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The effect of health benefits on climate change mitigation policies

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Abstract This paper studies the interplay between climate, health, and the economy in a stylized world with eleven heterogeneous regions, with special emphasis on USA, Europe, China, India, and Africa. We introduce health impacts into a simple economic integrated assessment model where both the local cooling effect of SO_2 and the global warming effect of CO_2 are endogenous, and investigate how these factors affect the equilibrium path. Regions do not respond in the same way to climate change. In particular, emission abatement rates and health costs depend on the economic and geographical characteristics of each region. Two policy scenarios are considered, Nash and Optimal, for which we present both global and regional results. Results for Africa and China are highlighted.

Keywords Climate change · Air pollution · Local dimming · Health · Economic growth

1 Introduction

Although climate change is a global phenomenon, its effects are not the same in every region. For example, the impact of increasing global temperature on human health varies significantly across regions, depending on the geography and the economic situation

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(IPCC 2007). The differences at a regional level will lead to different regional policies, which in turn will affect the response to climate change at a global level. Also, local environmental problems such as air pollution relate directly and indirectly to climate change. These global-local links create regional incentives to carbon mitigation, and, in terms of global efficiency, in sharing the cost of climate policies. In this paper we investigate the implications of these links using an economy-climate model with an emphasis on health impacts, accounting explicitly for the interplay between global and regional aspects of climate change and air pollution.

Global climate change and local air pollution interact in two ways. First, climate policies intended to reduce greenhouse gas emissions also reduce emissions of other substances such as sulfur dioxide (Swart et al. 2004; EEA 2004). Since these other substances are harmful to human health, this link provides an additional benefit, thus partly compensating the cost of climate policies and relaxing the public-bad nature of the problem. If we consider air pollution explicitly, then the location of the carbon emission reduction matters, even though its primary benefit (temperature decrease) is evenly distributed around the globe.

A second, less known but equally important, source of global-local interaction is the dimming effect of aerosols. Aerosols are small particles, such as sulfur dioxide, floating in the air and reflecting or absorbing sunlight. More aerosols means that less sunlight will fall on the Earth, thus producing a cooling effect (Wang et al. 2009; Vautard et al. 2009). This cooling effect is not negligible and the statistical evidence suggests that it is primarily a regional phenomenon (Magnus et al. 2011). The increasing trend of global temperature is thus partially counteracted by sulfate aerosols at a regional level, and a reduction of sulfur dioxide will have the unintended side-effect of increasing regional temperature. Europe, for example, experienced a period of solar brightening (the opposite of dimming) since 2000, caused by a decrease of aerosols due to European clean-air regulations (Wild et al. 2009). Locally emitted sulfur dioxide thus provides a trade-off between air quality and temperature, which is particularly harmful to developing regions with a high vulnerability to climate.

These global-local links may or may not influence the global analysis of climate change, but at the regional level they have important implications. While some regions are successful in controlling air pollution, we expect air quality to deteriorate in others. On the other hand, a reduction of some air pollutants such as sulfur dioxide would cause a temporary increase of regional temperature. Since the marginal damage from climate change is usually increasing in temperature, this suggests that climate-sensitive regions will have difficulty in controlling the regional air quality when global mean temperature is rising. The cooling effect of regional aerosols, which can be controlled by regional governments, may thus be essential for climate-sensitive regions.

To investigate how these global-local links affect the behavior and welfare of different regions, we use a simple integrated assessment model with a particular focus on health. We extend Nordhaus and Yang (1996)'s RICE model in three respects. First, we model regional sulfur emissions from economic activities in addition to carbon emission. Sulfur dioxide is an air pollutant with potentially serious health impacts at a regional level. At the same time, sulfur emissions are aerosols, thus diminishing the damage from temperature increase through their cooling effect. Second, we introduce both global and regional temperature dynamics. While carbon dioxide increases global temperature, sulfur dioxide decreases regional temperature. Third, we consider the contribution of human health to welfare both in terms of its intrinsic value and as an input to economic output.

The issue of global-local interactions in the context of climate change has not received much attention in the literature until recently. Bahn and Leach (2008) examine the welfare implications of carbon mitigation policies by incorporating both cooling and health effects of sulfur dioxide emissions in an overlapping generations model. Since they use a globally aggregated model, they can only consider the global cooling effect of aerosols. In contrast, we study the implications of regional cooling by considering multiple regions. Bollen et al. (2009a) provide a combined cost-benefit analysis based on the MERGE model in which they consider both regional air pollution and global climate change. Also, Bollen et al. (2009b) investigate possible synergies between climate policies and clean-air policies. A key difference between their model and ours is that we explicitly model region-specific temperatures as well as global mean temperature, and take decentralized and strategic decision-making by each region into account.

The paper is organized as follows. In Section 2 we present the climate-economy model of our stylized world. Section 3 defines the eleven regions and explains how the model is calibrated. Section 4 provides the main results based on the global and regional trajectories of some key variables. Section 5 concludes.

