross-emission coefficient σ^{ac}			
	Nash		Opt.		Nash		Opt.	
	low	high	low	high	small	large	small	large
USA	0.70	−0.79	3.71	−3.81	0.84	−0.80	0.38	−0.40
EUR	0.83	−0.90	2.76	−2.83	0.66	−0.63	0.43	−0.45
CHN	0.19	−0.23	3.95	−4.19	5.47	−4.43	3.98	−3.42
IND	0.29	−0.30	3.09	−3.22	3.31	−2.74	2.34	−2.09
AFR	0.41	−0.45	3.21	−3.33	1.84	−1.56	0.79	−0.71
Global	0.41	−0.46	3.40	−3.53	2.31	−1.96	1.45	−1.31

	local dimming effect τ^a's				climate damage γ's			
	Nash		Opt.		Nash		Opt.	
	weak	strong	weak	strong	small	large	small	large
USA	−0.68	0.72	−0.46	0.47	0.59	−0.56	4.60	−4.08
EUR	−0.37	0.39	−0.20	0.21	0.92	−0.84	3.50	−3.10
CHN	−0.52	0.53	−0.67	0.71	−0.01	0.02	4.78	−4.39
IND	−0.63	0.64	−0.44	0.45	0.00	0.00	3.72	−3.40
AFR	−0.93	0.94	−0.92	0.93	0.01	−0.01	3.75	−3.38
Global	−0.53	0.54	−0.47	0.50	0.27	−0.25	4.18	−3.75

	health damage (temperature) β_2^c				health damage (air pollution) β^a			
	Nash		Opt.		Nash		Opt.	
	small	large	small	large	small	large	small	large
USA	0.00	0.00	0.20	−0.06	1.59	−1.45	0.95	−0.96
EUR	0.00	0.00	0.18	−0.05	1.08	−1.01	0.69	−0.72
CHN	0.01	−0.01	0.33	−0.10	5.40	−4.99	4.14	−4.26
IND	0.02	−0.02	0.24	−0.07	3.65	−3.35	2.53	−2.63
AFR	−0.12	0.13	−0.07	0.02	2.62	−2.43	1.68	−1.73
Global	−0.01	0.02	0.22	−0.06	2.72	−2.49	1.84	−1.90

Table 17: Sensitivity of E^c in 2050 (percent change from benchmark) to changes in parameter values