2 The model

Our stylized world consists of $J = 11$ regions which we consider over $T = 40$ periods. One period is five years. At the beginning of period t there are $N_{j,t}$ inhabitants of region j, identical apart from the fact that some are healthy while others are ill. The healthy constitute the labor force $L_{j,t}$. There are two diseases: one caused by temperature (climate related), the other by aerosols (air-pollution related). The two diseases are not mutually exclusive, but they are independent.

Supply side The labor force together with the available capital stock generate GDP $Y_{j,t}$ through a Cobb-Douglas production function

$$Y_{j,t} = \psi_{j,t} K_{j,t}^{\epsilon} L_{j,t}^{1-\epsilon} \qquad (0 < \epsilon < 1), \tag{1}$$

where $K_{j,t}$ denotes the capital stock in region j at the beginning of period t, and $\psi_{j,t}$ is technological efficiency. Capital's share ϵ of income is set to 0.3 based on Nordhaus (2010). All stocks are measured at the beginning of the period. Capital is accumulated through

$$K_{j,t+1} = (1 - \delta^k) K_{j,t} + I_{j,t} \qquad (0 < \delta^k < 1), \tag{2}$$

where $I_{j,t}$ denotes investment and $\delta^k = 0.41$ is the depreciation rate of capital, assumed constant over time and over regions. The labor force $L_{j,t}$ is given by

$$L_{j,t} = (1 - p_{j,t}) N_{j,t}, \tag{3}$$

where $p_{j,t}$ denotes the proportion of the population suffering from a disease. We note that while $N_{j,t}$ is exogenous in our model, the proportion $p_{j,t}$, and hence the labor force $L_{j,t}$, is endogenous. Diseases thus cause a reduction of the labor force.

Demand side In each region j and period t, gross income is reduced by the damage $D_{j,t}$ due to climate change (excluding health impacts). Net income $Y_{j,t} - D_{j,t}$ can then be spent on consumption $C_{j,t}$, investment $I_{j,t}$, or emission abatement $A_{j,t}$:

$$Y_{j,t} - D_{j,t} = C_{j,t} + I_{j,t} + A_{j,t}. \tag{4}$$

We specify the abatement function in Eq. 7 and the damage function in Eq. 8.

Pollution Each region pollutes by emitting carbon dioxide CO_2 (c) and sulfur dioxide SO_2 (a), where SO_2 emissions are taken as a representative proxy to aerosol emissions throughout. Emissions $E^c_{j,t}$ (for CO_2) and $E^a_{j,t}$ (for SO_2) are defined by

$$\begin{pmatrix} E^c_{j,t} \\ E^a_{j,t} \end{pmatrix} = \begin{pmatrix} \sigma^{cc}_{j,t} & \sigma^{ca}_{j,t} \\ \sigma^{ac}_{j,t} & \sigma^{aa}_{j,t} \end{pmatrix} \begin{pmatrix} 1-\mu^c_{j,t} \\ 1-\mu^a_{j,t} \end{pmatrix} Y_{j,t}, \tag{5}$$

where $\mu^c_{j,t}$ and $\mu^a_{j,t}$ denote the abatement fractions for CO_2 and SO_2, respectively, and the $\sigma_{j,t}$ are technical parameters.

The two cross-influences $\sigma^{ca}_{j,t}$ and $\sigma^{ac}_{j,t}$ capture the fact that many traditional air pollutants and greenhouse gases have common sources such as fossil-fuel consumption (Swart et al. 2004). We shall assume that $\sigma^{ac}_{j,t} > 0$ and $\sigma^{ca}_{j,t} = 0$. The positive sign of σ^{ac} is intuitive, because any major climate policy requires the reduction of fossil-fuel consumption, so that CO_2 mitigation through μ^c affects SO_2 emissions. Empirical evidence is provided by Cifuentes et al. (2001) in a study of four large cities (Mexico City, New York City, Santiago, and São Paulo). A consequence of $\sigma^{ac} > 0$ is that a policy of increased CO_2 abatement will not only reduce CO_2 emissions, but also SO_2 emissions. The sign of σ^{ca} is less clear. SO_2 mitigation through μ^a may or may not affect CO_2 emissions. For example, the installation of end-of-pipe technologies to reduce SO_2 emissions does not affect the quantity of fossil fuel used for production. Hence we set $\sigma^{ca} = 0$ throughout.

Global carbon concentration M_t is given by

$$M_{t+1} = (1-\delta^c)M_t + \sum_{j=1}^{J} E^c_{j,t} \qquad (0 < \delta^c < 1), \tag{6}$$

where $\delta^c = 0.026$ is the depreciation rate of CO_2 (rate of removal from atmosphere).

Abatement Extending the often-used abatement cost function from one type of emission (as for CO_2 in Nordhaus, 2008) to two types of emission (CO_2 and SO_2), we write

$$A_{j,t} = \left(\alpha^c_{j,t}(\mu^c_{j,t})^{\xi^c} + \alpha^a_{j,t}(\mu^a_{j,t})^{\xi^a}\right) Y_{j,t}, \tag{7}$$

where the exponents ξ^c and ξ^a are chosen greater than one, so that abatement is convex in $\mu^c_{j,t}$ and $\mu^a_{j,t}$.

Damage and health 'Damage' is defined as the reduction of GDP due to an increase in temperature, excluding the health effect. We model damage as a region-specific proportion of GDP, such that the higher is regional temperature $Z_{j,t}$, the higher is the proportion:

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

Higher temperature causes diseases, so-called 'climate-related' diseases. In addition, SO_2 also causes diseases, so-called 'air-pollution-related' diseases. Let $p^c_{j,t}$ and $p^a_{j,t}$ be the fractions of the population suffering from climate-related diseases and air-pollution-related diseases, respectively. The fraction of healthy people in region j at time t is then given by $(1-p_{j,t}) = (1-p^c_{j,t})(1-p^a_{j,t})$, so that the labor force $L_{j,t}$ can be written as

$$L_{j,t} = (1-p^c_{j,t})(1-p^a_{j,t})N_{j,t}. \tag{9}$$

As explained in Section 3, we assume that $p^c_{j,t}$ and $p^a_{j,t}$ depend on regional temperature $Z_{j,t}$ and regional SO_2 emission $E^a_{j,t}$, respectively:

$$p^c_{j,t} = \beta^c_{1,j} + \beta^c_{2,j} Z_{j,t}^{\beta^c_{3,j}}, \qquad p^a_{j,t} = \beta^a_{j,t} E^a_{j,t}. \tag{10}$$

We note that $p^a_{j,t}$ represents only part of air-pollution-related health damages from fossil energy consumption, since we consider SO_2 as the representative air pollutant. In reality, where fossil energy combustion causes air pollution through a variety of fine particles, the corresponding health damage can be much larger. Also, while air-pollution-related diseases can be acute or chronic (caused by long-term exposure to SO_2 emission), we do not distinguish between acute and chronic diseases because we consider one period (five years) to be sufficiently long.

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

$$\begin{aligned} Z_{j,t+1} &= \tau_{0,j} + \tau_1 Z_{j,t} + \tau_2 Z_t + \tau^c_j \log(M_{t+1}) \\ &\quad + \tau^a_{1,j} E^a_{j,t+1} + \tau^a_{2,j} \log(1 + \tau^a_{3,j} E^a_{j,t+1}). \end{aligned} \tag{11}$$

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. This equation resembles the corresponding temperature equations in Magnus et al. (2011). In contrast to the Nordhaus model where the radiative forcing of aerosols is given exogenously, we have endogenous aerosol radiative forcing. 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.

Regional temperature is thus dynamically determined by its own past, but also by the (global) concentration of carbon dioxide and the (regional) emission of aerosols. More CO_2 leads to a higher temperature (global warming) through the greenhouse effect. In addition, aerosols reflect and absorb sunlight in the atmosphere, so that less sunlight reaches the Earth (local dimming). The (global) greenhouse effect and the (local) dimming effect thus work in opposite directions.

Welfare Welfare W_j of each region is defined by

$$W_j = \sum_{t=0}^{T} \frac{L_{j,t} \log(1 + C_{j,t}/N_{j,t})}{(1+\rho)^t}. \tag{12}$$

where $\rho = 0.159$ is the discount rate, the annualized value of which is 0.03. Health damage reduces the labor force, and hence affects both output and welfare. The health damage of climate change or air pollution does not only cause economic loss (market impact), but reduces also people's happiness (non-market impact). The market impact consists of the fact that the reduction of the labor force due to diseases causes productivity and income to decline, so that the resource constraint becomes tighter. The non-market impact is mainly due to the loss of healthy lives, which directly affects people's welfare through an increase in $p_{j,t}$.

Important is the relationship between output Y and labor L. More labor leads to more output through the production function (1). More output leads to more air pollution, more air-pollution-related disease, and less labor, through Eq. 9 and 10. Hence, output and labor are determined simultaneously, not sequentially.

3 Regions and parameter calibration

3.1 Regions

We divide the world into eleven regions: USA (United States of America and Canada), EUR (Western Europe), JPN (Japan), AUS (Australia and Oceania), FSU (Former Soviet Union and Eastern Europe), CHN (China and centrally planned Asia), IND (India and South Asia), SEA (South East Asia), LAM (Latin America and Caribbean), MEN (Middle East and North Africa), and AFR (Sub-Sahara Africa). The choice of regions is determined by geographical and political proximity and by similarity in human health vulnerability, and is based on the IPCC (2000) and WHO (2003) definitions.

Implicitly we assume that individual countries within each region coordinate their actions. Hence, for regions involving many countries (such as LAM and AFR) our results tend to overestimate their willingness to abate carbon emission in a strategic environment. While the policy scenarios are always in terms of all eleven regions, we shall report primarily on only five regions, namely USA and EUR (cold, rich), CHN (cold, poor), and IND and AFR (warm, poor). Our background document (Ikefuji et al. 2014) contains a complete report.

3.2 Calibration

In order to calibrate the model, we follow Nordhaus and Yang (1996) and consider a solution which maximizes Negishi-weighted social welfare under the constraint that $\mu^c_{j,t} = \mu^a_{j,t} = 0$ for all j and all t. We calibrate the model such that the economic and climate trajectories of this solution replicate the Intergovernmental Panel on Climate Change SRES A2 marker scenario (IPCC 2000). Hence any positive rate of $\mu^c_{j,t}$ and $\mu^a_{j,t}$ (the carbon and sulfur controls) should be interpreted as regional actions taken in addition to the underlying assumptions of the SRES A2 scenario. Calibrated on the A2 scenario, our model tends to generate high carbon emission trajectories because it does not allow for possible learning on carbon abatement technology nor technological spillovers. Apart from this obvious disadvantage, the A2 scenario serves well for our purpose. In the A2 scenario relatively less stringent sulfur control is assumed, so that the implementation of air-pollution reduction policies is left to decision makers. This feature enables us to analyze how the interaction between climate change and air pollution affects the incentive of decision makers to abate each pollutant.

Below we comment on our specification of health damage, emissions and abatement costs. In our background document (Ikefuji et al. 2014) we explain in detail on what grounds we have chosen our equations and how the parameters have been calibrated.

Health damage Our damage function is calibrated based on the 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 the health impacts, we first recalibrate the damage function so that the health impacts are excluded from $D_j(Z_{j,t})$. Then, following WHO (2008), we measure the burden of disease to society as the disability-adjusted life-years lost (DALYs). In particular, we define $p^c_{j,t}$ and $p^a_{j,t}$ as DALYs per capita: $p^c_{j,t} = \mathrm{DALY}^c_{j,t}/N_{j,t}$ and $p^a_{j,t} = \mathrm{DALY}^a_{j,t}/N_{j,t}$, where $\mathrm{DALY}^c_{j,t}$ and $\mathrm{DALY}^a_{j,t}$ are the DALYs due to climate-related and air-pollution-related diseases, respectively. The calibrated initial value of $p^c_{j,t}$ matches the estimate of age-standardized DALYs per capita provided by WHO (2008). The year for the estimated DALYs is 2004; a detailed explanation of our methodology is provided in Ikefuji et al. (2014). In calibrating the parameter values, we incorporate malaria, cardiovascular disease, diarrhoea, and malnutrition as climate-related diseases. Disease profiles are assumed to be fixed over time since any modification will be arbitrary. We then choose the values of $\beta^c_{1,j}$, $\beta^c_{2,j}$, and $\beta^c_{3,j}$ for each region based on the damage estimates in McMichael et al. (2004), who estimated the associated increase or decrease of disease burden in different regions under alternative projections of climate change. We note that, although carefully calibrated, our treatment of the climate-related health damage is simplistic and there are various features that are not taken into account in our model. See Kovats et al. (2003) and Ebi (2008a, b) for in-depth discussions on the health impacts of climate change.

Our air-pollution-related disease function is calibrated based on Spadaro and Rabl (1999), who estimated damage cost per tonne of sulfur dioxide. This gives

$$p^a_{j,t} = \beta^a_0(\mathrm{PD}_j/80)\left[(1 - r_{j,t}) + \nu r_{j,t}\right] E^a_{j,t}, \tag{13}$$

where β^a_0 is the marginal damage of sulfur emission in terms of DALYs per capita in typical cities with a population density of 80 persons/km^2, PD_j is the population density in urban areas of region j, $r_{j,t} \in [0, 1]$ is the fraction of population living in an urban area, and $\nu = 2$ is a scaling factor for the damage in highly urbanized areas. While β^a_0 is assumed constant across regions, the impact differs depending on population density. Data of population density are taken from CIESIN (2005), and the projected urbanization ratio is based on United Nations (2010). The calibrated initial value of $p^a_{j,t}$ matches the cost estimate of Spadaro and Rabl (1999) for Europe.

Emission intensities Our emission equations are calibrated based on Bollen et al. (2009b). 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, using Eq. 5,

$$\mu^{ac}_{j,t} = 1 - \frac{\sigma^{aa}_{j,t}Y_{j,t} + \sigma^{ac}_{j,t}(1-\mu^c_{j,t})Y_{j,t}}{\sigma^{aa}_{j,t}Y_{j,t} + \sigma^{ac}_{j,t}Y_{j,t}} = \frac{\sigma^{ac}_{j,t}/\sigma^{aa}_{j,t}}{1+\sigma^{ac}_{j,t}/\sigma^{aa}_{j,t}} \cdot \mu^c_{j,t}. \tag{14}$$

The ratio $\mu^{ac}_{j,t}/\mu^c_{j,t}$ represents how much sulfur emission is reduced due to carbon reduction policies, and can be estimated based on Bollen et al. (2009b). Thus we can compute $\sigma^{ac}_{j,t}/\sigma^{aa}_{j,t}$ from Eq. 14.

By normalizing $\mu^c_{j,t} = \mu^a_{j,t} = 0$, our emission equations can be written as

$$\sigma^{cc}_{j,t} = E^c_{j,t}/Y_{j,t}, \qquad \sigma^{aa}_{j,t} = \frac{E^a_{j,t}/Y_{j,t}}{1+\sigma^{ac}_{j,t}/\sigma^{aa}_{j,t}}. \tag{15}$$

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 the SRES A2 scenario, taken from CIESIN (2002). We construct a region-level emission projection under the SRES A2 scenario (based on EPA98 5i scenario), which uses the same atmospheric stabilization framework model with similar assumptions as the A2 scenario (Sankovski 1998).

Abatement costs Although our modeling of emission abatement technologies is highly stylized, the parameter values are carefully chosen so that they are consistent with the cost estimates in the literature. Abatement cost is given by Eq. 7 where we assume $\xi^c = \xi^a = 2.8$

based on Nordhaus (2010). Along the baseline path, the marginal abatement cost of 'last drop of carbon emission' is

$$-\left.\frac{\partial A_{j,t}}{\partial E^{c}_{j,t}}\right|_{\mu^{c}_{j,t}=1,\mu^{a}_{j,t}=0} = \frac{\xi^{c}\alpha^{c}_{j,t}}{\sigma^{cc}_{j,t}}. \tag{16}$$

This must be equal to the price of backstop technology ($m_{j,t}$), which is estimated by Nordhaus (2010). This equality determines the value of $\alpha_{j,t}$.

Regarding sulfur abatement cost we note that some sulfur mitigation measures are already assumed in the A2 scenario. Calibration of sulfur abatement cost must therefore 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 $\sigma^{aa}_{j,t}$. We approximate the global marginal abatement cost curve by

$$\mathrm{MAC}^{a}(\mu^{a}) = \frac{\xi^{a}\alpha^{a}\left(\mu^{a}\right)^{\xi^{a}-1}}{\bar{\sigma}^{aa}}, \tag{17}$$

where $\bar{\sigma}^{aa}$ is the output-weighted average of sulfur intensity $\sigma^{aa}_{j,0}$. Then we choose the value of α^{a} such that it replicates the current global marginal abatement cost curve in Bahn and Leach (2008) whose estimation is constructed upon the MESSAGE and RAINS models. The sulfur abatement cost captured by α^{a} is assumed to be time-dependent and declines over time in a similar way to carbon mitigation cost. Then we plug this back into the marginal abatement cost function of each region and obtain

$$-\frac{\partial A_{j,t}}{\partial E^{a}_{j,t}} = \frac{\xi^{a}\alpha^{a}_{t}\left(\mu^{a}_{j,t}\right)^{\xi^{a}-1}}{\sigma^{aa}_{j,t}}. \tag{18}$$

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 the A2 scenario.

4 Two policy scenarios

We consider two policy scenarios. The first scenario, hereafter called 'Nash', is non-cooperative. More precisely, we use the concept of open-loop Nash equilibrium, in which all control and state variables are chosen at the initial period. In the Nash solution each region correctly recognizes both climate damage and air pollution, and tries to find the best mixture of carbon and sulfur control policies at a regional level. Each region maximizes its own welfare, and benefits to other regions are *not* taken into account. While the Nash scenario is inefficient at a global level, Nash-based projections are likely to be realistic, unless substantial international coordination is realized.

From a computational viewpoint, we need to find a sequence of control and state variables which converges to an equilibrium where no region has a further incentive to adjust its path, given other regions' paths. To obtain such paths, we start with an arbitrarily chosen path for each region as an initial guess of the solution. Then we fix all control variables at the level of initial guess except for USA, and solve the utility maximization problem of USA. This gives the best response of USA given other regions' paths. Next we fix the control variables at the level obtained in the second step except for EUR, and solve the utility maximization problem of EUR, which gives the best response of EUR given other regions' paths. Continuing in this fashion, we find the best response of all eleven regions sequentially. We then return to the first region (USA) and repeat the procedure until convergence.

The second scenario, hereafter called 'Optimal', is cooperative. Regions now coordinate their actions and choose emission levels of carbon and sulfur that maximize Negishi-weighted social welfare, thus achieving global efficiency. Efficiency in this context involves balancing the global benefits of pollution reduction with the costs of abatement, as well as comparing the damages of climate change and air pollution. Although this is too ideal to be realistic, the optimal scenario provides a useful benchmark against which the Nash scenario can be evaluated.

In Table 1 we focus on the distinction between warm and cold regions by aggregating the six warm regions (AUS, IND, SEA, LAM, MEN, AFR) and the five cold regions (USA, EUR, JPN, FSU, CHN). The first three columns present the benchmark results for temperature and CO_2 and SO_2 emissions under the two scenarios as well as under the baseline A2 scenario. Temperature does not change uniformly around the world, but this is caused, in part, by our method of calibration. For example, the fact that cold regions experience a relatively large temperature change is due primarily to the fact that our calibration method takes into account that temperatures increase more rapidly in regions located at a higher latitude (Schlesinger et al. 2000).

Both carbon and sulfur emissions in the Nash scenario will be lower than in the baseline, since each region engages in mitigation activities of their own. These activities are not coordinated and therefore globally inefficient. The Optimal scenario is globally efficient, and cumulative CO_2 emission for the next 100 years is about 17% lower than in the Nash scenario, while cumulative SO_2 emission is about 9% lower. This shows that uncoordinated carbon or sulfur reductions entail potentially large inefficiencies.

To highlight the health impact of air pollution — one of the novel features of our model — we ran our simulations again, both with air pollution nullified ($\beta^a = 0$) and with its impact doubled ($\beta^a \times 2$), and the results are presented in Table 1. Let us first consider the case $\beta^a = 0$. When the health damage of SO_2 is ignored, there is no reason to implement

Table 1 Temperature and cumulative emissions for warm and cold regions, 2005-2100

		Benchmark result			$\beta^a = 0$		$\beta^a \times 2$	
		Base	Nash	Opt.	Nash	Opt.	Nash	Opt.
Temp change (°C)	Warm	2.86	2.67	2.43	2.83	2.51	2.57	2.36
	Cold	3.98	3.72	3.39	3.94	3.50	3.60	3.31
	Global	3.38	3.15	2.88	3.35	2.97	3.05	2.80
CO_2 emission (100GtC)	Warm	9.03	7.90	6.62	8.95	7.06	7.34	6.24
	Cold	9.43	8.08	6.70	9.17	7.17	7.51	6.31
	Global	18.46	15.99	13.32	18.12	14.24	14.85	12.56
SO_2 emission (100TgS)	Warm	48.51	41.87	37.79	48.72	42.10	38.17	34.72
	Cold	38.62	32.10	29.33	38.46	33.17	28.66	26.23
	Global	87.13	73.98	67.12	87.19	75.27	66.84	60.96

clean-air policy, especially since SO_2 has a cooling effect. The only reason that sulfur in this case is reduced is climate policy. The absence of air-pollution damage leads to an increase in the number of healthy people, a larger labor force, a higher growth rate, and larger carbon and sulfur emissions (in fact, larger than in the benchmark). Carbon emission in the Nash scenario becomes significantly larger than in the benchmark, while the optimal level of carbon emission is not much affected. This implies that consideration of air-pollution relates more to incentive than to efficiency. This observation is confirmed in the second case where the value of β^a is doubled. The Nash level of carbon emission then becomes closer to the optimal level.

Let us now return to the benchmark results. As indicated by the hypothetical experiments above, the air-quality benefits of climate policy play an important role from the viewpoint of regional decision, yielding an additional incentive to mitigate carbon emissions, at least in some regions. The top panel of Fig. 1 illustrates the trajectory of the carbon control rates $\mu^c_{j,t}$ in the Nash scenario. We see that CHN is more willing to reduce carbon dioxide than other regions, even without international coordination. In fact, CHN is the region with the highest equilibrium carbon control rate *in every period*. This is partly due to the relatively low cost of carbon abatement in CHN (Nordhaus 2010), but more importantly, to the large potential of air-quality benefits in the region. CHN has a strong incentive to reduce the increase in air pollution, caused by its rapidly expanding economy, in order to avoid heavy health damage. This is illustrated in the bottom panel of Fig. 1, where we plot the trajectory of the sulfur control rates $\mu^a_{j,t}$ in the Nash scenario. A reduction of SO_2 emissions can be achieved, not only through direct sulfur emission control, but also via climate policies. Consequently, CHN will introduce relatively stringent climate policies in the hope of reaping the secondary local benefit. We note that our baseline scenario projects a sharp decline of sulfur emission

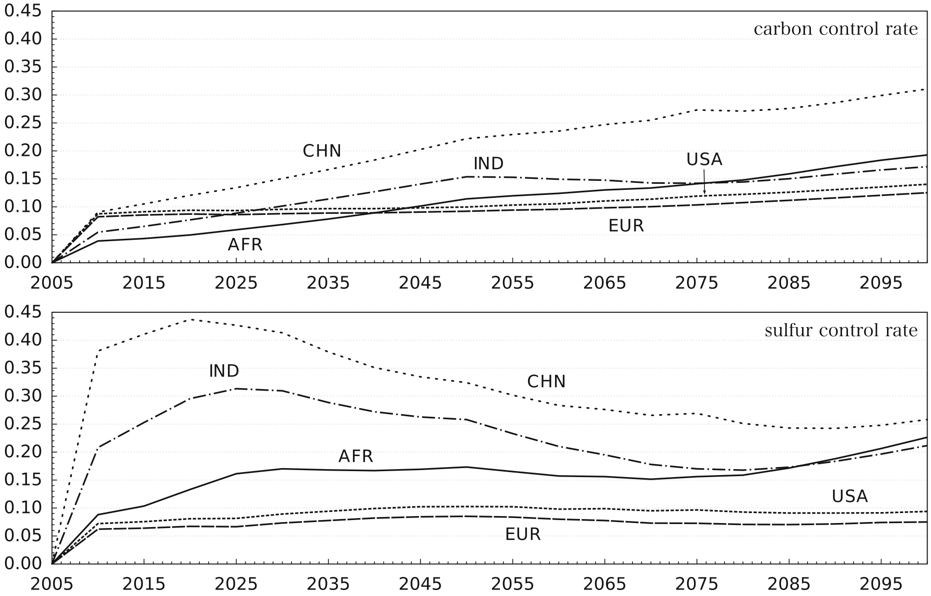

Fig. 1 Carbon control rate $\mu^c_{j,t}$ (*top*) and sulfur control rate $\mu^a_{j,t}$ (*bottom*) in Nash equilibrium

in IND and CHN after around 2040 even in the absence of additional sulfur control. This is a built-in feature of the IPCC A2 scenario, on which our baseline scenario is calibrated. Under an alternative baseline scenario which assumes no default sulfur reductions, those regions would have an even greater incentive to take advantage of the climate-pollution interaction.

In the Nash scenario, climate and clean-air policies are simultaneously introduced. To single out the impact of each policy, we consider a hypothetical scenario where *only* climate policy is implemented. Technically speaking, we run another simulation where we fix $\mu^a_{j,t} = 0$ for all regions and for all periods. The health benefits of this scenario are summarized in Table 2. They are measured in terms of the reduction in DALYs. Following WHO (2008), the benefits are discounted at 3% per year, so that a healthy year of life saved next year is worth 97% of a healthy year of life saved this year. The climate-related health benefit is largest in AFR, followed by IND, reflecting the fact that these regions are most climate-sensitive in terms of health damage. The table also shows that climate policy has a large health benefit of reducing air pollution, especially in CHN. For all regions, the air-pollution-related health benefit is much larger than the climate-related benefit. This is due, in part, to the fact that the two types of health benefits materialize at different times. The health benefit of better air quality is realized soon after the policy is implemented. But the climate-related benefit is only gradually felt and is therefore much more discounted. This also explains why policy interventions have no (that is, negligible) climate-related health benefits in USA and EUR.

The argument for carbon mitigation based on the benefit of avoiding air pollution damages is less relevant in IND and AFR. Although these regions are expected to experience a rapid decline of local air quality as their economies grow, the carbon abatement incentive due to ancillary local benefits appears to be less pronounced in these two regions. Since the equilibrium carbon control rate in AFR is overestimated because of our regional specification, the actual carbon mitigation incentive of individual African countries is even smaller. Also, Fig. 1 shows that the incentives in IND and AFR to curb sulfur emission seem relatively weak, especially in AFR. This means that AFR is less willing to control local air quality, and thus the logic of avoiding air pollution does not work as well for Africa as it does for China.

To explain this rather alarming result, we note that the benefit of 'avoiding air pollution damages' is not necessarily a benefit in our model. Carbon mitigation efforts can improve local air quality through Eq. 5 with $\sigma^{ac} > 0$, but such improvements might offset the effectiveness of climate policy through the (endogenous) local dimming effect of Eq. 11. It is this trade-off, together with differentiated vulnerability to climate change, that induces different reactions of different regions. In CHN, a temporary rise in temperature caused by SO_2 reduction (brightening effect) can be seen as a necessary side effect of better air quality because cold regions are less vulnerable to temperature increase. In other words, the marginal *damage* of reducing SO_2 emission in this region is small relative to its benefit. This

Table 2 Discounted present-value health benefits through 2005 to 2100 in a hypothetical scenario where only climate policy is implemented (millions DALYs)

	USA	EUR	CHN	IND	AFR
Air-pollution related	0.240	0.195	20.545	7.026	2.719
Climate related	0.000	0.000	0.036	1.215	1.800

is not the case in IND and AFR. These regions are likely to suffer from an intensification and expansion of climate-related diseases. Hence, the benefit of improved air quality is largely nullified by the endogenous brightening effect caused by SO_2 reduction.

The different regional impacts of local brightening on health are well illustrated if we hypothetically assume that *only* clean-air policy is implemented in the Nash scenario by fixing $\mu^c_{j,t} = 0$ for all regions and for all periods. In this case, regions can introduce sulfur-control measures, which directly reduce the air-pollution-related health burden, but indirectly increase the climate-related health burden. Table 3 summarizes the health benefits gained in this hypothetical scenario, which are again measured in terms of the reduction in DALYs. As the table shows, CHN can largely alleviate the air-pollution-related health burden without much harm to climate-related health. In IND and AFR, however, there exists a significant trade-off between air-pollution-related and climate-related diseases. The trade-off is especially severe in AFR, where only 2.5 years of life (present value) lost due to air pollution can be saved in return for an additional one-year loss due to climate-related diseases.

To avoid confusion, we should note that the results of Tables 2 and 3 are not comparable with each other. They are the results from two different hypothetical scenarios where the equilibrium values of control variables are endogenously chosen at different levels. In particular, the abatement costs for achieving these health benefits are quite different, with a lot more spent for climate policies. Hence, even though for some regions the air-pollution related health benefits of climate policy in Table 2 are larger than those of clean-air policy in Table 3, this does not imply that the climate policy is more effective as a measure for controlling air pollution. Those tables are meant to illustrate the fact that each policy have two distinct health outcomes (climate-related and air-pollution-related) and those outcomes are different across different regions.

In real-life decision making, it may not be the case that every region correctly recognizes the impact of local dimming due to sulfur emissions. If the local dimming effect of sulfur emissions is not appropriately incorporated, the real damage of climate change in warm poor regions will be underestimated. Hence, warm regions might mitigate a larger amount of sulfur emissions in the hope of better air quality, but they might end up with an increasing climate-related health burden. The adverse impact of this unanticipated outcome is even more pronounced when a temperature increase due to global warming is expected. In either case, our results suggest that more attention should be paid to the interplay between global climate change and related local issues such as air pollution and the dimming effect.

We have also analyzed the sensitivity of these results to changes in the assumed parameter values. In general, the equilibrium path does not change much when we use different values for exogenous parameters. Hence, the uncertainty surrounding parametrization does not appear to entail a serious problem in our model. For more details on the sensitivity analysis, see Ikefuji et al. (2014).

Table 3 Discounted present-value health benefits through 2005 to 2100 in a hypothetical scenario where only clean-air policy is implemented (millions DALYs)

	USA	EUR	CHN	IND	AFR
Air-pollution related	0.112	0.083	22.847	8.478	1.265
Climate related	0.000	0.000	−0.140	−0.899	−0.506

5 Conclusions

In this paper, we have presented a RICE-type integrated assessment model with eleven heterogeneous regions, designed to capture the links between local and global aspects of climate change through health impacts. Interaction among regions and interplay between global and local issues were simultaneously considered in the model. If the global-local interplay and regional differences are taken into account, then the two policy scenarios provide new insights, two of which are highlighted below.

First, introducing climate policies based on a potential air-quality benefit is effective in cold regions, especially in CHN. Hence there exists a basis for promoting more ambitious reduction targets in cold regions, and an incentive for China to participate in international climate agreements. However, in warm developing regions, especially Africa, this argument does not apply, because of the unfortunate trade-off between the two different health impacts.

Second, warm areas have a problem in addressing air pollution and climate change at the same time. In our model, a region can control its regional temperature either by reducing carbon emissions or by less stringent mitigation of air pollution. The second option brings with it an increase in the number of air-pollution-related patients. Hence, it might seem that the first option is always more attractive. However, the second option can be a better way of slowing down the temperature rise in the region. Global warming is a public bad, and hence the marginal benefit from additional mitigation efforts is limited. This is especially true in small African countries. These countries are the smallest contributors to global warming, and they have virtually no influence on the global trend of increased temperature. Increasing sulfur emissions can then be a reasonable way of controlling temperature, even though it is accompanied by increased air pollution. The burden of climate change is thus unequally distributed, not only because rising temperature is more harmful in already warm regions, but also because people living in warm regions will have to live with lower air quality.

The climate system is far more complex than assumed in our highly stylized model, and the results should therefore be interpreted with some care. The relationship between aerosols and temperature is not as knife-edged as the paper suggests, and aerosols also have non-temperature impacts on the climate system. Energy sectors were not explicitly modeled and our description of air pollution is simplistic. By focusing only on sulfur dioxide as a representative air pollutant, our model misses a substantial portion of air-pollution-related damages. The trade-off between climate-related and air-pollution-related health benefits is not as simple as described in this paper because the health benefits of climate policy are more uncertain than those of clean-air policy. Even in the absence of uncertainty, the pollution-health relationship is more robust in air pollution than in climate change.

Despite all these caveats, the insights obtained in this paper clarify important aspects of global-local interplay, which have not been given much attention. Our simple yet theoretically well-founded climate-economy model allows us to examine the interaction between climate change and air pollution, not as a separate phenomenon independent of the economy, but as an integrated part of economic activity. This type of general equilibrium analysis is particularly relevant with ‘large’ problems, and ours is a large problem. The model is sufficiently versatile to analyze not only efficiency, but also strategic aspects of decision-making. While the simplicity of the model can be criticized, it also has important advantages both in terms of the possibility to calibrate the model and in assembling relevant and reliable data.

Many tasks remain. For example, one could include not only SO_2, but also other air pollutants generated from fossil fuel consumption. If the damage of air pollution is modeled in a more comprehensive way, the trade-off between air pollution and temperature in warm areas might have different implications. Another question of interest is how these global-local links affect regional incentives to join or leave an international treaty for climate cooperation. In this line of research, designing an effective transfer scheme among developed and developing countries would be an interesting issue. An analysis of such schemes should enable us to derive further policy implications both from an environmental and from a socio-economic point of view.

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